Solar Active Facade Design and Development

A Framework for designing and developing building envelopes integrating solar cooling technologies

Hamza Basel Hamida

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A Framework for designing and developing building envelopes integrating solar cooling technologies

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by

Hamza Basel HAMIDA

This dissertation has been approved by the promotors.

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In the Name of Allah, the Most Gracious, the Most Merciful	**بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيم**
You were given only a little knowledge Surah al-Isra' (85)	**وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا (٨٥)** سورة الإسراء
Say, "My Lord, increase me in knowledge" Surah Ta-Ha (114)	**وَقُلْ رَبِّ زِدْنِي عِلْمًا (١١٤)** سورة طه

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وَاخْفِضْ لَهُمَا جَنَاحَ الذُّلِّ مِنَ الرَّحْمَةِ وَقُل رَّبِّ ارْحَمْهُمَا كَمَا رَبَّيَانِي صَغِيرًا (٢٤)

سورة الإسراء

And lower to them the wing of humility, out of mercy, and say,
“My Lord, have mercy on them, as they raised me from childhood.”
Surah al-Isra’ (17:24)

To my beloved father, Eng. Basel Hamida —

My wise role model and my greatest supporter. You have been there for me at every step of my life — not only during my PhD, but always. You taught me the true meaning of faith, kindness, honesty, and transparency, and showed me how to live by virtuous values and ethics through your own example. You have stood by me in times of hardship and in moments of joy, always reminding me that a pure heart is the strongest weapon, no matter how others behave. Thank you for your endless love, your guidance, and your unwavering belief in me. I owe so much of who I am to you.

To my beloved mother, Dr. Meisoun AlBaradie —

You are the pure source of love, kindness, and endless giving. You taught me patience through your strength, generosity through your actions, and compassion through your heart. Thank you for your endless sacrifices, for your sleepless nights, and for carrying my worries as your own. Your prayers, love, and gentle spirit have been the light guiding me through every challenge.

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I arrived in the Netherlands on the 21st of December, 2020. It was during the COVID period and on one of the shortest days of the year. My beloved siblings, Amneh and Mohammad, picked me up from Schiphol Airport, and we took an NS train to Delft. Although it was a difficult time, I received a kind email from my late promoter, **Prof. Dr.-Ing. Tillmann Klein**, containing the following positive and inspiring words:

“Hello Hamza,
We hope you had a good flight and that you are safely in the Netherlands. I guess the weather is a bit of a downer. Today is the winter solstice, which means things will start getting better from now on. Tillmann”

Tillmann, you are truly missed. You were a kind and supportive promoter, and your guidance during the first two years of my PhD had a significant influence on shaping this thesis. I am deeply thankful to you for your support. Tillmann was not only a creative expert in façade design and engineering, as well as in circularity in the built environment, but he was also a kind, motivating, and supportive person for researchers and students at the Faculty of Architecture and the Built Environment. He was not only my thesis’s first promoter during the first two years, but also a colleague and a friend from whom I learned a great deal. He continually motivated and supported me, even during difficult times.

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you taught me the true meaning of faith, kindness, honesty, and integrity, and showed me how to live with virtue and ethics. You have supported me in times of hardship and celebrated with me in moments of joy, always reminding me that a pure heart is the strongest weapon, regardless of how others act. Thank you for your boundless love, guidance, and unwavering belief in me. I owe so much of who I am to you.

Having encouraging, supportive, and caring siblings has been instrumental in my academic growth and achievements. From the bottom of my heart, thank you, **Abdullah**, **Amneh**, **Mohammad**, and **Adnan**. To my older brother, **Abdullah**, I express my sincere gratitude and appreciation for the video calls and the kind gatherings we shared in Saudi Arabia during the holidays, together with his lovely children, **Dalia** and **Omer.** My heartfelt thanks go to my sister, **Dr. Amneh**, and my twin brother, **Dr. Mohammad**, for their unwavering support and companionship throughout my graduate studies, and for the wonderful moments we shared—writing research proposals, learning Dutch, cooking, cycling, hiking, and traveling across Europe. Thank you so much for picking me up from Schiphol Airport on 21st December 2020, and for the onboarding you facilitated to help me start my life smoothly in the Netherlands. To my youngest brother, **Adnan**, heartfelt thanks for visiting us so often in the Netherlands and for all the fun experiences we shared in Delft. Thank you so much for the kind surprises and gifts you brought from Canada.

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Abbreviations	Description
$\sum Loss$	Sum of estimated percentages of energy losses at multiple stages, including solar energy collection, energy conversion, cooling generation, distribution, and storage
AEC	Architecture, engineering, and construction
A_{LP}	Annual loan payment
ANSI	American National Standards Institute
$A_{O\&M}$	Annual operation and maintenance cost
ASHRAE	American Society of Heating, Refrigerating, and Air–Conditioning Engineers
a–Si	Amorphous silicon
AW	Annual Worth
BAPV	Building–Attached Photovoltaics
BIM	Building Information Modelling
BIPV	Building–Integrated Photovoltaics
CdTe	Cadmium telluride
$COOL_{req}$	Average daily cooling demand (kWh/day) in the summer design week of a particular indoor environment
$COP_{coolsys}$	Coefficient of performance of the cooling technology
$COP_{solarsys}$	Efficiency of the applied solar collection system
CTE	Código Técnico de la Edificación (Spanish Technical Building Code)
DE	Double–effect
DSSC	Dye–synthesized solar Cells
E	East
EPS	Expanded polystyrene insulation
$ESCOOL_{out}$	Annual solar renewable energy produced by the selected technology, focusing on the whole summer as the time frame.
$ESOL_{input}$	Plane array irradiance available on a particular location/orientation, considering whole summer as the time frame
ETCs	Evacuated tube collectors
EVA	Ethylene Vinyl Acetate
F	Financial
FPCs	Flat–plate collectors

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Abbreviations	Description
GF	Ground Floor
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
I	Investment cost
$I_{chiller}$	Investment cost of chillers
IEA	International Energy Agency
I_{SCD}	Investment cost of solar collection devices and their auxiliaries
LCA	Life cycle analysis
LCC	The life cycle cost
LCC_{AW}	The life cycle cost in annual worth
LCOE	Levelized Cost of Energy
LCOC	Levelized Cost of Cooling
MEP	Mechanical, electrical, and plumbing
MS	Microsoft
N	North
N^*	System life span
O&M	Operation and maintenance
PCMs	Phase change materials
P&S	Process and stakeholder
PV	Photovoltaic
PVC	Polyvinyl Chloride
PVT	Photovoltaic–thermal (PVT)
PW	Present Worth
r	The interest rate
RIBA	The Royal Institute of British Architects
S	South
SAFs	Solar active façades
SAM	System Advisor Model
SCD_s	Solar collection devices
SCIFs	Solar cooling integrated facades
$SCOOL_{out}$	The cooling effect delivered by the selected technology to a specific indoor environment represents the heat removed by the cooling technology
SCTs	Solar cooling technologies
SE	Single–effect
SF	Solar Fraction
Si	Silicon
SOL_{arry}	Designed area for collection
SOL_{input}	The average daily solar radiation availability on a particular location/orientation, considering the month of the summer design week
SQ	Sub–question SQ

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Abbreviations	Description
STC	Solar Thermal Collector
STPV	Semi–transparent Photovoltaic
TES	Thermal energy storage
T&P	Technical and product
TE	Thermoelectric
UF	Rooftop use factor of solar collection devices (SCDs)
VAV	Variable Air Volume
VCC	Vapor–compression chiller
W	West
WWR	Window–to–Wall Ratio

Summary

The global demand for cooling in the built environment is expected to increase in the near future due to various factors, including climate change and the associated rise in temperature. Other factors include population and economic growth, along with the subsequent increase in quality of life and the affordability of air-conditioning units. It was estimated that the global air conditioner stock could increase by 50% in the coming years. Consequently, supporting the use of cooling systems that rely on renewable energy is becoming increasingly important to reduce greenhouse gas (GHG) emissions generated by the energy consumed by conventional cooling systems.

Solar cooling technologies represent one of the key options for addressing environmental challenges associated with the global increase in demand for space cooling in the built environment. Advantages of applying solar cooling technologies include saving primary and conventional sources of electricity, reducing peak energy demand for cost savings, being environmentally friendly, and having no ozone depletion effects. The concept of solar cooling technologies, which started in the seventies, is based on generating conditioned air or chilled water from solar energy. The technologies can be in the form of producing hot water through Solar Thermal Collectors (STC) or producing electricity through Photovoltaic (PV) panels. This represents two principal pathways for energy conversion to be used to produce a cooling effect from solar radiation, namely thermally driven processes or electrically driven processes.

Building facades present high potential for the integration of solar cooling technologies. The technical strategies and knowledge abundance associated with different scientific disciplines have recently enabled façade engineering to advance the building envelope industry. Building façades are moving toward being multifunctional components that are actively involved in the building energy system through integrating services that contribute to energy savings and building occupants' comfort. It should be noted that such integration represents an inclusion of extra functions into the façade as a next step when other measures, such as thermal insulations and shading systems, and also passive strategies, cannot sufficiently meet the indoor requirements. However, the widespread application of solar cooling integrated façades in the built environment is still far from what it could be. This is because there are various challenges affecting their widespread.

For instance, from a technical point of view, there are various factors that can be tackled, which vary from one technology to another, as each technology has its own technical attributes. Therefore, guiding relevant stakeholders to support the assessment of the current level of technology adoption, while addressing existing challenges, can play a key role in the successful adoption and integration of new technologies. This research project aimed at providing a product design and development framework for solar cooling integrated façades to support widespread application. Providing such a framework required different steps, including the determination of challenges and main aspects to be considered, identification of key enabling factors and prospects of future applications, development of key strategies guiding the façade design and evaluation, as well as identification, outlining, and validation of main decisions, required information, and involved stakeholders. The main research question of this dissertation is as follows:

– **How can the design and development of solar cooling integrated facades be guided to support their widespread application?**

Answering this research question involved, firstly, a determination of challenges and main aspects to be considered for supporting the widespread application through a literature review. The literature review was conducted on scientific papers published in conference proceedings and scientific journals, through considering two databases, namely Scopus and Web of Science. Then the study suggested the main aspects that need to be considered and integrated to support the application of solar cooling integrated façades. The aspects included technical and product (T&P)-related, financial (F)-related, as well as process and stakeholder (P&S)-related aspects.

Secondly, an interview guide was designed to involve these main aspects to be considered in order to identify the main factors enabling the widespread integration of solar cooling technologies in façades. Different criteria were considered to select the interviewees during the data collection, such as participants who worked on the application or façade integration of solar/solar cooling technologies in buildings. The findings obtained from a total of 23 interviews revealed that the most frequently mentioned factors are product performance and efficiency, facilitating the delivery of product information to architects and clients, aesthetic acceptability, multidisciplinary teamwork, and the ability to customize products. The factors were mapped in the context of façade design and construction processes to establish a matrix for implementing solutions in product development. The majority of the factors were linked to the design phase according to interviewees' perceptions. The results also indicated that newly built office buildings have been perceived to be one of the most relevant types of buildings to be considered for such technologies.

The identified enabling factors and prospects of future applications of solar cooling integrated facades (SCIFs) contribute to expanding the boundaries of knowledge in the field of building product development.

Thirdly, key strategies guiding the design and evaluation of façade products integrating solar cooling technologies were developed using a research-through-design methodology, considering a relevant context and a proposed evaluation set-up to assess techno-economic feasibility. The development of strategies involved mapping the design and evaluation of solar cooling integrated façades by identifying and relating key processes, inputs, outputs, design decisions, and tools within key design stages. The findings indicate that water-cooled vapor-compression chillers (VCC), combined with photovoltaic (PV) panels as an electrically driven solution, were the most relevant option for the selected case. The proposed multi-step techno-economic assessment method supports decision-making by systematically evaluating different scenarios. However, its results should be considered case-specific due to various factors such as project and building characteristics, climate context and geographic location, status of technological development, and stakeholders involved and prioritization of techno-economic requirements and design criteria. Analysis of the developed strategies shows that the first two stages—conception and strategic definition, as well as preparation and briefing—contained most steps, inputs, decisions, and outcomes. Early-stage processes significantly impact later phases, such as construction characteristics in detailed design.

Finaly, a participatory research methodology was employed to understand to integrated key aspects through identifying, outlining, evaluating, elaborating on, refining, and validating key decisions, information, and stakeholders supporting the design and development of solar cooling integrated façades This study involves identifying and outlining key decisions, the required information to support them, and relevant stakeholders that can be involved in the design and development of solar cooling integrated façades, based on desk research and a pre-workshop survey completed by relevant stakeholders. Subsequently, a co-creation workshop was conducted to evaluate and further elaborate on the outlined design decisions, information, and stakeholders. After that, the design decisions, along with the other aspects, were refined based on the workshop outcomes. Finally, these design and development aspects and stages were validated using a design experience survey. The key study findings revealed the following: The key study findings revealed that the integration of solar cooling technologies (or other solar technologies) into the façade should be considered at the conception stage where the owner, investor, and/or real estate/property developer, climate design, building physics, and building services, 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 decisions, as well as the criteria, tends 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.

Based on the findings of the aforementioned steps and considering the main research question, supporting the widespread application of solar cooling-integrated façades through the integration of technical and product (T&P)-related, financial (F)-related, as well as process and stakeholder (P&S)-related aspects is not a straightforward approach. It requires consideration of various factors within these aspects. Multiple improvements within these aspects can be drawn from the qualitative exploratory interviews and the participatory workshop. Such improvements can include, but are not limited to, the following points:

Technical and product (T&P)-related point of view:

- Development of prefabricated façade products that incorporate a degree of standardization while maintaining flexibility for various applications.
- Material improvements for thermally driven technologies to reduce maintenance, and technological advancements in solar collectors to simplify cleaning.

Financial (F)-related point of view:

- Subsidies could improve economic feasibility by reducing investment costs.

Process and stakeholder (P&S)-related point of view:

- Investigation of relevant business models with clearly defined roles and responsibilities can enhance collaboration among stakeholders.

However, to be able to integrate multiple aspects, guiding relevant stakeholders to support the assessment of the current level of technology adoption—while addressing existing challenges—can play a key role in the successful adoption and integration of new technologies. Accordingly, drawing on the lessons learned from the design strategies developed, as well as the outlined and validated aspects, a visualization of the framework that guides design and development through the integration of key aspects is provided through synthesizing the outcomes.

The guidance is structured into five stages: identifying possibilities for building integration, assessing the feasibility of the generated possibilities, selecting the relevant architectural façade technology, developing the detailed design for integrating the selected technology, and designing for the installation of façade components. This visualization is based on several assumptions focused on the key design and development stages of a new office building. However, it does not take into account the type of building ownership or the form of contracting, as each project is unique. Furthermore, it is intended to serve as a general guide for the investigation of various solar cooling technologies. This approach reflects the uniqueness of each project and acknowledges that the development and advancement of such technologies evolve.

This research project provides the following recommendations for future work:

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

- Future research should integrate environmental impact assessments, such as embodied energy and life cycle analysis (LCA), which can further enhance the evaluation of solar cooling technologies.

- Future work should address the development of prefabricated façade products that incorporate a degree of standardization while maintaining flexibility for various applications.

- It is recommended to investigate relevant business models with clearly defined roles and responsibilities that 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.

Samenvatting

De wereldwijde vraag naar koeling in de gebouwde omgeving zal naar verwachting toenemen in de nabije toekomst vanwege klimaatverandering en de daarbij bijbehorende temperatuurstijging. Andere factoren omvatten de toenemende bevolkingsgroei en welvaart, in combinatie met de daaropvolgende toename van levenskwaliteit en de betaalbaarheid van airconditioningapparaten. Volgens schattingen zal de wereldwijde hoeveelheid airconditioners de komende jaren met 50% kunnen toenemen. Bijgevolg wordt de toepassing van koelsystemen die gebruik maken van hernieuwbare energie steeds belangrijker, zodat hiermee de uitstoot van broeikasgassen (BKG's) te verminderen.

Zonnekoeltechniek heeft de potentie om de milieu-impact van koeling in de bebouwde omgeving te verminderen. De voordelen van zonnekoeltechniek omvatten het verminderen van het gebruik van primaire en conventionele elektriciteitsbronnen, alsmede het verlagen van de pieken in de energievraag (voor kostenbesparing). Daarbij is het milieuvriendelijker en vormt het geen bedreiging voor de ozonlaag. Het concept van zonnekoeltechniek stamt uit de jaren zeventig en is gebaseerd op het genereren van geconditioneerde lucht of gekoeld water uit zonne-energie. Zonnekoeltechniek omvat het produceren van warm water via zonnecollectoren of het produceren van elektriciteit via fotovoltaïsche panelen (PV). Beide technieken maken het mogelijk koeling te genereren uit zonnestraling; thermisch of elektrisch aangedreven.

Gevelconstructies hebben een grote potentie voor de integratie van zonnekoeltechniek. De beschikbare technische kennis en mogelijkheden vanuit verschillende wetenschappelijke disciplines maken het mogelijk de gevelindustrie verder door te ontwikkelen. Hierbij spelen gevels een toenemende rol in de energetische huishouding van gebouwen, door de integratie van energiebesparende en comfort verhogende maatregelen. Hierbij is het belangrijk op te merken dat de integratie van dergelijke nieuwe maatregelen leidt tot een toename van het aantal functies van een gevel. Dit komt doordat bestaande (passieve) functies zoals thermische isolatie en zonwering niet afdoende zijn voor het behalen van het uitgevraagde binnenklimaat. Ondanks deze ontwikkelingen in de gevelindustrie blijft een wijdverbreide toepassing van zonnekoeltechniek in de bouw uit. Dit is te wijten aan het feit dat er verschillende uitdagingen zijn die de verdere verspreiding tegenwerken. Vanuit een technisch perspectief zijn er enkele factoren, die afhankelijk van de technologie kunnen variëren. Daarom kan het verstrekken van begeleiding aan relevante belanghebbenden om de beoordeling van het huidige niveau van technologieadoptie te ondersteunen, terwijl bestaande uitdagingen worden aangepakt, een sleutelrol spelen in de succesvolle adoptie en integratie van nieuwe technologieën. Dit onderzoeksproject is gericht op het verstrekken van een raamwerk voor het ontwerpen en uitwerken van zonnekoeling-geïntegreerde gevels - om wijdverspreide toepassing te ondersteunen. De ontwikkeling van een dergelijk raamwerk vereist verschillende stappen, waaronder het bepalen van de te overwegen uitdagingen en hoofdaspecten, het identificeren van belangrijke bevorderende factoren en vooruitzichten van toekomstige toepassingen, de ontwikkeling van strategieën die het ontwerp en toetsing van de gevel begeleiden, alsmede de identificatie, het in hoofdlijnen uitzetten en de validatie van te nemen hoofdbeslissingen, de benodigde informatie en de betrokken belanghebbenden. De hoofdonderzoeksvraag van deze dissertatie is als volgt:

– **Hoe kan het ontwerp en de ontwikkeling van zonnekoeling-geïntegreerde gevels worden gestuurd om hun brede toepassing te ondersteunen?**

Het beantwoorden van deze onderzoeksvraag vroeg ten eerste om een bepaling van de te overwegen uitdagingen en hoofdaspecten voor het ondersteunen van wijdverspreide toepassing. Dit is gedaan met behulp van een literatuurstudie. Deze literatuurstudie is uitgevoerd op basis van wetenschappelijke artikelen (gepubliceerd in conferentieverslagen) alsmede wetenschappelijke tijdschriften. Hiertoe zijn twee wetenschappelijke databases geraadpleegd – te weten Scopus en Web of Science. De uitkomst van deze studie geeft een aantal hoofdaspecten die overwogen en geïntegreerd moeten worden voor het ondersteunen van de toepassing van zonnekoeling-geïntegreerde gevels. De aspecten omvatten technische en product (T&P)-gerelateerde, financiële (F)-gerelateerde, evenals proces en belanghebbende (P&B)-gerelateerde aspecten.

Ten tweede werd een interviewgids ontworpen om deze te overwegen hoofdaspecten te betrekken moeten worden om hoofdfactoren te identificeren die wijdverspreide integratie van zonnekoeltechnologieën in gevels mogelijk maken. Voor het selecteren van de geïnterviewden zijn verschillende criteria gebruikt, zoals deelname aan de toepassing of gevelintegratie van zonne-/zonnekoeltechnologieën in gebouwen. Uit de in totaal 23 afgenomen interviews blijkt dat de meest frequent genoemde factoren productprestatie en efficiëntie zijn, het faciliteren van productinformatielevering aan architecten en klanten, esthetische aanvaardbaarheid, multidisciplinair teamwerk, en het vermogen om producten aan te passen. Deze factoren werden in kaart gebracht in de context van gevelontwerp- en bouwprocessen om een matrix vorm te geven voor het helpen implementeren van oplossingen in productontwikkeling. Volgens de geïnterviewden zijn de meeste factoren van toepassing op de ontwerpfase. De interviewresultaten gaven ook aan dat nieuwbouw kantoorgebouwen een van de meest relevante typen te overwegen gebouwen is voor dergelijke technieken. De geïdentificeerde bevorderende factoren en vooruitzichten van toekomstige toepassingen van zonnekoeling-geïntegreerde gevels dragen bij aan het uitbreiden van kennisgrenzen in het veld van gebouwproductontwikkeling.

Ten derde werden belangrijke strategieën ontwikkeld die het ontwerp en de toetsing van gevelproducten die zonnekoeltechniek integreren begeleiden. Dit is gedaan met gebruik van een “research-through-design” methodologie, waarbij is rekening is gehouden met een relevante context en een voorgestelde evaluatieopstelling om techno-economische haalbaarheid te beoordelen. De ontwikkeling van strategieën behelsde het in kaart brengen van ontwerp en toetsing van zonnekoeling-geïntegreerde gevels door het identificeren en relateren van belangrijke processen, inputs, outputs, ontwerpbeslissingen, en hulpmiddelen tijdens relevante ontwerpstadia. De bevindingen geven aan dat watergekoelde dampdrukverdichters, gecombineerd met fotovoltaïsche panelen (PV) als elektrisch aangedreven oplossing de meest relevante optie waren voor het geselecteerde geval. De voorgestelde meerstaps techno-economische beoordelingsmethode ondersteunt besluitvorming door systematisch verschillende scenario’s te evalueren. Echter, de resultaten moeten als casus-specifiek worden beschouwd vanwege verschillende factoren zoals project- en gebouwkenmerken, klimaatcontext en geografische locatie, status van technologische ontwikkeling, betrokken belanghebbenden, prioritering van techno-economische vereisten en ontwerpcriteria. Analyse van de ontwikkelde strategieën toont aan dat de eerste twee ontwerpstadia -conceptvorming en strategische definitie evenals voorbereiding en briefing - de meeste stappen, inputs, beslissingen, en uitkomsten behelzen. De processen in de eerste ontwerpstadia beïnvloeden de latere ontwerpstadia aanzienlijk, zoals de verdere technische uitwerking.

Ten slotte werd een participatieve onderzoeksmethodologie toegepast om geïntegreerde belangrijke aspecten te begrijpen door het identificeren, schetsen, evalueren, uitwerken, verfijnen, en valideren van belangrijke beslissingen, informatie, en belanghebbenden die het ontwerp en de ontwikkeling van zonnekoeling-geïntegreerde gevels ondersteunen. Deze studie behelst het identificeren en omlijnen van belangrijke beslissingen, de vereiste informatie om ze te ondersteunen, alsmede relevante belanghebbenden die betrokken kunnen worden bij ontwerp en ontwikkeling van zonnekoeling-geïntegreerde gevels, gebaseerd op bureauonderzoek en een pre-workshop enquête ingevuld door relevante belanghebbenden. Vervolgens werd een co-creatie workshop toegepast om de geschetste ontwerpbeslissingen, informatie, en belanghebbenden te evalueren en verder uit te werken. Daarna werden de ontwerpbeslissingen, samen met de andere aspecten verfijnd op basis van de uitkomst van de workshop. Ten slotte werden deze ontwerp- en ontwikkelingsaspecten en stadia gevalideerd met gebruik van een ontwerp ervaring enquête. De belangrijkste bevindingen onthulden dat de integratie van zonnekoeltechniek (of andere zonnetechnologieën) in de gevel overwogen dienen te worden in de initiatieffase - waarin de eigenaar, investeerder, en/of vastgoed-ontwikkelaar, klimaatontwerper, bouwfysicus, installatie-expert, en architecten zijn geïdentificeerd als de belangrijke te betrekken deelnemers – om hiermee het besluitvormingsproces voor gevelintegratie te bevorderen. De belangrijkste vereiste informatie om beslissingen ten aanzien van de gevel-integratiemogelijkheden en de selectie van geschikte zonnekoeltechnieken voor de ontwikkeling van ontwerpoplossingen te ondersteunen hangt af van verschillende gegevensbronnen. De geïdentificeerde meest kritieke informatie voor het ondersteunen van ontwerpbeslissingen omvat de kosten van de zonnekoeltechniek, de prestaties en efficiëntie, de koelingsvraag, en de kenmerken van de thermische schil. De validatie van het ontwikkelde raamwerk gaf aan dat de prioritering van ontwerpbeslissing evenals criteria geneigd zijn consistent te zijn met het verfijnde raamwerk. De bevindingen gaven aan dat respondenten die onzeker waren over de integratie van zonnekoeltechniek (in de toegewezen ontwerpcase) geneigd waren hun onzekerheid toe te schrijven aan beperkte kennis van de techniek alsmede gebrek aan gedetailleerde kosteninformatie.

Op basis van bovengenoemde bevindingen en de hoofdonderzoeksvraag overwegend, is het ondersteunen van wijdverspreide toepassing van zonnekoeling-geïntegreerde gevels door integratie van technische en product (T&P)-gerelateerde, financiële (F)-gerelateerde, evenals proces en belanghebbende (P&B)-gerelateerde aspecten geen eenvoudige aanpak. Het vereist de overweging van verschillende factoren binnen deze aspecten. Het is duidelijk dat meerdere verbeteringen volgen uit de (kwalitatieve) verkennende interviews en de participatieve workshop. Deze verbeteringen omvatten in ieder geval de volgende punten:

Technisch en product (T&P)-gerelateerd:
- Ontwikkeling van geprefabriceerde gevelproducten die tot op zekere hoogte gestandaardiseerd zijn, maar ook de flexibiliteit behouden voor verschillende toepassingen.
- Materiaalverbeteringen voor thermisch aangedreven technologieën om de benodigde onderhoud te verminderen, en doorontwikkeling van zonnecollectoren om reiniging te vereenvoudigen.

Financieel (F)-gerelateerd:
- Subsidies zouden economische haalbaarheid kunnen verbeteren door investeringskosten te verminderen.

Proces en belanghebbende (P&B)-gerelateerd:
- Onderzoek naar relevante bedrijfsmodellen met duidelijk gedefinieerde rollen en verantwoordelijkheden kan de samenwerking tussen belanghebbenden verbeteren.

Echter, om meerdere aspecten te kunnen integreren, kan het verstrekken van begeleiding aan relevante belanghebbenden om beoordeling van het huidige niveau van technologieadoptie te ondersteunen - terwijl bestaande uitdagingen worden aangepakt - een sleutelrol spelen in succesvolle adoptie en integratie van nieuwe technologieën. Voortbouwend op de geleerde lessen uit de ontwikkelde ontwerpstrategieën, evenals de geschetste en gevalideerde aspecten, wordt een visualisatie van het raamwerk dat het ontwerp en de toetsing begeleidt door integratie van belangrijke aspecten verstrekt door het synthetiseren van de uitkomsten. De begeleiding is gestructureerd in vijf stadia: het identificeren van mogelijkheden voor gebouwintegratie, het beoordelen van haalbaarheid van gegenereerde mogelijkheden, het selecteren van relevante architecturale geveltechnologie, het ontwikkelen van gedetailleerd ontwerp voor integratie van geselecteerde technologie, en het ontwerpen voor installatie van gevelcomponenten. Deze visualisatie is gebaseerd op verschillende aannames gericht op belangrijke ontwerp- en ontwikkelingsstadia van een nieuw kantoorgebouw. Echter, het houdt geen rekening met type gebouweigendom of vorm van contractering, aangezien elk project uniek is. Bovendien is het bedoeld om te dienen als algemene gids voor onderzoek van verschillende zonnekoeltechnologieën. Deze benadering weerspiegelt de uniciteit van elk project en erkent dat ontwikkeling en vooruitgang van dergelijke technologieën evolueren over tijd.

Dit onderzoeksproject verstrekt de volgende aanbevelingen voor toekomstig werk:

- Toekomstige studies zouden het raamwerk moeten uitbreiden naar verschillende gebouwtypologieën (residentieel, administratief, industrieel) en variaties in thermische capaciteit en beglazing beoordelen. Het verkennen van geavanceerde technologieën zoals bifaciale zonnepanelen, fotovoltaïsch-thermische (PVT) collectoren, en droogmiddelkoelsystemen in verschillende klimaten zou de toepasbaarheid en impact van ontwikkelde strategieën verder kunnen verbeteren.

- Toekomstig onderzoek zou milieu-impactbeoordelingen moeten integreren, zoals belichaamde energie en levenscyclusanalyse (LCA), die evaluatie van zonnekoeltechnologieën verder kunnen verbeteren.

- Toekomstig werk zou de ontwikkeling van geprefabriceerde gevelproducten moeten aanpakken die een mate van standaardisatie incorporeren terwijl flexibiliteit voor verschillende toepassingen behouden blijft.

- Het wordt aanbevolen om relevante bedrijfsmodellen te onderzoeken met duidelijk gedefinieerde rollen en verantwoordelijkheden die samenwerking tussen belanghebbenden kunnen verbeteren. Dit zou helpen informatie-uitwisseling te faciliteren en knelpunten aan te pakken gerelateerd aan beperkte kennis en verschillende perspectieven op geveloplossingen tussen ontwerpers, eigenaren, en bouwers.

ملخص

من المتوقع أن يشهد الطلب العالمي على التبريد في البيئة المبنية زيادة في المستقبل القريب نتيجةً لعدة عوامل، من بينها تغيّر المناخ والارتفاع المصاحب في درجات الحرارة. وتشمل العوامل الأخرى النمو السكاني والاقتصادي، وما يترتب عليه من تحسّن في جودة الحياة وزيادة القدرة على تحمّل تكاليف وحدات تكييف الهواء. وقد قُدِّر أن مخزون أجهزة التكييف على مستوى العالم قد يزداد بنسبة 50٪ في السنوات القادمة. وبناءً عليه، فإن دعم استخدام أنظمة التبريد المعتمدة على مصادر الطاقة المتجددة يكتسب أهمية متزايدة للحد من انبعاثات غازات الدفيئة الناتجة عن استهلاك الطاقة في أنظمة التبريد التقليدية.

تُعدّ تقنيات التبريد الشمسي إحدى الخيارات الملائمة لمواجهة التحديات البيئية المرتبطة بالزيادة العالمية في الطلب على التبريد في البيئة المبنية. وتتمثل فوائد تطبيق تقنيات التبريد الشمسي في تقليل استهلاك مصادر الطاقة الأولية والتقليدية، وخفض الطلب على الطاقة خلال أوقات الذروة لتحقيق وفورات مالية، بالإضافة إلى كونها صديقة للبيئة ولا تتسبب في استنفاد طبقة الأوزون. ويعتمد مفهوم تقنيات التبريد الشمسي، الذي بدأ في سبعينيات القرن الماضي، على إنتاج هواء مُكيَّف أو ماء مُبرَّد باستخدام الطاقة الشمسية. ويمكن أن تتحقق هذه التقنيات إما من خلال إنتاج المياه الساخنة باستخدام المجمعات الشمسية الحرارية، أو من خلال توليد الكهرباء عبر الألواح الكهروضوئية، وهو ما يمثل مسارين رئيسيين لتحويل الطاقة الشمسية إلى تأثير تبريدي: أحدهما يعتمد على العمليات الحرارية، والآخر على العمليات الكهربائية.

تُعدّ واجهات المباني ذات إمكانات كبيرة لدمج تقنيات التبريد الشمسي. وقد أسهمت الاستراتيجيات الفنية وتوافر المعارف عبر التخصصات العلمية المختلفة مؤخراً في دفع هندسة الواجهات نحو تطوير صناعة الغلاف الخارجي للمباني. وتتجه الواجهات المعمارية نحو أن تكون عناصر متعددة الوظائف تُسهم بفعالية في نظام طاقة المبنى من خلال دمج خدمات تُسهم في تقليل استهلاك الطاقة وتحقيق الراحة لشاغلي المبنى. ويجدر بالذكر أن هذا الدمج يمثل خطوة تالية لإدخال وظائف إضافية إلى الواجهة بعد تطبيق الإجراءات التقليدية، مثل العزل الحراري وأنظمة التظليل والاستراتيجيات السلبية، والتي قد لا تكون كافية لتلبية المتطلبات الداخلية. ومع ذلك، لا تزال التطبيقات الواسعة النطاق للواجهات المدمجة بتقنيات التبريد الشمسي بعيدة عن الإمكانات المتاحة، وذلك بسبب وجود تحديات متعددة تعيق انتشارها. فعلى سبيل المثال، من الناحية التقنية، هناك العديد من العوامل التي يمكن معالجتها، والتي تختلف من تقنية إلى أخرى، حيث إن لكل تقنية خصائصها الفنية الخاصة. وبالتالي، فإن توفير الإرشادات لأصحاب المصلحة المعنيين لدعم تقييم مستوى تبنّي التكنولوجيا الحالي، مع معالجة التحديات القائمة، يمكن أن يلعب دوراً رئيسياً في اعتماد ودمج التقنيات الجديدة بنجاح.

هدف هذا المشروع البحثي إلى تقديم إطار لتصميم وتطوير منتجات الواجهات المدمجة بتقنيات التبريد الشمسي لدعم تطبيقها على نطاق واسع. وقد تطلّب تطوير هذا الإطار اتباع عدة خطوات، من بينها تحديد التحديات والجوانب الرئيسية التي ينبغي أخذها في الاعتبار، وتحديد العوامل التمكينية وآفاق التطبيقات المستقبلية، وتطوير استراتيجيات رئيسية تُرشد تصميم وتقييم الواجهات، بالإضافة إلى تحديد وتوضيح والتحقق من القرارات الأساسية والمعلومات المطلوبة وأصحاب المصلحة المعنيين.

وكان سؤال البحث الرئيسي لهذه الرسالة كما يلي:

كيف يمكن توجيه تصميم وتطوير الواجهات المدمجة بتبريد شمسي لدعم انتشار استخدامها على نطاق واسع؟

تطلّبت الإجابة على هذا السؤال البحثي أولاً تحديد التحديات والجوانب الرئيسية التي ينبغي مراعاتها لدعم التطبيق الواسع، من خلال مراجعة أدبيات علمية منشورة في مؤتمرات ومجلات علمية باستخدام قاعدتي بيانات. واقترحت الدراسة الجوانب الرئيسية التي ينبغي أخذها في الحسبان ودمجها لدعم تطبيق الواجهات المدمجة بتقنيات التبريد الشمسي، وتشمل هذه الجوانب: الجوانب الفنية والمنتجية، والجوانب المالية، بالإضافة إلى الجوانب المتعلقة بالعملية وأصحاب المصلحة.

ثانياً، تم تصميم دليل مقابلات لدمج هذه الجوانب الرئيسية بهدف تحديد العوامل الأساسية التي تُمكّن من دمج تقنيات التبريد الشمسي في الواجهات على نطاق واسع. وقد أُخذت عدة معايير في الاعتبار عند اختيار المشاركين، مثل مشاركتهم في مشاريع تتعلق بتطبيق أو دمج تقنيات شمسية أو تبريد شمسي في المباني. وكشفت نتائج 23 مقابلة أن العوامل الأكثر تكراراً كانت: كفاءة المنتج، وتيسير إيصال معلومات المنتج إلى المعماريين والعملاء، والقبول الجمالي، والعمل الجماعي متعدد التخصصات، والقدرة على تخصيص المنتج. وتم تمثيل هذه العوامل في سياق تصميم وتنفيذ الواجهات لتأسيس مصفوفة تُسهم في تنفيذ الحلول ضمن عملية تطوير المنتج. وربطت أغلب هذه العوامل بمرحلة التصميم من وجهة نظر المشاركين. كما أشارت النتائج إلى أن المباني المكتبية الجديدة تُعدّ من أبرز أنواع المباني المناسبة لتطبيق هذه التقنيات. وتُسهم العوامل التمكينية والآفاق المستقبلية التي تم تحديدها في توسيع حدود المعرفة في مجال تطوير المنتجات المعمارية.

ثالثاً، تم تطوير استراتيجيات رئيسية تُرشد تصميم وتقييم منتجات الواجهات المدمجة بتقنيات التبريد الشمسي باستخدام منهجية «البحث من خلال التصميم»، مع الأخذ بعين الاعتبار السياق الملائم، وإعداد نموذج تقييم للتحقق من الجدوى التقنية-الاقتصادية. وقد شمل تطوير الاستراتيجيات رسم خارطة لتصميم وتقييم الواجهات المدمجة بالتبريد الشمسي، عبر تحديد وربط العمليات الأساسية والمدخلات والمخرجات وقرارات التصميم والأدوات ضمن مراحل التصميم الرئيسية. وأظهرت النتائج أن نظام التبريد بالضغط باستخدام الماء، عند دمجه مع الألواح الكهروضوئية كحل كهربائي، يُعدّ الخيار الأنسب للحالة المختارة. ويدعم النهج متعدد الخطوات للتقييم التقني-الاقتصادي عملية اتخاذ القرار من خلال تقييم منظم لعدة سيناريوهات، إلا أن نتائجه تظل خاصة بكل حالة بناءً على عدة عوامل، مثل خصائص المشروع والمبنى، وسياق المناخ والموقع الجغرافي، ومستوى تطور التكنولوجيا، والأطراف المعنية وأولوياتهم. وتشير تحليلات الاستراتيجيات المطوّرة إلى أن المرحلتين الأوليين – أي مرحلة التصوّر والتحديد الاستراتيجي، ومرحلة الإعداد والتخطيط – تضمنتا معظم الخطوات والمدخلات والقرارات والمخرجات. كما تؤثر العمليات المبكرة بشكل كبير في المراحل اللاحقة، مثل خصائص التنفيذ في التصميم التفصيلي.

أخيراً، تم توظيف منهجية بحث تشاركية لفهم الجوانب المدمجة من خلال تحديد، وتوضيح، وتقييم، وتطوير، وتنقيح، والتحقق من القرارات الرئيسية والمعلومات وأصحاب المصلحة الداعمين لتصميم وتطوير الواجهات المدمجة بتقنيات التبريد الشمسي. وقد شمل ذلك جمع المعلومات من خلال أبحاث مكتبية، واستبيان أولي مع أصحاب مصلحة مختارين، تلاه تنظيم ورشة عمل تعاونية لتقييم وتطوير القرارات والمعلومات وأدوار المشاركين. ثم جرى تنقيح هذه العناصر بناءً على نتائج الورشة، وتم التحقق من صحتها باستخدام استبيان لتقييم تجربة التصميم. وكشفت النتائج أن دمج تقنيات التبريد الشمسي (أو غيرها من التقنيات الشمسية) في الواجهة يجب أن يُؤخذ في الاعتبار منذ مرحلة التصوّر، حيث تم تحديد المالك، والمستثمر، والمطوّر العقاري، ومهندسي التصميم المناخي، والفيزياء المعمارية، وخدمات المبنى، والمصممين المعماريين كأطراف رئيسيين في اتخاذ القرار. وتختلف المعلومات المطلوبة لدعم قرارات دمج هذه التقنيات حسب مصادر البيانات، غير أن أهم المعلومات تشمل: تكلفة التكنولوجيا، وكفاءتها، والطلب على التبريد، وخصائص الغلاف الحراري للمبنى. وأشارت نتائج التحقق إلى أن ترتيب أولويات قرارات التصميم والمعايير المتّبعة كان متوافقاً مع الإطار المُنقّح. كما أظهرت النتائج أن المشاركين غير المتأكدين من إمكانية دمج تقنيات التبريد الشمسي أرجعوا ذلك إلى محدودية المعرفة أو نقص معلومات التكلفة المفصّلة.

استناداً إلى نتائج المراحل السابقة، وبالنظر إلى سؤال البحث الرئيسي، فإن دعم التطبيق الواسع النطاق للواجهات المدمجة بتقنيات التبريد الشمسي من خلال دمج الجوانب الفنية والمنتجية، والمالية، والجوانب المتعلقة بالعملية وأصحاب المصلحة، ليس عملية بسيطة، بل يتطلب النظر في عدة عوامل داخل كل من هذه الجوانب. ومن الواضح أن هناك العديد من التحسينات الممكنة التي تم التوصل إليها من المقابلات النوعية الاستكشافية وورشة العمل التشاركية، ومنها على سبيل المثال لا الحصر:

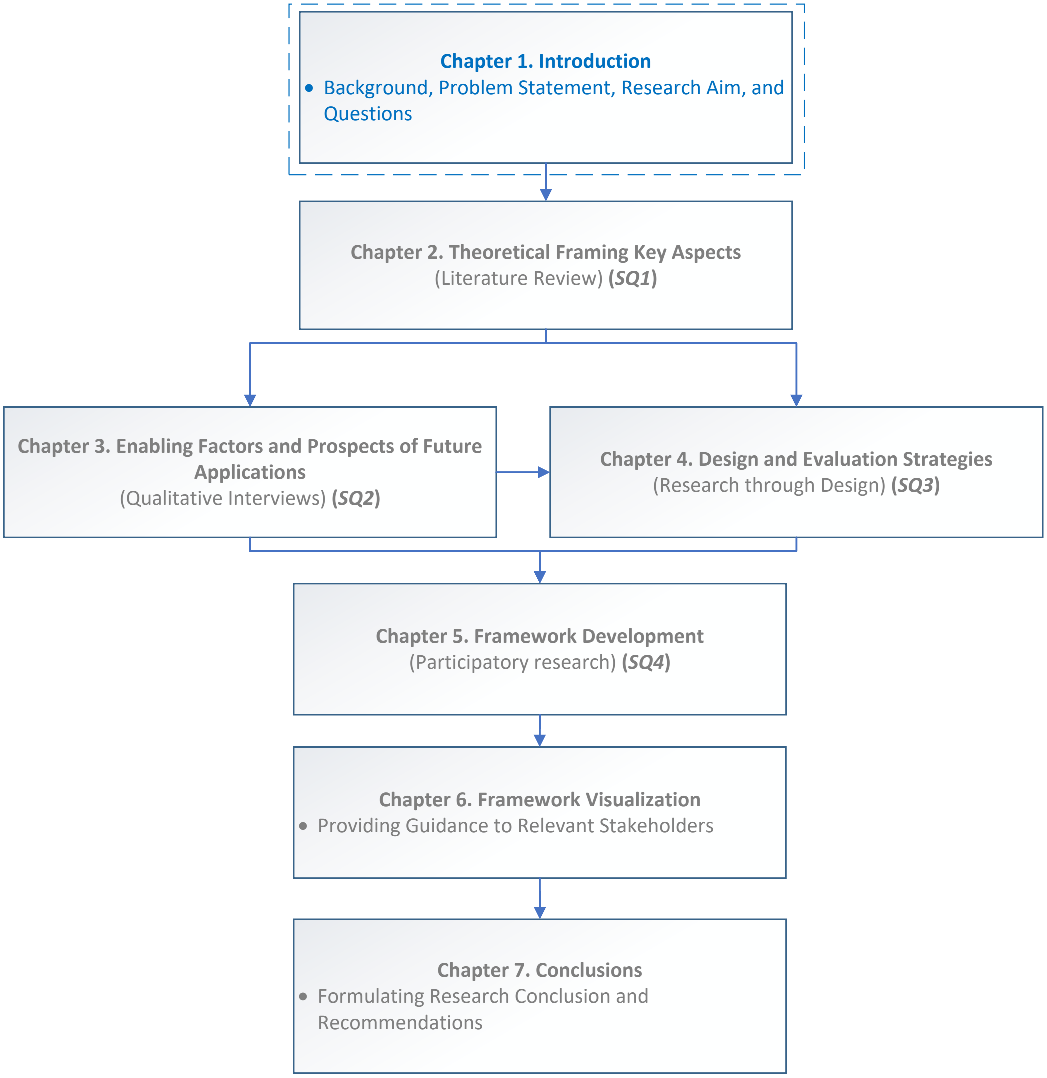
من المنظور الفني والمنتجي:
تطوير منتجات واجهات مسبقة الصنع تتمتع بدرجة من التقييس مع الحفاظ على مرونة التكيّف مع مختلف التطبيقات.
تحسين المواد المستخدمة في تقنيات التبريد الحراري لتقليل الصيانة، وتطوير المجمعات الشمسية لتسهيل عملية التنظيف.

من المنظور المالي:
يمكن أن تُسهم الإعانات المالية في تحسين الجدوى الاقتصادية من خلال خفض تكاليف الاستثمار.

من المنظور العملياتي وأصحاب المصلحة:
استكشاف نماذج أعمال ذات أدوار ومسؤوليات محددة يمكن أن يُعزّز التعاون بين الأطراف المختلفة.

ولكن، من أجل دمج هذه الجوانب المتعددة، فإن توفير إرشادات لأصحاب المصلحة لتقييم مستوى تبنّي التكنولوجيا ومعالجة التحديات الحالية يمكن أن يكون له دور محوري في نجاح تطبيق ودمج التقنيات الجديدة. وبناءً على الدروس المستفادة من استراتيجيات التصميم المطوّرة، والعناصر المحددة والمُتحقَّق منها، تم تقديم تصوّر لإطار يُرشد عملية التصميم والتطوير من خلال دمج الجوانب الأساسية. ويتكون هذا التوجيه من خمس مراحل: تحديد إمكانيات الدمج في المبنى، تقييم جدوى الإمكانيات المحددة، اختيار التقنية المناسبة لواجهة المبنى، تطوير التصميم التفصيلي لتكامل التقنية، وتصميم تنفيذ مكونات الواجهة. ويعتمد هذا التصوّر على عدة افتراضات تتعلق بمراحل التصميم والتطوير الأساسية لمبنى مكتبي جديد، دون أخذ نوع ملكية المبنى أو نوع التعاقد بعين الاعتبار، نظراً لاختلاف كل مشروع عن الآخر. كما يهدف هذا الإطار إلى أن يكون دليلاً عاماً يمكن تكييفه لدراسة تقنيات التبريد الشمسي المختلفة، مع الأخذ بعين الاعتبار تطور هذه التقنيات بمرور الوقت.

توصيات هذا المشروع البحثي لأعمال مستقبلية تشمل ما يلي:
ينبغي توسيع نطاق الإطار ليشمل أنماطاً معمارية مختلفة (سكنية، إدارية، صناعية)، مع تقييم الفروقات في السعة الحرارية ونسبة الزجاج.
دمج تقييمات الأثر البيئي، مثل الطاقة المُجسَّدة وتحليل دورة الحياة، لتحسين تقييم تقنيات التبريد الشمسي.
تطوير واجهات مسبقة الصنع تعتمد على التقييس المرن لمواكبة التطبيقات المتنوعة.
استكشاف نماذج أعمال مناسبة ذات أدوار واضحة لتعزيز التعاون وتسهيل تبادل المعلومات، ومعالجة التحديات المرتبطة بنقص المعرفة وتباين وجهات النظر بين المصممين والملاك والمقاولين.


Chapter 1. Introduction
• Background, Problem Statement, Research Aim, and Questions
Chapter 2. Theoretical Framing Key Aspects
(Literature Review) (SQ1)
Chapter 3. Enabling Factors and Prospects of Future Applications
(Qualitative Interviews) (SQ2)
Chapter 4. Design and Evaluation Strategies
(Research through Design) (SQ3)
Chapter 5. Framework Development
(Participatory research) (SQ4)
Chapter 6. Framework Visualization
• Providing Guidance to Relevant Stakeholders
Chapter 7. Conclusions
• Formulating Research Conclusion and Recommendations

1 Introduction

1.1 Background

1.1.1 Cooling Demand in the Built Environment

The global demand for cooling in the built environment is expected to increase in the near future due to various factors, including climate change and the associated rise in temperature (Sahin & Ayyildiz, 2020; Santamouris, 2016). Other factors include population and economic growth, along with the subsequent increase in quality of life and the affordability of air-conditioning units (Enteria & Sawachi, 2020; Santamouris, 2016). This is particularly true in cooling-dominated areas such as the Gulf region, where building cooling demands can account for 70% of their annual energy consumption (Rashid & Ara, 2020). It was estimated that the global air conditioner stock could increase by 50% in the coming years (**Figure 1.1**) (IEA, 2019, 2020). Hence, this necessitates the use of cleaner and greener cooling systems to meet the expected increase in demand for space cooling. Currently, there are different cooling approaches considered in building design to meet cooling demands in the built environment. The passive cooling approach involves the removal of indoor heat without energy consumption (Hu et al., 2023). It employs cooling strategies such as window-to-wall ratio, insulation, and shading devices (Ching, 2014; Prieto, Knaack, Auer, et al., 2018b). The potential impact of implementing such strategies is relevant in different climate contexts, with a more considerable effect in warm-dry regions compared to warm-humid areas. However, applying them alone does not guarantee significant reductions in energy consumption, as their effectiveness is influenced by climatic harshness and various building parameters (Prieto, Knaack, Auer, et al., 2018b). Furthermore, their potential is expected to decrease due to the increase in ambient temperatures resulting from climate change (Santamouris, 2016). Therefore, active cooling, representing a secondary approach, is still needed in many conditions, especially in warmer regions (Enteria & Sawachi, 2020; Prieto et al., 2019). Such approach employs complementary mechanical cooling systems to meet required cooling demands in buildings (Hu et al., 2023). Most of the current conventional mechanical cooling systems are dominated by technologies that have a considerable impact on global warming potential. These systems include, but are not limited to, the following (Ayou & Coronas, 2020):

- Packaged air conditioners, such as windows, rooftops, and portable units.
- Split-system air conditioners, which can be in the form of single and small room units, or large systems supplying the cooling for the whole building.
- Compression chillers, such as the centrifugal, screw-type compression, and reciprocating chillers.

According to Neyer et al. (2018), the estimated total global air-conditioning units sold in 2016 exceeded 100 million units. The increase in the use of such active cooling systems increases electricity consumption, which in turn exacerbates peak energy demand due to their reliance on power plants (Santamouris, 2016).

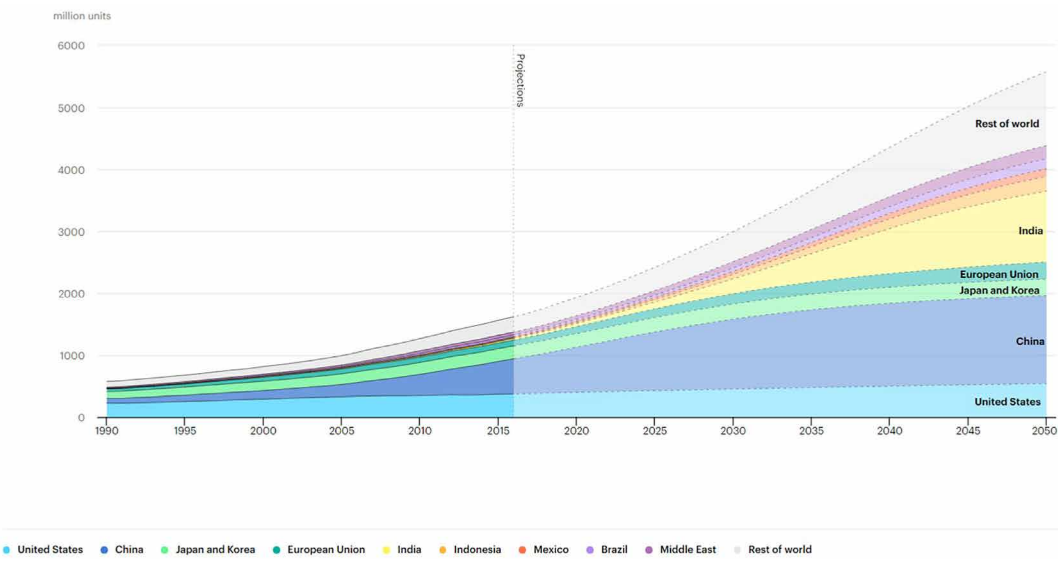


FIG. 1.1 Global air conditioner stock, 1990-2050 (IEA, 2019)

1.1.2 Solar Cooling Technologies and Building Façade

This section includes excerpts that were previously published in: "Hamida, H., Konstantinou, T., Prieto, A., & Knaack, U. (2023). Solar Cooling Integrated Façades: Towards investigating product applicability. In S. Roaf, & W. Finlayson (Eds.), Measuring Net Zero: *Carbon Accounting for Buildings and Communities (pp. 58-70). Ecohouse Initative Ltd.". The excerpts relate to the overview of different solar cooling technologies and the definition of solar cooling integrated façades.*

The production of cooling effects through solar radiation can be one of the suitable options intended to address the environmental challenges related to the increase in cooling demands in the built environment. In many cases, peak cooling demands can be proportional to solar intensities due to maximum sunlight hours (Otanicar et al., 2012; Tiwari et al., 2016). Advantages of applying solar cooling technologies include saving primary and conventional sources of electricity, reducing peak energy demand for cost savings, being environmentally friendly, and having no ozone depletion effects (Tiwari et al., 2016). The concept of solar cooling technologies, which started in the seventies, is based on generating conditioned air or chilled water from solar energy (He et al., 2019). The technologies can be in the form of producing hot water through Solar Thermal Collectors (STC) or producing electricity through Photovoltaic (PV) panels (Sarbu & Sebarchievici, 2016). This represents two principal pathways for energy conversion to be used to produce a cooling effect from solar radiation, namely thermally driven processes or electrically driven processes (**Figure 1.2**) (Alahmer & Ajib, 2020; Alsagri et al., 2020; He et al., 2019; Karellas et al., 2019; Neyer et al., 2018; Sarbu & Sebarchievici, 2016). The following sections provide an overview of solar cooling technologies and their integration into façades.

1.1.2.1 Thermally-Driven Technologies

Solar thermal energy is utilized in these technologies for the purpose of achieving one of the following options (Sarbu & Sebarchievici, 2016):

- Generators of sorption cooling systems are powered by thermal energy.
- Thermal energy is converted into mechanical energy, which is then used to produce cooling effects.

The solar collectors are the main components needed for all installations of solar thermal energy systems. Their main function is to capture and convert solar radiation into useful heat to be used for solar thermal applications. Such heat is transferred to heat transfer fluids. The fluids can be water, air, or oil that flow through solar collectors. Heat carried by heat transfer fluids can be utilized for the following options (Karellas et al., 2019):

- Satisfying heating or cooling loads
- Charging thermal energy storage systems. Such systems discharge the heat during night, cloudy, or foggy periods

There are different types of solar thermal collectors that are available on the market. The flat plate collector, evacuated tube collector, and parabolic trough collector are the main types of collectors (Alahmer & Ajib, 2020). **Figures 1.3** and **1.4** show cross-sectional views of flat-plate and evacuated tube collectors (Said et al., 2023; Tyagi et al., 2012).

Solar thermal cooling technologies can be categorized into closed sorption cycles, open sorption cycles, and thermomechanical cycles. In solar sorption cooling systems, either closed or open, the cooling effect is produced using the sorbent and sorbate (He et al., 2019).

Closed sorption cycles have two main divisions, according to the sorption material, which are liquid sorption and solid sorption. The absorption is referred to as liquid sorption, whereas the adsorption is referred to as solid sorption. The absorption cooling usually comprises sorbents, liquids, or solids that absorb refrigerant molecules into their inside and then change, either in a chemical and/or physical way, during the process (Alahmer & Ajib, 2020). It requires dissolving liquids or gases in the bulk of a sorbent in one phase and then releasing them in another phase, which is carried out through a closed loop comprising four steps. The steps include evaporation, absorption, regeneration, and condensation (He et al., 2019). The adsorption cooling comprises evaporating and condensing a refrigerant in combination with adsorption (He et al., 2019). It is a solid sorption process that involves the attraction of refrigerant molecules into the surfaces of the solid sorbent through physical or chemical forces, as well as without any changes in the sorbent form during the process (Alahmer & Ajib, 2020). The removal of adsorbed particles from surfaces can be carried out through heating adsorbents. An additional step is required for regenerating or exchanging exhausted adsorbents due to discontinuity in the adsorption cooling equipment process (He et al., 2019).

Open sorption cycles are commonly known as the desiccant cooling due to the use of a sorbent for humidifying air (Sarbu & Sebarchievici, 2016). The classification of open sorption cycle is either solid desiccant cooling systems or liquid desiccant cooling systems, which are used for dehumidification or humidification (Alahmer & Ajib, 2020). Solid desiccant cooling systems use rotary adsorption wheels as sorption materials, such as silica gel (He et al., 2019). The system generally consists of two slowly rotating wheels in addition to other various elements between two airstreams from as well as to the cooled space (Sarbu & Sebarchievici, 2016).

The achievement of the dehydration process in the liquid desiccant cooling systems is carried out by absorption (He et al., 2019). Desiccant wheels in liquid desiccant cooling systems are replaced by dehumidifiers and regenerators (He et al., 2019; Karellas et al., 2019). Liquid desiccant cooling systems involve a circulation of liquid desiccants between absorbers and regenerators that is similar to absorption systems (Karellas et al., 2019; Sarbu & Sebarchievici, 2016). Finally, thermomechanical cycles have three different forms, which include the following (He et al., 2019):

- Rankine Cycle, which consists of producing mechanical work from solar heat and then deriving conventional vapor compression cycles.
- Stirling cycle involves a volumetric change resulting from pistons that change both of temperature and pressure of the gas. However, this technology has practical limitations related to capacity and efficiency.
- Ejector systems are similar to the conventional vapor compression systems. However, the ejectors that consist of nozzles, mixing chambers, and diffusers are used in such systems instead of the mechanical compressors.

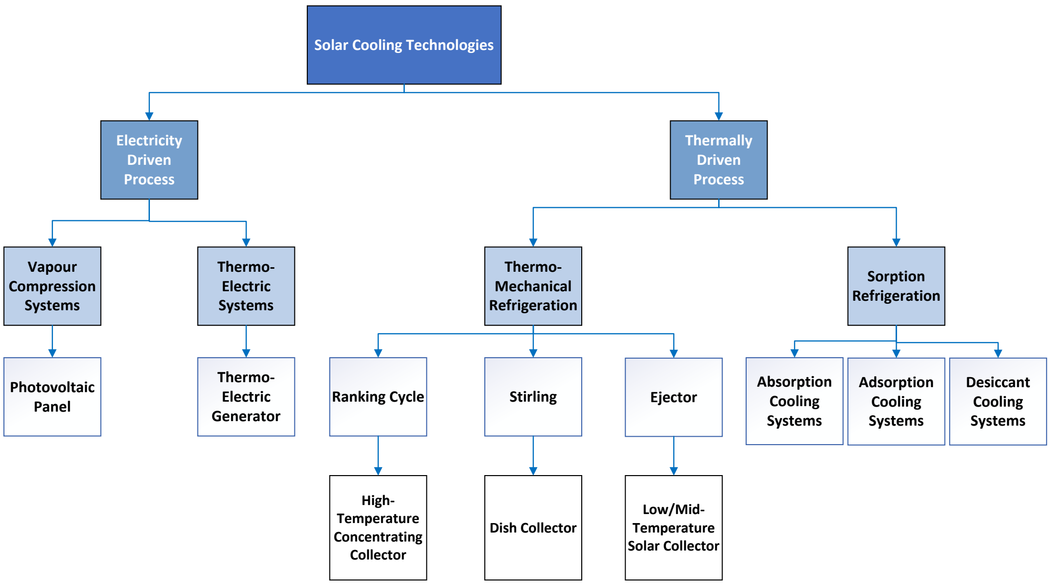


FIG. 1.2 Solar cooling technologies (reproduced from (Alsagri et al., 2020))

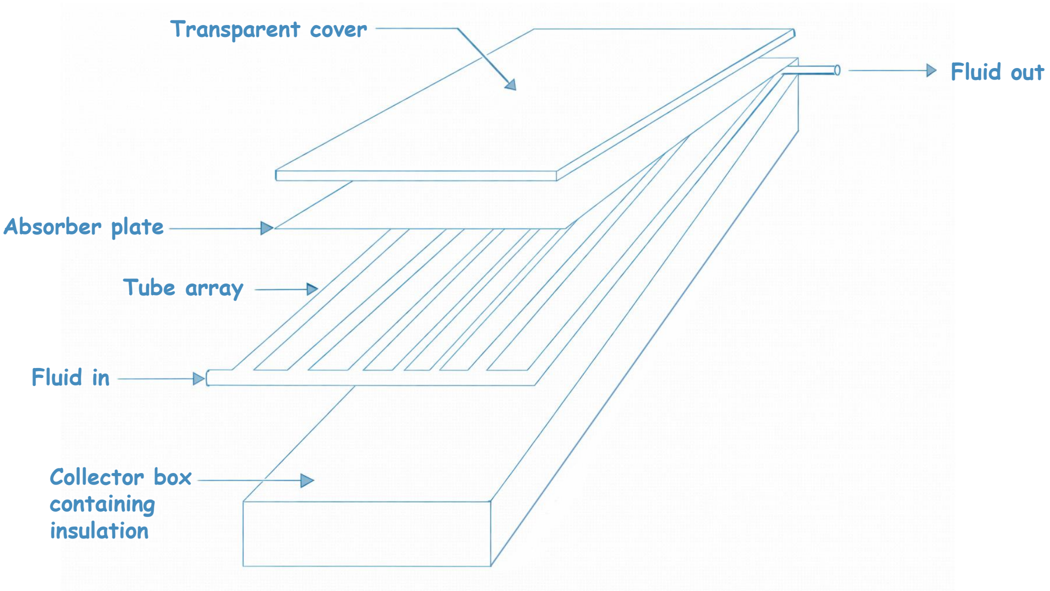


FIG. 1.3 Cross-sectional and isometric illustrations of the flat-plate collector (reproduced from (Tyagi et al., 2012))

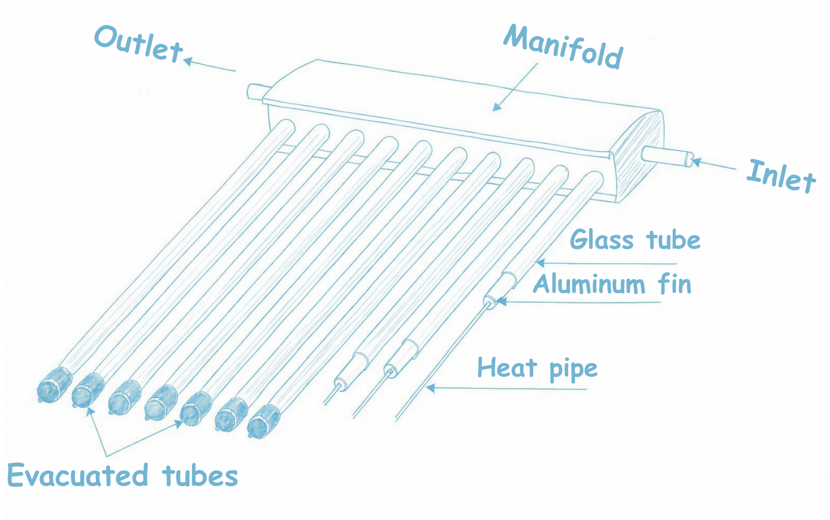


FIG. 1.4 Cross-sectional views of the evacuated tube collector (reproduced from (Said et al., 2023))

1.1.2.2 Electrically-Driven Technologies

The solar energy associated with such technologies is considered to be photovoltaic (PV)-based systems, which involve the conversion of solar energy into electricity that is then used to produce a cooling effect through conventional systems, such as vapor compression chillers or thermoelectric processes (Sarbu & Sebarchievici, 2016). The utilization of PV for cooling through coupling it with conventional vapor-compression units is considered to provide advantages related to construction simplicity and high efficacy (Sarbu & Sebarchievici, 2016). An example of such electric systems is the solar electric chillers that comprise PV panels, batteries, inverters, and electrically driven refrigeration devices. It should be noted that the refrigeration systems are recognized by the vapor compression cycles (Karellas et al., 2019). The consideration of vapor-compression air-conditioning equipment was identified as a relevant option due to the decrease in PV prices (Montagnino, 2017).

Solar thermoelectric systems involve a conversion of solar radiation to electrical energy through PV. Accordingly, the thermoelectric system is supplied by the produced electrical energy (He et al., 2019). A thermoelectric generator consists of thermocouples producing low thermoelectric power, which, however, can produce high electric currents. It provides benefits related to lowering the operational level of the heat source, which is useful for the conversion of solar energy to electricity. The thermoelectric refrigerator also comprises thermocouples made of semiconducting thermoelements, where the current produced by the generator runs (Sarbu & Sebarchievici, 2016).

Considering that electrically driven technologies are photovoltaic (PV)-based systems, applying PV panels on the building envelope can have different definitions. The term Building-Attached Photovoltaics (BAPV) refers to PV modules mounted directly on a building envelope. On the other hand, Building-Integrated Photovoltaics (BIPV) refers to cases where conventional building materials are replaced by PV modules (Haegermark & Dalenbäck, 2014; Singh et al., 2021). **Figure 1.5** summarizes the technologies and applications of BAPV and BIPV, including the façade. For instance, considering the two main types of crystalline PV technologies, namely monocrystalline and polycrystalline silicon, **Figure 1.6** provides a comparison (American Solar Energy Society, 2021). Regarding the application of PV technologies, **Figure 1.7** shows an example of a semitransparent photovoltaic (STPV) module that is composed of multiple layers: glass, encapsulation material (Ethylene Vinyl Acetate (EVA) sheet), PV cells, another layer of EVA sheet, glass, an air gap with a spacer, and an additional glass layer (Park et al., 2010).

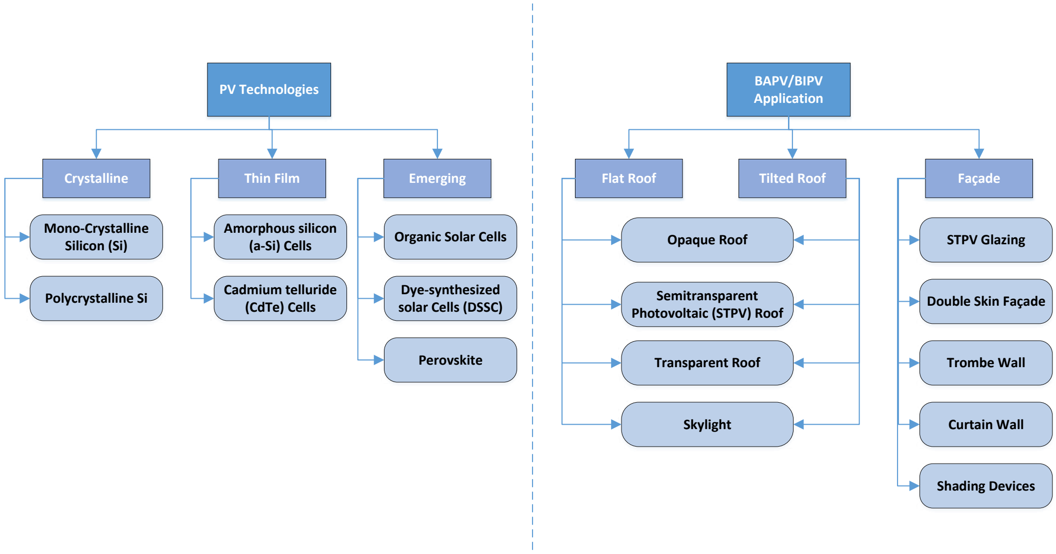


FIG. 1.5 PV technologies and applications of BAPV and BIPV (reproduced from (Singh et al, 2021))

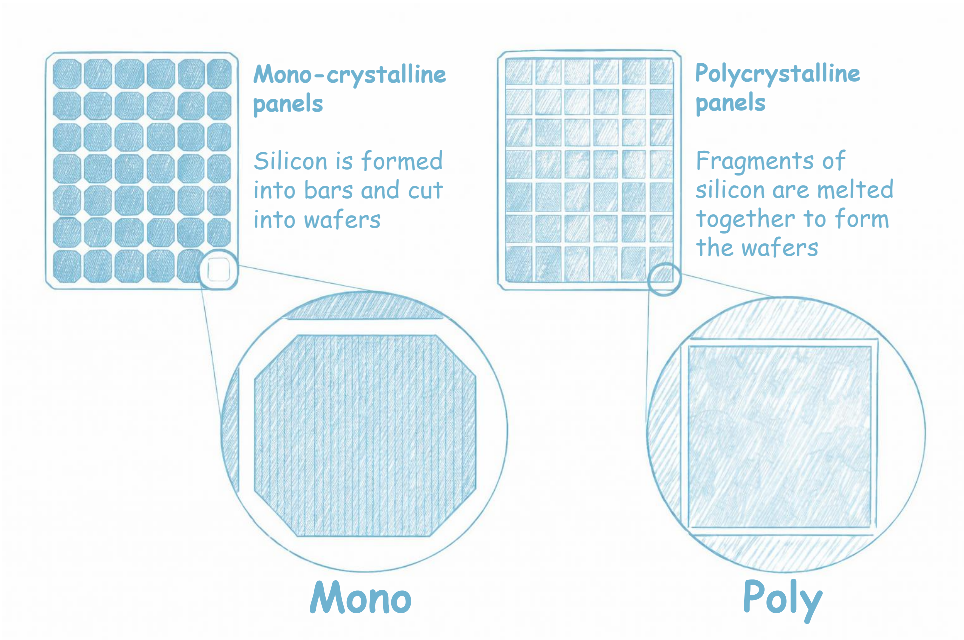


FIG. 1.6 A comparison of monocrystalline and polycrystalline silicon (reproduced from (American Solar Energy Society, 2021))

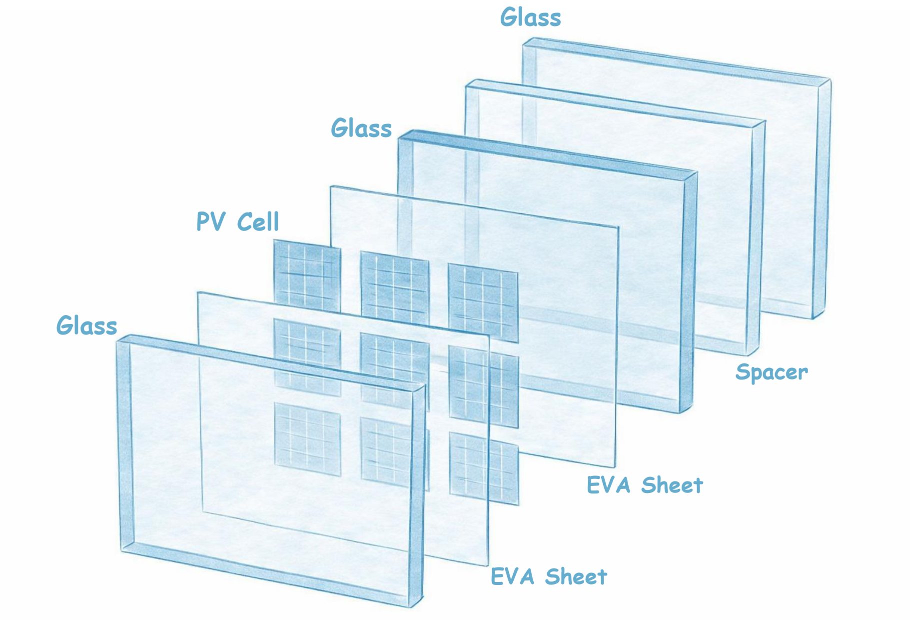


FIG. 1.7 Semitransparent photovoltaic (STPV) module (reproduced from (Park et al., 2010))

1.1.2.3 Façade Integration of Solar Cooling Technologies

Building facades present high potential for the integration of solar cooling technologies. This is because of their direct effect on the building's indoor thermal demand, and also their ability to provide external surfaces exposed to solar radiation (Prieto, Knaack, Auer, et al., 2018a). The technical strategies and knowledge abundance associated with different scientific disciplines have recently enabled façade engineering to advance the building envelope industry (Laufs & Verboon, 2013). Building façades are moving toward being multifunctional components that are actively involved in the building energy system through integrating services that contribute to energy savings and building occupants' comfort (Bonato et al., 2020; Ibraheem et al., 2017; Prieto, Klein, et al., 2017). For instance, one of the growing trends is the integration of advanced solar technologies into different elements of the built environment (Vasiliev et al., 2019). It should be noted that such integration represents an inclusion of extra functions into the façade as a next step when other measures, such as thermal insulations and shading systems, and also passive strategies, cannot sufficiently meet the indoor requirements (Prieto, Klein, et al., 2017). Taking into account that there are different types of solar active technologies, solar active façades (SAFs) were defined by the International Energy Agency-Solar Heating and Cooling Program IEA SCH Task 56 as follows (Ochs et al., 2020):

"The envelope systems entailing elements that use and/or control incident solar energy, having one or more of the following uses:
- *To deliver renewable thermal or/and electric energy to the systems providing heating, cooling, and ventilation to buildings.*
- *To reduce heating and cooling demands of buildings, while controlling daylight."*

When having an insight into the consideration of solar cooling technologies, solar cooling integrated façades (SCIFs) were previously defined as "*façade systems which comprise all necessary equipment to self-sufficiently provide solar-driven cooling to a particular indoor environment*", which indicated that the necessary equipment needed at least for cooling generation and distribution should be integrated by façade systems (Prieto, Knaack, et al., 2017a). While the definition stands from an academic standpoint, the nuances of reality dictate that the development of building products based on solar cooling should consider a certain flexibility, such as that not all components could or should be integrated into façades. Accordingly, in order to provide more flexibility while considering the two aforementioned definitions of SAFs and SCIFs by Ochs et al. (2020) and Prieto, Knaack, et al. (2017a), respectively, a more practical definition that can be considered in this research is as follows:

"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 a cooling effect in a particular indoor environment."

It should be noted that this adopted definition draws a distinction from other façade concepts, including BIPV. This is because BIPV refers to cases in which conventional building materials are replaced by PV modules (**Section 1.1.2.2**), whereas SCIF uses and/or controls solar radiation to deliver self-sufficient solar renewable electric (PV-based) and/or thermal (STC-based) energy needed to generate a cooling effect in a particular indoor environment. Additionally, taking this adopted definition as the scope of the dissertation, it is important to note that additional design criteria and indicators should be considered in real projects when designing façade modules integrating SCTs. These include the potential conflict between architectural design objectives and energy performance targets, particularly where the need for adequate daylight access and visual connection to the exterior limits the optimization of power generation (Attoye et al., 2017). Reduced indoor daylight levels can increase reliance on electric lighting to maintain visual comfort. Therefore, it is critical to design such façade systems to ensure sufficient daylight distribution within the building (Hosseini & Kim, 2024).

1.2 Problem Statement and Research Questions

Solar cooling technologies represent one of the key options for addressing environmental challenges associated with the global increase in demand for space cooling in the built environment. Some of these technologies are mature enough for building applications, such as for commercial purposes. Such technologies have not been applied massively in the built environment. Building facades present high potential for the integration of solar cooling technologies. This is because of their direct effect on the interior comfort of buildings, and also their ability to provide external surfaces exposed to sun radiation. However, the widespread application of solar cooling integrated façades in the built environment is still far from what it could be. This is because there are various challenges affecting their widespread (Prieto, Knaack, et al., 2017b). For instance, from a technical point of view, there are various factors that can be tackled, which vary from one technology to another, as each technology has its own technical attributes (**Section 1.1.2**). On the other hand, the consideration of financial as well as stakeholders' perspectives requires other factors to be considered, such as stakeholders' engagement during the project life cycle. The need to consider such multiple aspects shows that numerous social phenomena are interconnected with diverse knowledge domains across multiple academic disciplines (Jabareen, 2009). Therefore, guiding relevant stakeholders to support the assessment of the current level of technology adoption, while addressing existing challenges, can play a key role in the successful adoption and integration of new technologies (Chen et al., 2022). Accordingly, understanding how various key aspects are integrated can play a crucial role in developing the knowledge needed to support the widespread application of solar cooling integrated façades, which requires investigating both challenges and enablers across these aspects (Soltani et al., 2025). Hence, the main research question of this dissertation is as follows:

- **How can the design and development of solar cooling integrated facades be guided to support their widespread application?**

This research project provides a product design and development framework for solar cooling integrated façades to support widespread application. Providing such a framework required different steps, including the determination of challenges and main aspects to be considered, identification of key enabling factors and prospects of future applications, development of key strategies guiding the façade design and evaluation, as well as identification, outlining, and validation of main decisions,

TOC

required information, and involved stakeholders. Therefore, to answer the main research question, a set of different sub-questions needs to be investigated. The sub-questions (**SQ_s**) include the following:

- **SQ_1 –** What are the challenges and key aspects in the application of SCIFs?
- **SQ_2 –** What are the key enabling factors and prospects of future applications of SCIFs?
- **SQ_3 –** How can systematic early-stage design and feasibility assessment of SCIFs be supported?
- **SQ_4 –** How can an integrative framework guide the design and development of SCIFs?

1.3 Research Outline and Methodology

Apart from the first (introduction) and last (conclusion) chapters, the thesis is intended to answer the sub-questions in separate chapters (**Figure 1.8**). Each of these chapters presents a scientific article. Accordingly, each chapter has its own required data, research approach and methods, data analysis, and results and discussion. **Chapters 2** to **5** represent articles that have already been published and were intended to answer **SQ_1** to **SQ_4**, respectively. **Chapter 6** provides a visualization of the product design and development framework. Finally, **Chapter 7** presents the conclusion of the dissertation.

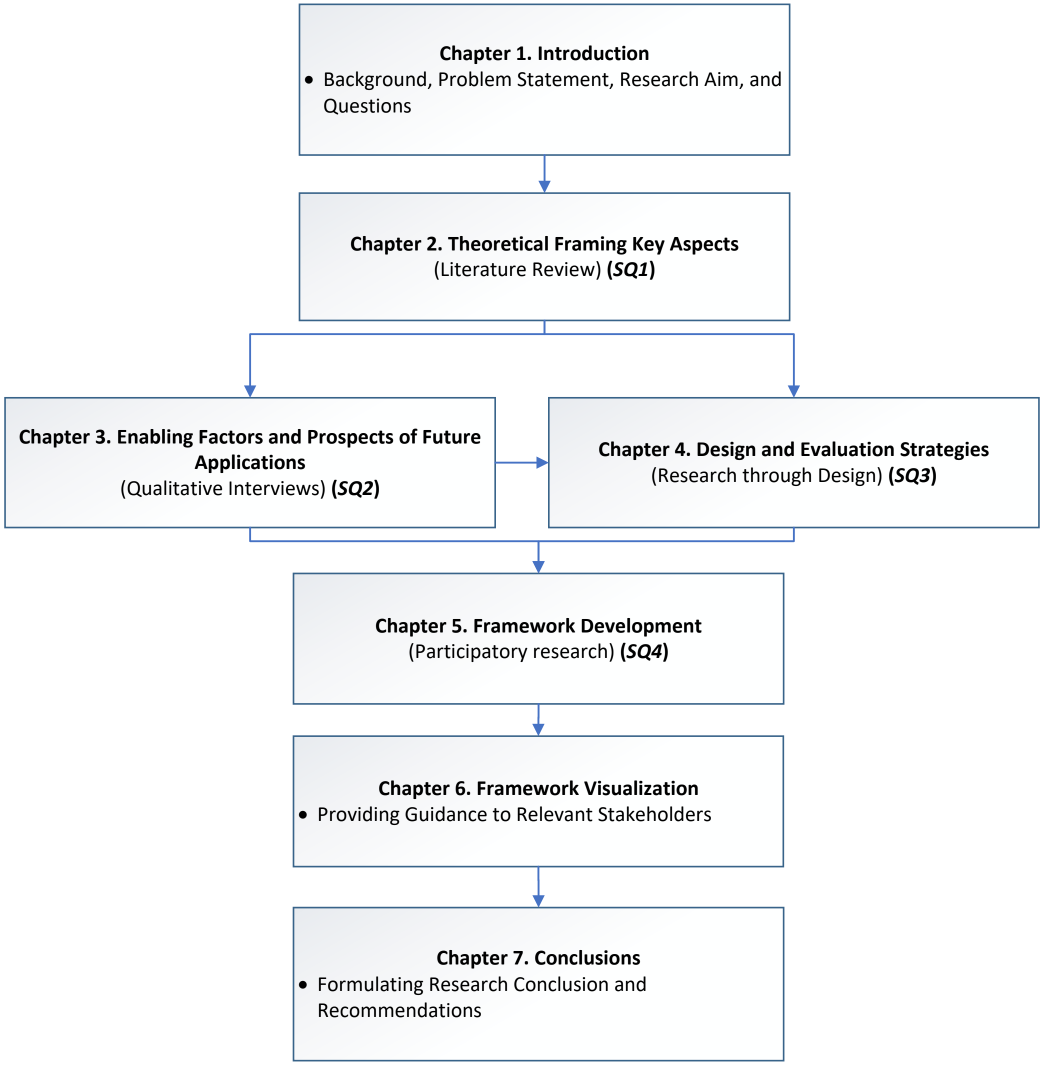


FIG. 1.8 Research outline and methodology

1.3.1 Chapter 2 (Theoretical Framing of Key Aspects)

– **SQ_1** – **What are the challenges and key aspects in the application of SCIFs?**

Answering this sub-question involved a determination of challenges and main aspects to be considered for supporting the widespread application. The chapter identified and categorized the main challenges through conducting a comprehensive literature review. The literature review was conducted on scientific papers published in conference proceedings and scientific journals, through considering two databases, namely Scopus and Web of Science. Then the study suggested main aspects to be considered and integrated for supporting the application of solar cooling integrated façades. The suggested aspects are considered for investigating the enabling factors and prospects of future applications in **Chapter 3**. They are also considered in the development of design and evaluation strategies in **Chapter 4**.

1.3.2 Chapter 3 (Enabling Factors and Prospects of Future Applications)

– **SQ_2** – **What are the key enabling factors and prospects of future applications of SCIFs?**

Answering this sub-question involved identifying the main factors enabling the widespread integration of solar cooling technologies in façades. The identification of enabling factors was carried out through qualitative interviews with stakeholders. An interview guide was designed to include the main aspects identified in **Chapter 2** to support widespread application. Different criteria were considered to select interviewees during the data collection, such as participants who worked on the application or façade integration of solar/solar cooling technologies in buildings. The outcomes of this chapter are used to select a relevant context —including building typology, relevant technologies, and geographic location— to develop design and evaluation strategies in **Chapter 4**. Furthermore, they are used to propose an evaluation set-up to assess different design scenarios.

1.3.3 Chapter 4 (Design and Evaluation Strategies)

– **SQ_3** – How can systematic early-stage design and feasibility assessment of SCIFs be supported?

Answering this sub-question involved developing key strategies guiding the design and evaluation of façade products integrating solar cooling technologies. The strategies were developed using a research-through-design methodology, considering a relevant context and a proposed evaluation set-up to assess techno-economic feasibility. The context—including building typology, relevant technologies, and geographic location—was selected based on the outcomes of **Chapter 3**. Furthermore, the evaluation set-up to assess the feasibility was proposed based on requirements primarily established from relevant literature, as well as lessons learned from professionals working in the façade and/or solar industries in **Chapter 3**. The development of strategies involved mapping the design and evaluation of solar cooling integrated façades by identifying and relating key processes, inputs, outputs, design decisions, and tools within key design stages.

1.3.4 Chapter 5 (Framework Development)

– **SQ_4** – How can an integrative framework guide the design and development of SCIFs?

Answering this sub-question involved identifying and outlining key decisions, the required information to support them, and relevant stakeholders that can be involved in the design and development of solar cooling integrated façades, based on desk research and a pre-workshop survey completed by relevant stakeholders. In addition to the desk research conducted on relevant topics, outlining key decisions and the required information to support them was based on the strategies developed in **Chapter 4**. Similar to **Chapter 4**, the context—including building typology, relevant technologies, and geographic location—was selected based on the outcomes of **Chapter 3**. Subsequently, a co-creation workshop was conducted to evaluate and further elaborate on the outlined design decisions, information, and stakeholders. After that, the design decisions, along with the other aspects, were refined based on the workshop's outcomes. Finally, these design and development aspects and stages within the framework were validated through a design experience survey that addressed key design decisions, the information required to make those decisions, and the stakeholders involved in the decision-making process.

1.3.5 Chapter 6 (Framework Visualization)

This chapter provides a visualization of a framework for the design and development of solar cooling integrated façades, with the goal of supporting their widespread application. To integrate multiple aspects, the framework offers guidance to relevant stakeholders in assessing the current level of technology adoption, thereby facilitating the successful adoption and integration of new technologies. Offering such guidance requires synthesizing key outcomes through a process-oriented approach. The framework was visualized based on the design strategies from **Chapter 4** and the validated aspects from **Chapter 5**. Additionally, **Chapter 6** reflects the challenges and enablers identified in **Chapters 2** and **3**, respectively. This includes consideration of the extent to which the framework can mitigate the challenges while incorporating the enabling factors.

1.3.6 Chapter 7 (Conclusions)

This chapter concludes the dissertation with the following points:

- Summarizing the answers to the research sub-questions by referring to the work carried out in **Chapters 2** to **5**.
- Presenting the conclusions and recommendations, including the overall conclusion and suggestions for future research.

1.4 Research Relevance

1.4.1 Scientific Relevance

The research expands the boundaries of knowledge in building product innovation by presenting a framework for integrating renewable energy technologies into buildings. This framework draws on multiple scientific disciplines, including façade design and engineering, sustainable built environments, and project business and process management.

It demonstrates a systematic approach that equips the architecture, engineering, and construction disciplines with the necessary information to connect diverse bodies of knowledge and support the investigation of technology applications. The framework covers key aspects such as the main stages of designing and developing solar cooling–integrated façades, the tasks and steps within each stage, the critical decisions to be made, the information required to support those decisions and tasks, and the potential stakeholders involved at each stage.

Furthermore, the research illustrates the adoption and integration of various research approaches and methods, including both quantitative and qualitative methodologies, to address these aspects. The application of such methodologies in design-based and participatory research guides the scientific community on how frameworks supporting the application of technologies can be systematically developed.

1.4.2 Societal Relevance

The societal relevance of this research lies in its contribution to accelerating the transition toward environmentally sustainable buildings, thereby supporting global efforts to mitigate climate change and improve public well-being. By advancing the adoption of environmentally friendly cooling technologies, this work helps reduce dependence on conventional mechanical cooling systems, which are major contributors to greenhouse gas (GHG) emissions. Lower emissions from the building sector can improve urban air quality, reduce energy costs, and contribute to greener built environments for communities.

The framework developed in this study equips practitioners with practical guidance on managing diverse stakeholders, streamlining complex decision-making processes, and ensuring efficient collaboration in façade design and development. Through clearer pathways for implementation, design teams can more effectively deliver solar cooling integrated façades that provide energy savings and promote sustainable urban development.

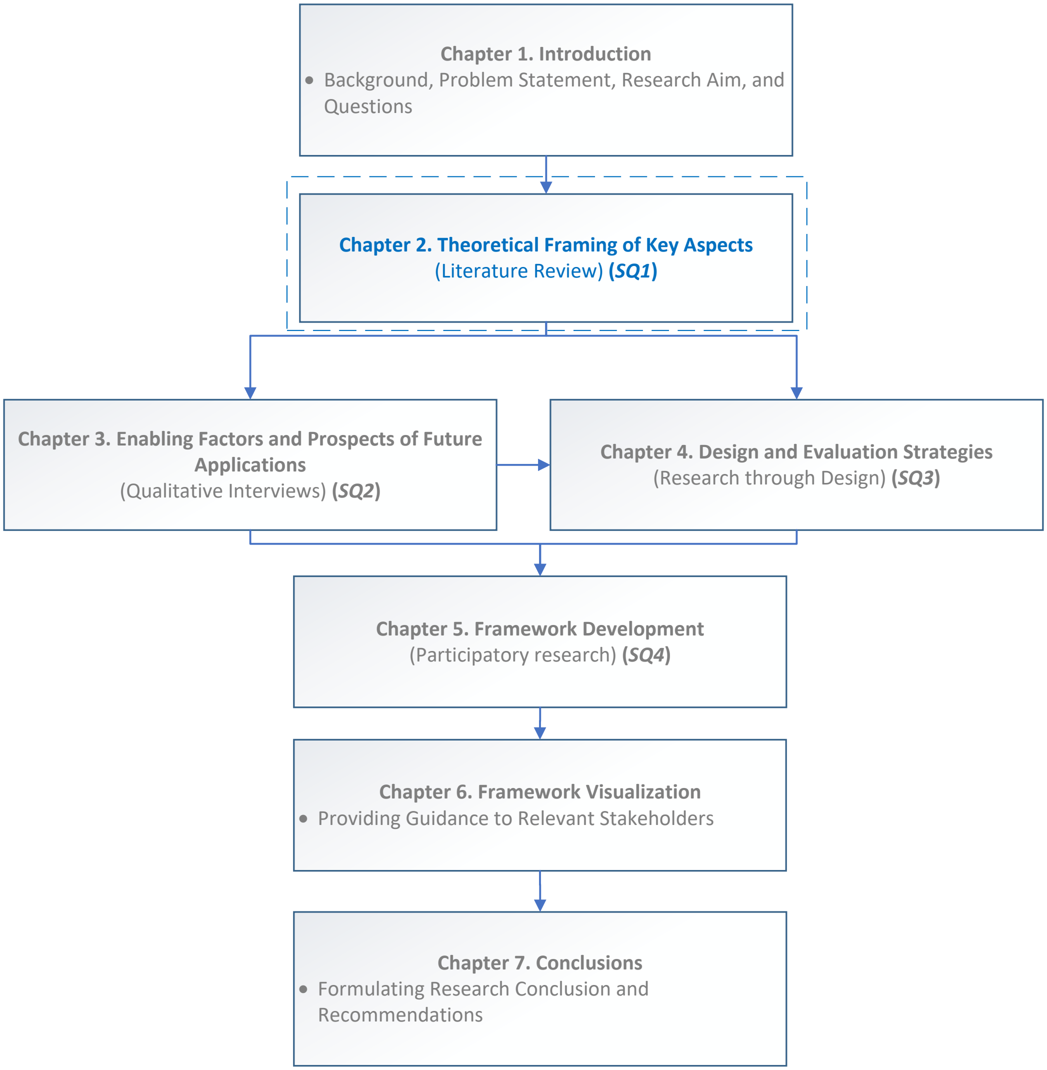
The societal benefits of this framework are reflected in the following key aspects:

- **Pre-technical feasibility assessment:** Enables informed decisions on the cost-effectiveness, performance, and efficiency of conceptual designs, ensuring that public resources and investments are directed toward solutions with tangible environmental and economic returns.

- **Space usability and compactness:** Encourages innovative designs that make efficient use of space, supporting higher-quality and more functional urban living environments.

- **Assembly, connection, and maintenance:** Promotes resilient and accessible systems that extend the lifespan of technologies while reducing waste.

By aligning technical feasibility with societal needs, the research contributes to the creation of climate-responsive buildings that are more energy-efficient.


Chapter 1. Introduction
Background, Problem Statement, Research Aim, and Questions
Chapter 2. Theoretical Framing of Key Aspects
(Literature Review) (SQ1)
Chapter 3. Enabling Factors and Prospects of Future Applications
(Qualitative Interviews) (SQ2)
Chapter 4. Design and Evaluation Strategies
(Research through Design) (SQ3)
Chapter 5. Framework Development
(Participatory research) (SQ4)
Chapter 6. Framework Visualization
Providing Guidance to Relevant Stakeholders
Chapter 7. Conclusions
Formulating Research Conclusion and Recommendations

2 Theoretical Framing of Key Aspects

Chapter 2 aims to answer the first sub-question:
SQ_1 – What are the challenges and key aspects in the application of SCIFs?

Answering this sub-question required identifying the challenges and key aspects that should be considered to support widespread application. The sub-question was answered in the following publication: "Hamida, H., Konstantinou, T., Prieto, A., Klein, T., & Knaack, U. (2022). Solar Cooling Integrated Façades: *Main Challenges in Product Development for Widespread Application. In CLIMA 2022 - 14th REHVA HVAC World Congress: Eye on 2030, Towards digitalized, healthy, circular and energy efficient HVAC Article 1294 TU Delft OPEN Publishing. https://doi.org/10.34641/clima.2022.353".* ***Chapter 2*** *is a modified version of this publication. The modifications include replacing the phrase "This paper" with "This chapter" to ensure consistency with academic thesis writing conventions.*

ABSTRACT

Global attention to solar cooling systems has increased over the last years as a result of the expected growth in the world cooling demand. Such systems encompass the use of renewable energy as the main driver for mitigating indoor temperatures. Currently, some of these technologies are mature enough for their commercial application in buildings. Building facades present high potential for the integration of such technologies. This is because of their direct effect on the indoor comfort of buildings, and also their ability to provide external surfaces exposed to solar radiation. However, there are different challenges affecting the widespread application of solar cooling integrated façades. This chapter aims to identify and categorize these challenges through conducting a comprehensive literature review. A literature review was conducted on scientific papers published in conference proceedings and scientific journals, through considering two databases, namely Scopus and Web of Science. Then the study suggested three main potential dimensions that should be tackled and integrated when supporting the widespread application of the façade integration of a particular solar cooling technology. The dimensions include technical, financial, as well as process and stakeholder-related aspects. Such proposed dimensions represent an initial step for identifying important aspects to be considered for supporting the product's widespread application in the built environment.

2.1 Introduction

The global need for space cooling in buildings is expected to increase in the future due to various factors, such as climate change and the associated temperature increase (Sahin & Ayyildiz, 2020; Santamouris, 2016). Other factors comprise the population and economic growth, with the subsequent increase in the quality of life, and the affordability of air-conditioning units (Enteria & Sawachi, 2020; Santamouris, 2016). It has been demonstrated that the global energy demand for building space cooling may increase by 50% in 2030 if no considerable improvements take place in the efficiency of cooling equipment (IEA, 2020).This is particularly true in cooling-dominated areas such as the Gulf region, where the building cooling demands in countries such as Saudi Arabia and the United Arab Emirates account for 70% of their annual energy consumption (Rashid & Ara, 2020). Hence, this necessitates the use of environmentally friendly cooling systems to meet the expected increase in the demand for space cooling and energy consumption.

There are different cooling approaches considered in building design that are intended to meet cooling demands in the built environment. The passive cooling approach involves the removal of indoor heat without energy consumption (Hu et al., 2023). It employs cooling strategies such as the window-to-wall ratio, insulation, and shading devices (Ching, 2014; Prieto, Knaack, Auer, et al., 2018b). The potential impact of implementing such strategies is relevant in different climate contexts, with a considerable impact in warm-dry regions compared to the warm-humid areas. However, applying them alone does not guarantee relevant reductions in energy consumption, since their effectiveness is influenced by the climatic harshness and other various building parameters (Prieto, Knaack, Auer, et al., 2018b). Furthermore, their potential is expected to decrease due to the increase in ambient temperatures resulting from global warming (Santamouris, 2016).

Therefore, active cooling, representing a secondary approach, is still needed in many conditions, especially in warm regions such as hot and humid climates (Enteria & Sawachi, 2020; Prieto et al., 2019). Such an approach employs complementary mechanical cooling systems to meet the required cooling demands in buildings (Hu et al., 2023). According to Neyer et al (2018), the estimated total global room air-conditioning units sold in 2016 exceeded 100 million units. The increase in the use of such active cooling systems increases electricity consumption, which in turn exacerbates peak energy demand due to their reliance on power plants (Santamouris, 2016).

The production of a cooling effect through sunlight tends to be one of the promising options intended to address such an environmental challenge. The peak cooling demands are proportional to the solar intensities due to maximum sunlight hours (Otanicar et al., 2012; Tiwari et al., 2016). The potential main advantages of solar cooling technologies include saving the primary and conventional sources of electricity, reducing peak demand of energy for cost saving, and being friendly to the environment and having no ozone depletion effects (Tiwari et al., 2016). The concept of solar cooling technologies, which started in the seventies, is based on generating conditioned air or chilled water from solar energy (He et al., 2019). The technologies can be in the form of producing hot water through Solar Thermal Collectors (STC) or producing electricity through Photovoltaic (PV) panels (Sarbu & Sebarchievici, 2016). This represents two principal pathways for energy conversion to be used to produce cooling from solar radiation, namely thermally-driven processes or electrically-driven processes (Alahmer & Ajib, 2020; Alsagri et al., 2020; He et al., 2019; Karellas et al., 2019; Neyer et al., 2018; Sarbu & Sebarchievici, 2016). Some of these technologies are mature enough for building applications, such as the solar absorption cooling technologies (Alahmer & Ajib, 2020; Kalair et al., 2021).

Building facades present high potential for the integration of solar cooling technologies. This is because of their direct effect on the indoor comfort of buildings, and also their ability to provide external surfaces exposed to solar radiation (Prieto, Knaack, Auer, et al., 2018a). They are moving toward being multifunctional components that are actively involved in the building energy system through integrating technologies that contribute to energy savings and building occupants' comfort (Bonato et al., 2020; Ibraheem et al., 2017; Prieto, Klein, et al., 2017). It should be noted that such integration represents an inclusion of extra functions into the façade as a next step when other measures, such as thermal insulations and shading systems, cannot sufficiently meet the indoor requirements (Prieto, Klein, et al., 2017; Prieto, Knaack, et al., 2017a). The integration can be achieved through two different design approaches, namely integral or modular paths (**Figure 2.1**) (Prieto, Knaack, et al., 2017a). The functions and components associated with integral products are mapped based on a many-to-one approach. In addition to that, they have coupled interfaces, which means that making a change in one component (in the case of having a coupled interface of two components), a change to be carried out on the other interface. On the other hand, the functions and components associated with modular products are mapped based on a one-to-one approach. The connection of components is based on using modular interfaces, which allows changing the interfaces separately (Klein, 2013).

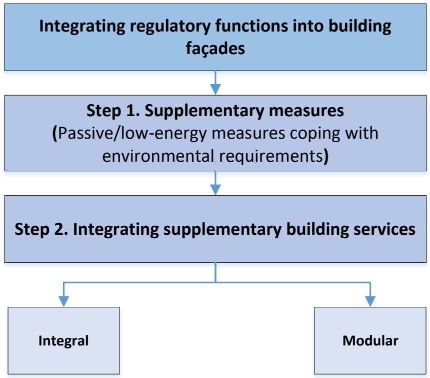
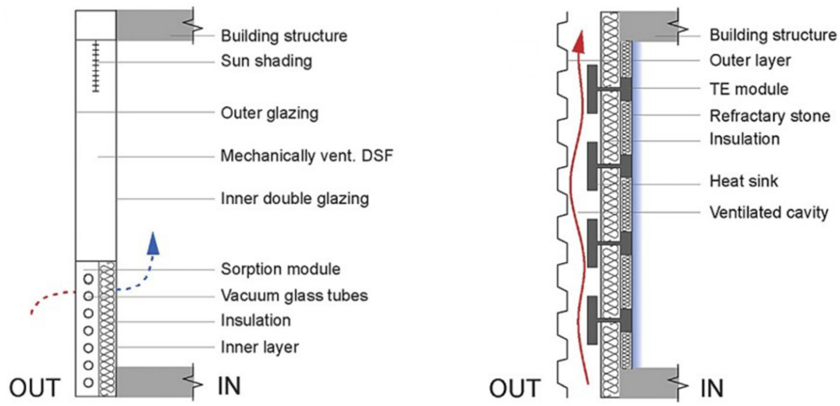


FIG. 2.1 Decision-making process for integrating regulatory functions into building façades (Prieto, Knaack, et al., 2017a)



a) Solar-thermal sorption cooling façade *b) Solar solid-based cooling thermoelectric facades*

FIG. 2.2 Concepts of solar cooling integrated facades (Prieto, Knaack, et al., 2017a)

When having an insight into the consideration of solar cooling technologies, solar cooling integrated façades have been previously defined as *"façade systems which comprise all necessary equipment to self-sufficiently provide solar-driven cooling to a particular indoor environment"*, which indicates that the necessary equipment needed at least for cooling generation and distribution should be integrated by façade systems (Prieto, Knaack, et al., 2017a). **Figure 2.2** indicates different examples of solar cooling integrated façades concepts. However, there are various challenges affecting the widespread application of integrating solar cooling technologies into building facades. This chapter aims to identify and categorize those challenges through conducting a comprehensive literature review in order to propose the main potential dimensions that should be considered and integrated to support the widespread application of solar cooling integrated façades.

2.2 Research Approach and Methods

A literature review was conducted on scientific papers published in conference proceedings and scientific journals. The review includes a literature search, using the concepts indicated in **Table 2.1**, through considering two databases, namely Scopus and Web of Science. The assessment of a particular article's relevance involved different criteria, which include the scope of the journal and the article's novelty (from 2015 to 2021). Such criteria were set in order to narrow down the number of documents to be reviewed and also ensure the relative modernity of information obtained from the reviewed papers. Different journals were found to provide relevant articles, namely Journal of Façade Design and Engineering, Renewable and Sustainable Energy Reviews, and Journal of Cleaner Production. In addition to that, various conference papers were considered in the review process.

It should be noted that there were different initial trials that were carried out before finalizing **Table 2.1**. For instance, one of the most relevant trails included only the first four concepts. This combination provided irrelevant papers that did not provide information related to the challenges affecting product widespread application. Some of these articles were related to conducting experiments or performing numerical analysis on thermal storage tanks to be used for building heating. Accordingly, the consideration of the fifth concept assisted in narrowing the outcomes and providing more relevant articles. Besides, various articles were excluded during the search process when considering such concepts. The excluded articles are the ones that were found to provide no information regarding the issues affecting the widespread use of solar technologies in the built environment. Based on that, a total of thirteen relevant references were found to provide reliable information regarding the main challenges affecting the widespread use of solar cooling integrated façades. All the information obtained from the 13 articles is presented and discussed in **Section 2.3**.

TABLE 2.1 Concepts included in the literature search

	Concepts No. (Combined with AND)				
Synonyms and Related Terms (Combined with OR)	1	2	3	4	5
	challenges	solar	cooling	façade	widespread
	barriers	renewable	air–conditioning	building integrated	application
	obstacles	photovoltaic	–	integration	implementation
	–	collector	–	envelope	–

2.3 Results and Discussion

The results obtained from the literature revealed that there are various forms of challenges stated by different scholars. Therefore, an appropriate way to differentiate and simplify such variation is needed to facilitate the ability to gain insight into it. Hence, the challenges were divided into two main forms, which are as follows:

- Challenges associated with the integration of solar technologies into building façades in general, regardless of the technology type.
- Specific product-related challenges are precisely linked to different solar cooling technologies, which vary from one technology to another.

Regarding the general challenges, a categorization of them was adapted from (Prieto, Knaack, et al., 2017b). It includes a total of six main groups, namely financial, product-related, knowledge, information, processes, and interest. **Table 2.2** summarizes the general challenges and their categories. Regarding the product-related challenges precisely linked to different solar cooling technologies, the literature pointed out that such barriers vary from one technology to another. This variation is because various solar cooling technologies have different barriers and attributes related to performance and size. These product-related challenges associated with different solar cooling technologies were analyzed by Prieto et al. (2019).

Having such various forms of challenges illustrates the complexity of supporting the widespread application of solar cooling integrated façades in the construction market. Narrowing the challenges as a first step can assist in simplifying the problem, so that particular dimensions can be tackled to support the widespread application of a particular technology. Accordingly, to minimize the complexity of the problem, the study suggested three main potential dimensions that should be tackled and integrated when supporting the widespread application of the façade integration of a particular solar cooling technology (**Figure 2.3**). The dimensions include technical, financial, as well as process- and stakeholder-related aspects. Such proposed dimensions represent an initial step for identifying important aspects to be considered for supporting the product's widespread application in the built environment.

TABLE 2.2 Challenges affecting product development and widespread application of solar technologies integrated façades

Category	Issues related to such challenges	References
Product–Related Challenges	Performance and efficiency	(Curpek & Cekon, 2020; Ghosh, 2020; Klysner et al., 2021; Z. Liu et al., 2021; Prieto, Knaack, et al., 2017b; Visa et al., 2017; Visa & Duta, 2016)
	Technical considerations (complexities, space availability, and interrupting other building services)	(Kalogirou, 2015; Klysner et al., 2021; Prieto, Knaack, et al., 2017b; Visa & Duta, 2016)
	Availability of products appropriate for quality integration	(Prieto, Knaack, et al., 2017b)
	Maintenance and Durability	(Irshad et al., 2019; Prieto, Knaack, et al., 2017b; Visa et al., 2017)
	Aesthetics	(Klysner et al., 2021; Prieto, Knaack, et al., 2017b; Visa et al., 2017)
Financial Challenges	High Costs (Initial, operation, and maintenance)	(Blackman & Bales, 2015; Irshad et al., 2019; Kalogirou, 2015; Klysner et al., 2021; Z. Liu et al., 2021; Montagnino, 2017; Prieto, Knaack, et al., 2017b; Visa & Duta, 2016)
	Long payback period	(Klysner et al., 2021; Montagnino, 2017; Prieto, Knaack, et al., 2017b)
	Current energy prices are low	(Prieto, Knaack, et al., 2017b)
	Lack of incentives/subsidies to execute such technologies	(Kalair et al., 2021; Kalogirou, 2015; Z. Liu et al., 2021; Prieto, Knaack, et al., 2017b)
Challenges Related to the Knowledge	Lack of technical knowledge and experience of architects/engineers about technical aspects related to solar technologies	(Klysner et al., 2021; Prieto, Knaack, et al., 2017b)
	End users' lack of knowledge associated with operating the systems	(Blackman & Bales, 2015; Prieto, Knaack, et al., 2017b)
	Required workforce experience for installing the products	(Blackman & Bales, 2015; Kalogirou, 2015; Prieto, Knaack, et al., 2017b)
Challenges Related to the Information	Need for documenting the properties of technologies appropriately	(Prieto, Knaack, et al., 2017b)
	Lack of standards/guidelines related to the technology, such as those related to building integration	(Klysner et al., 2021; Prieto, Knaack, et al., 2017b)
	Uncertainties associated with changes in legal legislation	(Klysner et al., 2021)
Challenges Related to the Design and Construction Processes Challenges Related to the Interest	Need to consider integration during the early stages of the project (considering close collaboration among various disciplines)	(Klysner et al., 2021; Prieto, Knaack, et al., 2017b)
	Need for design–oriented tools so that (A/E)s are involved in technical issues during early design stages	(Prieto, Knaack, et al., 2017b)
	Ability to provide various forms of products for attracting customers	(Klysner et al., 2021)
	Lack of interest in the field of solar designs by designers, developers, and clients	(Prieto, Knaack, et al., 2017b)

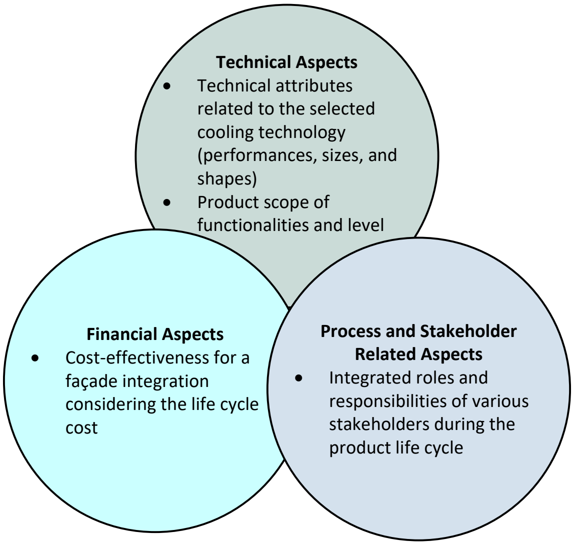


FIG. 2.3 Proposed main potential dimensions to be tackled for supporting the application of a façade integration of solar cooling technologies

2.3.1 Technical Aspects

The development of an appropriate building product with the required technical attributes, such as product shape, performance, and sizes, is a primary step supporting its penetration into the construction market. Technical challenges related to current products, such as technical complexities and aesthetics, result in challenges related to interest as well as financial aspects. The resulting challenges include the lack of incentives to execute such technologies. Accordingly, the lack of such incentives leads to challenges related to the knowledge and information in the building industry, such as the lack of technical knowledge and experience of architects/engineers about technical aspects related to solar technologies. Consequently, this can have a direct influence on the design and construction processes in a way that there is a lack of consideration of the integration during the early design stages of buildings.

Accordingly, technical developments of building products need to go hand in hand with the financial, as well as stakeholders and process-related aspects. Tackling technical aspects associated with façade integration of a solar cooling technology requires an understanding of the specific aspects related to the selected cooling technology (Prieto et al., 2019). This is because such aspects vary from one technology to another. In addition to that, understanding the definition of products and how they are linked to building façades is needed for tackling such aspects.

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Products can be defined as tangible and quantifiable goods that are produced for customers, which can be end items in themselves or component items (Foster, 2017; PMI, 2017). Additionally, they do have a scope that indicates their features and functions (PMI, 2017). Based on that, building façades represent a form of products that serve the different customers' needs, such as building occupants. In addition, they do have a scope of various functions, such as providing an appropriate insulation with respect to noise, heat, and cold (Knaack et al., 2014). Since products can be end items in themselves or component items (PMI, 2017), façades have been identified to have different product levels that range from the material (base ingredients) to the building (Klein, 2013). Therefore, it is essential to have a well-defined product scope of functionalities and level for the integration of particular solar cooling technology into the building façade.

2.3.2 Financial Aspects

High initial costs of solar cooling systems and the low energy prices can result in challenges related to interest, namely the lack of interest in the field of solar designs by designers, developers, and clients. This illustrates that achieving cost-effective solutions is needed to increase the attention of various stakeholders to adopt the technology in the market. It should be noted that not only is the initial cost the only parameter to be considered. Other parameters should be included, which may include the maintenance cost as well as the potential for energy savings. Accordingly, considering the life cycle cost can aid in investigating cost-effectiveness for the integration of particular solar cooling technology into the building façade.

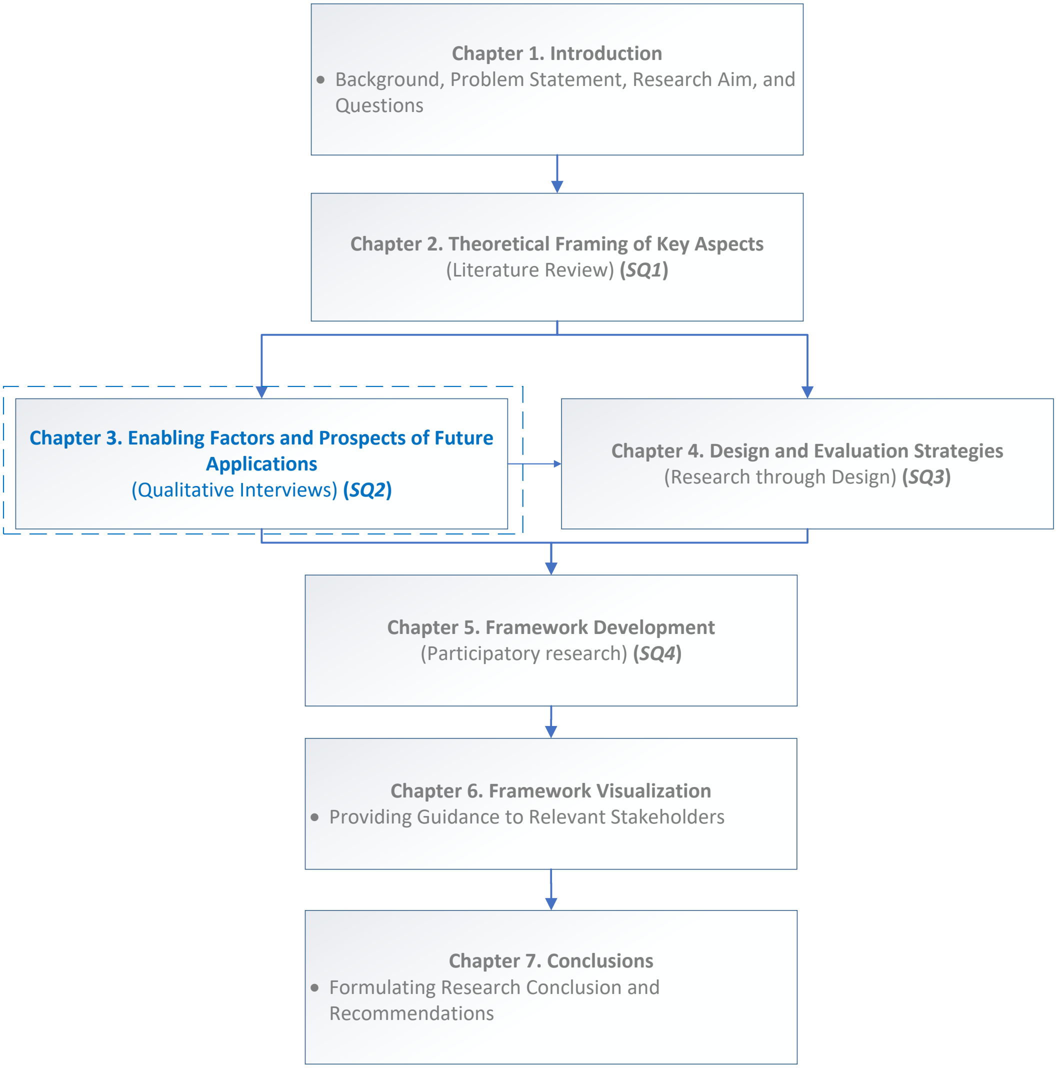
2.3.3 Process and Stakeholder Related Aspects

Products are developed through a process consisting of a sequential set of activities aiming to cause particular end results (PMI, 2017). Having an insight into façade products, they were traditionally identified to have various processes contributing to their design and development in the built environment, which start from the system design till the assembly, use, and end of life. Moreover, the role of different stakeholders has been identified in façade processes, which include suppliers, façade builders, general contractors, architects, consultants, and clients (Klein, 2013).
For instance, façade builders represent one of the important stakeholders in the architecture, engineering, and construction (AEC) industry. They are usually involved in the translation of architectural design into achievable construction and ensure the

overall façade performance. They also work on integrating various subcomponents, which require putting effort into planning and logistical arrangements. Such stakeholders take into account the necessity of establishing relationships with architects and general contractors. Therefore, it is essential to shed light on processes and stakeholders when considering the integration of solar cooling technology into the building façade. Tackling such dimensions can involve identifying the potential integrated roles and responsibilities of various stakeholders during the product life cycle. Such identification can contribute to addressing issues affecting interest and providing stakeholders with the required knowledge of information supporting product development and use.

2.4 Conclusion

This chapter presents a comprehensive literature review conducted to identify and categorize challenges affecting the widespread application of façade integration of solar cooling technologies in the built environment. The results obtained from the literature search revealed that there are various forms of challenges that were divided into two main forms. The first form includes challenges associated with the integration of solar technologies into building façades, regardless of the type of technology. The second from covered specific product-related challenges precisely linked to different solar cooling technologies, which vary from one technology to another. Taking into account that having various forms of challenges illustrates the complexity for supporting the widespread application in the construction market, the paper suggested three main potential dimensions to be tackled. The dimensions include technical, financial, as well as process and stakeholder-related aspects. Such proposed dimensions represent an initial step for identifying important aspects to be considered for supporting the product's widespread application in the built environment. Based on the identified three main dimensions to be tackled, future work should consider investigating a further breakdown of the aspects to more specific opportunities and bottlenecks in order to develop a framework for supporting product widespread application of solar cooling integrated façades as building products in the construction market. Such a framework would tackle and combine the three main aspects.


Chapter 1. Introduction
• Background, Problem Statement, Research Aim, and Questions
Chapter 2. Theoretical Framing of Key Aspects
(Literature Review) (SQ1)
Chapter 3. Enabling Factors and Prospects of Future Applications
(Qualitative Interviews) (SQ2)
Chapter 4. Design and Evaluation Strategies
(Research through Design) (SQ3)
Chapter 5. Framework Development
(Participatory research) (SQ4)
Chapter 6. Framework Visualization
• Providing Guidance to Relevant Stakeholders
Chapter 7. Conclusions
• Formulating Research Conclusion and Recommendations

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3 Enabling Factors and Prospects of Future Applications

Chapter 3 aims to answer the second sub-question:
SQ_2 – What are the key enabling factors and prospects of future applications of SCIFs?

Answering this sub-question involved identifying the main factors enabling the widespread integration of solar cooling technologies in façades. The identification of enabling factors was carried out through qualitative interviews with stakeholders. The sub-question was answered in the following publication: "Hamida, H., Konstantinou, T., Prieto, A., & Klein, T. (2023). Solar Cooling Integrated Façades: Key perceived enabling factors and prospects of future applications. Journal of Building Engineering, 76, Article 107355. https:*//doi.org/10.1016/j.jobe.2023.107355". ***Chapter 3*** is a modified version of this publication. The modifications to the chapter and its appendices include providing the full interview guide, not only the questions. Additionally, the phrase "This paper aims to" was replaced with "This study aims to" to better reflect the formal style of dissertation writing. The question has been rephrased to be consistent with other sub-questions and more concise and focused. In the revised question, the phrase "façade products integrating SCTs" has been replaced by SCIFs (Solar Cooling Integrated Façades). Additionally, the wording shifts from "perceived enabling factors" to simply "enabling factors" to be more concise.*

ABSTRACT

Solar cooling integrated façades (SCIFs) have the potential to reduce primary energy consumption for space cooling. Identifying key enabling factors in the context of technical and product (T&P), financial (F), as well as process and stakeholder (P&S) related aspects represents an important step in providing relevant knowledge for implementing solutions supporting widespread application. This study aims to identify the main factors enabling the widespread integration of SCTs in façades from the point of view of various professionals. An interview guide was designed to tackle the main aspects to be considered for supporting the widespread application. Different criteria were considered to select the interviewees during the data collection, such as participants who worked on the application or façade integration of solar/SCTs in buildings. The findings obtained from a total of 23 interviews revealed that the most frequently mentioned factors are product performance and efficiency, facilitating the delivery of product information to architects and clients, aesthetic acceptability, multidisciplinary teamwork, and the ability to customize products. The factors were mapped in the context of façade

design and construction processes to establish a matrix for implementing solutions in product development. The majority of the factors were linked to the design phase according to interviewees' perceptions. The results also indicated that newly built office buildings have been perceived to be one of the most relevant types of buildings to be considered for such technologies. The identified enabling factors and prospects of future applications of solar cooling integrated facades (SCIFs) contribute to expanding the boundaries of knowledge in the field of building product development.

3.1 Introduction

The global need for cooling is expected to increase in the future due to climate change (Sahin & Ayyildiz, 2020; Santamouris, 2016), in addition to other factors comprising the population and economic growth, with the subsequent increase in the quality of life, and the affordability of air-conditioning units (Enteria & Sawachi, 2020; Santamouris, 2016). Furthermore, it was estimated that the global energy demand for building space cooling may increase by 50% in 2030 (IEA, 2019, 2020). The increase in the use of conventional mechanical cooling systems can increase greenhouse gas (GHG) emissions, due to their dependency on electricity generated in power plants (Santamouris, 2016). Hence, this necessitates the use of cooling systems that can meet the expected increase in the demand for space cooling, while avoiding systems contributing to increased greenhouse gas (GHG) emissions.

The production of a cooling effect through solar radiation is one of the strategies to be considered for reducing challenges related to the increase in the required cooling demands in the built environment. The potential advantages of solar cooling technologies (SCTs) include saving primary energy and reducing peak demand for energy cost savings (Tiwari et al., 2016). The technologies can be in the form of producing hot water through Solar Thermal Collectors (STC) or producing electricity through Photovoltaic (PV) panels (Sarbu & Sebarchievici, 2016). This represents two principal pathways for energy conversion to be used to produce a cooling effect from solar radiation, namely, thermally driven processes or electrically driven processes (Alahmer & Ajib, 2020; Alsagri et al., 2020; He et al., 2019; Karellas et al., 2019; Neyer et al., 2018; Prieto, Knaack, et al., 2017a; Sarbu & Sebarchievici, 2016). Building façades provide opportunities to integrate SCTs, as they provide external surfaces exposed to solar radiation, while also impacting indoor thermal comfort (Prieto, Knaack, Auer, et al., 2018a). The knowledge development and abundance

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associated with different scientific disciplines have enabled façade engineering to advance the building envelope industry (Laufs & Verboon, 2013). Building façades are moving toward being multifunctional components that are actively involved in the building energy system through integrating services that contribute to energy savings and building occupants' comfort (Bonato et al., 2020; Ibraheem et al., 2017; Prieto, Klein, et al., 2017). When having an insight into the consideration of solar cooling technologies, solar cooling integrated façades (SCIF) were previously defined as "façade systems which comprise all necessary equipment to self-sufficiently provide solar-driven cooling to a particular indoor environment", which indicated that the necessary equipment needed at least for cooling generation and distribution should be integrated by façade systems (Prieto, Knaack, et al., 2017a).

It should be noted that the widespread application of such defined façade concepts in the construction industry is far from what it could be due to different forms of challenges. Hamida et al. (2022) identified and categorized these challenges and proposed three main aspects to be tackled to enable the widespread application of SCIFs. The aspects include Technical& Product(T&P)-related, Financial (F)-related, and Process& Stakeholder (P&S)-related (**Figure 3.1**). Such proposed aspects demonstrate that fact that many social phenomena are associated with various bodies of knowledge belonging to a set of different disciplines (Jabareen, 2009). For instance, considering the T&P dimension, products tend to have a particular scope of certain features and functions (PMI, 2017). Facades as building products are intended to have multiple functions during the use phase, including insulation with respect to heat, cold, and noise (Knaack et al., 2014). Regarding the integration of SCTs into façades, various technical attributes have been considered to affect the product applicability of SCIFs, including sizes and the number of required components (Prieto et al., 2019). Accordingly, investigating key factors enabling product applicability within such aspects can play a vital role in future developments of SCIFs. Having an insight into the F-related aspects, cost is one of the most common barriers affecting the widespread application of such technologies (Prieto, Knaack, et al., 2017b). Consequently, investigating the key factors enabling the achievement of cost-effective products through lowering the requirement related to the upfront capital can support the market penetration (Azcarate-Aguerre et al., 2018). For the P&S dimension, various stakeholders are involved in the product life-cycle (design, production, assembly, and operation phases) (Klein, 2013). Accordingly, considering this dimension requires focusing on identifying factors that enable stakeholders to adopt such technologies through considering key relevant aspects, such as the knowledge and experience (Prieto et al., 2023).

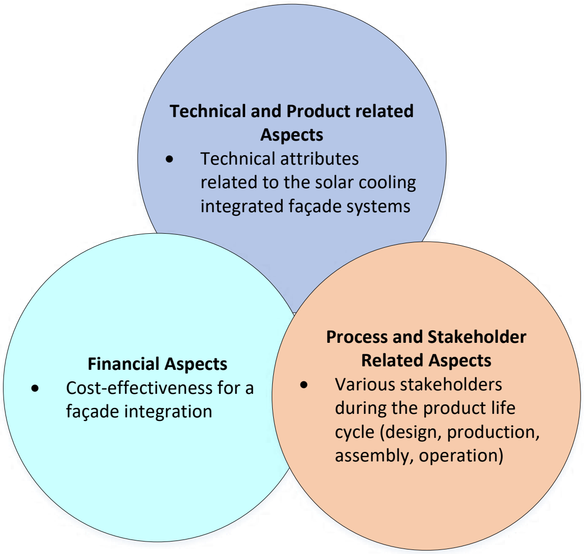

FIG. 3.1 Proposed aspects to be tackled for supporting the application of SCIFs (Hamida et al., 2022)

Based on the previous paragraph, it is obvious that tackling proposed aspects requires grounding them in key factors enabling widespread application within the context of these different disciplines. The identification of such factors can help in providing relevant knowledge needed for investigating the future product applicability in the construction industry. Consequently, in order to deal with such multiple bodies of knowledge related to the proposed aspects, a multidisciplinary research approach and methods are required. Qualitative research methods provide relevant tools needed to understand phenomena linked to different disciplines (Jabareen, 2009). Hence, this study focuses on grounding the aspects qualitatively into key enabling factors. This study aims to identify key perceived enabling factors and prospects of future applications related to the widespread application of SCIFs, which can provide relevant knowledge needed for future product development. With respect to that, the main research question to be explored in this study corresponds to:

– **What are the key enabling factors and prospects of future applications of SCIFs?**

In order to answer this research question, this study involved 23 qualitative interviews with various professionals who can provide relevant information related to the key perceived factors within the context of different aspects. The research approach and methods section presents all aspects related to the design of the interview guide, criteria for selecting interviewees, and the analysis of collected data. Following this,

Sections 3.3 and **3.4** illustrate the results and discussion, respectively. Finally, the conclusion section discusses the findings, limitations, and future research scope.

Such outcomes can facilitate establishing a matrix for implementing the solutions in product development. Such an established matrix of enabling factors obtained from this exploratory study provides information that can be considered and investigated in future works related to the development of frameworks supporting the widespread application of SCIFs. Such frameworks can consider the applicability of particular SCTs in particular contexts.

3.2 Research Approach and Methods

To identify the key factors that can enable the widespread integration of SCTs in façades, this study adopted the research approach and methods indicated in **Figure 3.2**:

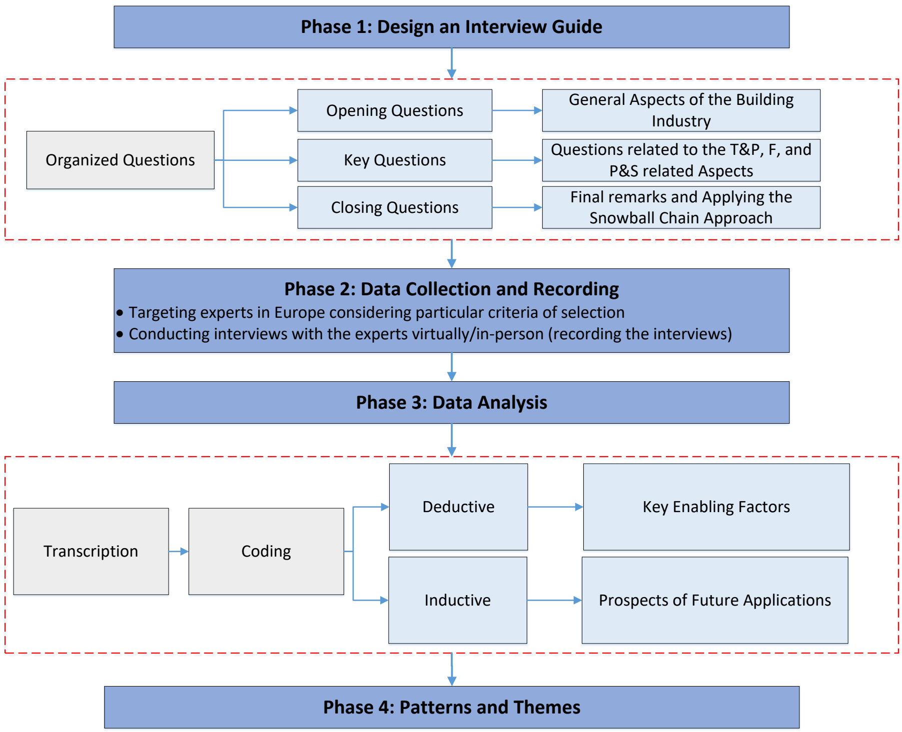

FIG. 3.2 Research approach and methods

3.2.1 Design of Interview Guide

In order to ground the aspects to key enabling factors, qualitative interviews with professionals were considered in order to reach an in-depth understanding of perceptions and insights of experts on such a particular topic (Hauashdh et al., 2022; Ying et al., 2021). Such a research approach can help in capturing the voices of experts through a one-to-one discussion between the interviewer and interviewee on a specific topic (Hennink et al., 2011; Ying et al., 2021). It should be noted that it is essential to identify and screen out the phenomena to be examined from the environment of study in order for a qualitative research to reach a yielded conclusion (Groat & Wang, 2013). Accordingly, the core of the qualitative interviews revolved around the three identified groups of aspects. To collect the data appropriately, it is essential to have an organized interview guide that includes an introductory part, opening questions, key questions, and closing questions (Creswell & Creswell, 2018; Hennink et al., 2011). The opening and closing questions are intended to collect supplementary information that includes the perception of participants about general aspects, such as opinions about the type of buildings considered to be relevant for supporting widespread application of façade products integrating such technologies. Apart from the opening and closing questions, the key questions, representing the core of the qualitative interviews, are intended to cover the three aspects. The design of the interview guide was prepared and revised among the research team members and colleagues in the research group, and was tested with the following two experts:

- A director of a research and consultancy firm that focuses on the indoor environment in buildings.
- A professor in the field of climate-responsive design and building technologies.

The purpose of testing the interview guide is to check the time it takes to complete the interview as well as the clarity of questions, words, and sentences. It also involved checking the logical order of questions (Hennink et al., 2011). Based on these two testing interviews, the questions were revised. The interview guide, including the interview questions, is provided in **Appendix A**.

3.2.2 Data Collection

The qualitative interviews in this study targeted practitioners and applied researchers who are experts in the European building industry. The interviews were based on a purposive, non-probabilistic sampling (Groat & Wang, 2013; Ying et al., 2021). This is because this exploratory study focuses on investigating the key factors enabling the widespread application of SCIFs in the context of the three main aspects, considering a particular group of experts. Hence, it is essential to have predetermined criteria to select the participants (Ajayi et al., 2016; Durdyev et al., 2022). Accordingly, considering the technical and product (T&P) related aspects, it is essential to have practitioners and applied researchers who are experts in the application or façade integration of solar or solar cooling technologies. For the financial (F) as well as process and stakeholder (P&S) related aspects, broadening the sample through involving practical experience from the building industry by involving experts in the facade design and construction is important. Consequently, the main criteria considered for selecting interviewees include that experts should achieve one or more of the following conditions to ensure their competence:

- Involvement in the façade design and construction industry (design, production, assembly, and/or operation/maintenance).
- Involvement in projects related to the application or façade integration of solar/solar cooling technologies.
- Involvement in the research& development (R&D) or applied research in relevant fields, such as multi-functional façades, including prototyping façade products integrating solar/solar cooling technologies or other relevant subjects.

The snowball chain approach was also applied in this study, in which participants are allowed to propose other potential interviewees who are relevant to participate in this study (Bryman, 2016; Fellows & Liu, 2015). This approach has been adopted in previous studies to reach interviewees who have relevant experience (Ajayi et al., 2016; Ying et al., 2021). Taking into account all of the previously mentioned criteria, the finalized number of interviews to be conducted was considered to be between 20 and 30 to ensure a relevant number of participants, as it has been indicated by (Bryman, 2016; Creswell & Creswell, 2018). The interviews were designed to be conducted virtually via the Microsoft Teams platform that is provided by the research institution, as well as in person. The research team obtained ethical approval from the institutional human research ethics committee before conducting the interviews. The authors followed the committee regulations, including the interview tools for recording as well as obtaining the interviewee’s signature in a consent form.

3.2.3 Data Analysis

The analysis of data collected from the qualitative interviews included the following steps:

- **Transcription:** For virtual interviews, the automatic transcription service provided by Microsoft Teams was used. For the in-person interviews, a Tascam DR-05 V2 digital audio recorder was used, and then transcribed automatically using the Microsoft Office Online provided by the research institution. All transcripts have been revised through listening to the recordings and correcting the wrongly captured words. The transcripts were also edited by removing repeated words.

- **Coding:** A hybrid coding approach, both deductive and inductive, was considered in the data analysis, as it has been adopted in previous studies (Chan et al., 2019). Coding the transcriptions was carried out using ATLAS.ti software (ATLAS.ti, 2023). For the deductive approach, a set of a priori defined codes focusing on the three main aspects was considered. These codes include T&P, F, and P&S-enabling factors. The inductive coding was also considered to obtain additional information from the data, such as perceptions about current technologies as well as perceptions about the applicability in future applications.

3.2.4 Patterns and Themes

This part involves mapping the enabling factors in the context of façade design and construction processes, which include design, production, assembly, operation, and end-of-life phases. Considering these phases as the main focus of the analysis was appropriate because they illustrate where and when the key factors should be considered, as well as enable the widespread application of SCIFs. Furthermore, it can indicate which phase most participants linked the factors to, as well as whether some factors were linked to one or more phases. Accordingly, mapping the factor is intended to establish a matrix to implement the solutions in product development.

3.3 Results

A total of 23 interviews were conducted between May 19th, 2022, and September 26th, 2022. All interviews, except one, were conducted virtually using Microsoft Teams, and all of them were conducted in English. The research team obtained informed consent from all participants involved in the study. **Appendix B** summarizes the interviewees' profile that includes different information, such as their professional years of experience (**Figure B.1**). Having an insight to the 23 interviewees, the most frequent educational and technical background among all interviewees was architecture (11 interviewees), followed by mechanical engineering (5 interviewees) and building physics (4 interviewees) (**Figure B.2**). **Figure 3.3** provides information about the field of professional experiences. Taking into account the criteria considered to select participants (**Section 3.2.2**), **Figure 3.4** indicates how many participants were involved in different types of projects. It is obvious that many of participants interviewees were directly involved in the façade design and construction as well as the application of solar technologies, which stand for 22 and 18 interviewees, respectively. However, this is not the same for the application of solar cooling technologies in buildings, since it is still in the early adoption in real buildings. The following two points provide more information about their experience:

- **Façade Design and Construction:** All of the 23 interviewees declared to have been involved in the design phase (**Figure B.3**).
- **Application and/or Façade Integration of Solar/Solar Cooling Technologies**: Many interviewees declared to have been involved in the application and/or façade integration of Photovoltaic panels compared to other solar/SCTs (**Figures B.4 and B.5**).

All of the interviewed participants are professionals working in Europe. Regarding the location of projects mainly experienced by these participants, most of them have worked in projects in the Netherlands, followed by Germany, Spain, and the United Kingdom (**Figure B.6**). However, 9 interviewees have been involved in projects outside Europe, such as the United States, United Arab Emirates, and China (**Figure B.7**).

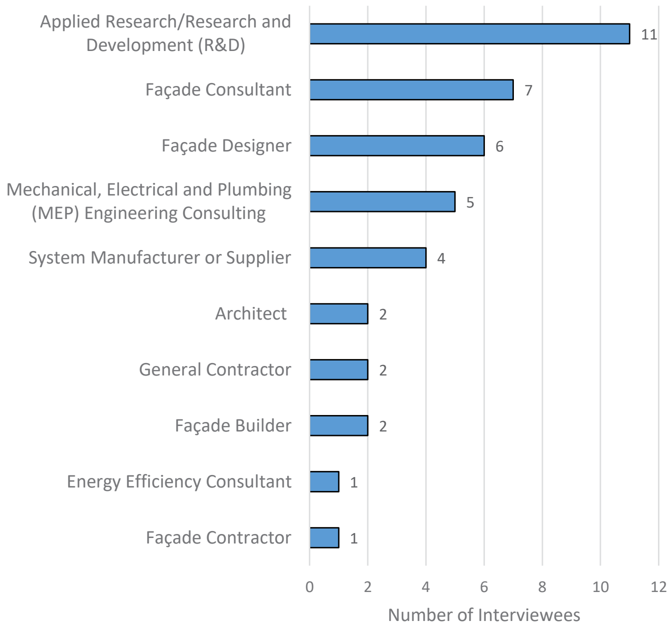

FIG. 3.3 Field of professional experiences

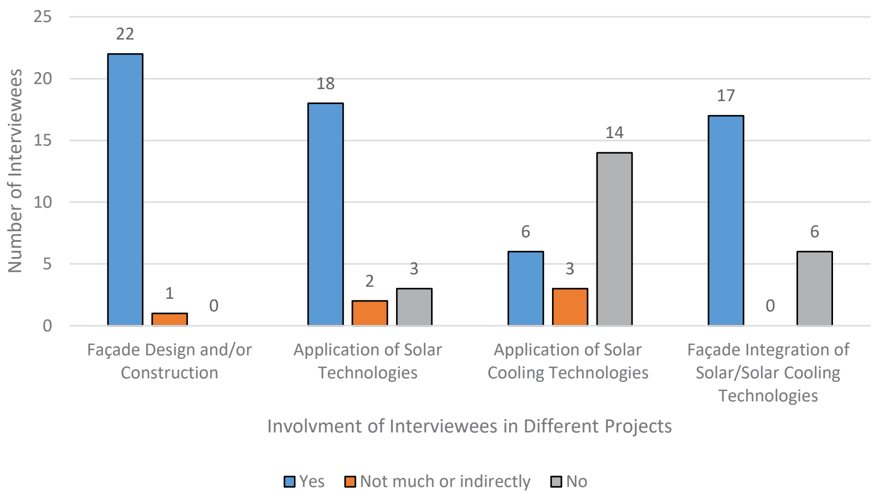

FIG. 3.4 Involvement of interviewees in different projects

The findings obtained from the 23 interviews are divided into two main parts. The first part presents the identified enabling factors from the deductive approach (**Section 3.3.1**). The second part presents the findings obtained from the inductive approach, which are related to the perceptions about current technologies as well as perceptions about future applications (**Section 3.3.2**).

3.3.1 Key Enabling Factors

This section presents the key factors that have been identified to support the widespread application of SCIFs. It presents the results obtained from the deductive approach, which are related to the three main aspects. The frequency of identified factors in the context of the three main aspects, namely T&P, F, and P&S related aspects, is summarized in **Figure 3.5,** considering a descending order of the frequencies. **Appendix C** provides interpretations and descriptions of the identified key perceived factors (**Table C.1**). The most frequently mentioned factors are product performance and efficiency, facilitating the delivery of product information to architects and clients, aesthetic acceptability, multidisciplinary teamwork, ability to customize products, and ability to disassemble (**Figure 3.5**). All of the identified factors have been linked to the P&S aspects, as well as majority of them have been linked to the façade design and construction processes, as discussed in **Table C.1**. For instance, product performance and efficiency as a T&P-attribute have been perceived to be considered in design standards and guidelines for practitioners involved in the design phase. At the same time, the ability of the product to maintain its performance during the operation phase has been perceived as a motivating factor that increases of clients and developers to adopt the technology. This is the same when considering the aesthetic acceptability of products, which has been linked to the design phase. Accordingly, visualising the link between the factors and process can provide a matrix to implement the solutions in product development. Hence, the factors were mapped in these processes based on the link that was declared by interviewees. **Figures C.1** and **C.2** map the factors considering the descending order of the frequencies indicated in both **Figure 3.5** and **Table C.1**. The factors were mapped in two separate figures (**Figures C.1** and **C.2**) to ensure the clarity and readability of the factors and their relations to different façade design and construction processes. Although majority of factors have been linked to the design phase, there couple of factors that have been considered to take place in both of design and production phases, including ability to customize products, ability to disassemble (this factor has been also linked to the end of life), reusability, and mass production (**Figures C.1**)**.** The modularity as well as standardization and off-the-shelf products were linked to their sequential phases, namely design, production, and assembly. Aspects related to circularity, including reusability as well as recyclability, have been considered to be taken into account during the design phase while such factors in order to be achieved at the end of life. However, there are a few factors, such as the increase in energy prices, taxes, and fees, as well as the role of education and training of architects and engineers, that haven't been linked to any phase. Such factors are influenced by public bodies, such as energy policies, as well as public education institutions.

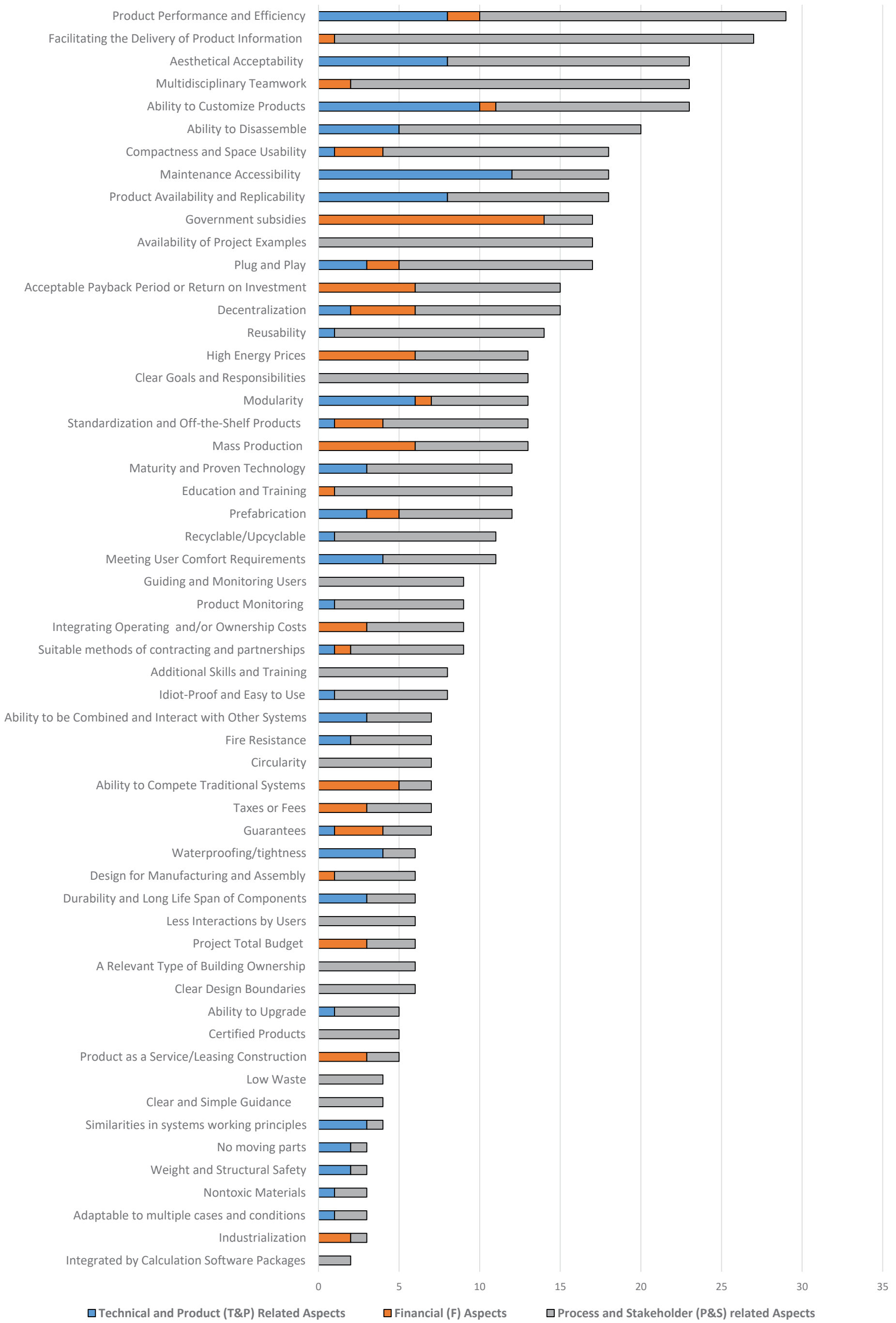

FIG. 3.5 Frequency of the identified key enabling factors

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3.3.2 Prospects of Future Applications

These results were obtained from the inductive approach, which is related to the perceptions about current technologies as well as perceptions about the applicability in future applications. The findings present perceptions related to integrating current solar cooling technologies into facades in terms of both factors supporting their application as well as concerns influencing their applicability. Additionally, the results outline the perceived suitable contexts for applying SCIFs, which include relevant building and project types. Finally, the findings show factors identified to affect the application of SCIFs based on the location and climate conditions.

3.3.2.1 Perceptions of the Status of Current Technologies

Various factors have been perceived to support the widespread application of integrating current electrically-driven technologies based on photovoltaic (PV) panels and thermally-driven technologies based on solar thermal collectors (STC) (**Figure 3.6**). On the other hand, different concerns were mentioned regarding the integration of both types of technologies into facades (**Figure 3.7**). **Table 3.1** provides a description and an interpretation of the perceived factors and concerns. According to **Figures 3.6** and **3.7,** as well as **Table 3.1**, solar electrically-driven technologies (based on Photovoltaic modules) tend to be one of the most promising technologies. This is obvious in terms of the number of supporting factors and their frequencies. Apart from these two types of technologies, there are some perceptions related to potential future improvements in the widespread integration of other technologies in the building industry, such as photovoltaic–thermal (PVT) technology. These perceptions were indicated by interviewees 1, 8, and 21. Regarding the widespread application of integrating thermoelectric (TE) technologies into façades, interviewee 19 declared different factors supporting its application, which are related to the simplicity in the assembly and connections, as well as in the working principle. On the other hand, the interviewee declared different concerns related to the façade integration of TE solar cooling technologies, which are related to the low product performance and efficiency, as well as some complexities in the working principles, such as problems with thermal bridges.

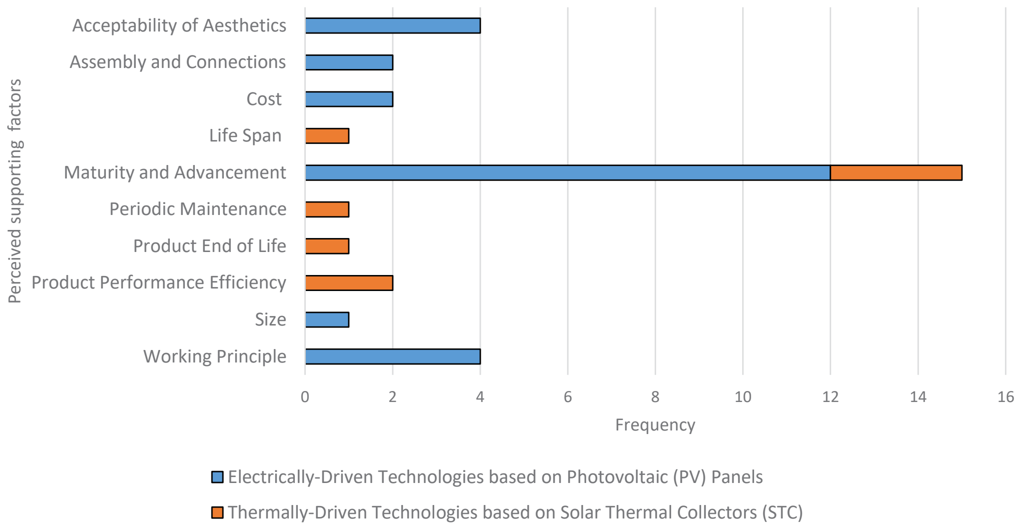

FIG. 3.6 Perceived factors supporting the widespread application of façade integration of current technologies

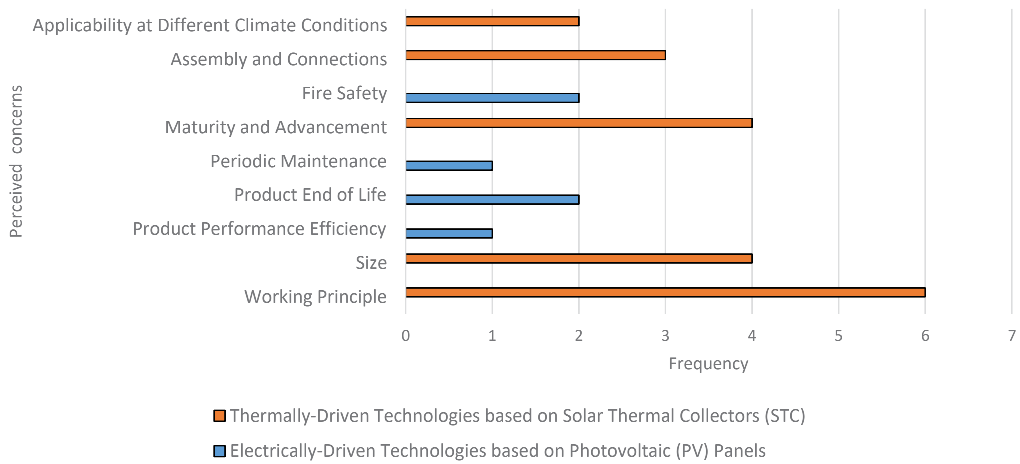

FIG. 3.7 Perceived concerns related to the façade integration of current technologies

TABLE 3.1 Perceived factors and concerns related to the façade integration of current technologies

Aspect	Electrically-Driven Technologies based on Photovoltaic (PV) Panels		Thermally-Driven Technologies based on Solar Thermal Collectors (STC)	
	Perceived as a supporting factor	Perceived as a concern	Perceived as a supporting factor	Perceived as a concern
Acceptability of Aesthetics	In comparison to other technologies, the aesthetics of current PV products have been perceived to be easily accepted by various stakeholders in the building industry, since they can have various colours that can be accepted regardless of their performance.	–	–	–
Applicability at Different Climate Conditions	–	–	–	Some concerns are related are associated with the applicability of some thermally–driven technologies at different climate conditions.
Assembly and Connections	PV technologies have been perceived to be simple products, since the assembly and connections of components can be carried out easily on–site.	–	–	The connections and installations of solar thermal technologies have been perceived to be complex due to the involvement of hydraulic components: Interviewee 14: “And then when you start with solar thermal and then even bringing solar cooling systems into the façade, then it becomes even more complex where the façade contractor says “I’m not doing hydraulic, I’m not doing water, I’m not doing electricity. I’m just installing simply set panels or façade units. But all these technical components that are more MEP driven are not my field of expertise.”
Cost	The costs of PV technologies have been perceived to decrease over time, and it is becoming more financially feasible, compared to other technologies, such as thermally driven technologies.	–	–	–

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TABLE 3.1 Perceived factors and concerns related to the façade integration of current technologies

Aspect	Electrically-Driven Technologies based on Photovoltaic (PV) Panels		Thermally-Driven Technologies based on Solar Thermal Collectors (STC)	
	Perceived as a supporting factor	Perceived as a concern	Perceived as a supporting factor	Perceived as a concern
Product End of Life	–	To minimize the carbon footprint, building regulations support the low amount of waste generated at the end of the life of building products. However, the amount of waste related to the end of life of PV technologies has been perceived to be crucial.	Thermally driven technologies are perceived to have less harmful effects on the environment at the end of their life.	–
Fire Safety	–	The fire safety associated with some current PV technologies has been perceived as a critical concern affecting the widespread application.	–	–
Life Span	–	–	Some of the thermally driven technologies are perceived to have a long life span.	–
Maturity and Advancement	The maturity of PV technologies has been perceived to be in an advanced stage, with ongoing improvement. The level of knowledge in the building industry regarding their integration into building facades is perceived to have increased during the last years due to the availability of specialized companies working on them. Additionally, PV technologies have been perceived to have flexibility in their use, considering different sizes of buildings.	–	There are some perceptions that are related to the future improvements in the use of solar thermal technologies in buildings, such as the use of flat plate collectors that can be customized in terms of colours.	The development and widespread application of façade products integrating solar thermal technologies is perceived to be slower than solar electrically–driven technologies.

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TABLE 3.1 Perceived factors and concerns related to the façade integration of current technologies

Aspect	Electrically-Driven Technologies based on Photovoltaic (PV) Panels		Thermally-Driven Technologies based on Solar Thermal Collectors (STC)	
	Perceived as a supporting factor	Perceived as a concern	Perceived as a supporting factor	Perceived as a concern
Periodic Maintenance	–	The concern has been perceived by Interviewee 2, which is related to the number of periodic maintenance required for the system and the time consumed in maintaining the technologies: "The maintenance required for the photovoltaic and the compression system usually is more time–consuming and should be done more regularly, especially for the compression cooling system. It has to be maintained at least once a year with the re–fuelling of the cooling agent, the Freon, and these gases."	The amount of periodic maintenance can be low for some absorption chillers: "You have the absorption cooling, for example, where you only have to maintain it once every two years" (Interviewee 2).	–
Product Performance Efficiency	–	Some solar thermal technologies have been perceived to have higher efficiencies compared to some of the solar electrically–driven technologies.	Some of the solar thermally–driven cooling technologies can reach high efficiencies: Interviewee 2: (1) "while solar thermal can reach 80% or higher depending on the type of collector and quality and so on", Interviewee 22: (2) "Although if you have good use cases, you can collect more energy overall with the thermally–driven technologies and if you can make use of them they might be worth well considering".	–

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TABLE 3.1 Perceived factors and concerns related to the façade integration of current technologies

Aspect	Electrically-Driven Technologies based on Photovoltaic (PV) Panels		Thermally-Driven Technologies based on Solar Thermal Collectors (STC)	
	Perceived as a supporting factor	Perceived as a concern	Perceived as a supporting factor	Perceived as a concern
Size	PV technologies have been considered to be simple technology due to their compact sizes compared to thermally-driven technologies.	–	–	The application of some of the solar thermal cooling technologies can be challenging in small-sized projects. They have been considered to have complexities in terms of their sizes due to the availability of bulky components.
Working Principle	PV technologies have been perceived to have simpler working principles compared to other technologies, since they neither involve the use of any flowing liquids nor the use of hydraulic components.	–	–	The working principles of some thermally-driven technologies have been perceived to be complex, as decentralizing solar thermal cooling technologies requires the incorporation of different types of fluids that need to be circulated within the system. Furthermore, other concerns have been perceived are related to the potential risks of water freezing, water tightness, as well as dealing with the collected heat that cannot be used for other purposes, compared to the electricity generated by photovoltaic.

3.3.2.2 Perceptions of the Future Applications Based on Building Type

Figure 3.8 summarizes the perceptions of future applications based on building types. It is obvious that office buildings have been considered to be the most relevant building type for applying SCIFs due to the internal heat gains, such as office equipment, and the required cooling demand. The relevance was also linked to the fact that office buildings are used during the daytime when solar radiation is available. The owners or the investors of office buildings have been perceived to be willing to invest in sustainable solutions. Public buildings, such as governmental or educational buildings, were considered to be relevant due to the possibility of having

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a higher total project budget. Furthermore, they were considered to be suitable due to the potential of having an owner who can be representative of public bodies interested in lowering energy consumption. On the other hand, public buildings have been perceived to be irrelevant by interviewee 15, considering an example of the Spanish context, because regulations associated with procurements in such types of buildings do not allow the selection of a particular company supplying particular products. Regarding residential buildings, many interviewees have perceived them to be irrelevant due to various factors, such as a low amount of cooling demand in such buildings in many European countries. Furthermore, the irrelevancy has been linked to the mismatch between the peak energy demand for cooling during the daytime, when the building occupants are outside at workplaces. In addition, building occupants in residential buildings have been perceived to prefer living in traditional buildings, rather than implementing new technologies. Finally, residential apartment buildings having multiple tenants were perceived to be irrelevant due to the potential difficulties associated with energy payments per apartment, as well as convincing every tenant about new technologies.

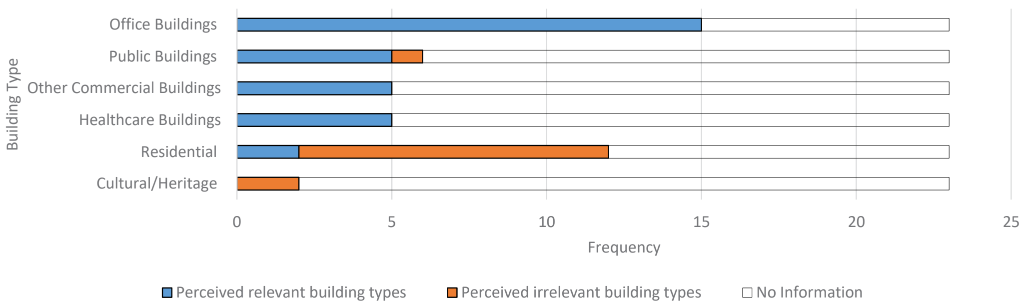

FIG. 3.8 Perceptions of the future applications based on building type

3.3.2.3 Perceptions of the Future Applications Based on Project Type

As indicated in **Figure 3.9**, new building construction projects have been perceived to be more relevant types of projects, since integrating new technologies can be considered during early design stages, where there is more design freedom. Renovation projects have been perceived to be relevant in the case of heaving compact products that can be integrated into building facades, especially when there are constraints with the available rooms or floor heights. Hence, building

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facades have been considered a suitable option to integrate new technologies. On the other hand, renovation projects have been perceived to be irrelevant due to various factors, such as when local building regulations do not allow adding new technologies or making any changes in existing buildings. Furthermore, the irrelevancy was linked to a lack of design freedom in such projects, such as in the case of having bulky components and the restrictions with the available space or the potential of adding high loads in existing building structures. Furthermore, issues related to disturbing building occupants have also been considered as a challenge when considering such technologies.

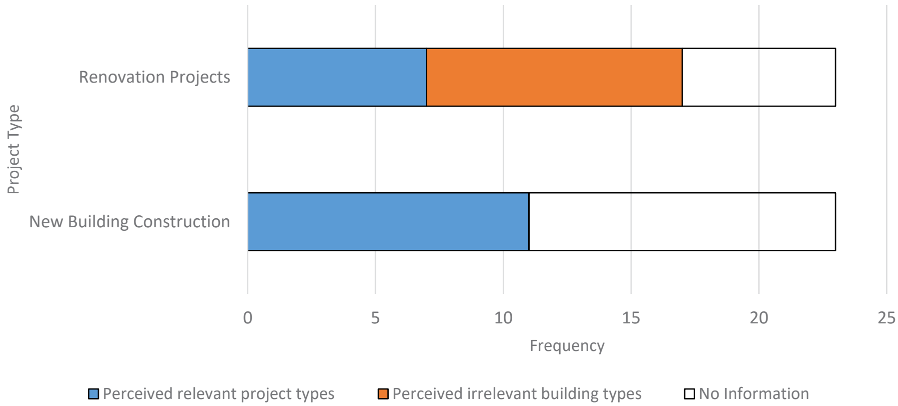

FIG. 3.9 Perceptions of the future applications based on project type

3.3.2.4 Perceptions of the Future Applications Based on the Location and Climate Conditions

As indicated in **Figure 3.10**, various factors have been perceived to affect the application of SCIFs based on the location and climate conditions, which are as follows:

- **Geographic Location:** Geographic locations of buildings have been considered a key factor affecting the application of SCIFs. Southern European countries, such as Italy, Greece, and Cyprus, as well as Mediterranean climates, were perceived to be relevant to applying such technologies. Middle Eastern countries, such as Saudi Arabia and the United Arab Emirates, were also identified to be suitable for such technologies.

- **Urban Effect:** The urban effect of surrounding buildings has been identified as a key factor affecting the application of SCIFs. Avoiding the shading effect has been perceived to be taken into account in order to ensure proper performance of such technologies.
- **Building Orientation:** The building orientation and the façade exposure to solar radiation have been considered to affect the application of SCIFs, such as considering the application in south-oriented facades in Northern areas.
- **Solar Radiation Availability:** The availability of solar radiation has been identified to be a key factor influencing the applicability of SCIFs. Different perceptions have been mentioned by the interviewee. Some interviewees have mentioned the importance of having more solar radiation areas, whereas others have mentioned the importance of having a moderate amount of solar radiation to avoid overheating issues. On the other hand, interviewees 14 and 23 declared that such a factor depends on every project.
- **Cooling Demand in Buildings:** Cooling demand in buildings has been perceived to affect the applicability of SCIFs. Buildings located in areas where cooling demands are high have been considered to be more relevant, such as when cooling demands are required more than six months a year, or they account for more than 70% of the total energy consumption.
- **Humidity Effect:** Humid climates have been identified as a key factor affecting the application of SCIFs, since the applicability of some thermally driven technologies can be challenging due to difficulties associated with heat rejection.

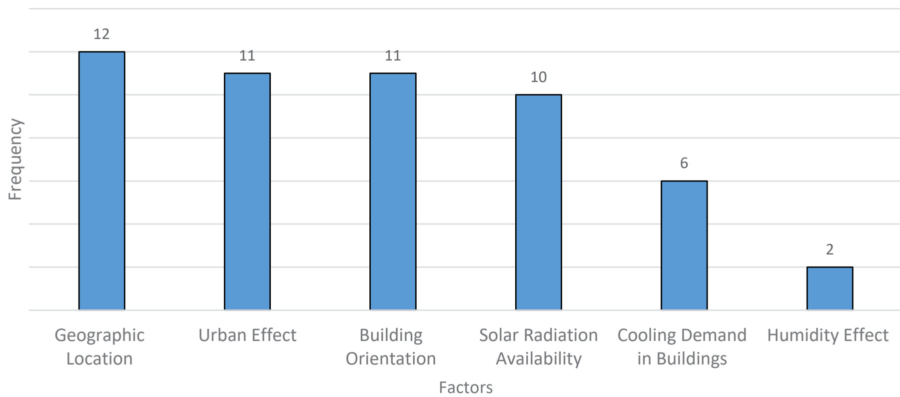

FIG. 3.10 Perceived factors affecting the application of SCIFs based on the location and climate conditions

3.4 Discussion

This study aimed to identify key perceived enabling factors and prospects of future applications related to the widespread application of SCIFs from the point of view of various professionals, including participants who worked in projects involving the application or façade integration of solar/SCTs. Having an insight into the identified and mapped key factors in **Figure 3.5**, **Table C.1**, **Figures C.1** and **C.2**, it is obvious that the majority of factors have been linked to the design phase. Although this can be related to the fact that all of the 23 interviewees declared to have been involved in the design phase of building facades (**Figure B.3**), early decisions regarding the application of new technologies should be taken into account early stages in order to simplify the installation of components. Furthermore, such decisions consider the importance of having a proper system operation during the use phase in order to avoid various issues related to the inefficient use of the technology. Accordingly, it is essential to tackle such a critical phase, which may include the involvement of different identified enabling factors as key performance indicators to be used in the design and evaluation of SCIFs. Furthermore, tackling the design phase may take into account the importance of identifying key stakeholders involved in the project, since the multidisciplinary teamwork and facilitating the delivery of product information to architects and clients were among the most frequently mentioned factors. However, the determination of such factors requires considering different aspects, including the type of technology to be integrated into the façade, the nature of the project, as well as the local context of the building industry. Accordingly, the applicability of the perceived enabling factor obtained from this exploratory study depends on various aspects, including the project size and stakeholders involved, location, technologies to be considered, building typology, and project type (existing, various newly built). For example, although prefabrication has been identified as an enabling factor, Interviewee 1 has some concerns related to the fact that on-site work is still common in many countries (**Table C.1**).

Apart from the design phase, the majority of the key factors that have been linked to the end-of-life phase are the ones that are related to the circularity concepts, as well as R-strategies, such as reusability and recyclability. This can be due to the fact that several efforts and initiatives are moving towards minimizing the amount of waste generated from the building industry.

Although standardizing and customizing products tend to be two opposite factors, both of them have been considered to enable the widespread application. Standardization has been identified to reduce production costs, as well as increase the knowledge and experience of architects, since they can become more familiar with the same product when it is used for more than one project. On the other hand, the ability to customize, including colours, shapes, and/or sizes, was perceived to support the widespread application, especially when considering the role of aesthetics in the widespread application. However, the mass customization, such as in the automobile industry, where the core of products can be similar with different external layers, has been declared by interviewee 4 to enable the widespread application of SCIFs.

Having an insight into the perceptions of the status of current technologies, it is obvious that the maturity and advancement of PV technologies have been perceived as the main factor supporting the widespread application of integrating current electrically-driven solar cooling technologies into building façades. Although this perception can be linked to the fact that the majority of interviewees have worked in projects involving the application (17 interviewees according to **Figure B.5**) or façade integration (13 interviewees according to **Figure B.4**) of solar technologies using PV panels, this cannot deny the fact that PV technologies have been improved over time.

Although various justifications have been mentioned regarding the relevance of office buildings as suitable building types to apply such technologies, such relevance might be different in contexts other than Europe. Regarding the relevance or irrelevance of applying SCIFs in renovation projects, it should be noted that various aspects can affect the application of such technologies in existing buildings, such as the compactness of the technology as well as the project nature, including the size of the building.

3.5 Conclusion

Solar cooling technologies (SCTs) have the potential to reduce primary energy consumption for space cooling. Building façades provide an opportunity to integrate SCTs because they provide external surfaces exposed to solar radiation, and also have an impact on the indoor thermal comfort. Enabling the widespread application of integrating SCTs into façades can be challenging due to the involvement of technical and product (T&P), financial (F), as well as process and stakeholder (P&S) related aspects. Identifying key enabling factors in the context of various aspects is an important step, providing relevant knowledge for implementing solutions supporting the widespread application. Accordingly, this study aims to identify the main factors enabling the widespread integration of SCTs in façades from the point of

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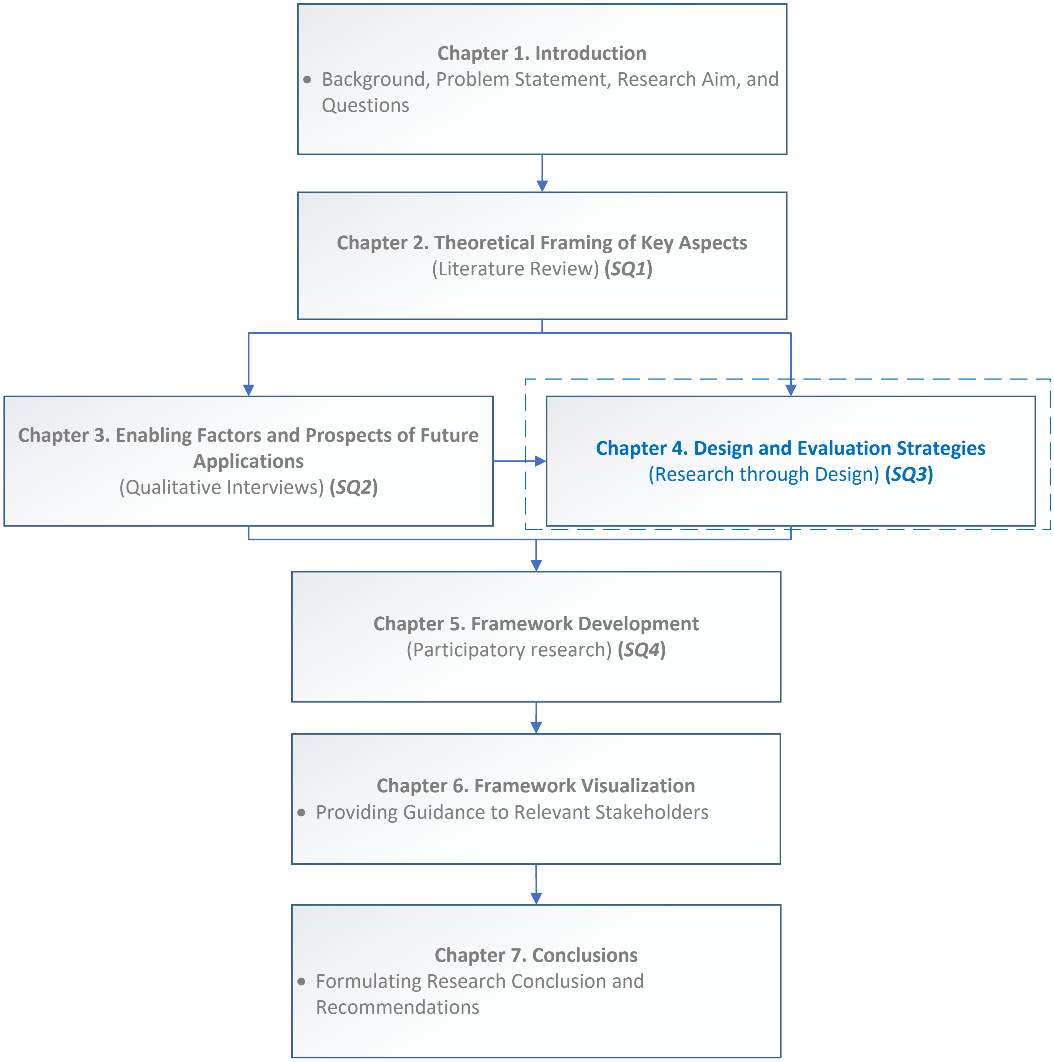
view of various experts. An interview guide was designed to tackle the main aspects to be considered for supporting the widespread application, including T&P, F, and P&S-related aspects. Different criteria were considered to select the interviewees during the data collection, such as having participants worked in projects involving the application or façade integration of solar/SCTs in buildings. The data analysis involved a hybrid approach, combining deductive and inductive coding. The findings revealed that there are key factors supporting the widespread application, such as product performance and efficiency, multidisciplinary teamwork, and facilitating the delivery of product information to architects and clients, aesthetic acceptability, and the ability to customize products. The enabling factors were mapped in the context of façade design and construction processes to establish a matrix for implementing solutions in product development. The results also indicated that solar electrically-driven technologies (based on Photovoltaic modules) tend to be one of the most promising technologies. Furthermore, office buildings have been perceived to be one of the most relevant types of buildings to be considered for such technologies. The identified enabling factors and prospects of future applications of solar cooling integrated facades (SCIFs) contribute to expanding the boundaries of knowledge in the field of building product development. The established matrix of enabling factors obtained from this exploratory study provides information that can be considered and investigated in future works related to the development of frameworks supporting the widespread application of SCIFs, since the applicability of perceived factors depends on various aspects. The aspects include project size and stakeholders involved, location, technologies to be considered, building typology, and project type (existing, various newly built). Accordingly, future framework developments can consider the applicability of particular SCTs in particular contexts, such as investigating the future application of these technologies in newly built office buildings.

This study was limited to the key perceived enabling factors and prospects of future applications based on the European perspective. Accordingly, the findings of this study can be more relevant for the European context. Accordingly, future research scope can investigate the application of SCIFs in a relevant European context, such as newly built office buildings, by considering some of the identified enabling factors as Key Performance Indicators (KPIs) to evaluate the developed concepts of façade products.

Acknowledgement

The authors are grateful to Prof. Dr.-Ing. Tillmann Klein, one of the co-authors of this paper, sadly passed away during the review process of this article. The authors would also like to thank members and colleagues in the Architectural Facades and Products research group who provided insights into the interview guide. Also, they would like to express their gratitude and appreciation to all participants involved in testing the interview guide as well as during the data collection phase. Special thanks to Prateek Wahi for his kind help in the proofreading of the paper.

This study was approved by the Human Research Ethics Committee (HREC) at TU Delft on 04-April-2022. The research team obtained informed consent from all participants involved in the study. The authors followed the committee regulations, including the interview tools for recording as well as obtaining the interviewee's signature in a consent form. The audio recording for the virtual and in-person interviews was conducted by the Microsoft Teams platform and the Tascam DR-05 digital recorder, respectively. The interviewees signed the consent form virtually, agreeing to the audio-recording of the interviews that will be stored on the institutional storage drive, where it will have restricted access only among the study team. Furthermore, they agreed on using, processing, and publishing the anonymized transcriptions of the interviews.


Chapter 1. Introduction
Background, Problem Statement, Research Aim, and Questions
Chapter 2. Theoretical Framing of Key Aspects
(Literature Review) (SQ1)
Chapter 3. Enabling Factors and Prospects of Future Applications
(Qualitative Interviews) (SQ2)
Chapter 4. Design and Evaluation Strategies
(Research through Design) (SQ3)
Chapter 5. Framework Development
(Participatory research) (SQ4)
Chapter 6. Framework Visualization
Providing Guidance to Relevant Stakeholders
Chapter 7. Conclusions
Formulating Research Conclusion and Recommendations

4 Design and Evaluation Strategies

Chapter 4 aims to answer the third sub-question:
SQ_3 – How can systematic early-stage design and feasibility assessment of SCIFs be supported?

Answering this sub-question involved developing key strategies guiding the design and evaluation of façade products integrating solar cooling technologies. The strategies were developed using a research-through-design methodology, considering a relevant context and a proposed evaluation set-up to assess techno-economic feasibility. The sub-question was answered in the following publication: "Hamida, H., Prieto, A., Beneito, L., Konstantinou, T., & Knaack, U. (2025). Design and Evaluation Strategies for Solar Cooling Integrated Façades: A case study in a Southern European office building. Journal of Building Engineering, 105, Article 112440. https:*//doi.org/10.1016/j.jobe.2025.112440". ***Chapter 4*** is a modified version of this publication. The modifications include revising figures related to the research approach and methods section to ensure they are aligned with the section numbers in the thesis. Additionally, the research question has been rephrased to be shorter and more focused. In the revised version, the term "solar cooling integrated façade" has been replaced with the acronym SCIFs. The wording also shifts to emphasize the support of a systematic early-stage design and feasibility assessment.*

ABSTRACT

Integrating solar cooling technologies into building façades can play a crucial role in reducing reliance on conventional cooling systems. However, incorporating various aspects at the early stages of a project can be challenging for designers due to the diverse types of information, steps, and decisions required. This study aimed to develop strategies for design teams to facilitate the early-stage design and evaluation of building façades integrating solar cooling technologies. The strategies were developed using a research-through-design methodology, considering the Spanish context and a proposed evaluation set-up to assess techno-economic feasibility. The development of strategies involved mapping the design and evaluation of solar cooling integrated façades by identifying and relating key processes, inputs, outputs, design decisions, and tools within key design stages. Consequently, a systematic design and evaluation process was carried out, including the identification and assessment of potential integration scenarios for solar electrically driven and thermally driven technologies based on relevant techno-economic criteria. The findings indicate that water-cooled vapor-compression chillers (VCC),

combined with photovoltaic (PV) panels as an electrically driven solution, were the most relevant option for the selected case. Additionally, the developed strategies revealed that early-stage decisions significantly impact later processes, as they involve a greater number of steps, required information, and design choices. These strategies serve as guidelines to support designers in adopting a systematic design approach, helping to manage the complexities associated with processing diverse technical and economic information. Providing such structured methodologies to professionals with limited experience in solar cooling technologies is crucial for enabling their broader application.

4.1 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 & Sawachi, 2020; Sahin & Ayyildiz, 2020; Santamouris, 2016). This demand increase can lead to a rise in the use of cooling systems, depending on the 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 (GHGs) emissions generated from energy consumed by conventional cooling systems.

Producing a cooling effect through solar radiation is one of the suitable options intended to mitigate challenges related to cooling demand in the built environment. The peak cooling demands can be proportional to the solar intensities due to the maximum sunlight hours (Otanicar et al., 2012; Tiwari et al., 2016). The main advantages of applying such techniques, namely solar cooling technologies, include lowering peak energy demand to reduce costs and being environmentally friendly, with no impact on ozone depletion (Tiwari et al., 2016). Solar cooling technologies, introduced in the 1970s, are designed to produce conditioned air or chilled water using solar energy (He et al., 2019). These technologies can generate hot water using Solar Thermal Collectors (STC) or produce electricity through Photovoltaic (PV) panels (Sarbu & Sebarchievici, 2016). Accordingly, this highlights two main approaches for converting solar energy into a cooling effect: thermally driven processes and electrically driven processes (Alahmer & Ajib, 2020; Alsagri et al., 2020; He et al., 2019; Karellas et al., 2019; Neyer et al., 2018; Sarbu & Sebarchievici, 2016).

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Having an insight into the built environment, building facades present high potential for integrating solar cooling technologies. Such a part of the built environment can have a crucial effect on the indoor thermal requirements. At the same time, they can provide a considerable amount of surfaces exposed to solar radiation (Prieto, Knaack, Auer, et al., 2018a). The wealth of technical strategies and interdisciplinary knowledge has boosted façade engineering, driving advancements in the building envelope industry (Laufs & Verboon, 2013). Building façades have become multifunctional components that have an active role in the building energy system. These multifunctional components integrate technologies contributing to energy savings and meeting thermal requirements (Bonato et al., 2020; Ibraheem et al., 2017; Prieto, Klein, et al., 2017). Although there are different definitions in literature related to solar active façades of solar cooling integrated façades (Ochs et al., 2020; Prieto, Knaack, et al., 2017a), the following definition can be relevant as it provides more flexibility when it comes to building integration (Hamida, Konstantinou, Prieto, & Knaack, 2023):

"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 a cooling effect in a particular indoor environment."

The design and development of solar cooling integrated façades should take into account various aspects, which include the following (Hamida et al., 2022):

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

Such multiple aspects are linked to the fact that various social phenomena are connected to multiple bodies of knowledge across different disciplines (Jabareen, 2009). However, addressing these aspects at the early stages of a project can be challenging, as it introduces complexities for the design team due to the diverse types of information, steps, and decisions required. This includes considering regulatory and passive measures, weather data, cooling demand, supplementary building services, and façade integration pathways (Noaman et al., 2022; Prieto, Knaack, et al., 2017a; Prieto, Knaack, Auer, et al., 2018a). Therefore, it has been emphasized that providing design approaches to professionals with limited experience in such technologies plays a vital role in enabling their widespread application (Saini & Weiss, 2023). In response, this study aims to develop key strategies for guiding the design and evaluation of solar cooling integrated façades to support broader adoption. These strategies serve as guidelines to help designers adopt a systematic design approach, managing the complexities associated with processing diverse technical and economic information related to both quantitative and qualitative criteria. Providing such structured methodologies to professionals is crucial for facilitating their broader implementation, contributing to the broader goal of sustainable building practices by reducing reliance on conventional cooling systems. The main research question to be investigated in this study is as follows:

- **How can systematic early-stage design and feasibility assessment of SCIFs be supported?**

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

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

Section 4.2 explains the research approach and methods adopted to develop the aforementioned strategies. Then, **Section 4.3** provides the findings related to the case study steps based on the adopted research methodology, which cover the systematic design and evaluation of solar cooling integrated façades. After that, **Section 4.4** presents the development of key strategies guiding the design and evaluation of solar cooling integrated façades. **Section 4.5** discusses the findings obtained from the case study and the developed strategies. Finally, the study ends with the conclusion section (**Section 4.6**) that states the future research scope.

4.2 Research Approach and Methods

To develop key strategies guiding the design and evaluation of SCIFs, the methodology of this study is based on a research through design approach and methods (**Figure 4.1**), which involves gathering and organizing relevant information and mapping key decisions required to design and evaluate solar cooling integrated facades, considering the definition of (Hamida, Konstantinou, Prieto, & Knaack, 2023). Hence, the scope of designing such integrated façades assumes having a standalone building envelope system using and/or controlling solar radiation to deliver self-sufficient solar renewable electric and/or thermal energy needed to generate a cooling effect in a particular indoor environment. Therefore, the harvested solar energy from solar collection devices is considered to be used for cooling purposes. The following sections describe the research approach and methods adopted to develop the strategies, which include the study context (**Section 4.2.1**), key design stages (**Section 4.2.2**), evaluation set-up (**Section 4.2.3**), and the development of key design strategies (**Section 4.2.4**).

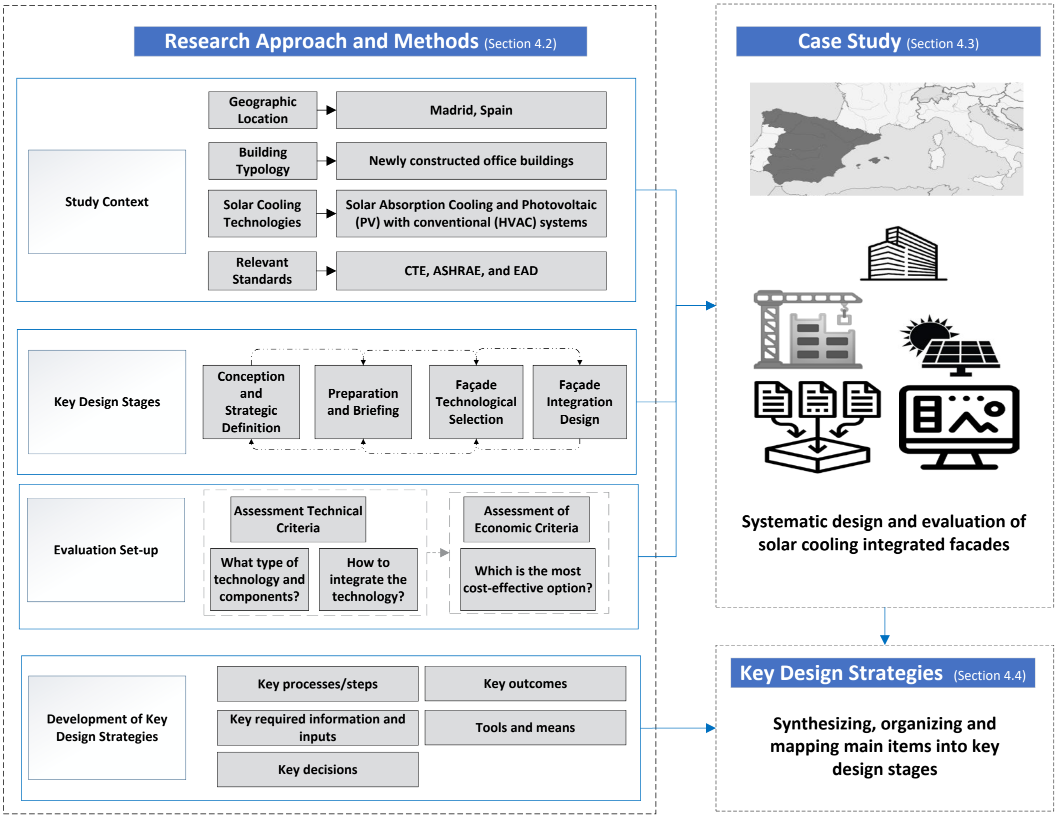

FIG. 4.1 Research methodology for the development of strategies

4.2.1 Study Context

The design and development of building façades integrating solar cooling technologies should consider particular scope and boundary conditions (Hamida, Konstantinou, Prieto, & Knaack, 2023). This includes having a particular geographic location and climate conditions, as well as a certain building typology.

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4.2.1.1 Geographic Location

Firstly, the strategies consider the application in Southern European regions, which have been identified by experts in the European building industry to be one of the relevant contexts due to the urgency in terms of cooling demand requirements (Hamida, Konstantinou, Prieto, & Klein, 2023b). Furthermore, the applicability of various solar cooling technologies, including absorption, adsorption, as well as thermoelectric systems, in hot-summer Mediterranean climates tends to be feasible (Prieto, Knaack, Auer, et al., 2018a; Prieto, Knaack, Klein, et al., 2018). Accordingly, for the sake of this study, the Spanish context has been selected. The country has different climate conditions, which cover the predominant Mediterranean feature (Valencian Institute of Building, 2011). Madrid city was the focus of the study, which has a cold semi-arid climate according to the Köppen-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 increased by around 2.6 times during the last four decades (Inspain News, 2023). Furthermore, Madrid tends to have a large office market and investments. The country had a total of €728 million invested in the offices in the first half of 2023, and it 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).

4.2.1.2 Building Typology

The strategies focus on integrating solar cooling technologies into new building construction. Such projects tend to allow a greater degree of design freedom when applying new technologies compared to existing buildings (Hamida, Konstantinou, Prieto, & Klein, 2023b; Oropeza-perez & Østergaard, 2018). Furthermore, the strategies are intended for office buildings, as they are considered the most relevant building type for such applications compared to residential buildings (Hamida, Konstantinou, Prieto, & Klein, 2023a).This building typology typically experiences high heat gains, which result from various sources, including office equipment, lighting systems, and building occupants (Raji et al., 2017). Additionally, office buildings are particularly relevant since they are primarily used during periods of available solar radiation. Owners and investors of these buildings are also perceived to be more inclined to invest in sustainable solutions compared to other building types, such as residential buildings (Hamida, Konstantinou, Prieto, & Klein, 2023a). Therefore, this study focuses on newly constructed office buildings. It should be noted that previous studies have primarily examined a single, simplified office room, without considering an entire building (Bonomolo et al., 2023; Noaman et al., 2022; Prieto, Knaack, Auer, et al., 2018a). The inclusion of a typical building case in a specific context helps demonstrate the practical applicability of these strategies.

The building industry and office façade typologies are fragmented with various construction materials and systems (Ebbert, 2010). Many of the existing office buildings tend to have a combination of various façade types and elements, such as curtain walls, double façades, shading devices, and overhangs. Accordingly, developing the strategies based on a generic typical office with various façade types and elements is essential to demonstrate its applicability in practice through determining different possibilities for façade integration. The selected building case is a generic 5-story office building (**Table 4.1**). 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 & Donn, 2017). This includes the fact that the majority of the external walls consist of glazed units attached to a concrete structure, although the backside of the building consists mainly of opaque walls (window-to-wall ratio of about 1%).

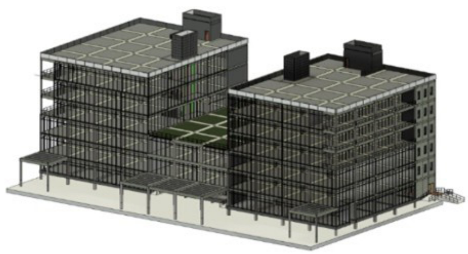
4.2.1.3 Solar Cooling Technologies

Since the strategies focus on supporting the process of designing and evaluating solar cooling integrated façades at early project stages, the study involves relevant and available solar cooling technologies. Therefore, sizes, performances, and efficiencies are based on available components. It was essential to focus on particular technologies to be considered in the process of generating and evaluating scenarios with respect to design criteria. Hence, this study aimed to involve relevant options for solar electrically-driven and thermally-driven technologies. For electrically-driven systems, the use of Photovoltaic (PV) for cooling through coupling it with conventional heating, ventilation, and air conditioning (HVAC) systems provides advantages related to construction simplicity and high efficacy. Furthermore, the maturity and advancement of PV technologies were considered as a key factor supporting the widespread integration of electrically-driven solar cooling technologies into façades (Hamida, Konstantinou, Prieto, & Klein, 2023b). For thermally-driven technologies, solar absorption cooling was identified to be a relevant option, as the literature pointed out that solar absorption chilling is found to have the highest growth rate compared to all the other solar thermal cooling systems (Alsagri et al., 2020). Solar absorption cooling technologies were found to have relevant technical feasibility in hot summer Mediterranean and hot desert climate contexts, which indicates their potential for being a promising candidate to be applied at different warm regions (Prieto, Knaack, Auer, et al., 2018a; Prieto, Knaack, Klein, et al., 2018). 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 & Ajib, 2020).

4.2.1.4 Relevant Standards

Because it is essential to understand key aspects to be considered in the decision-making process for integrating technologies into building façades, (Prieto, Knaack, et al., 2017a) demonstrated that the design and development of solar cooling integrated façades involve the inclusion of additional functions into façades, which represent a secondary step to be considered when other passive and regulatory measures are unable to meet indoor requirements. Accordingly, the study aims to reduce energy and cooling demand using relevant guidelines. Although various guidelines can be applied during the design process, this study involved the use of the Spanish Technical Building Code (CTE) when selecting the U-value of the thermal envelope to align with current construction practices (CTE, 2022). Although the study focused mainly on the CTE code as a main standard to establish the reference model, it also involved referring to the ventilation for acceptable indoor air quality standard published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the American National Standards Institute (ANSI) to set some ventilation requirements (ANSI/ASHRAE Standard 62.1- 2019, 2019; Cortiços & Duarte, 2022). Finally, EAD 090062-01-0404, Kits for external wall cladding mechanically fixed, was adopted as a relevant reference standard to demonstrate the façade detailing and connections (EOTA, 2021).

TABLE 4.1 Overview of the selected building case

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

4.2.2 Key Design Stages

The scope of developing key strategies guiding design decisions considers that it supports designers at different early key design stages with guidelines that can enable ending up with suitable façade solutions. This is due to the fact that having a proper design can avoid many issues, as well as ensure proper assembly and operation (Hamida, Konstantinou, Prieto, & Klein, 2023b, 2023a). There are various ways and categorizations of design and construction stages that are available in the literature (Klein, 2013; Oliveira & Melhado, 2011; Prieto et al., 2023; RIBA, 2020). Hence, it is essential to have a structuring of the key design stages that can be used for the strategies. The structured key design stages are as follows:

1. **Conception and Strategic Definition:** The key outcomes of the conception and strategic definition stage include the possibilities for façade integration. The stage is intended to establish a reference model as a benchmark for investigating different scenarios (Ochs et al., 2020). Accordingly, it was essential to identify constant parameters to define the basis of the reference model (Ferrari & Zanotto, 2016). The assumptions of constant parameters include climate contexts, internal heat loads (occupancy schedule and density), heating, cooling, and air conditioning (HVAC), and air infiltration. Also, establishing the model requires identifying construction characteristics of the thermal envelope elements according to national energy saving guidelines.

2. **Preparation and Briefing:** This stage aimed to assess the feasibility of the generated possibilities, considering relevant design criteria related to key aspects affecting façade integration.

3. **Façade Technological Selection:** This stage aims to select the relevant architectural façade technology, based on the outcomes of the preparation and briefing phase, namely, technical and economic feasibility.

4. **Façade Integration Design:** This stage aims to present the detailed design of integrating the selected technology into the façade, considering the characteristics of key elements as well as relevant reference standards for component connections (Alvarez-Alava et al., 2023).

Although these stages may not be linear, as the nature of the design process can depend on regular feedback (Knaack et al., 2014). Such structuring facilitates having a framework for designing solar cooling integrated façades systematically, and also developing the design strategies.

4.2.3 Evaluation Set-Up

To assess the feasibility of façade integration during early design stages, it is crucial to have an evaluation setup that can enable an appropriate comparison of different design alternatives with respect to relevant criteria. This section explains the proposed evaluation set-up to assess design scenarios during the case study. The scope of the proposed evaluation setup consisted of a techno-economic assessment methodology (Dehwah et al., 2020; Gabbrielli et al., 2016; Lai et al., 2024), corresponding mainly to T&P-&F-related, as they can be assessed and compared with certain criteria. The stepped methodology adopted consisted of two parts, which aimed to assess the technical (**Section 4.2.3.1**) and economic (**Section 4.2.3.2**) criteria, respectively.

Considering this design-based research, it was essential to have a well-established compilation of parameters, requirements, measurable criteria, and indicators using both quantitative and qualitative techniques (Rodrigues et al., 2023; Wahi et al., 2023). **Figure 4.2** and **Table 4.2** provide an overview of the design evaluation setup and criteria, which are described in the following subsections. The established requirements were primarily based on relevant literature, incorporating lessons learned from professionals working in the façade and/or solar industries (Hamida, Konstantinou, Prieto, & Klein, 2023b; Prieto et al., 2019). The assessment of technical and economic criteria is described in **Sections 4.2.3.1** and **4.2.3.2**.

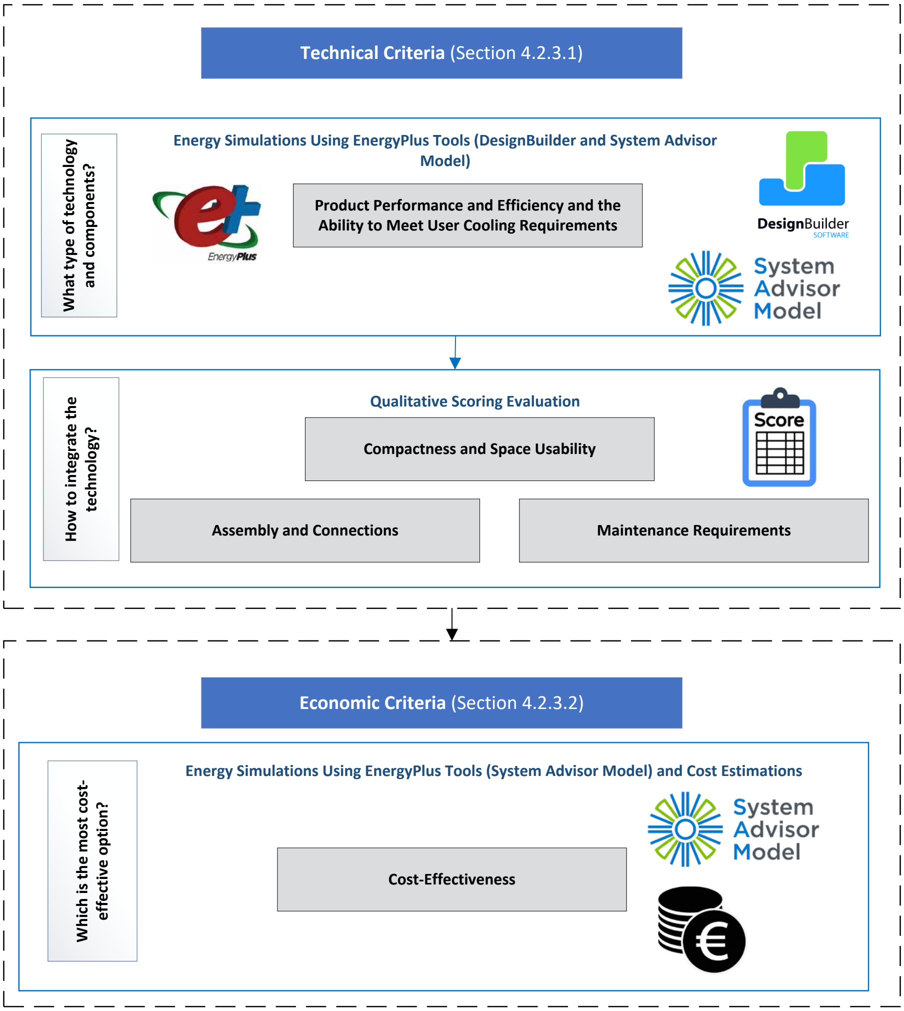


FIG. 4.2 Multi-stepped evaluation methodology

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TABLE 4.2 Overview of design criteria and requirements involved in the multi-stepped evaluation methodology

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

4.2.3.1 Technical Criteria

The step of evaluating technical feasibility can involve various parameters. For instance, Prieto et al. (2019) qualitatively evaluated different technologies in terms of potential façade integration. The aspects were based on the suitability of the technology in addressing key product-related barriers defined by the authors. These aspects included performance, physical integration, feasibility of integrating the system into façade modules, durability and maintenance, aesthetics, and availability. On the other hand, Hamida, Konstantinou, Prieto, & Klein (2023b) identified various aspects from qualitative interviews that were perceived as either supporting factors or concerns related to the façade integration of solar electrically-driven or thermally-driven technologies. Aspects identified and covered included aesthetic acceptability, applicability in different climate conditions, costs, product end-of-life, fire safety, lifespan, maturity and advancement, periodic maintenance, product performance and efficiency, sizes, and working principles. Considering these various aspects, it was essential to synthesize them into relevant evaluation criteria. Hence, a total of four evaluation criteria were adopted to assess technical feasibility, evaluated in two phases, as follows:

What type of technology and products?

This phase considers the first design criterion, namely product performance and efficiency, as well as the ability to meet user cooling requirements. This criterion is assessed using the Solar Fraction (SF) as an indicator (**Table 4.2**). The SF is one of the most commonly used metrics for evaluating the technical feasibility of solar cooling-integrated façades (Ibrahim et al., 2024; Noaman et al., 2022; Prieto, Knaack, Auer, et al., 2018a). This indicator is calculated by dividing two main parameters: the cooling effect delivered by the selected technology and the cooling demand of a particular indoor environment. This type of analysis serves as a numerical method to determine the required surface area to meet the building's cooling demand. It also facilitates the comparison of different scenarios and technological configurations in terms of their ability to provide the self-sustaining solar energy needed to generate cooling in a specific indoor environment at early design stages. However, previous studies have used a simplified equation to assess the SF, considering only losses in components related to cooling generation while neglecting losses associated with storage and distribution components (Hamida et al., 2024; Noaman et al., 2022; Prieto, Knaack, Auer, et al., 2018a). It should be noted that storage and distribution components have been identified as having a critical effect on energy loss in solar cooling systems, depending on various factors, including how properly insulation is applied to the components (Shirazi et al., 2018). Therefore, improving the accuracy of SF assessment should ensure a more precise representation of energy losses by incorporating all stages, including generation, conversion, storage, and distribution. Equations 1 and 2 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 the summer season according to the weather data file. Scenarios having an SF value of one or more are considered in phase 1.2.

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$$SF = SCOOL_{out} / COOL_{req}$$ [EQ.1]

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

The following points describe the parameters associated with equations 1 and 2:

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

How to integrate the technology and operate it?

Considering identified scenarios having SF values of 1 or more, it is essential to involve a second level of technical evaluation of these scenarios. Such an evaluation should include aspects related to how to integrate the technology and operate it. This phase considers the following set of design criteria (**Table 4.2**):

- **Compactness and Space Usability:** The compactness and space usability aim to assess the amount of used area and space by solar cooling components, mainly solar collection devices, and also the feasibility of integrating the system in façade modules. Depending on the applied components of components, the amount of space may vary.

Key aspects covered within this criterion are related to the bulkiness of products, namely the amount of used area and space by solar collection devices and their compactness. It also includes structural support requirements based on the weight density.

- **Assembly and Connections:** The assembly and connections of components aim to assess the complexity of the connection of components, physical integration, and the nature of the working principle of applied components. Hence, key aspects covered within this criterion include the use of hydraulic components based on pipe lengths and their amounts, and the number of connections.

- **Maintenance Requirements:** The maintenance requirements aimed to assess aspects related to maintenance complexity, which included working materials and periodic maintenance, the complexity of product cleaning, as well as the complexity of product accessibility.

Measuring the three aforementioned criteria can be a challenging task, as there are available features related to these criteria that lack measurable numbers. Having a measurement tool facilitating transforming such key features into quantifiable measures represents a key step to enable the evaluation of scenarios (Hamida & Alshibani, 2021; Konstantinou et al., 2015; Prieto et al., 2019). A four-scale qualitative scoring and rating technique was adopted to evaluate design scenarios in order to provide a simplified tool for designers to deal with complexity while enabling objective evaluation (**Table 4.3**).

TABLE 4.3 Qualitative scoring matrix for evaluating the compactness and space usability, assembly and connections, and maintenance requirements

Level (Status): Score	Key Features of Differences within Each Level for the Criteria		
	Compactness and space usability	Assembly and Connections	Maintenance Requirements
Level A (Extremely acceptable): 1.00	• Rooftops only, compact sizes of solar collection devices, and extremely simple structural support requirements to install components, • Rooftops only, moderate compactness of solar collection devices, simple structural support requirements to install components, or • Façade only, compact sizes of solar collection devices, and extremely simple structural support requirements to install components	• Rooftops and façades, and no use of hydraulic components among the cooling system components	• Low periodic maintenance complexity, low cleaning complexity of solar collection devices, and low accessibility complexity

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TABLE 4.3 Qualitative scoring matrix for evaluating the compactness and space usability, assembly and connections, and maintenance requirements

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

4.2.3.2 Economic Criteria

The application of renewable energy technologies to buildings requires assessing their economic feasibility in order to estimate the cost-effectiveness and worthiness of investments. There can be various parameters that can influence such an assessment (Hamida, Konstantinou, Prieto, & Knaack, 2023). Furthermore, there are different techniques that have been adopted to assess renewable energy projects economically (Delapedra-silva et al., 2022). Therefore, two main indicators were adopted to evaluate the economic feasibility, namely the life cycle costs (LCC) and the levelized cost of energy (LCOE) (Dehwah et al., 2020; Delapedra-silva et al., 2022; Sajid & Bicer, 2021). LCC covers the system life costs, which include the investment as well as the operation and maintenance (O&M) costs. Cost estimation in building design varies in accuracy and level of detail depending on the design stage. As the design progresses, cost estimates become more detailed and precise. Initial estimates rely on general assumptions and historical data, whereas later estimates incorporate specific project details. Different classifications of cost estimates have been established. For instance, some frameworks define five classes, ranging from the least detailed (order-of-magnitude estimate) to the most detailed (detailed estimate). These classifications include the feasibility estimate, which assesses project viability and compares alternatives. Such a class has an accuracy range of -30% to +50% (Singfield, 2021). As this study aimed to map the process of designing and evaluating solar cooling integrated façades to provide a comparative assessment of early feasibility across different scenarios and technologies, the assessment of LCC costs was based on the feasibility estimate.

Since a solar cooling system can consist of various elements and components, estimating investment and maintenance costs at the early feasibility stage can be challenging. To reduce complexities in the early design stages, this study focuses on estimating the investment and maintenance costs of cooling generation components, namely solar collection devices (SCDs) and chillers. These components have been identified as accounting for 47% to 61% of investment costs, corresponding to small- to medium-capacity systems, respectively (Mugnier et al., 2017). Furthermore, the cost of the auxiliary and mounting structure of SCDs was assumed to be the same regardless of the variations in tilt angles. Although the LCC can be presented in different forms, such as Present Worth (PW) or Annual Worth (AW), this study focuses on presenting it in AW. Hence, the life cycle cost in annual worth (LCC_{AW}) (**Table 4.2**) was adopted, as it facilitates estimating the LCOE. Regarding the LCOE, its main concept involves the identification of the unit cost of energy over the technology/project life by dividing all costs related to the energy system by the energy output from that system (Delapedra-silva et al., 2022). As the scope focuses on the comparison among scenarios and configurations related to renewable solar cooling systems, the main indicator is based on the levelized cost of cooling (LCOC) (Behzadi et al., 2021; Gabbrielli et al., 2016; Teles et al., 2024). Hence, LCOC is estimated by dividing the lifetime costs of the system (in the form of annual equal amounts) by the annual solar renewable energy produced by the selected technology. For the sake of simplicity, the estimated LCOC focused on the annual energy produced for cooling during the summer season only (**Table 4.2**). Equations 3 to 8 indicate the assessment of all parameters needed to estimate the LCC and LCOC.

$$I = I_{SCD} + I_{chiller} \tag{EQ.3}$$

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

$$A_{O\&M} = (\%I) \times \left[\frac{r \times (1+r)^{N^*}}{(1+r)^{N^*} - 1} \right] \tag{EQ.5}$$

$$LCC_{AW} = A_{LP} + A_{O\&M} \tag{EQ.6}$$

$$ESCOOL_{out} = ESOL_{input} \times SOL_{arry} \times COP_{solarsys} \times COP_{coolsys} \times \left[1 - \sum Loss\right] \tag{EQ.7}$$

$$LCOC = \frac{LCC_{AW}}{ESCOOL_{out}} \tag{EQ.8}$$

The following points describe the parameters associated with equations 3 and 8:

- I: Investment cost (€) that includes solar collection devices and their auxiliaries (I_{SCD}) and also chillers ($I_{chiller}$). It is calculated by using equation 3, and also referring to the cost estimation models for chiller, collector, and auxiliary costs published in technical reports/previous studies (Gabbrielli et al., 2016; IEA, 2022; Mugnier et al., 2017; Neyer et al., 2015; Saez et al., 2023).
- A_{LP}: Annual loan payment (€/year), which is calculated using equation 4.
- $A_{O\&M}$: Annual operation and maintenance cost (€/year). It is calculated by using equation 5, and also referring to the cost estimation models for chiller, collector, and auxiliary costs published in technical reports/previous studies.
- N^*: System life span, which is assumed to be 20 for all scenarios (Gabbrielli et al., 2016)
- *r*: The interest rate, which is assumed to be 6% (IEA, 2022).
- LCC_{AW}: Life cycle cost (€/year) of the system in the form of annual equal amounts, annual worth (AW), which is calculated by using equation 6

- $ESOL_{input}$: Plane array irradiance (kWh/m²/year$_{summer}$) available on a particular location/orientation, considering the whole summer as the time frame. It is calculated using dynamic energy simulation software, namely SAM 2023.12.17.
- ∑Loss: Sum of estimated percentage of energy losses at multiple stages, including solar energy collection, energy conversion, cooling generation, distribution, and storage, which is obtained from published technical reports/case studies
- $ESCOOL_{out}$: Annual solar renewable energy produced by the selected technology (kWh/year), focusing on the whole summer as the time frame. It is calculated using equation 7.
- LCOC: Levelized cost of cooling (€/kWh/ year), which is calculated using equation 8.

4.2.3.3 Techno-Economic Feasibility

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

- The score of product performance and efficiency, and the ability to meet user cooling requirements and represents the SF of the scenario, which is equal to or more than 1.
- The scores of compactness and space usability, assembly and connections, and maintenance requirements correspond to the score for the assigned level for a particular scenario. The scores can have a value of 1.0, 0.75, 0.5, or 0.0 for levels A, B, C, or D, respectively.
- The scores of LCC_{AW} and LCOC are obtained by mapping the domains of the values of LCC_{AW} and LCOC linearly. The lines have a score of 1.0 for the lowest LCC_{AW} and LCOC, while a score of 0.0 for the highest LCC_{AW} and LCOC. Hence, scores of LCC_{AW} and LCOC for a scenario (n) can be obtained by applying equations 9 and 10, respectively. Constructing such lines facilitates transforming the costs into unitless indicators, such as the ones obtained from the SF and the assigned levels.

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

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

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4.2.4 Development of Key Design Strategies

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

4.3 Case Study Results

This section aims to present the results of designing and evaluating solar cooling integrated facades based on the approach and methods (**Section 4.2**). The following subsections indicate findings of the systematic design and evaluation of solar cooling integrated facades, considering four key design stages (**Section 4.2.2**).

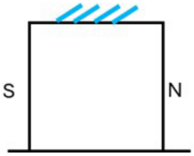
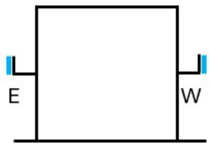
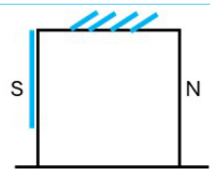
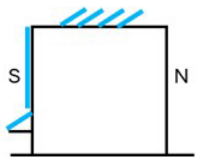
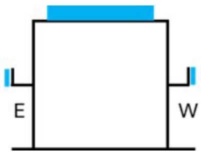
4.3.1 Conception and Strategic Definition

Obtaining the possibilities for façade integration required the establishment of a reference building model, assessment of the building performance of the reference model, and identification of possibilities for façade integration. The establishment of the reference model involved considering relevant regulatory requirements, data collection, and market survey. The aspects include construction characteristics of the thermal envelope elements (**Table D.1**) and the assumptions of constant parameters for the base case (**Table D.2**). Consequently, the performance of the established model was assessed through performing dynamic energy simulations using DesignBuilder 7.0.2.006. The simulations comprised different orientations of the building's main entrance (**Table D.3**). The results of the simulated base model, considering all orientations, had a range between 227.02 and 230.96 [kWh/m^2/year] for orienting the building's main entrance to the North and South, respectively. Considering the simulated hypothetical large office case by Cortiços &

Duarte (2022) across different European climates and Spanish energy-saving requirements, the annual energy consumption in Madrid was estimated to be between 192.2 and 242.23 kWh/m², corresponding to pre- and post-COVID-19 conditions, respectively. This indicates that the building energy consumption lies within the range of the simulated case. Consequently, orienting the building's main entrance to the North has been selected as the building base case for generating and evaluating the scenarios, as it tends to have the lowest building energy use intensity and cooling demand intensity. Such a model has an opaque façade on the south side as well as shaded balconies on the east and west sides.

The possibilities for integrating relevant solar electrically driven and thermally driven technologies considered in this study (**Section 4.2.1.3**) into the façades were identified by determining key configurations of the selected technologies and identifying possibilities for façade integration. The generation of suitable products that integrate solar absorption cooling technologies into façades can have various forms (**Table D.4**) (Prieto et al., 2019; Prieto, Knaack, et al., 2017a). Considering the fact that the small-scale integration of such technologies into façades still remains large due to the variations in the sizes of system components, the partial integration of solar absorption technologies into building façades tends to be an appropriate path for outlining the possibilities (Prieto et al., 2019). The identification of possibilities focused on water-air heat exchanger cooling delivery components, namely fan-coil units. A total of three main configurations related to the components of cooling generation were considered, namely single-effect (SE) absorption chillers with flat-plate collectors (FPCs), SE absorption chillers with evacuated tube collectors (ETCs), and double-effect (DE) absorption chillers with ETCs. Moving to electrically-driven systems, the use of PV for cooling through coupling it with a conventional HVAC system was considered to be the basis for generating the scenarios. The cooling generation device included the use of a water-cooled vapor-compression chiller (VCC), whereas a Variable Air Volume (VAV) terminal box was considered for the distribution (Cortiços & Duarte, 2022). Regarding the solar collection device used for energy conversion, Polycrystalline panels were considered (Singh et al., 2021; SolarWorld, 2014).

TABLE 4.4 Identified possibilities for façade integration

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 angle (30°) and orientation (S), and different use factors (UF) (0.15, 0.25, 0.40, 0.50, and 0.60)	
B. Façade only	**B.I.** Only vertical attachment of solar collection devices along the external layer of the opaque façades (Backside of the building–opposite to the main entrance)	
	B.II. Same as B.I with additional overhangs on the top of windows of the first floor eating rooms for installing the collector at different tilt angles (60°, 30°, and 0°)	
	B.III. Same as B.II, with additional vertical attachment of solar collection devices along the external layer of balcony rails and roofs	
C. Rooftops & Façades	**C.I.** Combination of A.I and B.I	
	C.II. Combination of A.I and B.II	
	C.III. Combination of A.I and B.III	

Based on the determined configurations, façade integration possibilities were identified by analyzing project characteristics and building drawings. The process explored three installation approaches: rooftops only, façades only, and a combination of both, enabling effective scenario evaluation. As indicated in **Table 4.4**, various installation types and numbers of installed units depend on the building characteristics. To estimate SOL_{arry}, three groups were established, ranging from minimal to maximum spaces and surface utilization:

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

4.3.2 Preparation and Briefing

The following sections present the findings of assessing the feasibility of the generated possibilities in **Table 4.4** through applying the multi-stepped evaluation methodology (**Figure 4.2** and **Table 4.2**).

4.3.2.1 Assessed Technical Criteria

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

The identification of relevant types of technologies and components was based on assessing the product performance and efficiency, considering SF as an indicator. Scenarios having an SF value of 1 or more were considered for investigating how technologies can be integrated and operated. To calculate the SF values (Equations 1 and 2), $COOL_{req}$ was based on the selected base model which is having an orientation of the building main entrance to the North (**Table D.3**). The solar energy input to the façade system was assessed by estimating the average daily solar radiation availability on a particular location/orientation (SOL_{input}) (kWh/m^2/day) considering the month of summer design week of Madrid, July (**Figure E.1**). Such assessment was performed using the simulation tool of System Advisor Model (SAM) 2023.12.17 software and EnergyPlus weather file (Madrid 082210 (IWEC)).

Regarding the SOL_{arry}, the amounts and areas of installed units of solar collection devices were estimated in m^2 based on the identified possibilities (**Table 4.4**). The values of $COP_{solarsys}$ and $COPc_{oolsys}$ were obtained from published technical reports or case studies (**Table 4.5**). Regarding the ∑Loss of electrically driven technologies, solar panels lose efficiency as temperatures rise, with crystalline silicon panels losing about 0.3%–0.5% per °C above 25°C. At 60°C, this can lead to a 10–15% reduction in power output. Additional losses occur in inverters (around 3%) and wiring (typically 2%, but reducible to 1% with optimized design) (8msolar, 2024; Aurorasolar, n.d.; PV Magazine, 2023). Consequently, the ∑Loss of water-cooled VCC and PV panels was assumed to be 14%. For thermally driven technologies, determining energy loss percentages in solar absorption cooling systems is challenging due to variations in design, components, and operation. While exact figures for cooling distribution and thermal energy storage (TES) losses are not universally defined, studies provide useful insights:

- Cooling Distribution Losses: Heat loss from storage tanks and piping is a major concern, emphasizing the need for proper insulation and system design (Shirazi et al., 2018).
- TES Losses: The solar collector accounts for up to 70% of total losses, while the generator and absorber contribute 6–14%. Although the study examines entropy generation in system components, it highlights the importance of optimizing TES to improve overall efficiency (Abdulateef et al., 2019).

As this study aimed to map the process of designing and evaluating solar cooling-integrated façades to provide a comparative assessment of early feasibility across different scenarios, the loss of thermally driven technologies was also assumed to be 14%. Therefore, $SCOOL_{out}$ and SF values for all scenarios were assessed. **Figures 4.3**, **4.4**, and **4.5** summarize the SF values for all scenarios, including losses, while **Figure E.2** summarizes the SF values for all scenarios related to envelope possibilities (A), excluding losses. While previous studies have used a simplified equation to assess the SF—considering only losses in components related to cooling generation while neglecting losses associated with storage and distribution—it is clear that the SF value can be significantly affected by the inclusion or exclusion of these losses. Accordingly, based on the results of assessing the SF (including losses) for different envelope configurations across various scenarios, the following possibilities were considered for investigating how to integrate and operate the technologies, as they have SF values greater than 1:

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

Consequently, the matrix of assessing how technologies can be integrated and operated (**Table 4.3**) was applied on the aforementioned identified relevant types of technologies and components. The information was collected from relevant literature as well as available product specifications. **Tables D.5** to **D.6** show results of applying the matrix while considering collected relevant information (Alahmer & Ajib, 2020; Chelmer heating solutions, 2014; Prieto et al., 2019; SolarWorld, 2014).

TABLE 4.5 Key information required to investigate the type of technology and products (Alahmer & Ajib, 2020; Ayou & Coronas, 2020; Cortiços & Duarte, 2022; Mugnier et al., 2017; Prieto, Knaack, Auer, et al., 2018a)

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

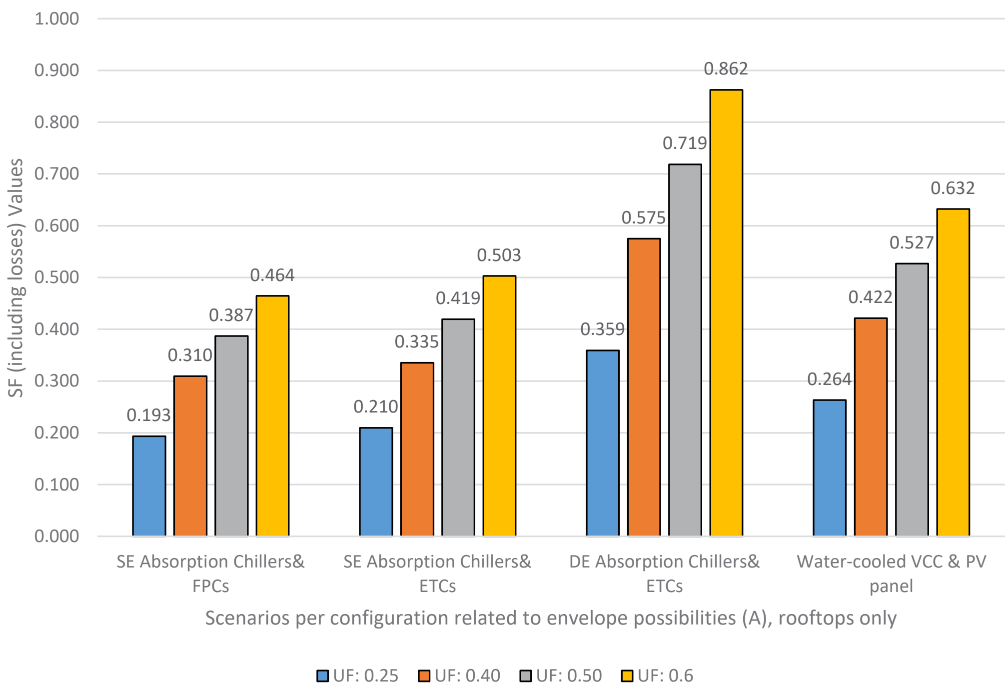


FIG. 4.3 SF values (including losses) for scenarios related to envelope possibilities (A) and rooftops only, considering different use factors (UF)

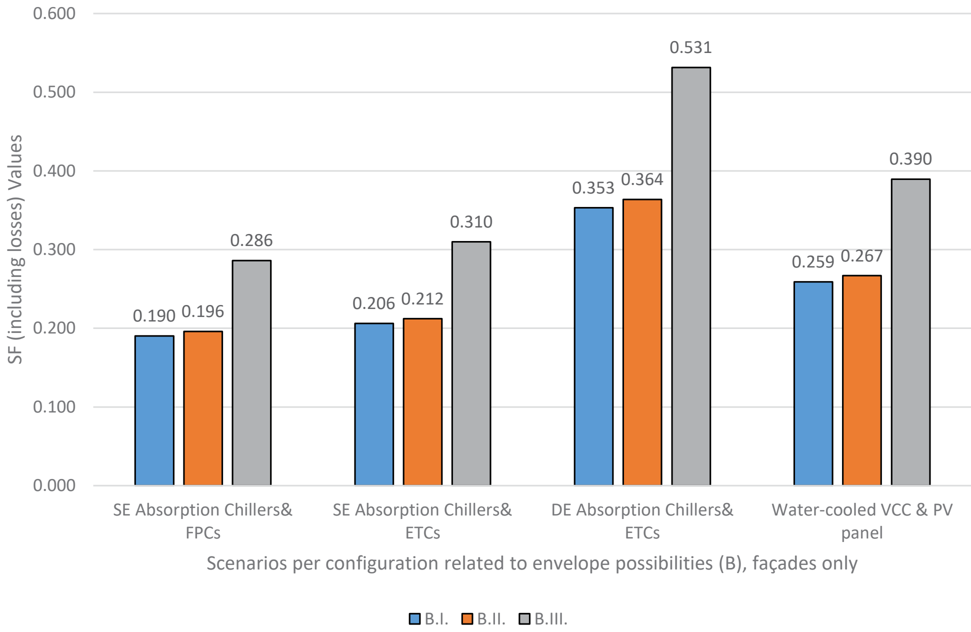


FIG. 4.4 SF values (including losses) for scenarios related to envelope possibilities (B), façades only

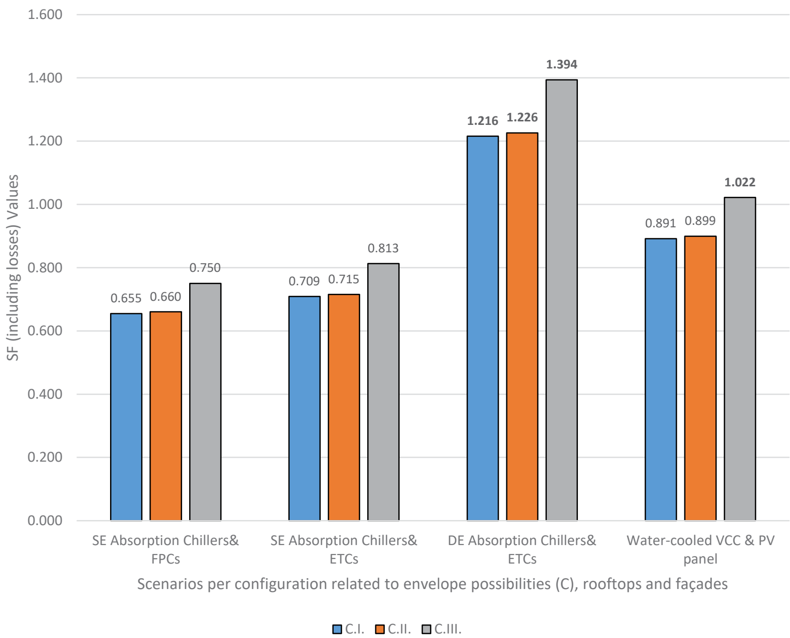


FIG. 4.5 SF values (including losses) for scenarios related to envelope possibilities (C), rooftops, and façades

4.3.2.2 Assessed Economic Criteria

The economic feasibility of scenarios with an SF equal to or greater than one was assessed using equations 3 to 8 to evaluate the LCC_{AW} and LCOC. The analysis covered the two groups of configurations that met the required SF value (**Section 4.3.2.1**). The values related to the I_{SCD}, $I_{chiller}$, $O\&M_{SCD}$, and $O\&M_{chiller}$, were obtained from published technical reports/previous studies as well as market survey (**Table D.7**). **Figure E.3** shows the $ESOL_{input}$ obtained from SAM 2023.12.17 software. Accordingly, **Figure 4.6** summarises the results of assessing LCC_{AW} and LCOC for all scenarios having SF equal to or more than 1. The lowest and highest LCC_{AW} were associated with the water-cooled VCC and PV panels (C.III: rooftops & façades with a rooftop use factor (UF) of 0.6) and DE absorption chillers with ETCs (C.III: rooftops & façades with a rooftop use factor of 0.60 and overhangs), accounting for €52,838.36 and €115,877.24 per year, respectively. However, when considering the LCOC, the lowest and highest values were associated with the water-cooled VCC and PV panels (C.III: rooftops & façades with a rooftop use factor of 0.60 and overhangs with a tilt angle of 0°) and DE absorption chillers with ETCs (C.III: rooftops & façades with a rooftop use factor of 0.4 and overhangs with a tilt angle of 60°), accounting for €0.0589 and €0.1076 per kWh per year (summer), respectively.

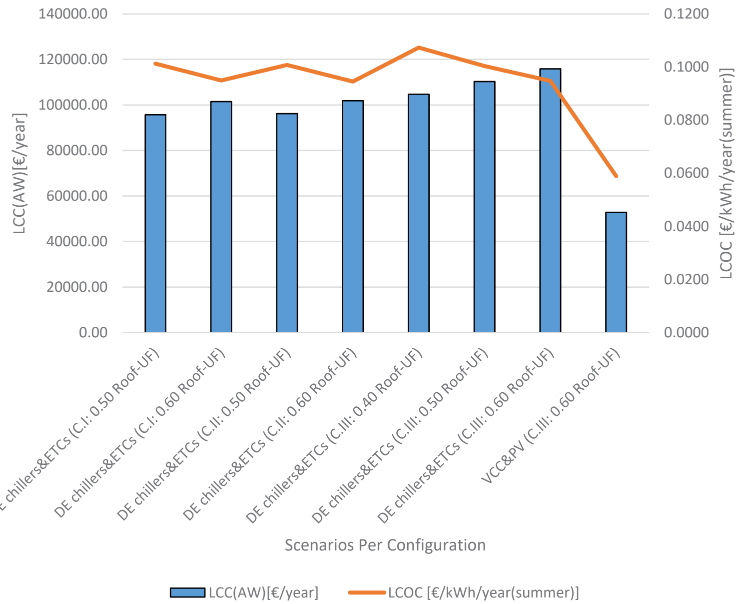


FIG. 4.6 Cost-effectiveness based on LCCAW and LCOC for scenarios involving Double-Effect (DE) absorption chillers with Evacuated Tube Collectors (ETCs) (thermally driven) and water-cooled VCC and PV panels (electrically-driven), considering those with Solar Fraction (SF) values of 1 or higher

4.3.3 Façade Technological Selection

The selection of the relevant architectural façade technology involved summarising the techno-economic feasibility (**Section 4.2.3.3**). Given the large number of radar charts generated, representative charts for each group of configurations were selected, as follows (**Figure 4.7**):

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

Having analysed the radar charts and the total scores (**Figure 4.7**), the most suitable option was the water-cooled VCC and PV panels (Rooftops & Façade). In contrast, DE absorption chillers with ETCs (Rooftops & Façade) appear to be the least suitable option, despite having the highest SF values. Based on these findings, the selected configuration was the water-cooled VCC and PV panels (C.III: Rooftops & Façade with a rooftop use factor of 0.60 & overhangs).

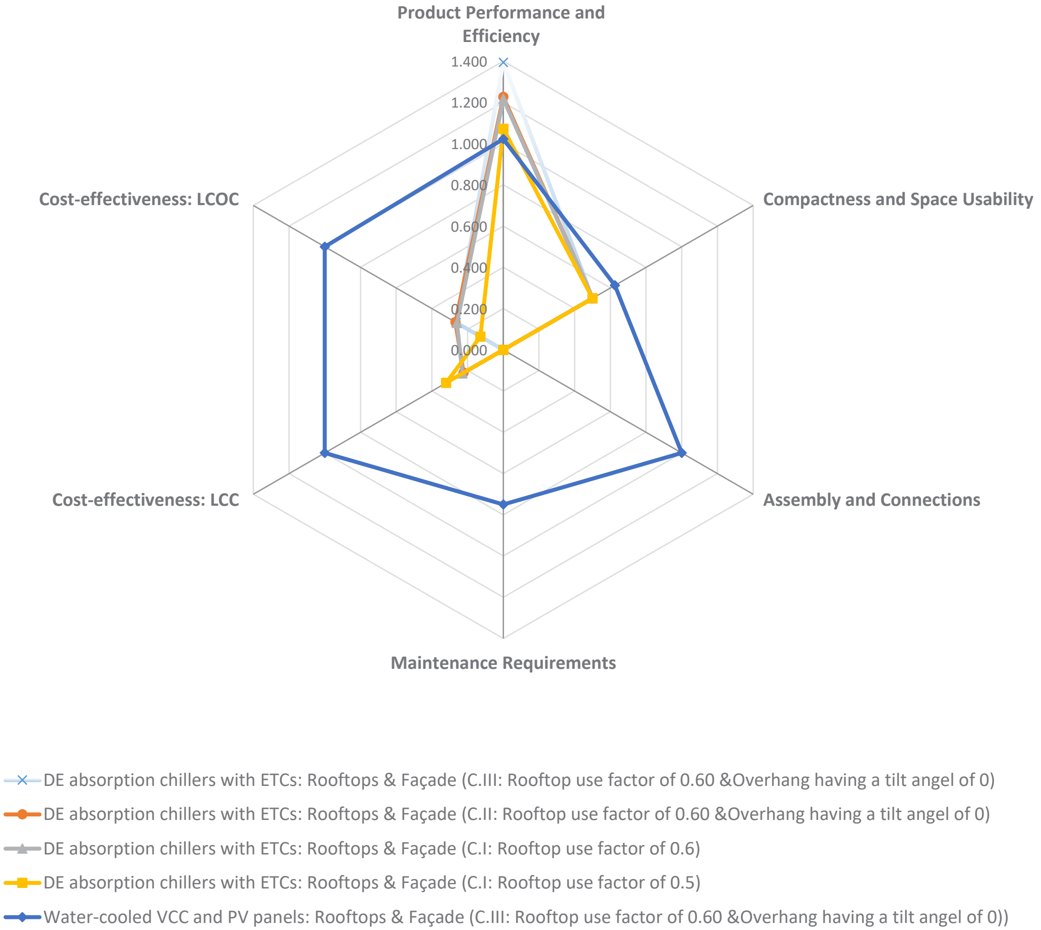


FIG. 4.7 Summarised techno-economic feasibility

4.3.4 Façade Integration Design

The detailed design for integrating the selected technology involved determining the characteristics of key elements, considering relevant reference standards for component connections. Given that the selected technology was water-cooled VCC and PV panels (C.III: Rooftops & Façade with a rooftop use factor of 0.60 & overhangs), the detailed design focused on this system while also providing a comparison to the competing technology, DE absorption chillers with ETCs. Therefore, the characteristics of key elements were identified using graphic design software, with a focus on key components related to the selected architectural façade technology to conceptualise their features. These key elements pertained to façade components, as rooftops are among the most widespread applications of PV panels. Consequently, the graphic design covered façade elements, specifically the vertical installation of PV panels on the opaque façade along the building's backside. The detailed design was demonstrated by representing façade components, connections, and element dimensions to provide construction details that translate design intent into technical representations. To ensure compliance with relevant reference standards, EAD 090062-01-0404 ("Kits for external wall cladding mechanically fixed") was adopted. Additionally, to facilitate various aspects related to installation, maintenance, and disassembly, the cladding kits family G was chosen as the connection method in accordance with the standard. The main element connections consisted of cladding element, cladding fixing, subframe, substrate, anchor, thermal insulation, and others (air Cavity, waterproofing, internal cladding layer of gypsum curry, and base plaster). Hence, **Figure 4.8** provides information and demonstrates the detailed design of the selected technology—water-cooled VCC and PV panels—while at the same time presenting comparisons with the competing technology, DE absorption chillers with ETCs. The purpose of including ETCs is to highlight some of the complexities involved in this option compared to PV panels.

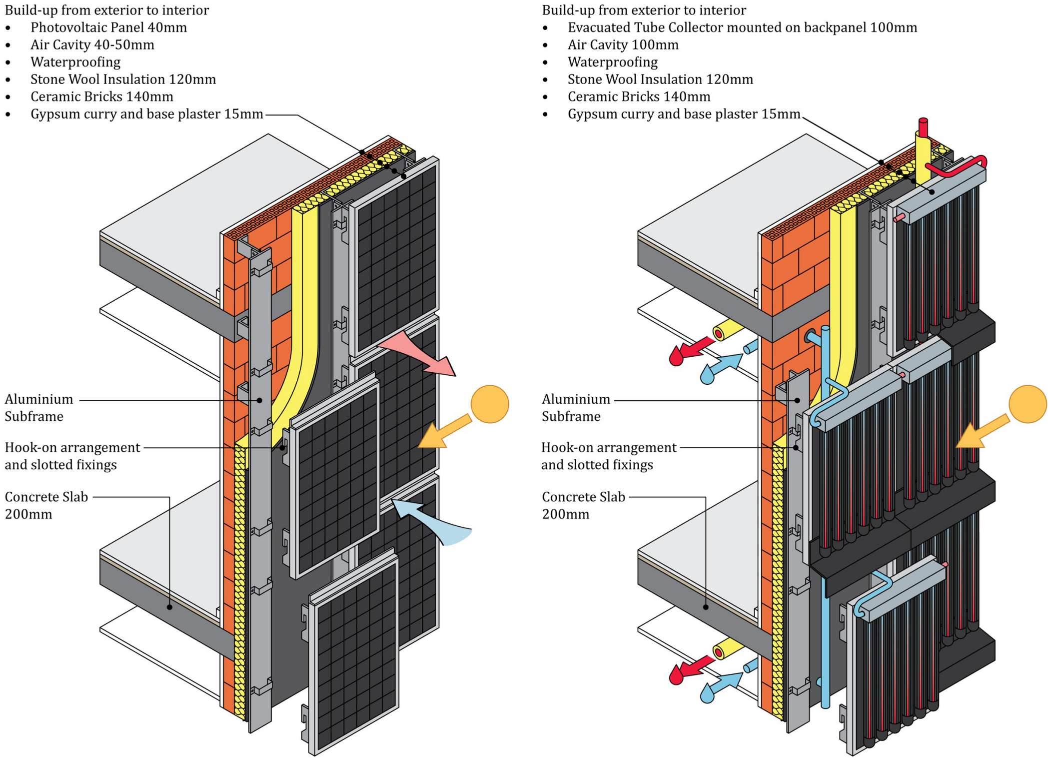


FIG. 4.8 Demonstration of a detailed design of the PV façade (left side) and the ETC façade (right side)

4.4 Key Façade Design and Evaluation Strategies

This case study maps the process of designing and evaluating solar cooling integrated façades at early project stages, highlighting key lessons to guide design strategies. These strategies equip the early-stage project team with essential knowledge for informed decisions. Based on **Section 4.3**, this section develops key strategies by synthesizing case study outcomes, linking steps, inputs, decisions, outputs, and tools to design stages (**Section 4.2.4**). **Table 4.6** summarizes the resulting façade design and evaluation strategies.

TABLE 4.6 Key façade design and evaluation strategies

Stage	Key processes/ steps	Key required information and inputs	Key decisions	Key Outcomes	Tools and means to obtain the outcomes
Conception and Strategic Definition	• Establishment and assessment of the reference model	• Regulatory requirements • Project characteristics/ building drawings/ building use profile • Weather, geographic, and urban data	• Determine relevant measures to optimize building design • Select a building–optimized and suitable model	• Construction characteristics of the envelope • Building the required cooling demand of the optimized and suitable model	• Data collection and market survey • Energy simulation
	• Identification of possibilities for façade integration	• Construction characteristics of the envelope of the optimized suitable model • Relevant solar cooling technologies	• Determine configurations of cooling generation, distribution, and delivery components • Identify available envelope possibilities for technological integration based on the selected model and relevant solar cooling technologies	• Possibilities for façade integration	

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TABLE 4.6 Key façade design and evaluation strategies

Stage	Key processes/ steps	Key required information and inputs	Key decisions	Key Outcomes	Tools and means to obtain the outcomes
Preparation and Briefing	• Investigation of the type of technology and components	• Building requirements in terms of cooling demand • Performances and efficiencies of technologies • Technical design criteria and performance requirements	• Determine available envelope possibilities meeting cooling demand	• Assessed product performance and efficiency of generated possibilities, meeting cooling demand	• Data collection and market survey • Energy simulation • Cost estimation
	• Evaluation of how the technology can be integrated and operated	• Sizes, weights, working materials, and maintenance requirements • Technical design criteria and performance requirements	–	• Evaluated technological potentials for building integration	
	• Assessment of economic viability	• Cost of technologies • Economic design criteria and requirements	–	• Cost–effectiveness of possibilities meeting cooling demand	
Façade Technological Selection	• Summarisation of techno–economic feasibilities	• Assessed techno–economic feasibility of the generated possibilities • Design criteria and techno–economic requirements	–	• Summary of techno–economic feasibilities	• Data visualization • Multi–criteria analysis
	• Selection of architectural façade technology	• Summary of techno–economic feasibilities	• Determine the scenario having the highest scores with respect to design criteria and selected relevant architectural façade technology	• Relevant architectural façade technology	

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TABLE 4.6 Key façade design and evaluation strategies

Stage	Key processes/ steps	Key required information and inputs	Key decisions	Key Outcomes	Tools and means to obtain the outcomes
Façade Integration Design	• Determination of characteristics of key elements	• Selected relevant architectural façade technology	–	• Features of the main elements of the selected technology	• Graphic and detailed design
	• Demonstration of detailed design	• Relevant safety requirements and standards	• Determine means of connections according to the standards	• Façade composition and construction details	

4.5 Discussion

This section aims to discuss the main outcomes from the case study (**Section 4.5.1**) and the developed key design strategies (**Section 4.5.2**).

4.5.1 Case Study Outcomes

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

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

- **Project and building characteristics:** Every project is unique, as each building has its own size, energy load profile, architectural design, and construction characteristics. Consequently, design outcomes vary from one project to another due to differences in energy and cooling demands.

- **Climate context and geographic location:** The availability of solar radiation varies from one location to another, influenced by factors such as shading from the surrounding environment. This, in turn, affects cooling demand, the required number of solar cooling devices (SCDs), and the system's energy input.

- **Status of technological development:** The development of solar technologies is an ongoing process, meaning that performance, sizes, working principles, and costs can change over time. As a result, the outcomes of techno-economic assessments are time-dependent.

- **Stakeholders involved and prioritization of techno-economic requirements and design criteria:** The case study outcomes, such as generated radar charts, were based on an equal prioritization of technical and economic criteria. However, since every project is unique, stakeholders—such as investors—may have different priorities, which can influence the selection of the most suitable option.

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

4.5.2 Developed Design Strategies

Analysis of the developed strategies (**Table 4.6**) shows that the first two stages—conception and strategic definition, as well as preparation and briefing—contained most steps, inputs, decisions, and outcomes. Early-stage processes significantly impact later phases, such as construction characteristics in detailed design. This is due to the need for thorough early investigations, including regulatory measures, passive strategies, and project requirements. Although the case study focuses on Madrid, these strategies can assist design teams working in similar semi-arid or Southern European climates. However, local technical evaluations should incorporate region-specific weather data, regulations, and energy-saving requirements, as building envelope criteria vary by location. Since each project is unique, aspects of the developed strategies depend on project-specific factors, including size, stakeholder priorities, and investor goals. For instance, determining optimization measures and selecting an appropriate model in the first stage depend on project objectives.

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

4.6 Conclusion

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

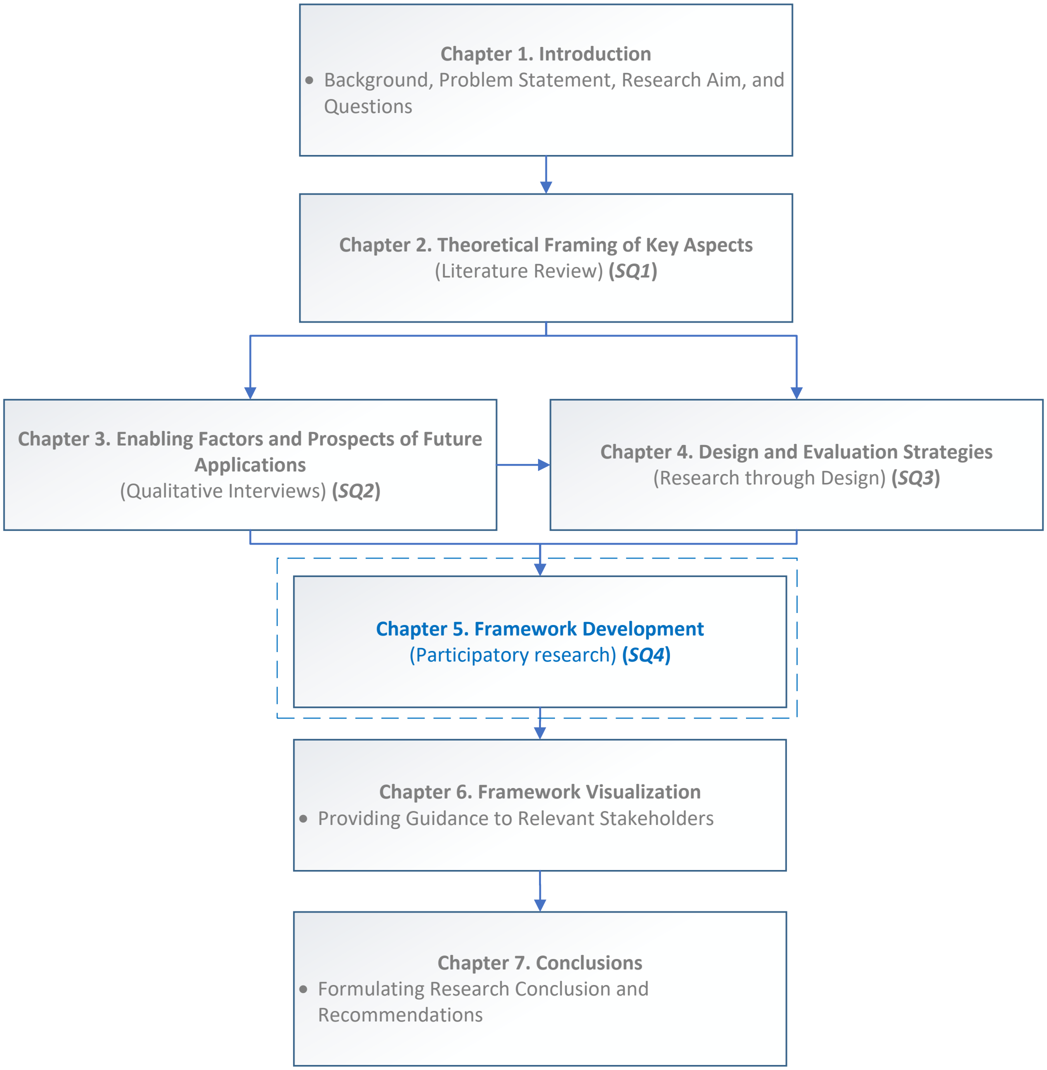
The research mapped the early-stage design and evaluation process, identifying critical design decisions. The first two stages—conception & strategic definition and preparation and briefing—were found to involve the highest number of decisions, with early-stage outcomes significantly influencing later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

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

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

Acknowledgement

The authors express their sincere gratitude to Mohammad Hamida for providing the architectural design and drawings for the office case. They also acknowledge with gratitude Ruben van der Plas for his assistance in demonstrating the detailed design of the case study outcomes.


Chapter 1. Introduction
• Background, Problem Statement, Research Aim, and Questions
Chapter 2. Theoretical Framing of Key Aspects
(Literature Review) (SQ1)
Chapter 3. Enabling Factors and Prospects of Future Applications
(Qualitative Interviews) (SQ2)
Chapter 4. Design and Evaluation Strategies
(Research through Design) (SQ3)
Chapter 5. Framework Development
(Participatory research) (SQ4)
Chapter 6. Framework Visualization
• Providing Guidance to Relevant Stakeholders
Chapter 7. Conclusions
• Formulating Research Conclusion and Recommendations

5 Framework Development

Chapter 5 aims to answer the last sub-question:
SQ_4 – How can an integrative framework guide the design and development of SCIFs?

Answering this sub-question involved a participatory research methodology in order to identify and outline key decisions, the required information to support them, and relevant stakeholders that can be involved in the design and development of solar cooling integrated façades. The sub-question was answered in the following publication: "Hamida, H. B., Prieto, A., Konstantinou, T., & Knaack, U. (2025). Supporting the Design and Development of Solar Cooling Integrated Façades: A Framework of Decisions, Information, and Stakeholder Involvement. Sustainability, 17(17), Article 7745. https:*//doi.org/10.3390/su17177745". ***Chapter 5*** is a modified version of this publication. The phrase "from the first four publications we analyzed" was replaced with "from the first four publications that were analyzed" to better reflect the formal style of dissertation writing. Finally, the appendices for this chapter were revised to provide more comprehensive information, including all tables from the desktop research, complete survey forms, and detailed materials related to the workshop guide.*

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.

5.1 Introduction

Given the global challenges arising from climate change, relevant, promising methods to expedite the energy transition are essential (Enteria & Sawachi, 2020; Fallmann & Emeis, 2020; Sahin & Ayyildiz, 2020; Santamouris, 2016). 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 (Prieto, Knaack, et al., 2017a). 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 (Tiwari et al., 2016).

Solar cooling technologies, which emerged in the 1970s, utilize solar energy to produce either conditioned air or chilled water (He et al., 2019). 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 (Sarbu & Sebarchievici, 2016). Consequently, this gives rise to two fundamental methods for achieving a cooling effect from solar energy: thermally driven systems and electrically driven systems (Alahmer & Ajib, 2020; Alsagri et al., 2020; He et al., 2019; Karellas et al., 2019; Neyer et al., 2018; Sarbu & Sebarchievici, 2016) (**Figure 5.1**). 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 (Sarbu & Sebarchievici, 2016). 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 (Alahmer & Ajib, 2020). 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 (Heier et al., 2015; Xiao et al., 2021). 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 (Sarbu & Sebarchievici, 2016). 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 (Karellas et al., 2019). 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 (Sarbu & Sebarchievici, 2016).

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 (Noaman et al., 2022; Suwannapruk et al., 2020). 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 (Hamida et al., 2025b). Although there have been developments in the technological advancement of solar cooling systems, their integration into façades in real projects has been limited (Huang & Zheng, 2018; Kohlenbach et al., 2025). 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 (Rong et al., 2010). 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 (Yang et al., 2023). 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 (Voigt et al., 2023; Wuni & Shen, 2020). 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 (Brusselaers et al., 2021; Ebekozien et al., 2024; Martinez & Olander, 2015). 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 the architecture, engineering, and construction (AEC) sector is strongly influenced by social and business factors, which often rival or even outweigh technical considerations (Bakht & El-Diraby, 2015).

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 5.2 outlines the research approach and methods used to build, evaluate, refine, and validate the framework. Then, **Section 5.3** 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 5.4**. Finally, **Section 5.5** offers conclusions and recommendations for future research.

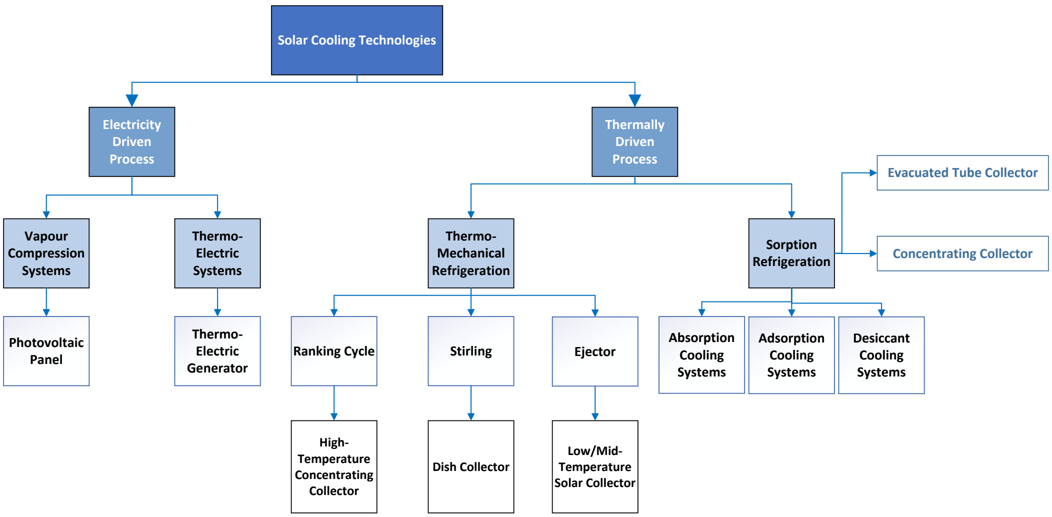


FIG. 5.1 Solar cooling technologies (reproduced from (Alsagri et al., 2020))

5.2 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 (Calissano et al., 2023; Ducci et al., 2023; Gemperle et al., 2023; R. Liu et al., 2025; Nofal, 2023). **Figure 5.2** presents the study research approach and methods, which are explained in the following sections.

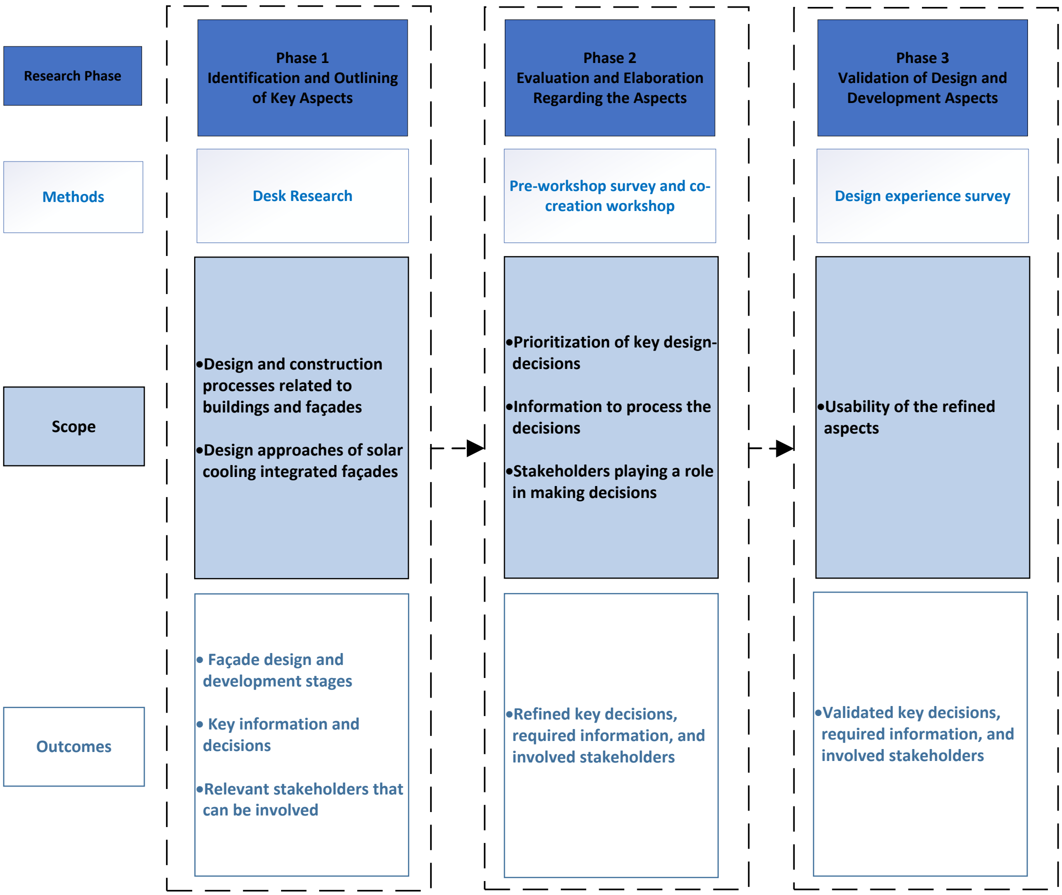


FIG. 5.2 Research approach and methods of this study

5.2.1 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 (Fellows & Liu, 2015). It entails reviewing published reports, academic articles, studies, and other publicly accessible sources to gather relevant insights and support informed decision-making (Gell, 2023). 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 (Hamida et al., 2025b; Klein, 2013; Oliveira & Melhado, 2011; Prieto et al., 2023; RIBA, 2020). 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 in 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 (RIBA, 2020) provided a structured overview of project stages across disciplines, while Oliveira & Melhado (2011) highlighted coordination challenges in both new builds and retrofits. To address energy efficiency in housing, Prieto et al., (2023) outlined critical phases for zero-energy renovations. Insights into façade workflows were drawn from Klein, (2013), particularly regarding the curtain wall industry, and Hamida et al. (2025b) 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 5.3**. 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 (Knaack et al., 2014), this structured approach facilitates the systematic organization of information within the framework.

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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 (Klein, 2013; Oliveira & Melhado, 2011; RIBA, 2020). 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 the 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.

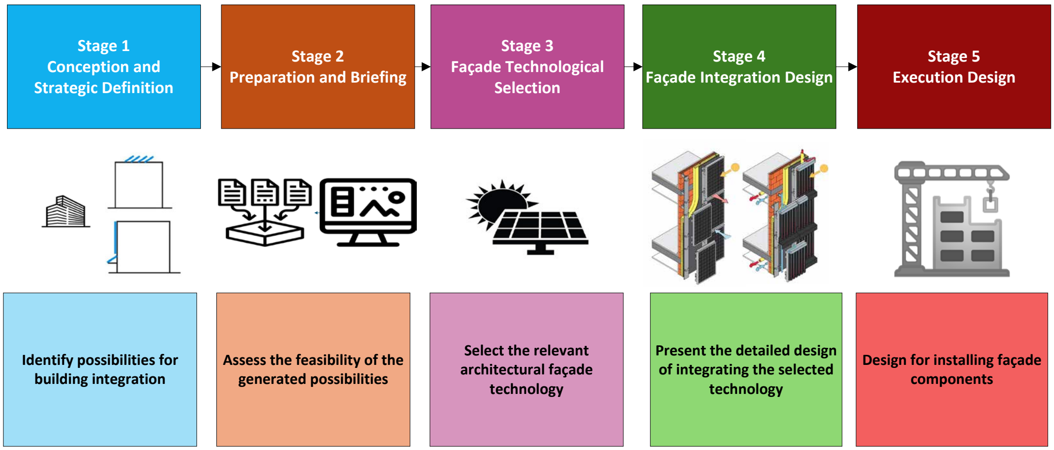

FIG. 5.3 Research design and development stages

5.2.2 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.

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5.2.2.1 Pre-Workshop Survey

Identifying and outlining key aspects involved in designing, testing, and distributing an online pre-workshop questionnaire survey for identified relevant stakeholders. The survey was distributed using Microsoft Forms (Microsoft Corporation, n.d.-a), 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 5.3**). 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 (Groat & Wang, 2013; Ying et al., 2021). 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 (Tajik et al., 2024). Accordingly, to ensure the presence of relevant representatives from the key stakeholders, 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:
  - Experience in the European façade design and construction industry, including design, production, or assembly.
  - 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 G**).

5.2.2.2 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 (Storvang et al., 2018):

- 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 (Creswell & Creswell, 2018; Katz-Buonincontro, 2022). 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 (Thoring et al., 2020). 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 H** 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 H.5**) 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

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playing a role in making decisions. The hypothetical case was based on an office building case and its outcomes (Hamida et al., 2025b, 2025a).

2 Participants, in the reflection part, were asked to identify any parts related to the outlined aspects that were not addressed (**Appendix H**).

Consequently, the workshop was moderated virtually using the Microsoft Teams platform and Microsoft Whiteboard (Microsoft Corporation, n.d.-b, n.d.-c), 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.

5.2.2.3 Refinement of Identified and Outlined Aspects

The refinement of identified and outlined aspects involved reporting, analysing, 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 (Thoring et al., 2020). Hence, the aspects were refined based on the outcomes obtained from the workshop, which included contextualizing them at a deeper level.

5.2.3 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 (Lamy et al., 2010). To facilitate this validation, a design experience survey was used. The survey was developed using Microsoft Forms (Microsoft Corporation, n.d.-a) 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 (Hamida et al., 2025b, 2025a). 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 (Hamida et al., 2025b).
- 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 I** 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 5.2.2.1**), in order to gather detailed and contextually meaningful data.

5.3 Results

This section presents the study findings. **Section 5.3.1** presents the findings related to identifying and outlining the key aspects based on desk research. **Section 5.3.2** 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 5.3.3** provides the validation results obtained from the design experience survey.

5.3.1 Identifying and Outlining Key Aspects

The desk research findings were synthesized through considering the main stages, processes, inputs, requirements or considerations, decisions, outcomes, and also the main stakeholders involved in the design stages. Starting with processes related to the design and development of building façades, from the first four publications that were analysed (**Tables F.1** to **F.6**) (Klein, 2013; Oliveira & Melhado, 2011; Prieto et al., 2023; RIBA, 2020), it was obvious that there are different ways to categorize design stages depending on the context. Furthermore, Hamida et al. (2025b) 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.

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5.3.2 Evaluated and Refined Aspects

5.3.2.1 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 G.2** to **G.10** 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.

5.3.2.2 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 summarised 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 5.1** to **5.3** as well as **Figure 5.4** 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 5.1 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 the 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	–	–	–	–

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TABLE 5.2 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 5.3 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 construction details
Regulatory requirements	Costs of technologies	CE marking for existing products	Façade composition and construction details	Building drawings
Building use profile	Regulatory requirements (fire safety)	Detailed cost calculation data	Main elements of the solar cooling technology (storage, evaporation, electrically driven heat pump)	Tendering documents
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	–	–	–	–

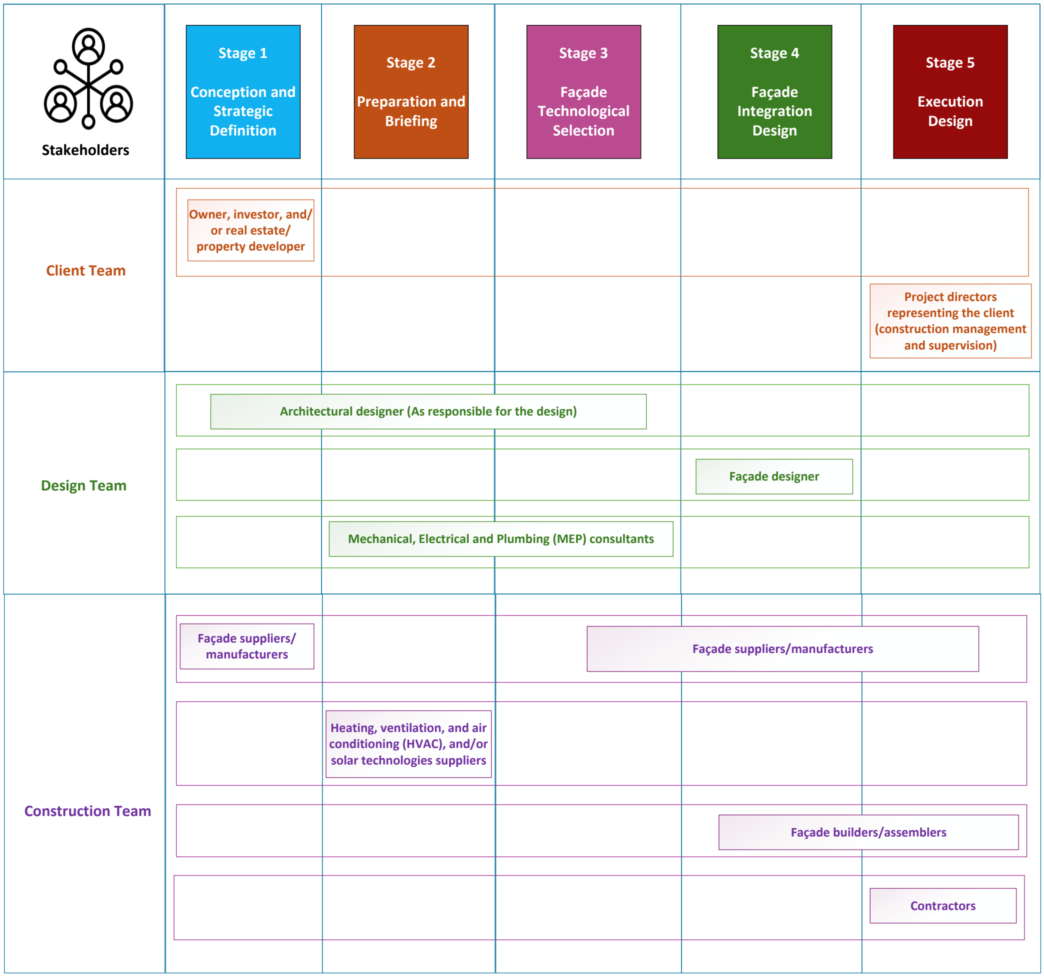

FIG. 5.4 Modified list of identified and outlined stakeholders involved in decision-making

5.3.3 Validation Results

A total of twenty-seven responses were collected, as summarized in **Figures I.6** to **I.10**. The following sections summarize 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.

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5.3.3.1 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 sh1ould be involved in the decision-making process for façade integration (**Figure 5.5** and **Figure 5.6**):

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.

Compared to the refined framework (**Figure 5.4**), 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 5.4**) and climate design, building physics, and building service consultants in the validation results (**Figure 5.6**). 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 5.3.2.2**.

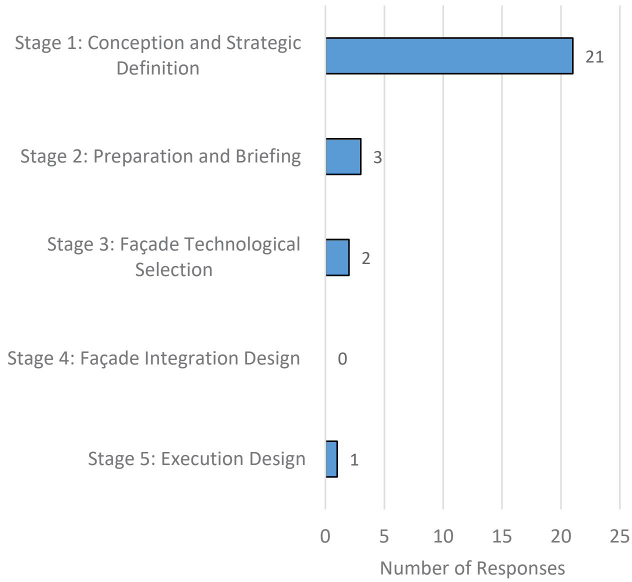


FIG. 5.5 The relevant stage at which the integration of solar cooling technologies (or other solar technologies) into façades should be considered

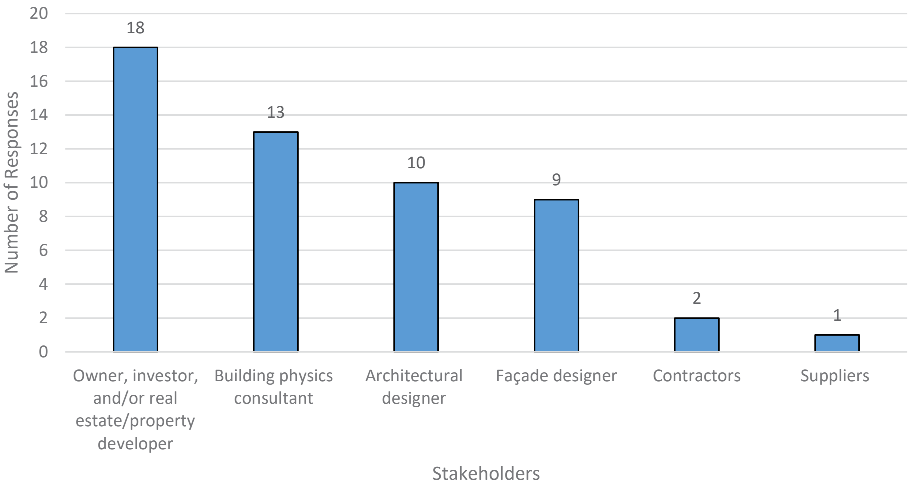


FIG. 5.6 Key stakeholders identified to be involved in making the decision to integrate solar cooling technologies (or other solar technologies)

5.3.3.2 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 5.7**). 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 5.3.3.1** 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 5.8** and **5.9**).

- 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 5.9**). 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 5.10**).

Overall, the prioritization of design decisions as well as criteria (**Figure 5.8** and **Figure 5.9**) tends to be consistent with the refined aspects (**Table 5.1**), 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 the installation process, considering auxiliary elements, avoiding conflicts.

Finally, among the various factors influencing the selection of a design solution (**Figure 5.10**), efficiency and life cycle costs were perceived as playing a crucial role in the decision-making process.

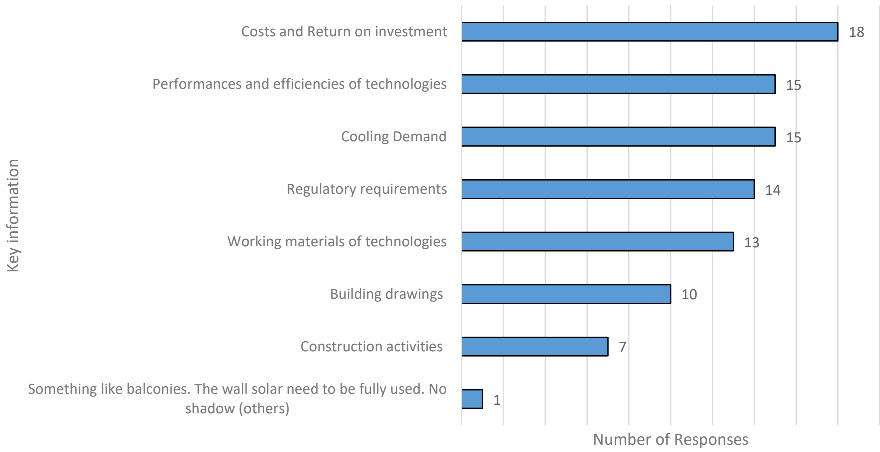


FIG. 5.7 Key information required to support decisions on envelope integration possibilities (rooftops/façades)

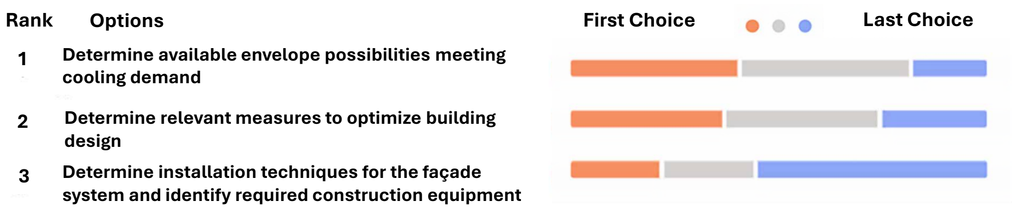


FIG. 5.8 Prioritization of design decisions

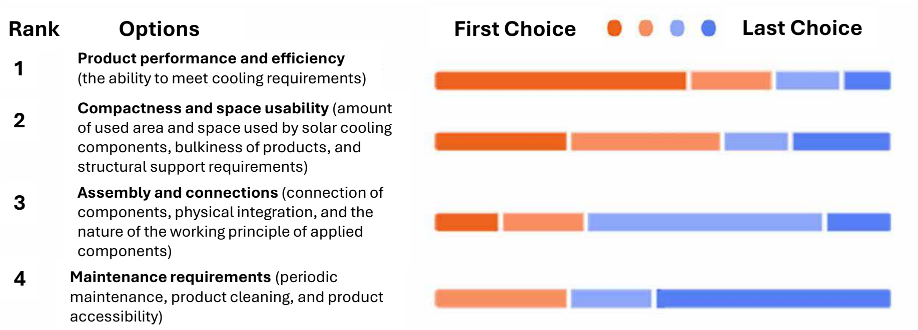


FIG. 5.9 Prioritization of design criteria

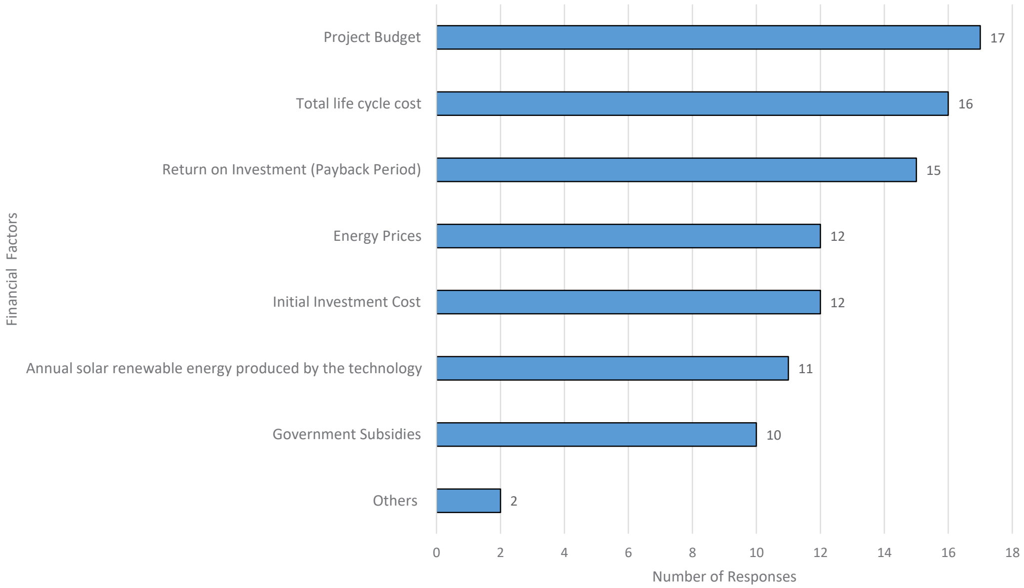


FIG. 5.10 Financial factors to be considered to evaluate the design solutions

5.3.3.3 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 5.11** and **5.12**).

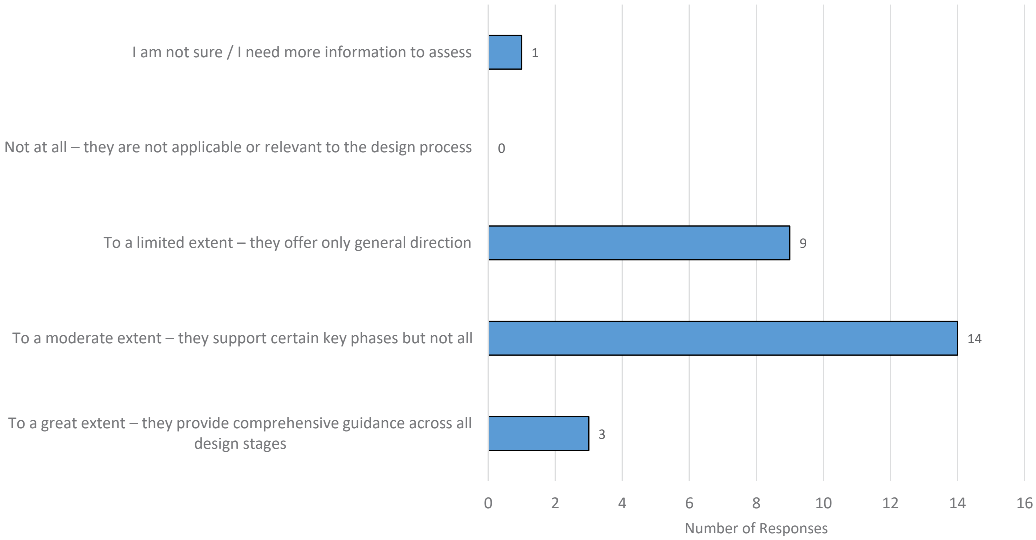


FIG. 5.11 Participants' perspectives on the information provided throughout the design and development process

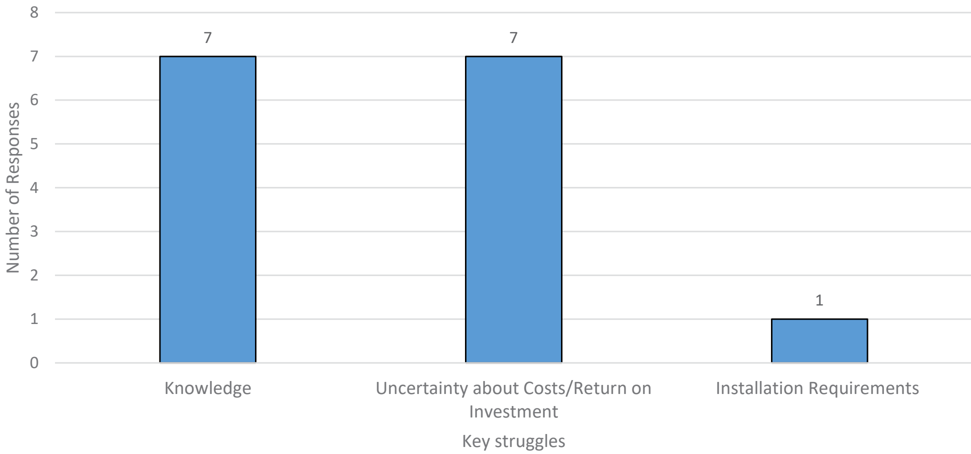


FIG. 5.12 Key struggles faced by participants when making decisions

5.4 Discussion

This section discusses the outcomes of this study (**Section 5.4.1**) and draws lessons learned for framework application (**Section 5.4.2**).

5.4.1 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 decisions as well as criteria tends 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 5.1**) can vary from one project to another, as every project is unique, clients often assess façades based on return on investment/payback periods (**Section 5.3.2.2**).

5.4.2 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:

- Analysing 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 neighbourhoods, 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.

5.5 Conclusion

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 decisions as well as criteria tends 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.

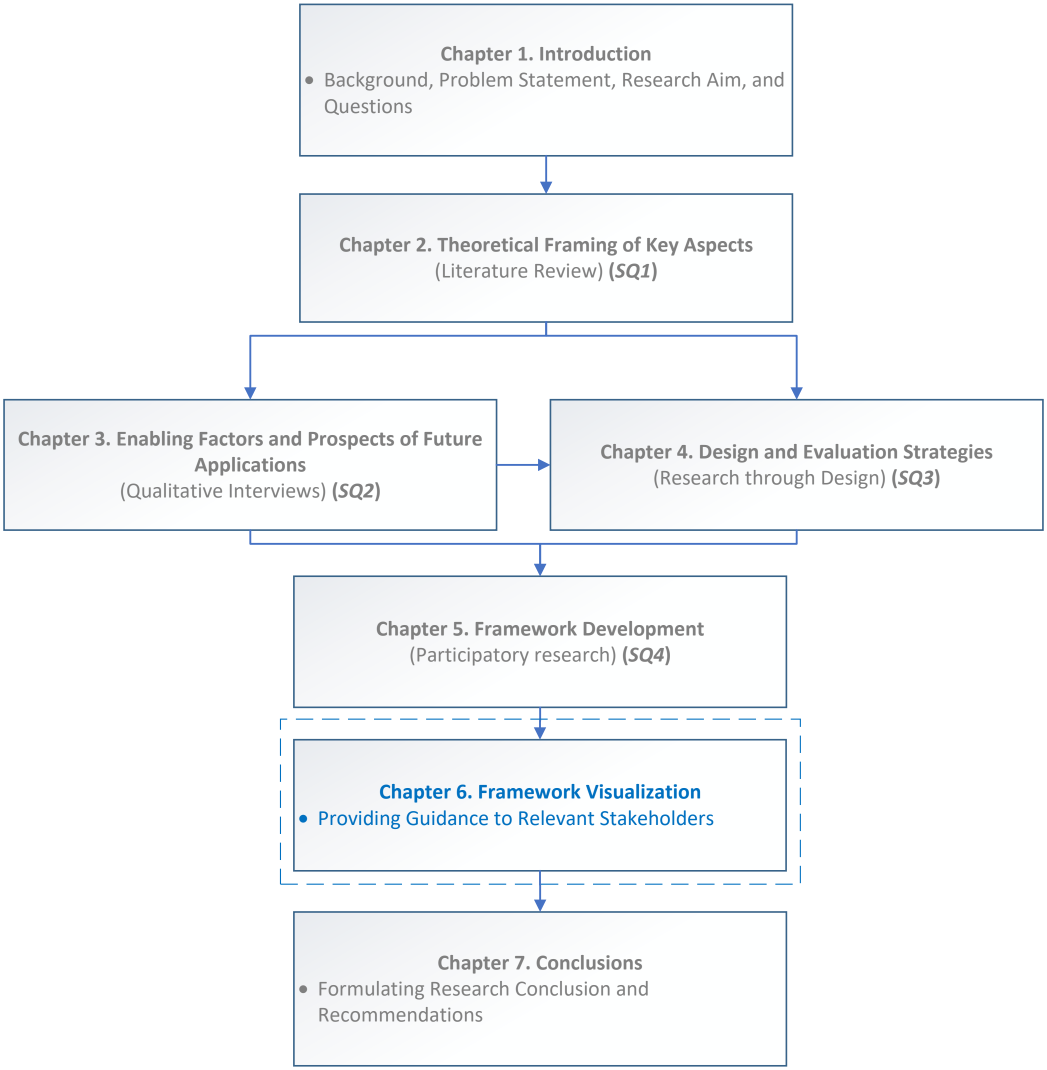
Based on these findings, future work should address the development of prefabricated façade products that incorporate a degree of standardization while maintaining flexibility for various applications. Furthermore, investigating relevant business models with clearly defined roles and responsibilities 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.

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.

Acknowledgement

The authors would like to thank the members and colleagues of the Department of Architectural Engineering and Technology, as well as the Architectural Façades and Products research group at Delft University of Technology, for providing insights into the workshop protocol and questionnaire surveys.


Chapter 1. Introduction
Background, Problem Statement, Research Aim, and Questions
Chapter 2. Theoretical Framing of Key Aspects
(Literature Review) (SQ1)
Chapter 3. Enabling Factors and Prospects of Future Applications
(Qualitative Interviews) (SQ2)
Chapter 4. Design and Evaluation Strategies
(Research through Design) (SQ3)
Chapter 5. Framework Development
(Participatory research) (SQ4)
Chapter 6. Framework Visualization
Providing Guidance to Relevant Stakeholders
Chapter 7. Conclusions
Formulating Research Conclusion and Recommendations

6 Framework Visualization

6.1 Introduction

This research project provides a framework for the design and development of solar cooling integrated façades, with the goal of supporting their widespread application. To integrate multiple aspects, the framework offers guidance to relevant stakeholders in assessing the current level of technology adoption, thereby facilitating the successful adoption and integration of new technologies. Offering such guidance requires synthesizing key outcomes through a process-oriented approach. The framework in this chapter was visualized based on the design strategies from **Chapter 4** and the validated aspects from **Chapter 5**. **Section 6.2** presents and describes the visualized framework. **Section 6.3** provides a discussion on the framework's application. After that, a reflection on challenges and enablers identified in **Chapters 2** and **3**, respectively, is provided in **Section 6.4**. This includes consideration of the extent to which the framework can mitigate the challenges while incorporating the enabling factors. Finally, the chapter concludes in **Section 6.5**.

6.2 Visualized Framework

To integrate multiple aspects, the framework offers guidance to relevant stakeholders in assessing the current level of technology adoption, thereby facilitating the successful adoption and integration of new technologies. **Figure 6.1** presents the key aspects to be considered in supporting the application of solar cooling integrated façades, based on the outcomes of this dissertation. The key stakeholders considered are:

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

Offering such guidance requires synthesizing key outcomes through a process-oriented approach. Based on the design strategies from **Chapter 4** and the validated aspects from **Chapter 5**, **Figures 6.2** to **6.6** present a visual summary of the framework. The shape legends used in the visualization are listed in **Table 6.1**. The guidance is structured into five stages, as adopted in **Chapter 5**, which is described in the following sections.

TABLE 6.1 Shape legends employed in the framework visualization (Figures 6.2–6.6)

Shape	Description
	Flowlines represent the direction of the process
Process	Rectangles represent the steps in processes
Input/ Output	Parallelograms represent the entry of data (inputs) or the results obtained (outputs)
Decision	Diamonds represent decisions
Stakeholders Involved	Circles represent the main stakeholders involved in each stage

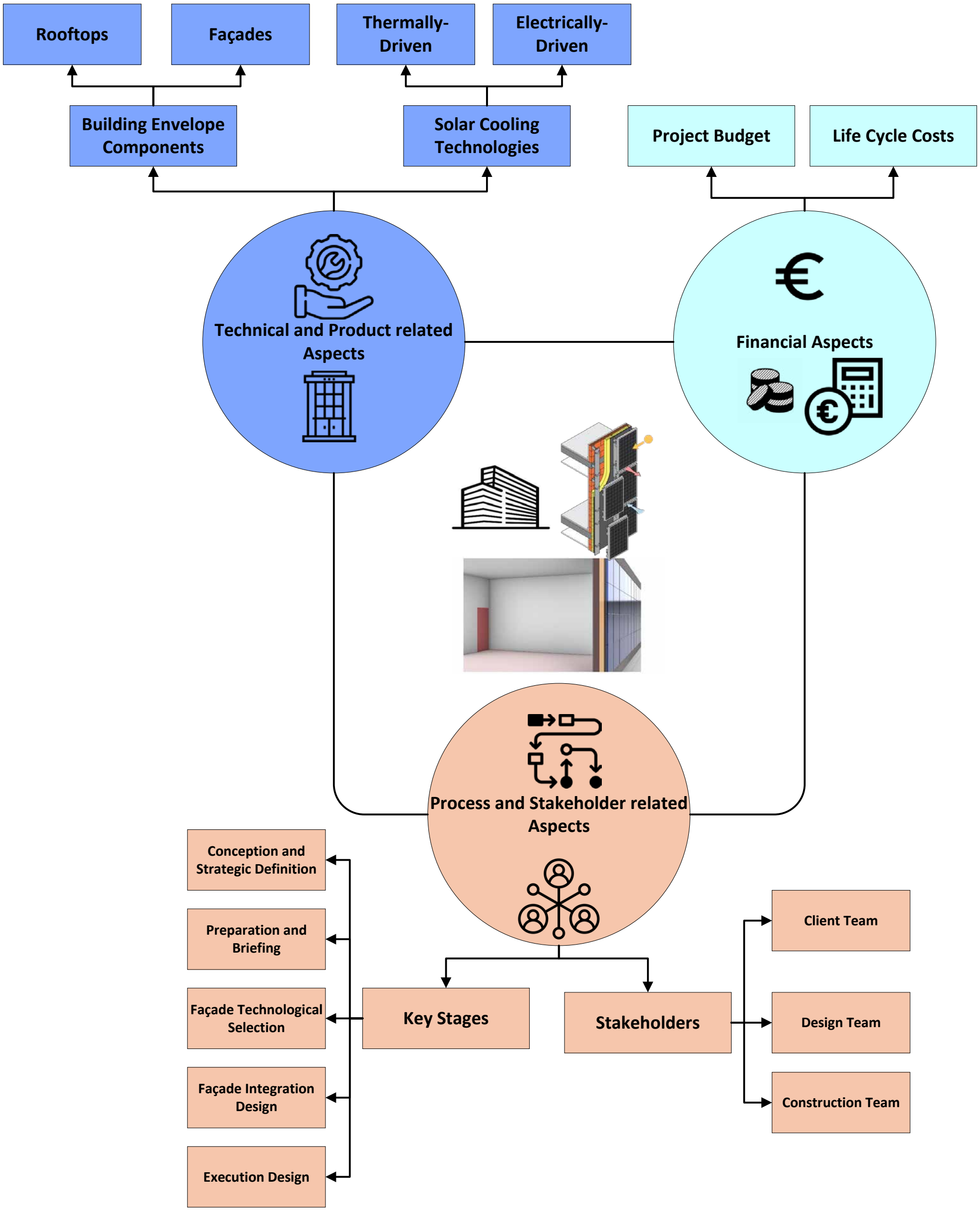


FIG. 6.1 Grounding the key aspects to be considered in supporting the application of solar cooling integrated façades, based on the dissertation outcomes

6.2.1 Identifying Possibilities for Building Integration

This stage comprises various steps, including assessment of energy performance and cooling demand, identification of possibilities for building integration, and preliminary analysis of the sequence of construction activities. The key stakeholders to be involved in this stage include owners, investors, and/or real estate/property developers, architectural designers, façade suppliers/manufacturers, as well as climate design, building physics, and building services consultants (**Figure 6.2**).

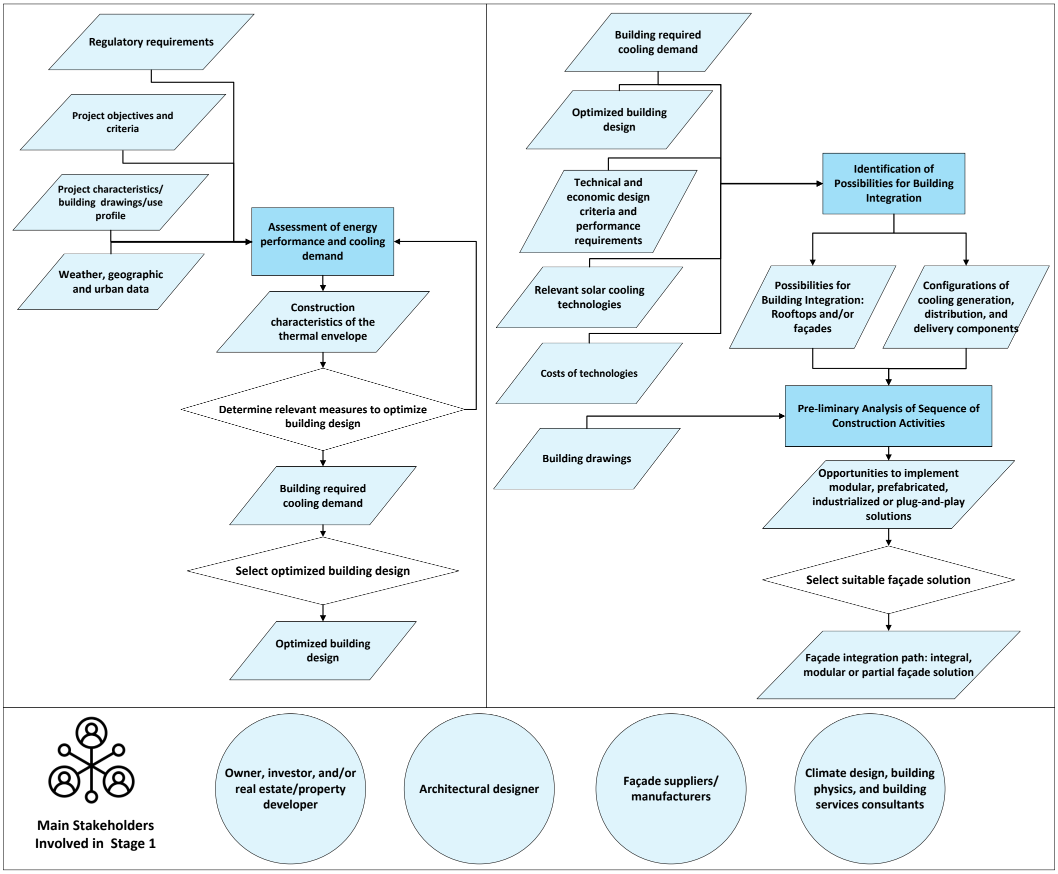


FIG. 6.2 Guidance for identifying possibilities for building integration (Stage 1)

6.2.2 Assessing the Feasibility of the Generated Possibilities

The stage involves assessment of pre-technical feasibility, evaluation of how technology can be integrated and operated, and assessment of economic feasibility. The key stakeholders to be involved in this stage consist of the architectural designer, mechanical, electrical, and plumbing (MEP) consultants, heating, ventilation, and air conditioning (HVAC), solar technologies, and/or other suppliers (**Figure 6.3**).

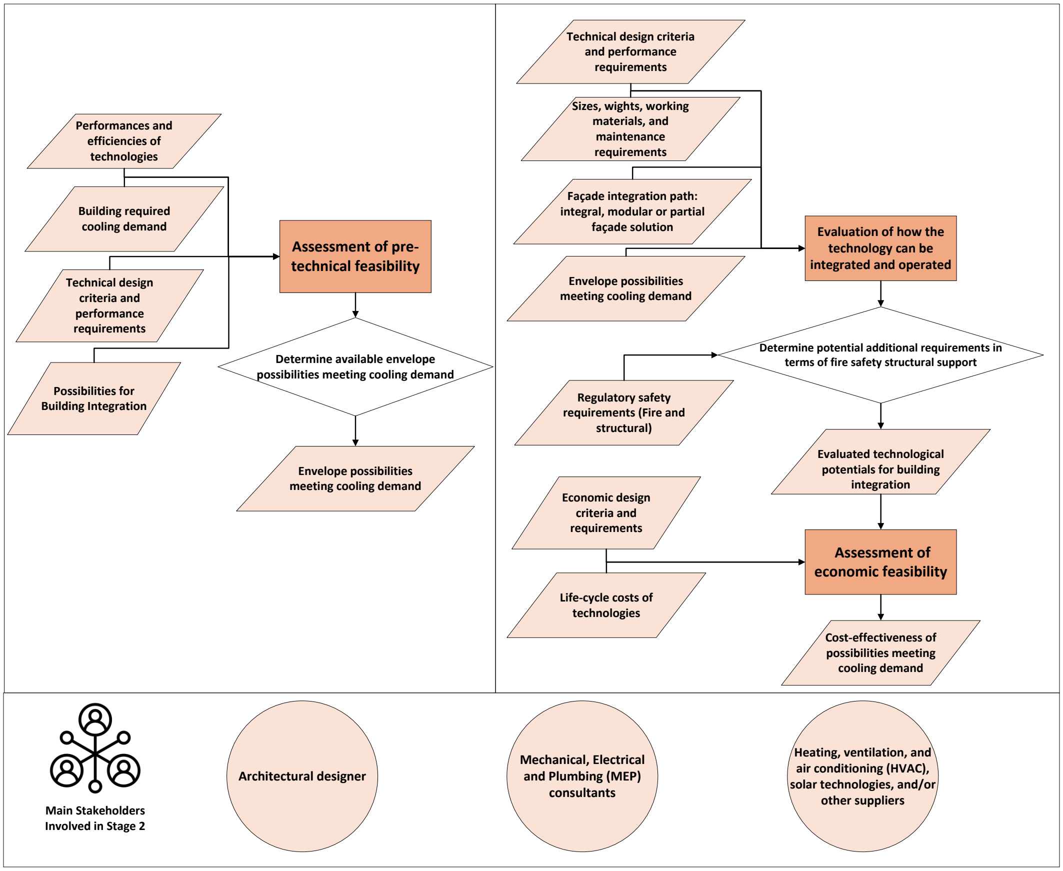


FIG. 6.3 Guidance for assessing the feasibility of the generated possibilities (Stage 2)

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6.2.3 Selecting the Relevant Architectural Façade Technology

The selection stage includes verification of techno-economic feasibility, summarization of techno-economic feasibility, and selection of architectural façade technology. The architectural designer, mechanical, Electrical, and Plumbing (MEP) consultants, and façade suppliers/manufacturers represent the key stakeholders to be involved in this stage (**Figure 6.4**). Given that each project possesses unique characteristics, and prefabrication has been recognized as a critical enabling approach, the decision to adopt prefabrication is contingent upon client approval. Accordingly, if prefabrication is proposed as part of the selected technological solution, the building design may necessitate substantial modifications. Consequently, a re-verification of the techno-economic feasibility must be undertaken, as illustrated in **Figure 6.4**.

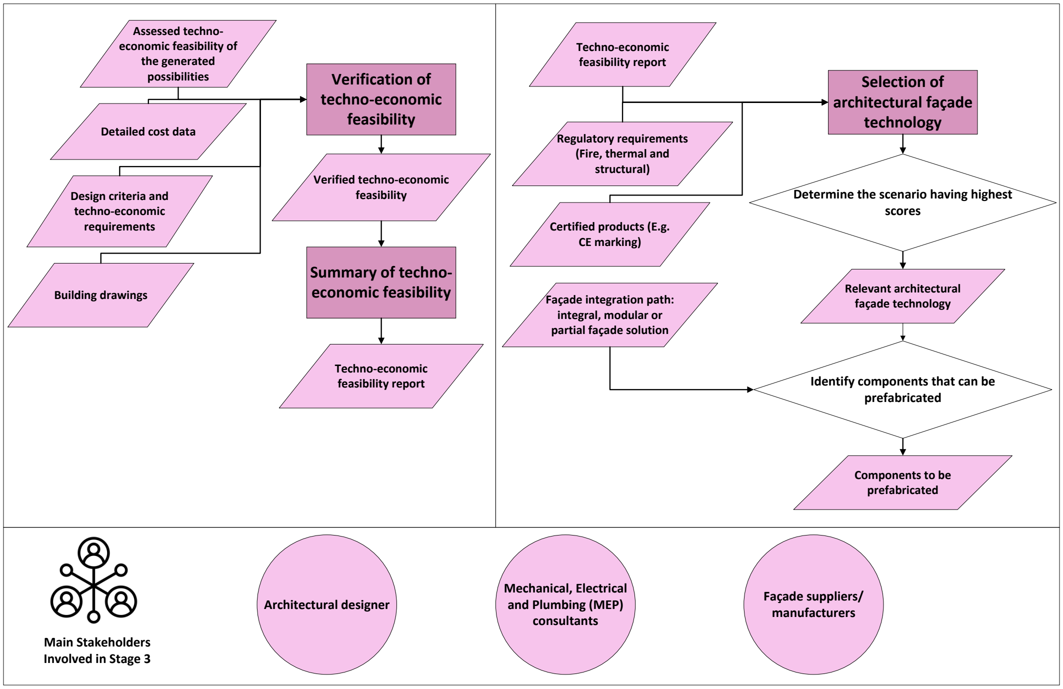

FIG. 6.4 Guidance for selecting the relevant architectural façade technology (Stage 3)

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6.2.4 Developing the Detailed Design for Integrating the Selected Technology

The detailed design stage comprises the determination of the characteristics of key elements and the means of connections. Developing the detailed design requires different stakeholders, namely, the façade designer, façade suppliers/manufacturers, and façade builders/assemblers (**Figure 6.5**).

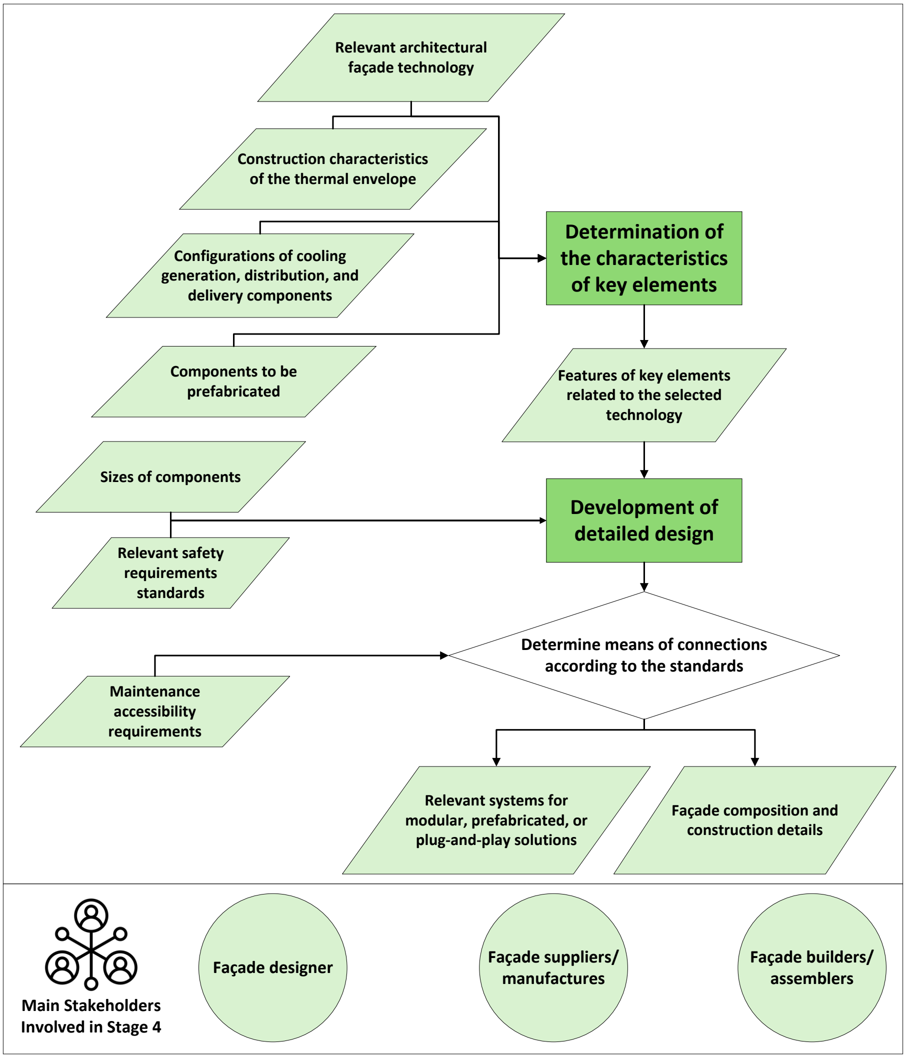


FIG. 6.5 Guidance for developing the detailed design of integrating the selected technology (Stage 4)

6.2.5 Designing for the Installation of Façade Components

This execution design stage involves design elaboration and completion, special coordination, production and assembly design, and project planning and scheduling. Project directors representing the client (construction management and supervision), façade suppliers/manufacturers, façade builders/assemblers, and contractors represent the key stakeholders to be involved in this stage (**Figure 6.6**). As the adoption of an appropriate contracting method or the establishment of effective partnerships among relevant stakeholders is perceived to facilitate the development of affordable and financially viable products, the design for component installation may take various forms depending on the contracting method. Nevertheless, an appropriate contracting approach, such as a Design–Build–Maintain–Operate (DBMO) contract, should be considered to promote close collaboration during this stage.

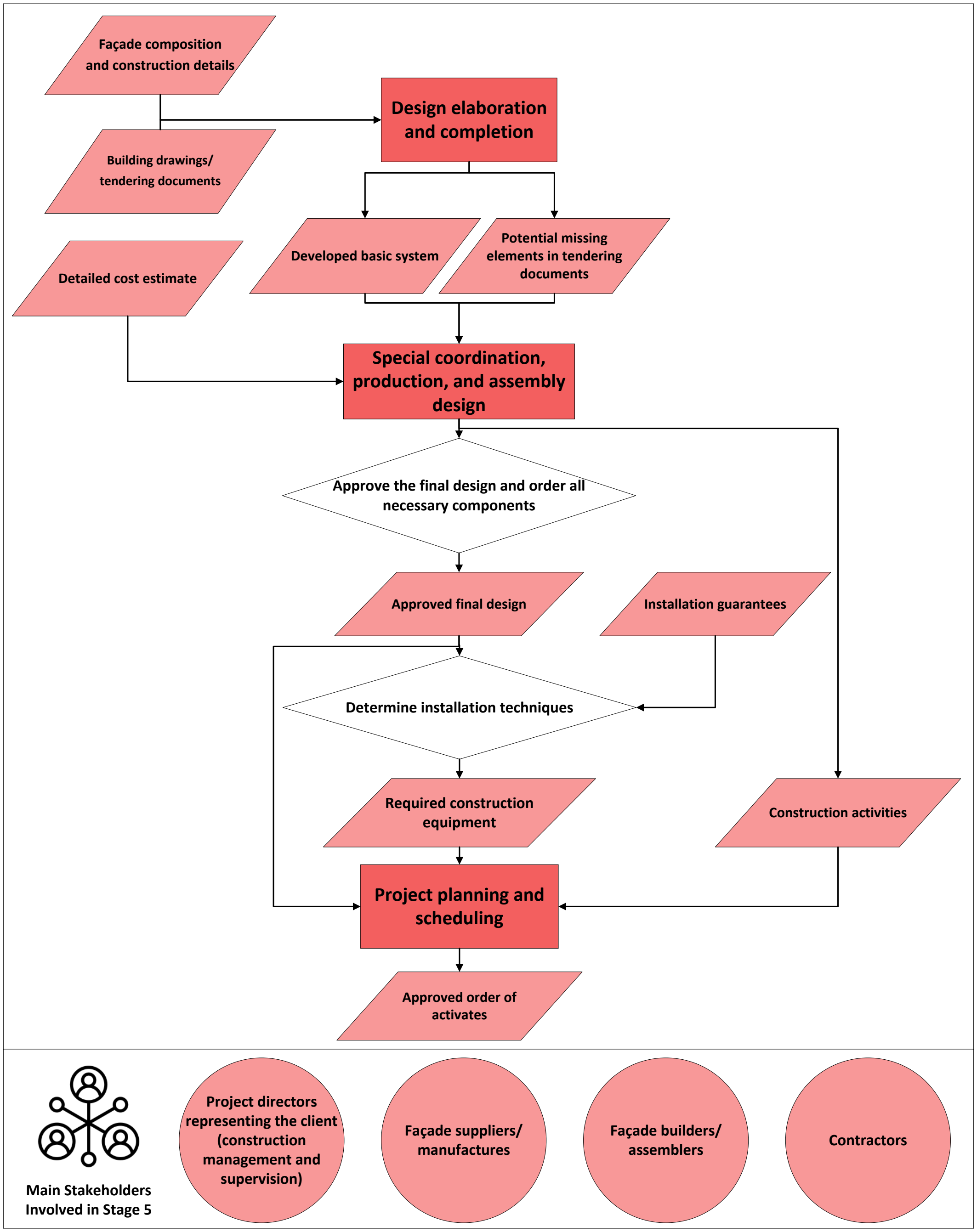


FIG. 6.6 Guidance for design for the installation of façade components (Stage 5)

6.3 Discussion of the Application of the Framework

The visualization of the framework was based on several assumptions related to the key design and development stages of a new office building. It is intended to serve as a general guide for exploring various solar cooling technologies. This includes considering appropriate façade integration paths—namely, integral, modular, or partial façade integration—depending on the solar cooling technology incorporated during the design process (Prieto, Knaack, et al., 2017a). This approach reflects the uniqueness of each project and acknowledges that the development and advancement of such technologies evolve over time.

Although these sequential stages may not follow a strictly linear order due to the iterative, feedback-driven nature of the design process, the structured approach ensures systematic organization of information within the framework. The framework is visualized in five diagrams (**Figures 6.2** to **6.6**) due to the variability of required information to be processed and/or generated, as well as the stakeholders to be involved. However, as the design process is iterative, it is clear that certain types of information are required as inputs into different processes, steps, and decisions. For example, the project objectives and criteria are required for assessing energy performance and cooling demand, as well as for determining relevant measures to optimize building design (**Figure 6.2**). Building drawings are also needed both for identifying possibilities for building integration and for conducting a preliminary analysis of construction activities.

On the other hand, different processes require different types of information to generate the required outputs. For instance, building drawings, relevant solar cooling technologies, and technology costs are required to identify possibilities for building integration. Additionally, to perform a preliminary analysis of the sequence of construction activities, building drawings, identified possibilities for building integration, and the configuration of cooling generation, distribution, and delivery components are required in order to determine opportunities to implement modular solutions (**Figure 6.2**).

The framework recognizes that, as the design process advances, cost estimates become progressively more detailed and accurate. Preliminary estimates are generally derived from broad assumptions and historical datasets, whereas subsequent estimates are informed by project-specific parameters and contextual information. For example, approximate estimates of technology costs are required to identify opportunities for building integration (**Figure 6.2**), while a more comprehensive assessment of life cycle costs is necessary to evaluate the economic feasibility of alternative design scenarios (**Figure 6.3**). At later stages, detailed cost estimates are essential for coordinating specialized tasks, as well as for production and assembly design (**Figure 6.6**). The following points are important to highlight regarding the framework application:

6.3.1 Role of the Client

The client can play a key role in defining project goals, objectives, and criteria, which may influence the feasibility of different design scenarios as well as the selection of technologies to be integrated into the façade. Based on these defined goals, objectives, and criteria, architectural designers, climate designers, building physicists, and building services consultants collaborate to inform the client by assessing pre-technical feasibility (**Figures 6.2** and **6.3**). This may involve evaluating the product's performance and efficiency, its capacity to meet cooling requirements, and providing a preliminary estimate of the return on investment for different conceptual designs.

6.3.2 Status of Technology

The status, availability, and maturity of solar cooling technologies are influenced by local technology suppliers/developers. Hence, the presence of locally available and mature technologies, both technically and economically, plays an essential role in supporting their widespread adoption. This is because the technical features affect how the technology can be integrated and operated, which is directly related to analyzing compactness and efficient space use, including the area occupied by solar cooling components, product dimensions, and required structural support. In addition, these features are directly linked to evaluating the requirements for assembling, connecting, and maintaining products, such as component integration, operational principles, periodic maintenance, cleaning, and accessibility. Technology providers are therefore required to supply relevant details on installation needs and maintenance aspects, including materials used, accessibility, and cleaning.

6.3.3 Local Building Regulations

Local building regulations—particularly those related to energy savings and product certification—play a crucial role in improving energy efficiency and supporting the integration of renewable energy technologies. In **Chapter 4**, nonnational standards were applied in the hypothetical new office building case to define outdoor air ventilation rates. This approach was justified by the study's objective to map the early-stage design process and develop guiding strategies for the design and evaluation of building façades integrating solar cooling technologies, enabling the results to be directly comparable to international research. It is emphasized that in real-world projects, all applicable local and national standards and building regulations must be followed to ensure regulatory compliance. Additionally, product certification serves as an additional motivating factor for widespread adoption, with its influence reinforced by evolving building regulations. Finally, accounting for local regulatory requirements related to building typologies and neighborhood aesthetics is crucial, as these regulations affect how new technologies are integrated into the building envelope.

6.3.4 Framework Adaptation to Other Contexts

The visualized framework may need to be adapted for use in other contexts, as the study was conducted with a focus on the European setting. This adaptation involves considering the local market structure and stakeholder landscape, since the building industry varies across contexts in terms of role distribution, local practices, and cultural factors. Understanding local climate conditions and comfort requirements is another essential consideration, as these factors can influence the technical feasibility of solar cooling technologies. As the case study focused on mapping the design process, urban effects were not incorporated when assessing solar energy input. Therefore, it is essential to consider such effects in real contexts in order to identify how the urban environment can impact the actual energy generated by the developed design scenarios. This includes investigating the effects of diffuse and indirect radiation, as well as polluted environmental contexts, on system performance.

6.4 Reflection on Challenges and Enablers

This section reflects on the extent to which the framework can mitigate the challenges identified in **Chapter 2** while incorporating the enabling factors discussed in **Chapter 3**. **Sections 6.4.1** and **6.4.2** focus on the challenges and enablers, respectively.

6.4.1 Challenges in the Application of SCIFs

Chapter 2 identified and categorized main challenges through conducting a comprehensive literature review. The literature review was conducted on scientific papers published in conference proceedings and scientific journals, through considering two databases, namely Scopus and Web of Science. The results obtained from the literature review revealed that various forms of challenges have been identified by different scholars. The challenges identified in **Chapter 2** were divided into two main categories:

- **General challenges associated with integrating solar technologies into building façades, regardless of the technology type.**
- **Specific product-related challenges linked to different solar cooling technologies, which vary from one technology to another.**

Having insight into these various forms of challenges, the framework primarily seeks to address those related to the first category (**Table 2.2**), which fall under the following areas:

- **Challenges Related to Knowledge:** The framework can provide key stakeholders involved in the design and development stages with the necessary knowledge, including guidance on the steps and decisions to be taken.
- **Challenges Related to Information:** The framework facilitates the flow of information required to support various design decisions throughout different stages.
- **Challenges Related to Design and Construction Processes:** *The* framework can mitigate these challenges by providing guidance on establishing a collaborative network of experts across different stages.

- **Challenges Related to Interest:** The framework offers guidance on the steps necessary to deliver relevant information to clients and designers, thereby increasing their interest in integrating such technologies at early stages.

On the other hand, the framework is less effective in addressing the other categories of challenges, which include:

- **Specific product-related challenges linked to different solar cooling technologies:** The framework focuses on guiding stakeholders in assessing the current level of technology adoption, recognizing that the development and advancement of these technologies evolve over time. However, such challenges can be addressed by technology developers, depending on the specific technology, through measures such as enhancing materials to minimize maintenance requirements and advancing solar collector designs to facilitate easier cleaning.

- **Financial challenges:** Technology costs can vary between different products and change over time. While subsidies may play a role, such financial support can differ significantly from one country to another.

6.4.2 Enablers of SCIF Application

The identification of enabling factors was carried out through qualitative interviews with stakeholders. An interview guide was designed to involve the main aspects proposed in **Chapter 2**. Different criteria were considered to select interviewees during the data collection, such as participants who worked on the application or façade integration of solar/solar cooling technologies in buildings. While the study focused on professionals based in Europe, which may be seen as a limitation, this choice was intentional to ensure the relevance of the identified enablers within the European context. The insights gathered were then applied as lessons learned in a Southern European case study (**Chapter 4**) and informed the participatory research (**Chapter 5**). Professionals from outside Europe were not included because the study specifically aimed to investigate European contexts, which could differ significantly in terms of regulatory, cultural, and organizational factors. Additionally, although several participants were directly engaged in façade design and construction and in the implementation of solar technologies, the number of interviewees involved in the application of solar cooling technologies in buildings was lower due to the early adoption of these technologies in real buildings. Nevertheless, the identified enablers remain relevant, as they capture the perspective of integrating innovative technologies into the building envelope.

Various enabling factors were identified through the qualitative interviews presented in **Chapter 3** (**Figure 3.5**, **Table C.1**, and **Figures C.1** and **C.2**). The findings from 23 interviews revealed that the most frequently mentioned factors include:

- Product performance and efficiency
- Facilitating the delivery of product information to architects and clients
- Aesthetic acceptability
- Multidisciplinary teamwork
- Ability to customize products

The evaluation setup developed in **Chapter 4** to assess the feasibility of design scenarios was proposed by requirements derived primarily from relevant literature and lessons learned from the interviews. This included reference to various aspects identified through the qualitative analysis that were perceived either as supporting factors or as concerns related to the façade integration of solar technologies—whether electrically or thermally driven. Key factors such as performance and efficiency, component compactness, maintenance requirements, and life-cycle costs were incorporated into the framework. Furthermore, the framework integrated the consideration of prefabricated products during the design and development stages. However, other essential factors—such as aesthetic acceptability, product customization, standardization, and reusability—were not included. Hence, while the case study in **Chapter 4** focused on connection methods that facilitate various aspects of installation, maintenance, and disassembly, it is important to note that in future research and real projects, addressing factors that enable circularity is essential. The ability of façade products to incorporate circular economy principles is considered a crucial factor during both the design and end-of-life stages (**Figure 3.5**, **Table C.1**, and **Figures C.1** and **C.2**):

- **Design for disassembly:** The ease of disassembling components is a key factor for maintenance and durability, particularly when parts need to be repaired off-site or replaced.

- **Reusability:** The ability of these façade products to be reused after disassembly is an important factor in promoting wider adoption.

- **Recyclability/upcyclability:** The potential of façade products to be recyclable or upcyclable—for example, through the use of appropriate materials—supports their broader adoption.

Incorporating such principles is essential as the solar technologies industry, mainly PV panels, continues to grow, and developing effective strategies for the end-of-life management of these products is essential to ensuring long-term viability and environmental benefits (Pivatto et al., 2025).

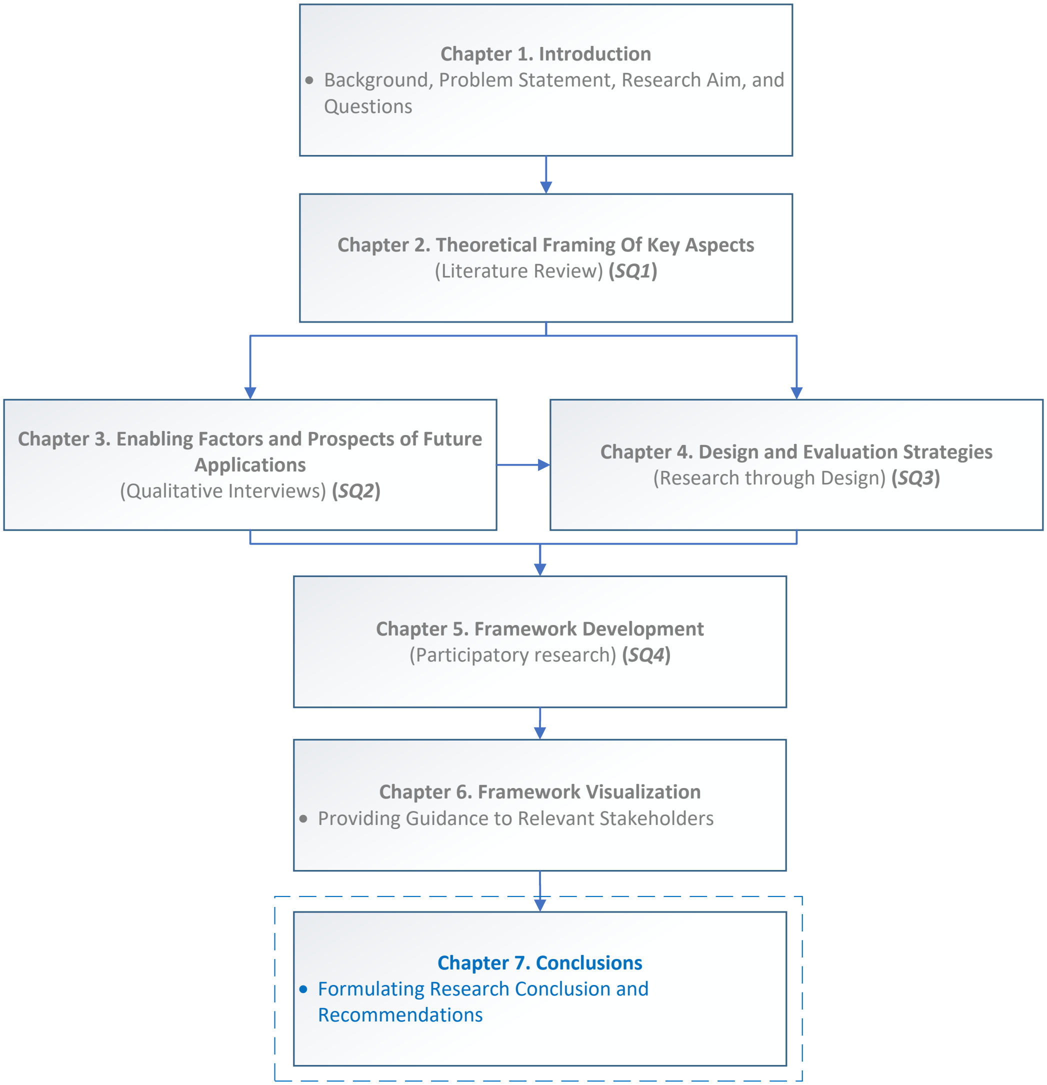
Finally, **Chapter 5** builds on the lessons learned from the qualitative interviews by addressing enabling factors primarily related to process and stakeholder (P&S) aspects, including the facilitation of product information delivery to architects and clients and the promotion of multidisciplinary collaboration. These factors serve as key enablers for enhancing the knowledge and expertise of architects and engineers while fostering greater interest among designers and clients.

6.5 Conclusion

This research project provides a framework for the design and development of solar cooling–integrated façades, with the goal of supporting their widespread application. To integrate multiple aspects, the framework offers guidance to relevant stakeholders in assessing the current level of technology adoption, thereby facilitating the successful adoption and integration of new technologies. Offering such guidance requires synthesizing key outcomes through a process-oriented approach.

The framework in this chapter was visualized based on the design strategies and validated aspects. The key stakeholders considered include the client team, design team, and construction team. The guidance is structured into five stages: identifying possibilities for building integration, assessing the feasibility of the generated possibilities, selecting the relevant architectural façade technology, developing the detailed design for integrating the selected technology, and designing for the installation of façade components. Although these sequential stages may not follow a strictly linear order due to the iterative, feedback-driven nature of the design process, the structured approach ensures systematic organization of information within the framework.

The visualization of the framework was based on several assumptions related to the key design and development stages of a new office building. It is intended to serve as a general guide for exploring various solar cooling technologies. This approach reflects the uniqueness of each project and acknowledges that the development and advancement of such technologies evolve over time. Accordingly, various points were highlighted regarding the framework's application, including the role of the client, the status of technology, local building regulations, and framework adaptation to other contexts. Finally, a reflection on the challenges and enablers identified in Chapters 2 and 3, respectively, was provided. This includes consideration of the extent to which the framework can mitigate the challenges while incorporating the enabling factors.


Chapter 1. Introduction
Background, Problem Statement, Research Aim, and Questions
Chapter 2. Theoretical Framing Of Key Aspects
(Literature Review) (SQ1)
Chapter 3. Enabling Factors and Prospects of Future Applications
(Qualitative Interviews) (SQ2)
Chapter 4. Design and Evaluation Strategies
(Research through Design) (SQ3)
Chapter 5. Framework Development
(Participatory research) (SQ4)
Chapter 6. Framework Visualization
Providing Guidance to Relevant Stakeholders
Chapter 7. Conclusions
Formulating Research Conclusion and Recommendations

7 Conclusions

7.1 Introduction

Solar cooling technologies represent one of the key options for addressing environmental challenges associated with the global increase in demand for space cooling in the built environment. Building facades present high potential for the integration of solar cooling technologies. However, the widespread application of solar cooling integrated façades in the built environment is still far from what it could be. This is because there are various challenges affecting their widespread use. Providing guidance to relevant stakeholders to support the assessment of the current level of technology adoption, while addressing existing challenges, can play a key role in the successful adoption and integration of new technologies. This research project aimed at providing a product design and development framework for solar cooling integrated façades to support widespread application. Providing such a framework required different steps, including the determination of challenges and main aspects to be considered, identification of key enabling factors and prospects of future applications, development of key strategies guiding the façade design and evaluation, as well as identification, outlining, and validation of main decisions, required information, and involved stakeholders.

This chapter concludes the dissertation by summarizing the answers to the research sub-questions (**Section 7.2**) and presenting the conclusion and recommendations (**Section 7.3**), including the general conclusion and suggestions for future research.

7.2 Addressing Sub-Questions

To answer the main research question — *How can the design and development of solar cooling integrated facades be guided to support their widespread application?* — a set of different sub-questions was required to be investigated. This section summarizes the answers to the research sub-questions (**SQ_s**). **Sections 7.2.1** to **7.2.4** summarize the answers to **SQ_1** to **SQ_4**, respectively.

7.2.1 What are the challenges and key aspects in the application of SCIFs?

Answering the first sub-question was the focus of **Chapter 2**. Understanding how various key aspects are integrated plays a crucial role in developing the knowledge required to support the widespread application of solar cooling integrated façades. Therefore, investigating the different forms of challenges was considered a first step in proposing a theoretical framework of the key aspects to be considered. Hence, **Chapter 2** identified and categorized main challenges through conducting a comprehensive literature review. The literature review was conducted on scientific papers published in conference proceedings and scientific journals, through considering two databases, namely Scopus and Web of Science. The results obtained from the literature review revealed that various forms of challenges have been identified by different scholars. The challenges were divided into two main forms, which are as follows:

- Challenges associated with the integration of solar technologies into building façades in general, regardless of the technology type.
- Specific product-related challenges precisely linked to different solar cooling technologies, which vary from one technology to another.

The diversity of these challenges highlights the complexity involved in supporting the widespread application of solar cooling integrated façades. To simplify this complexity, **Chapter 2** proposed three main aspects to be considered and integrated:

- Technical and product (T&P)-related aspects, which comprise sizes, performances, and efficiencies of components.
- Financial (F)-related aspects which are associated with different costs during the product life cycle.

- Process and stakeholder (P&S)-related aspects include various design and development processes, as well as the roles and responsibilities of various stakeholders during the product life cycle.

It should be noted that this framing represents a fundamental assumption that defines the scope and boundary conditions for investigating the enablers and developing the product design framework presented in this dissertation. Therefore, this assumption significantly influences the scope and findings of the subsequent chapters—for example, the formulation of interview questions, the parameters and design criteria considered in the evaluation setup, and the structuring of information in the participatory research process.

7.2.2 What are the key enabling factors and prospects of future applications of SCIFs?

Chapter 3 aimed to investigate the second sub-question. Answering this sub-question involved identifying the main factors enabling the widespread integration of solar cooling technologies in façades. The identification of enabling factors was carried out through qualitative interviews with stakeholders. An interview guide was designed to involve the main aspects proposed in **Chapter 2**. Different criteria were considered to select interviewees during the data collection, such as participants who worked on the application or façade integration of solar/solar cooling technologies in buildings. The findings obtained from a total of 23 interviews revealed that the most frequently mentioned factors are as follows:

- Product performance and efficiency
- Facilitating the delivery of product information to architects and clients
- Aesthetical acceptability
- Multidisciplinary teamwork
- Ability to customize products

The factors were mapped in the context of façade design and construction processes to establish a matrix for implementing solutions in product development. The majority of the factors were linked to the design phase according to interviewees' perceptions. The identified enabling factors of solar cooling integrated façades (SCIFs) contribute to expanding the boundaries of knowledge in the field of building product development. This includes technical considerations related to product features, such as relevant plug-and-play solutions, as well as process-oriented improvements, such as the adoption of suitable contracting methods that facilitate the delivery of product information and promote collaboration among different disciplines.

7.2.3 How can systematic early-stage design and feasibility assessment of SCIFs be supported?

To answer this sub-question in **Chapter 4**, key strategies were developed to guide the design and evaluation of façade products integrating solar cooling technologies. Their development comprised the following parts:

- Identifying key design stages as a framework for designing solar cooling integrated façades systematically. The stages included identifying possibilities for façade integration, assessing the feasibility of the generated possibilities, selecting the relevant architectural façade technology, and developing the detailed design for integrating the selected technology.

- Proposing an evaluation set-up to assess design scenarios during the case study. To assess the feasibility of façade integration during early design stages, it was crucial to have an evaluation setup that could enable an appropriate comparison of different design alternatives with respect to relevant criteria. The scope of the proposed evaluation setup consisted of a techno-economic assessment methodology, corresponding mainly to T&P-&F-related aspects as they can be assessed and compared with certain criteria:

  - **Technical Criteria**
    - *Product Performance and Efficiency and the Ability to Meet User Cooling Requirements:* The solar fraction (SF) was the key indicator to assess this criterion.
    - *Compactness and Space Usability:* Qualitative scoring and rating techniques to translate qualitative criteria into quantifiable measures were the key indicators.
    - *Assembly and Connections:* Qualitative scoring and rating techniques to translate qualitative criteria into quantifiable measures were the key indicators.
    - *Maintenance Requirements*: Qualitative scoring and rating techniques to translate qualitative criteria into quantifiable measures were the key indicators.

  - **Economic Criteria**

- *Cost Effectiveness:* Life-Cycle Cost (LCC) and Levelized Cost of Cooling (LCOC) were the key indicators to assess this criterion.

- Designing and evaluating solar cooling integrated façades within a relevant context and selected case, taking into account the two aforementioned points. The strategies incorporated solar cooling technologies into newly constructed buildings, which generally offer more flexibility for implementing innovative solutions than existing structures. Various scenarios were generated for building envelope integration of electrically driven systems (water-cooled vapor-compression chillers (VCC) combined with photovoltaic (PV) panels) as well as thermally driven systems (solar absorption chillers combined with flat-plate collectors (FPCs) and evacuated tube collectors (ETCs)). The scenarios included rooftops only, façades only, and rooftops & façades.

  The findings indicate that water-cooled vapor-compression chillers (VCC), combined with photovoltaic (PV) panels as an electrically driven solution, were the most relevant option for the selected case. While electrically driven technologies proved more feasible for façade integration, thermally driven systems showed competitive performance but scored lower in maintenance and cost-effectiveness. Hence, material enhancements should be considered for thermally driven technologies to reduce maintenance requirements. Additionally, technological advancements in solar collectors to simplify cleaning represent important considerations. Finally, subsidies could improve their economic feasibility by reducing investment costs.

  The proposed multi-step techno-economic assessment method supports decision-making by systematically evaluating different scenarios. Analysis of the developed strategies shows that the first two stages—conception and strategic definition, as well as preparation and briefing—contained most steps, inputs, decisions, and outcomes. Early-stage processes significantly impact later phases, such as construction characteristics in detailed design. This is due to the need for thorough early investigations, including regulatory measures, passive strategies, and project requirements. Providing structured methodologies to professionals with limited experience in solar cooling technologies is crucial for enabling their broader application. However, the results of applying the proposed multi-step techno-economic assessment method should be considered case-specific due to various factors such as:

- Each building has its own size, energy load profile, architectural design, and construction characteristics.
- The availability of solar radiation varies from one location to another, influenced by factors such as shading from the surrounding environment.
- The development of solar technologies is an ongoing process, meaning that performance, sizes, working principles, and costs can change over time.

- The case study outcomes, such as generated radar charts, were based on an equal prioritization of technical and economic criteria. However, since every project is unique, stakeholders—such as investors—may have different priorities, which can influence the selection of the most suitable option.

7.2.4 How can an integrative framework guide the design and development of SCIFs?

Answering the last sub-question was the focus of **Chapter 5**. Answering **SQ_4** involved 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. Outlining key decisions and the required information to support them was based on the strategies developed in **Chapter 4**. Similar to **Chapter 4**, the context—including building typology, relevant technologies, and geographic location—was selected based on the outcomes of **Chapter 3**. Furthermore, this chapter considered the lessons learned from the qualitative interviews in **Chapter 3** by addressing the identified enabling factors primarily related to process and stakeholder (P&S) aspects, including facilitating the delivery of product information to architects and clients, as well as supporting multidisciplinary teamwork. These factors serve as key enablers for enhancing the knowledge and expertise of architects and engineers while fostering greater interest among designers and clients. However, to collect information related to stakeholder involvement, additional sources of data were required. These included desk research on relevant topics such as design and construction processes, as well as the key stakeholders involved in the façade design and construction stages—for example, curtain wall systems. Additionally, an online pre-workshop questionnaire was distributed, and a workshop was conducted to evaluate, elaborate on, and refine the identified aspects. Finally, the design and development aspects and stages were validated through a design experience survey. Based on the outcomes of this chapter, integrating the key aspects required to support the design and development process of SCIFs should take the following points into consideration:

- Managing relationships among diverse stakeholder groups helps mitigate procedural complexities by supporting effective team coordination and management
- Applying the outlined and validated aspects should be tailored to address bottlenecks associated with limited knowledge of the technologies and the lack of detailed cost information.

Hence, the following considerations are outlined to support the design and development process of SCIFs:

- Convincing the client by assessing pre-technical feasibility represents a key step. This involves evaluating product performance and efficiency, its ability to meet cooling requirements, and roughly estimating the return on investment for various conceptual designs. This may require collaboration among the client, architect, and climate design, building physics, and building services consultants.

- 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 architect, climate design, building physics, and building services consultants, façade designers, façade suppliers/manufacturers, and technology providers.

- Evaluating requirements for assembly, connections, and maintenance of products, including component integration, working principles, periodic maintenance, product cleaning, and accessibility. This may require collaboration among the architect, façade designers, façade suppliers/manufacturers and technology providers, and façade assemblers/builders.

7.3 Conclusion and Recommendations

This section aims to provide the conclusion and recommendations of this dissertation by providing a general conclusion (**Section 7.3.1**) and offering recommendations for future work (**Section 7.3.2**).

7.3.1 General Conclusion

Facilitating the widespread application of solar cooling integrated façades through the integration of technical and product (T&P)-related, financial (F)-related, and process and stakeholder (P&S)-related aspects constitutes a complex and non-linear undertaking. It requires consideration of various factors within these aspects. For instance, from a technical and product (T&P) perspective, several improvements can be considered, including the development of prefabricated façade products that incorporate a degree of standardization while maintaining flexibility for various applications. Additionally, material enhancements for thermally driven technologies to reduce maintenance requirements, as well as technological advancements in solar collectors to simplify cleaning, represent important considerations. From a financial (F) perspective, subsidies could improve economic feasibility by reducing investment costs. From a process and stakeholder (P&S) perspective, the investigation of relevant business models with clearly defined roles and responsibilities can enhance collaboration among stakeholders and represent an essential improvement.

To answer the main research question — *How can the design and development of solar cooling integrated facades be guided to support their widespread application?* — this study provided a product design and development framework for solar cooling integrated façades to support widespread application. To integrate multiple aspects, the framework offers guidance to relevant stakeholders in assessing the current level of technology adoption, thereby facilitating the successful adoption and integration of new technologies. The guidance is structured into five stages, which are as follows:

1. **Identifying possibilities for building integration:** This stage comprises various steps, including assessment of energy performance and cooling demand, identification of possibilities for building integration, and preliminary analysis of the sequence of construction activities. The key stakeholders to be involved in this stage include owners, investors, and/or real estate/property developers, architectural

designers, façade suppliers/manufacturers, as well as climate design, building physics, and building services consultants

2. **Assessing the feasibility of the generated possibilities:** The stage involves assessment of pre-technical feasibility, evaluation of how technology can be integrated and operated, and assessment of economic feasibility. The key stakeholders to be involved in this stage consist of the architectural designer, mechanical, electrical, and plumbing (MEP) consultants, heating, ventilation, and air conditioning (HVAC), solar technologies, and/or other suppliers.

3. **Selecting the relevant architectural façade technology:** The selection stage includes verification of techno-economic feasibility, summarization of techno-economic feasibility, and selection of architectural façade technology. The architectural designer, mechanical, Electrical, and Plumbing (MEP) consultants, and façade suppliers/manufacturers represent the key stakeholders to be involved in this stage. Given that each project possesses unique characteristics, and prefabrication has been recognized as a critical enabling approach, the decision to adopt prefabrication is contingent upon client approval. Accordingly, if prefabrication is proposed as part of the selected technological solution, the building design may necessitate substantial modifications. Consequently, a re-verification of the techno-economic feasibility must be undertaken.

4. **Developing the detailed design for integrating the selected technology:** The detailed design stage comprises the determination of the characteristics of key elements and the means of connections. Developing the detailed design requires different stakeholders, namely, the façade designer, façade suppliers/manufacturers, and façade builders/assemblers.

5. **Designing for the installation of façade components:** This execution design stage involves design elaboration and completion, special coordination, production and assembly design, and project planning and scheduling. Project directors representing the client (construction management and supervision), façade suppliers/manufacturers, façade builders/assemblers, and contractors represent the key stakeholders to be involved in this stage. As the adoption of an appropriate contracting method or the establishment of effective partnerships among relevant stakeholders is perceived to facilitate the development of affordable and financially viable products, the design for component installation may take various forms depending on the contracting method. Nevertheless, an appropriate contracting approach, such as a Design–Build–Maintain–Operate (DBMO) contract, should be considered to promote close collaboration during this stage.

Although these sequential stages may not follow a strictly linear order due to the iterative, feedback-driven nature of the design process, the structured approach ensures systematic organization of information within the framework. The framework was provided based on these stages due to the variability of required information to be processed and/or generated, as well as the stakeholders to be involved. The framework recognizes that, as the design process advances, cost estimates become progressively more detailed and accurate. Preliminary estimates are generally derived from broad assumptions and historical datasets, whereas subsequent estimates are informed by project-specific parameters and contextual information. The framework is intended to serve as a general guide for exploring various solar cooling technologies. This includes considering appropriate façade integration paths—namely, integral, modular, or partial façade integration—depending on the solar cooling technology incorporated during the design process. This approach reflects the uniqueness of each project and acknowledges that the development and advancement of such technologies evolve over time.

Taking into account that this dissertation focuses on supporting widespread application by providing guidance for the design and development processes, future research should concentrate on proof-of-concept testing of modular and prefabricated façade solutions in pilot projects. The development of such solutions can be guided by the framework presented in this dissertation. Hence, to facilitate the dissemination of these tested concepts, the incorporation of relevant theoretical perspectives—such as Rogers' diffusion of innovation theory—can be considered (Gledson & Greenwood, 2017; Kaushalya et al., 2024; Shibeika & Harty, 2016).

Finally, the main concluding remarks of this dissertation are summarized in the following points:

- Encouraging multidisciplinary collaboration and streamlining the dissemination of product information are crucial factors in facilitating product development. However, the client can play a key role in defining project goals, objectives, and criteria, which may influence the feasibility of different design scenarios as well as the selection of technologies to be integrated into the façade. Based on these defined goals, objectives, and criteria, architectural designers, climate designers, building physicists, and building services consultants collaborate to inform the client by assessing pre-technical feasibility.

- The status, availability, and maturity of solar cooling technologies are influenced by local technology suppliers/developers. Hence, the presence of locally available and mature technologies, both technically and economically, plays an essential role in supporting their widespread adoption. This is because the technical features affect how the technology can be integrated and operated, which is directly related to analyzing compactness and efficient space use, including the area occupied by solar cooling components, product dimensions, and required structural support.

- Establishing clear accountability is a critical factor in the successful integration of innovative façade systems. Involving suppliers in overseeing the installation process can help ensure that the necessary expertise is retained throughout implementation.

- Educating and training architects and engineers about these technologies during their academic studies can promote their widespread adoption. Therefore, integrating the principles of the proposed framework into architecture and engineering school curricula can play a crucial role. Additionally, ongoing education for industry professionals can be supported through online courses or certified training programs offered by specialized organizations, such as associations related to metal windows and façades. This approach is regarded as a key factor in fostering the development and implementation of façade solutions in real projects.

- The potential for these façade products to be integrated into design-phase calculation software serves as a motivating factor that increases interest in adopting such technologies. Consequently, embedding the principles of the proposed framework into digital design tools, such as Building Information Modeling (BIM), can play a vital role in promoting the adoption of environmentally friendly cooling technologies.

- To enable broader future adoption, addressing factors that allow façade products to incorporate circular economy principles is crucial during both the design and end-of-life stages, including design for disassembly, reusability, and recyclability/upcyclability. Incorporating such principles is essential as the solar technologies industry, mainly PV panels, continues to grow, and developing effective strategies for the end-of-life management of these products is essential to ensuring long-term viability and environmental benefits.

7.3.2 Recommendations for Future Work

This section provides the key recommendations for future work. Firstly, the framework provided in this dissertation can be further refined through future research by involving stakeholders such as the construction team and exploring additional considerations, including:

- Technical and operational interfaces covering components, elements, and systems.

- Interfaces related to façade use and maintenance, including cleaning equipment, inspection accessibility, and real-time monitoring systems. This is because monitoring façade products that incorporate these technologies enables optimal use during the operational phase, allowing actual performance to be evaluated against the intended design.
- Detailed estimations for real-world projects and accurate evaluation of economic viability, considering a detailed analysis of long-term operations, such as performance degradation of components and repair costs.
- Integration of environmental impact assessments, such as embodied energy and life cycle analysis (LCA), which can further enhance the evaluation of solar cooling technologies

Secondly, future studies should expand the framework to different building typologies (residential, administrative, and industrial). This could also include exploring advanced technologies such as bifacial solar panels and photovoltaic-thermal (PVT) collectors, as well as addressing the development of prefabricated façade products that incorporate a degree of standardization while maintaining flexibility for various applications.

Finally, it is recommended to investigate relevant business models with clearly defined roles and responsibilities that 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. Additionally, the influence of evolving regulations and subsidy schemes on the adoption of solar cooling technologies can be examined, with particular attention to how these factors differ across countries.

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Appendices

APPENDIX A

Interview Guide

A.1 General Information about the Interviewee

1 **What is your main educational and technical background?**

- ☐ Architecture
- ☐ Building Physics
- ☐ Civil Engineering
- ☐ Mechanical Engineering
- ☐ Electrical Engineering
- ☐ Others: ______________________

2 **What is your field of professional experiences?**

- ☐ Façade Designer
- ☐ Façade Consultant
- ☐ Façade Builder
- ☐ General Contractor
- ☐ System Manufacturer or Supplier
- ☐ Mechanical, Electrical and Plumbing (MEP) Engineering Consulting
- ☐ Applied Research: ______________
- ☐ Others: ______________________

3 **Professional years of experience**

- ☐ 5 to 10 years
- ☐ 11 to 15 years
- ☐ 16 to 20 years
- ☐ More than 20 years

4 **In which countries have most of projects on which you have worked been located? (up to 4 countries)**

[1] ______________________ [3] ______________________
[2] ______________________ [4] ______________________

5 **Have you been involved in the design and/or construction of building facades?**

☐ Yes ☐ Not much or indirectly ☐ No

Which of the following phases have been involved in?

☐ Design ☐ Production ☐ Installation (Assembly) ☐ Maintenance/ operation

6 **Have you worked on projects involving the application of solar technologies in buildings?**

☐ Yes ☐ Not much or indirectly ☐ No

Which of the following technologies were involved?

☐ Photovoltaics (PV) ☐ Solar Thermal Collectors (STC) ☐ Others: ______________

7 **Have you worked on projects involving the application of solar cooling technologies in buildings?**

☐ Yes ☐ Not much or indirectly ☐ No

Which of the following technologies were involved?

☐ Electrically-driven systems
☐ Photovoltaic (PV)-assisted vapor-compression air-conditioning equipment
☐ Thermoelectric

☐ Thermally-driven systems
☐ Absorption
☐ Adsorption
☐ Desiccant cooling
☐ Thermomechanical

☐ Others: ______________

8 **Have you worked on projects involving façade integration of solar/solar cooling technologies?**

☐ Yes ☐ Not that much/indirectly ☐ No

Which of the following technologies were involved?

☐ Photovoltaics (PV) ☐ Solar Thermal Collectors (STC) ☐ Solar Cooling ______________ ☐ Others: ______________

A.2 Short Introduction

Integrated Façades

Building façades have a direct effect on the indoor comfort of buildings. They are also generally exposed to solar radiation. Multifunctional façades integrate components actively involved in the building energy system. A multifunctional façade system could, for example, include the integration of solar technologies such as photovoltaic (PV) modules or solar thermal collectors.

The concept of solar cooling technologies is based on generating conditioned air or chilled water from solar energy. Two main categories of solar cooling technologies are those which produce hot water through Solar Thermal Collectors (STC) or produce electricity through Photovoltaic (PV) panels. This represents two principal pathways for energy conversion to produce a cooling effect from solar radiation, namely thermally driven processes or electrically driven processes.

Currently, there are various forms of technical, financial, as well as process-related, and stakeholder-related challenges affecting their widespread application as building products in the construction market. This interview aims to discuss the challenges and potential solutions related to the widespread application of the integration of solar cooling technologies into building façades in the construction industry.

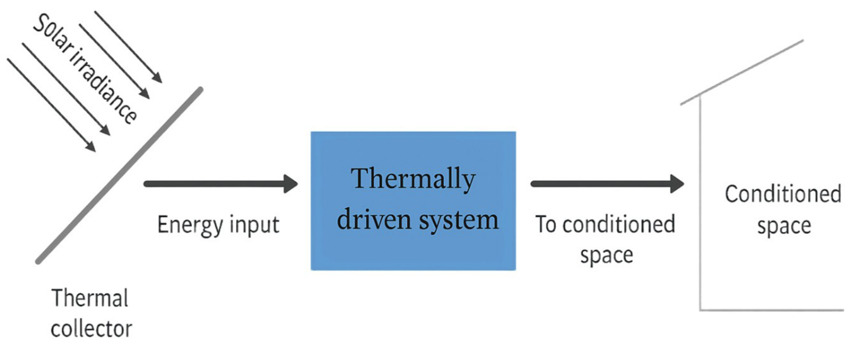

FIG. A.1 Main concept of thermally driven solar cooling technologies (Rehman et al., 2020)

FIG. A.2 Double-glazed flat plate collectors (Mugnier et al., 2017)

FIG. A.3 Evacuated tube collectors (Olczak et al., 2020)

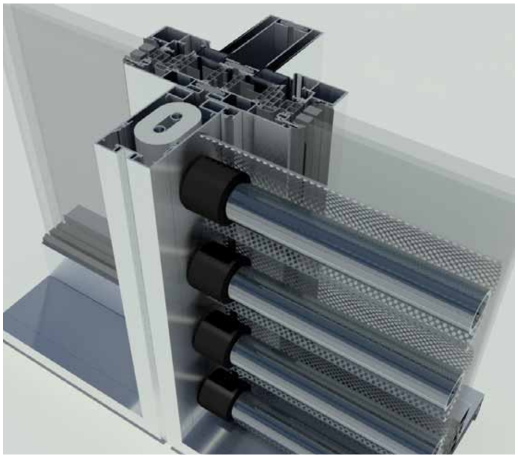

FIG. A.4 Solar Thermal Tubes in Façades: CPC Office/System Wicona (Behling & Hieber, n.d.)

FIG. A.5 Ammonia/water (NH3/H2O) absorption chiller used in Office building Feistritzwerke (thermally driven system) (Mugnier et al., 2017)

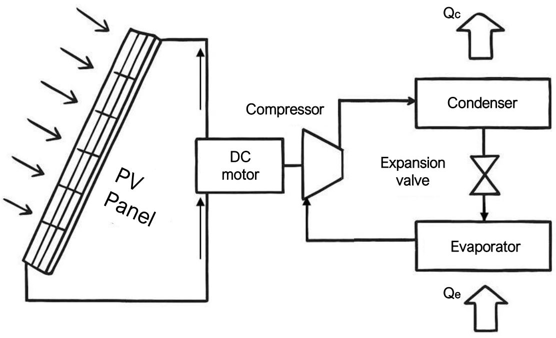

FIG. A.6 Graphical representation of solar PV-driven vapor-compression cooling (Sarbu & Sebarchievici, 2016)

FIG. A.7 PV facade in ZSW building, Stuttgart, Germany (ZSW, 2017)

A.3 Interview Questions

A.3.1 Opening Questions

- In your experience, what is the current level of knowledge in the building industry regarding the application of multifunctional façade components integrating solar cooling technologies?
- In your experience, what are the motivating factors for the application of multifunctional façade components integrating solar cooling technologies?
- In your experience, what are the concerns regarding the application of multifunctional façade components integrating solar cooling technologies?

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- How would you address such concerns?
- How can the type of project, such as new building construction or building renovation, influence the applicability of solar cooling integrated façades?
- How can the building type (e.g., office, residential, health care, educational, etc.) influence the applicability of such façade products?
- In your experience, how do the locations and climate conditions of buildings affect the performance of solar cooling integrated façades?
- Which locations and climate conditions would you suggest for applying façade products integrating solar cooling technologies?
- Do you think the choice of solar cooling technology, namely electrically-driven or thermally-driven, would affect the application of such façade products in a particular building project?

A.3.2 Key Questions

A.3.2.1 Questions about Technical and Product-Related Aspects

- In your opinion, what makes solar cooling integrated façades complex products?
- How would you address these complexities?
- How could we address challenges related to the space availability or interrupting other building services?
- What are the key aspects to consider for the maintenance and durability of solar cooling integrated facades?
- How do you see the role of aesthetics in the widespread application of building façades integrating solar technologies?

A.3.2.2 Questions about Financial Aspects

- In your experience, how can the industry develop affordable and financially feasible façade products integrating such technologies?
- What are the potential financial incentives that can support the widespread application of solar cooling integrated façades?

A.3.2.3 Questions about Process and Stakeholder Related Aspects

Kindly have a look at the following graph (**Figure A.8**).

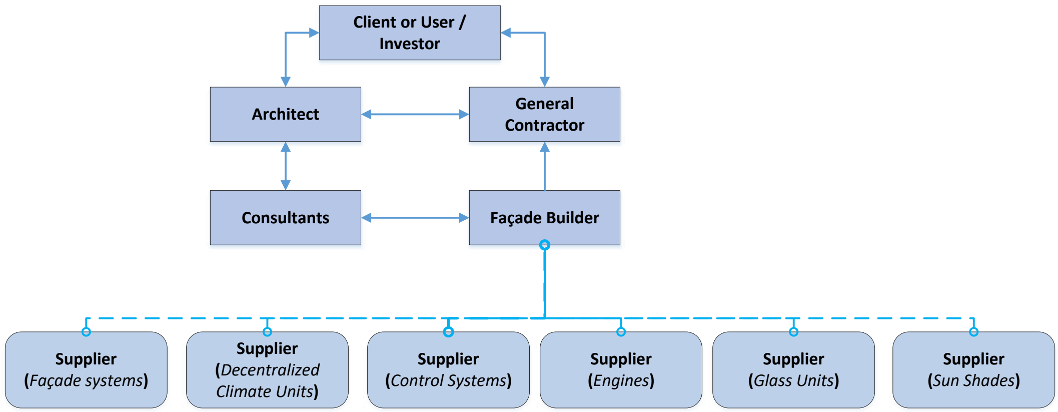

FIG. A.8 Relationships between stakeholders in façade construction (Klein, 2013)

- In your experience, which of these stakeholders can support the application of solar cooling integrated façades?
- How can we increase the knowledge and experience of architects/engineers regarding the technical aspects of integrating such technologies into building facades?
- What are the key elements that should be in standards and guidelines for architects and engineers related to the integration of solar cooling technologies into façades?
- How can the industry increase the variety of products to attract customers to apply solar cooling integrated façades?
- How can we increase the interest of designers, developers, and clients in solar cooling integrated façades?
- How can changes in building regulations affect the widespread application of solar cooling integrated façades?
- What about changes in energy policies?

Kindly have a look at the following graph (**Figure A.2**).

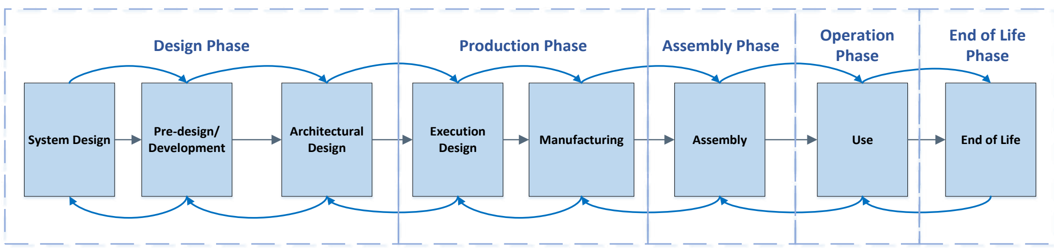

FIG. A.9 Processes of façade products (Klein, 2013)

- In your experience, which phase is key for boosting the integration of solar cooling technologies into building façades?
- What are the main aspects to consider during the design phase of solar cooling integrated façades?
- In your opinion, how can we achieve a closer collaboration between various stakeholders and disciplines during the early design stages of solar cooling integrated facades?
- What are the key aspects to consider during the production phase of solar cooling integrated façades?
- What about the assembly phase of solar cooling integrated façades (including the required workforce)?
- What about the operation phase of solar cooling integrated façades (including the end users' knowledge)?
- What about the end of life of solar cooling integrated façades?

A.3.3 Closing Questions

- Do you have any final remarks about the widespread application of solar cooling integrated façades as building products?
- What do you think about the application of solar cooling integrated façades for enabling energy transition?
- Do you mind proposing potential participants to be interviewed for this study?

APPENDIX B

Interviewees' Profiles

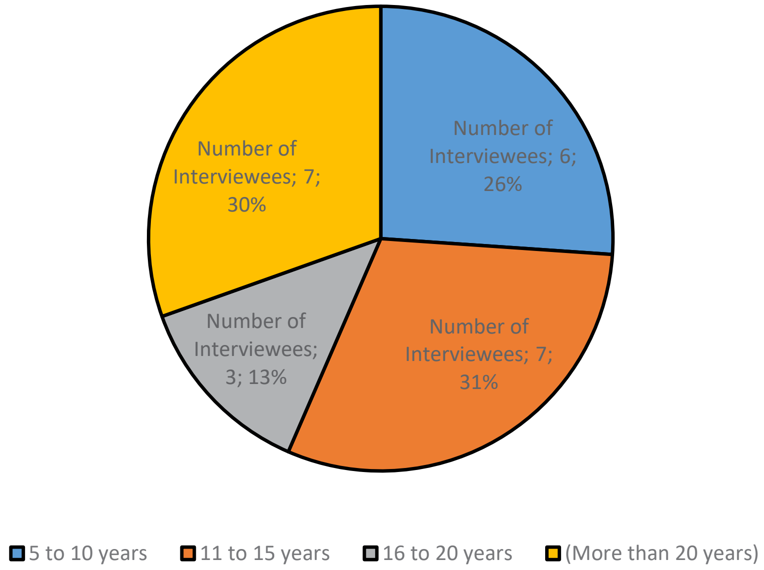

FIG. B.1 Professional Years of Experience

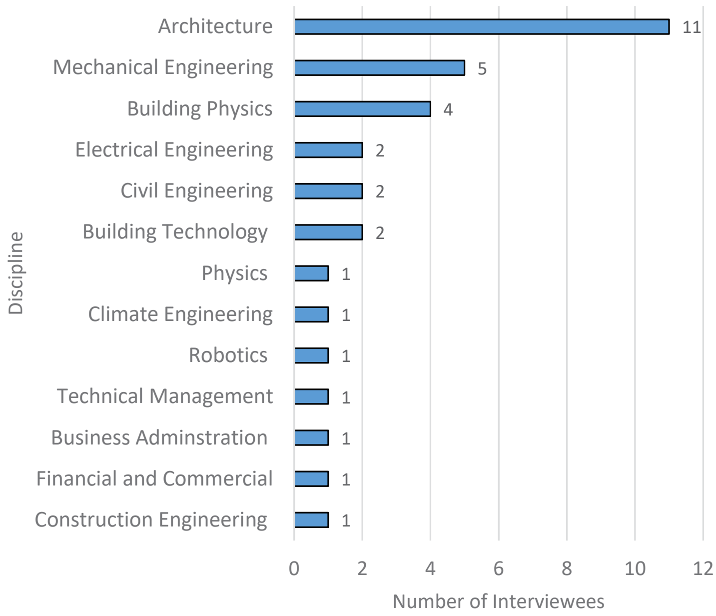

FIG. B.2 Educational and Technical Background

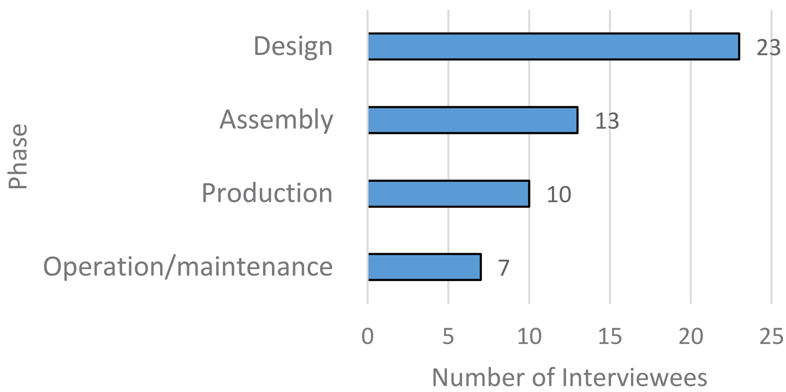

FIG. B.3 Phases have been Mainly Involved in the Façade Design and Construction

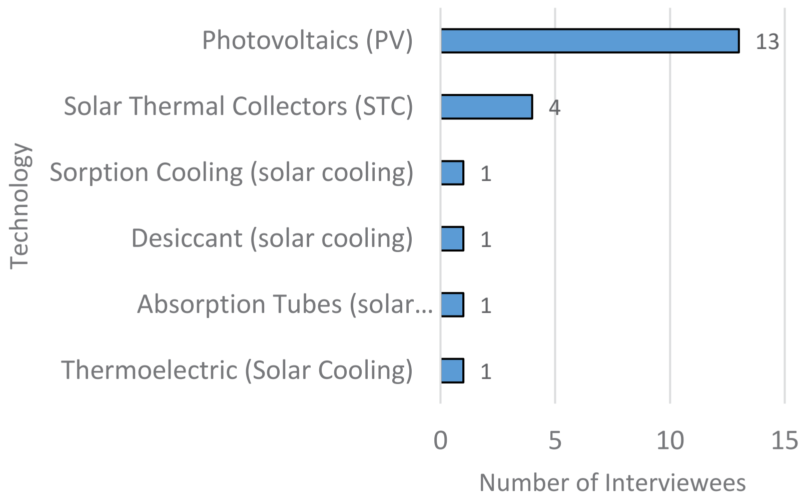

FIG. B.4 Experience of Interviewees on the Integration of solar/solar cooling technologies into Facades

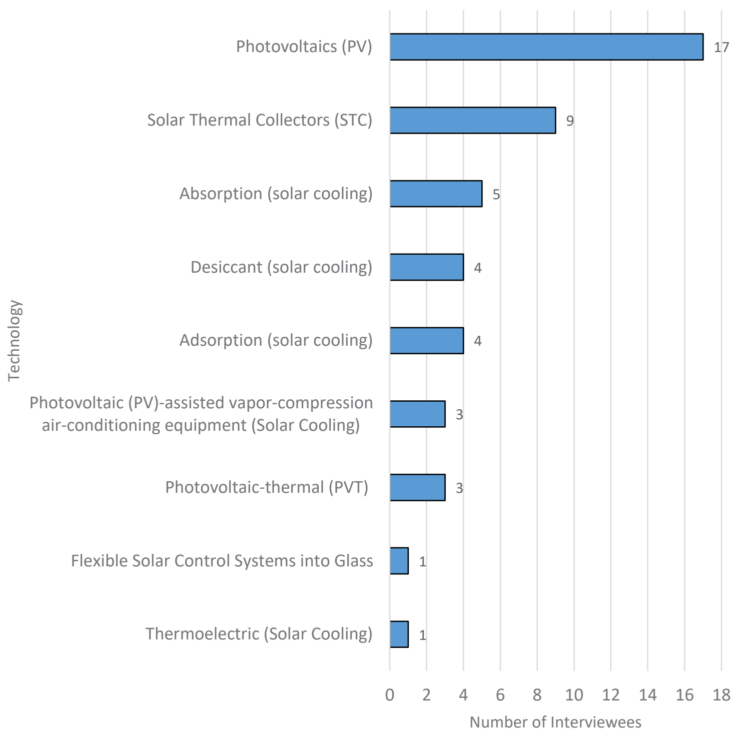

FIG. B.5 Experience of Interviewees on the application of solar/solar cooling technologies in buildings

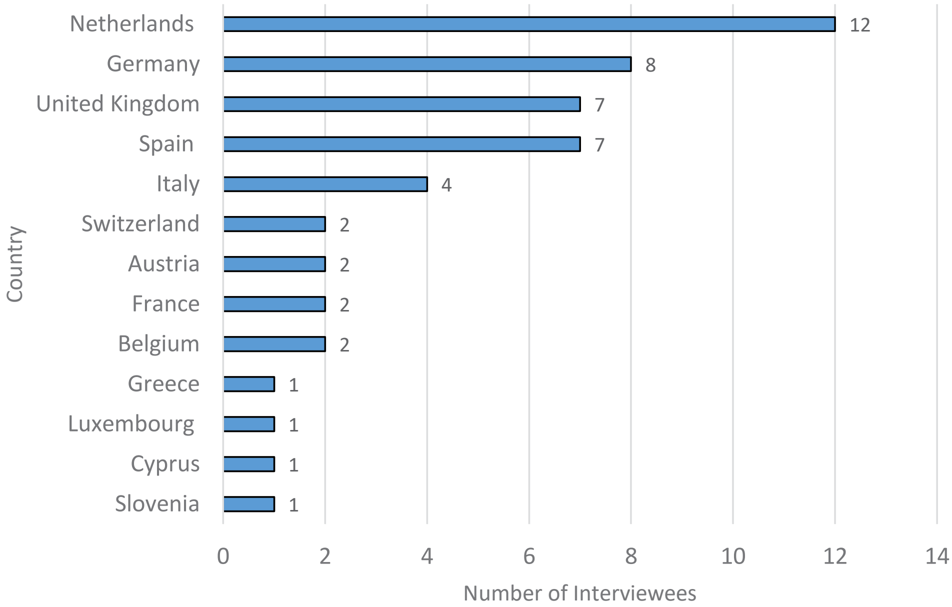

FIG. B.6 Locations of projects mostly experienced by interviewees (in Europe)

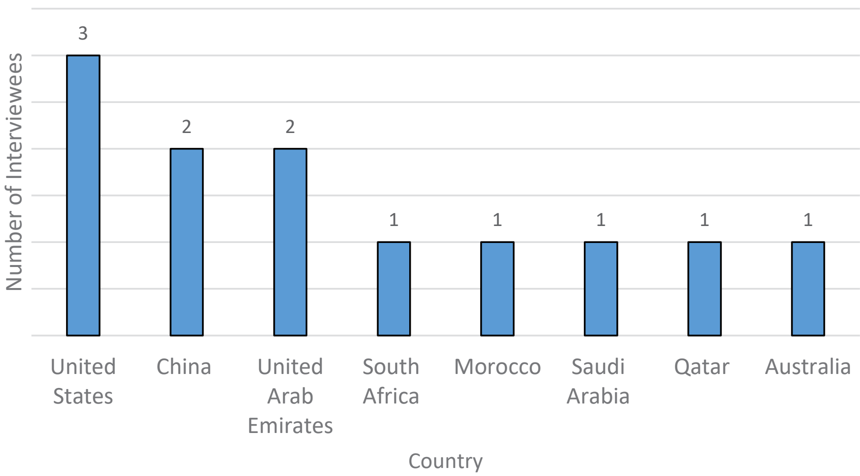

FIG. B.7 Locations of projects experienced by interviewees (outside Europe)

APPENDIX C

Identified Key Enabling Factors

TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Product Performance and Efficiency	8	2	19	29	The ability of the whole façade system, which includes various components such as collectors and cooling devices, to maintain proper performance and efficiency during the operation phase has been perceived to support the widespread application. The whole facade system should be able to still perform as a normal façade even when there are potential malfunctions in a certain component. The factor was considered to be a financial incentive supporting the widespread application, as well as a motivating factor that increases the interest of designers, developers, and clients. It has been perceived to be considered in standards and guidelines for practitioners involved in the design phase
Facilitating the Delivery of Product Information	0	1	26	27	Facilitating the delivery of product information, such as product marketing, has been considered to enable developing financially feasible facade products, and also increasing the knowledge and experience of architects and engineers, as well as the interest of designers and clients. The factor has been linked to early design stages where architects should have clear information about products, such as the investment costs, sizes, and dimensions, as well as the appearance, including simple sketches instead of providing technical specifications. Delivering such information can be carried out in different ways, such as arranging frequent meetings between architects and suppliers, consultants, or facade builders. Other approaches include marketing and advertisements in webinars, fairs, and sponsored events
Ability to Customize Products	10	1	12	23	The ability to customize, including colours, shapes, and/or sizes, has been perceived to support the widespread application. Most of the interviewees have related this enabling to the role of aesthetics in the widespread application. Although it may depend on the type of technology and the materials used, the factor was considered to be a financial incentive, especially when materials and components can be easily customized by suppliers and/or manufacturers. The factor has been perceived to increase the interest of architects and clients, especially when architects have some freedom during the design, where they have different options to choose from in order to generate their own unique design. The factor was linked to the production phase, where there should be some fixed and adaptable elements, such as the case of mass customization in the automobile industry, where the core of products can be similar with different external layers

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Multidisci-plinary Team-work	0	2	21	23	Multidisciplinary teamwork consisting of experts from different fields, such as architectural as well as mechanical, electrical, and plumbing (MEP) disciplines, was considered to contribute to the development of affordable and financially feasible products. The experts can focus on a particular technology and investigate its application, while considering different boundaries, such as a project's total budget. Considering this factor during the design phase can be carried out through different approaches. For example, it has been perceived that experts from specialized companies can be involved in the design phase in order to support architects. The factor was also linked to the assembly phase, where technology suppliers can provide clear instructions related to the assembly of components to the installing company, but at the same time, they can be present on–site in order to ensure proper installation
Aesthetic Acceptability	8	0	15	23	Aesthetical acceptability has been perceived to have a key role in aesthetics in the widespread. Different perceptions have been considered to illustrate the aesthetic acceptability, such as having a normal facade appearance, while others linked it to its ability to be acceptable for many years. Such an enabling factor has been perceived to increase the interest of designers, developers, and clients. It has been linked to the effect of changes in building regulations in the widespread application. Such a factor was identified to be taken into account during the design phase. Some of the concerns related to the aesthetics include having certain parts of the façade that have a different appearance from the whole building. Others are related to the risk of having a perception that such a façade is outdated after some years. Some concerns are related to the fact that having policies that focus on the production of renewable sources of energy without taking into account the aesthetics of the built environment.
Ability to Disassemble	5	0	15	20	The ability to disassemble components was considered to be a key factor related to the maintenance and durability, where components are required to be repaired off–site or replaced. This factor has been linked to the design and production phases to ensure that components can be easily removed at their end of life, where the system can be upgraded, or some of the disassembled components can be reused or recycled
Product Availability and Replicability	8	0	10	18	Product availability and replicability were perceived to be important factors related to the maintenance and durability, especially in the case of sudden damage or malfunctions. The factor was considered to be taken into account during the design phase for both the operation and end–of–life phases. This is because the life span of some of the integrated technologies can be shorter than the life span of the main facade
Maintenance Accessibility	12	0	6	18	The ability to access was perceived to be dependent on the size and height of the building. Having an inside accessibility is perceived to be relevant for high–rise buildings in order to avoid costs associated with the use of external equipment. On the other hand, external product accessibility has been perceived to have an advantage that is related to avoiding the disturbance of building occupants. Such a factor has been perceived to be taken into account during the design phase in order to ensure proper product accessibility during the assembly and operation phases.

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Compactness and Space Usability	1	3	14	18	Miniaturizing façade products integrating solar cooling technologies has been considered to be one of the potential financial incentives, since it can provide more usable space for building owners, which can be rented. Accordingly, this can attract various customers, such as owners of high–rise buildings where there are space limitations on the roof, to apply such products. Such a factor has been considered to be taken into account during early design stages.
Plug and Play	3	2	12	17	This factor has been perceived to enable plugging and unplugging components easily. Plug–and–play systems were considered to support the development of an affordable and financially feasible façade, since the on–site combination of different fields, such as mechanical and building installations, can be costly. Such a factor was linked to the production phase to avoid any concerns associated with the assembly phase. It has been perceived to be able to address contractors' concerns who are not experts in dealing with technologies, such as having uneducated laborers who are required to handle installing components.
Availability of Project Examples	0	0	17	17	The availability of relevant project examples indicating the technological application was found to support the widespread application. Such a factor was considered a main contributor to increasing the knowledge and experience of architects and engineers, as well as to increasing the interests of other stakeholders, such as clients and developers. There were different perceptions about demonstrating a relevant project example, such as built prototypes, small pilot projects, or real projects.
Government subsidies	0	14	3	17	Government subsidies, either at a local, national, or European level, have been perceived to be a key factor supporting the development of affordable and financially feasible facade products, since they can address concerns related to high investment costs and long payback periods. Such an enabling factor has been linked to both of design and assembly phases. It has also been perceived to be linked to the effect of changes in energy policies on the widespread application of façade products integrating solar cooling technologies. Although it was considered to be a key enabling factor, some concerns associated with such a factor were mentioned by interviewees 3 and 5. The concerns were related to the availability and political acceptability related to providing such incentives.
Decentralization	2	4	9	15	Having decentralized SCIFs was perceived to address challenges related to space availability or interrupting other building services, as well as reducing the amount of failure rates due to the redundancy in ventilation units. It was also considered to have a key role in minimizing costs related to installing centralized ventilation systems, such as costs related to air ducts. Furthermore, having decentralized ventilation systems that are based on renewable sources of energy reduces the electricity bills, especially when energy prices are increasing. They tend to be a motivating factor for being included in building regulations. Moreover, the factor was identified to be considered between the design and end of life phases, since it can be compared with other options, such as centralized systems, as well as to be considered for renovation works that take place in existing buildings. Although it has been identified as an enabling factor, there are some concerns related to it. One of them is related to the potential increase in the use of materials and components, which can have some issues from a circularity point of view. Furthermore, such an increase in the use of components may lead to an increase in maintenance requirements. Furthermore, decentralized solutions might be more expensive than centralized ventilation systems.

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Acceptable Payback Period or Return on Investment	0	6	9	15	The ability of the façade products to have an acceptable payback period or return on investment was perceived to demonstrate the financial feasibility. It has been indicated that most people would prefer short periods, such as 10 to 15 years, as a main goal. However, it has been declared that when clients start to accept longer periods, such as 20 to 25 years, the widespread application of such products would be higher. The ability to demonstrate such a factor using relevant graphs can increase the interest of various stakeholders.
Reusability	1	0	13	14	The ability of such façade products to be reusable after disassembling them has been perceived to be a key factor supporting the widespread application. Such a factor has been recognised in design, production, as well as end–of–life phases. However, the majority of interviewees mentioned it when discussing key aspects to consider for the end of life.
Mass Production	0	6	7	13	Mass production was considered to be one of the main factors contributing to the development of affordable and financially feasible products. The increase in the production volume of standardized products can reduce the prices of products. However, the mass production depends on the demand and may require some time to be achieved, since the demand for new innovative products is lower at the beginning. This factor was linked to the design and production phases to reduce the cost of façade products.
Standardization and Off–the–Shelf Products	1	3	9	13	The availability of standardized and off–the–shelf façade products was perceived to be a key factor to be considered for the maintenance and durability. Having such products was considered to reduce costs, since standardized products can be easily produced while reducing production costs. The availability of standardized façades can contribute to increasing the knowledge and experience of architects, since they can become more familiar with the same product when it is used for more than one project. Accordingly, this can accelerate the design phase, as well as it can also help in having standardized manufacturing, which results in lower cost of products. Moreover, the assembly phase of building facades is expected to be easier when dealing with standardized products.
Modularity	6	1	6	13	Having modular SCIF systems, such as in many office buildings, was considered to be an important factor for the maintenance and durability, since it can facilitate accessing, disassembling, and replacing components. Interviewee 14 linked the modularity with standardization as key enabling factors supporting the development of affordable and financially feasible facade products that can be easily produced. Modularity has been perceived as being considered in design guidelines for architects. Considering such a key factor during the design phase can facilitate the achievement of mass production. It has also been linked to the assembly phase when considering plug–and–play systems and the connectivity of components. Furthermore, the modularity has been perceived to be a key factor to be considered for the end of life when considering the disassembly of the integrated technology that would have a shorter life span than the main facade.

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Clear Goals and Responsibilities	0	0	13	13	The ability to define and clarify goals and responsibilities of all parties, including interfaces, points of separation, and handover, has been perceived to enable achieving a close collaboration among various stakeholders during early design stages. It involves all parties being interested in the technology and understanding each other's concerns, roles, and goals. Such a factor can be achieved by having transparency among all stakeholders, which can be discussed in webinars and workshops, including key actors. Having well–defined interfaces can be considered for the assembly phase, such as defining companies supplying the mounting systems for installers.
High Energy Prices	0	6	7	13	The increase in energy prices was considered a potential financial incentive supporting the widespread application of SCIF facades. Such a factor has been perceived to increase the interest of various stakeholders, such as designers, developers, and clients, in the application of such façade products. It has been linked to the effect of changes in energy policies as well as building regulations in the widespread application.
Prefabrication	3	2	7	12	Having prefabricated SCIFs facades has been perceived to address challenges related to space availability or interrupting other building services, as well as contribute to improving the quality of components, since they are assembled in a controlled environment. Prefabrication was identified to be a key enabling factor to be considered for the assembly phase, since it can ensure the quality of façade products and also minimize the amount of work to be carried out on–site. Therefore, the installation time can be reduced. Although prefabrication has been identified as an enabling factor, Interviewee 1 has some concerns related to the fact that on–site work is still common in many countries.
Education and Training	0	1	11	12	Educating and training architects and engineers during their studies about such technologies can support the widespread application. This includes providing courses in schools of architecture and engineering that cover aspects related to design calculations as well as the properties of cooling systems. Furthermore, this includes educating and training current practitioners in the industry through providing online courses or certified training programs by specialized associations, such as associations related to metal windows and facades. Such a factor has been perceived to enable the development of affordable and financially feasible facade products.
Maturity and Proven Technology	3	0	9	12	Having mature and proven technologies that can work as they are supposed to without any defects can enable widespread application. Such a factor has been perceived to increase interest in SCIFs. The ability to have proven concepts that can be integrated into the façade was identified as an aspect to be taken into account during the design phase.
Meeting User Comfort Requirements	4	0	7	11	The ability of such façade products to meet user comfort requirements was perceived to be a key factor to be considered in standards and guidelines for practitioners involved in the design phase, to ensure the comfort of users living behind the façade during the operation phase, such as avoiding any potential noise generated by the integrated elements.

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Recyclable/ Upcyclable	1	0	10	11	The ability of façade products to be recyclable/upcyclable, such as considering the use of aluminium, has been perceived to support the widespread application. Such factor has been recognised in both of design as well as end of life phases. However, the majority of interviewees mentioned it when discussing key aspects to consider for the end of life.
Suitable methods of contracting and partnerships	1	1	7	9	Suitable methods of contracting have been perceived to be a key factor related to the maintenance and durability of facade products, such as having maintenance contracts provided by installers or another specialized company. Such a factor can address concerns related to any malfunction. Although it depends on the technology and the project nature, as well as other aspects, having an appropriate contracting method or partnerships among the relevant stakeholders was perceived to support the development of affordable and financially feasible products. Such a key factor was perceived to enable a close collaboration during the design phase as well as to ensure an appropriate operation phase. Different methods of contracting were mentioned by interviewees, such as Integrated Project Delivery (IPD) contracts and Design–Build–Maintain–Operate (DMBO) contracts.
Integrating Operating and/ or Ownership Costs	0	3	6	9	Operating and/or ownership costs were considered as key aspects to be taken into account for the maintenance and durability of such façade products. Having clients who consider these aspects was perceived to enable the widespread application. The ability to develop a total cost of ownership for clients has been identified as a main financial incentive. Such a factor has been perceived to be considered during early design stages. Taking into account such type of costs was considered a motivating factor for various stakeholders, due to the increase in energy prices.
Product Monitoring	1	0	8	9	The ability to monitor façade products integrating such technologies has been perceived to be a key enabling factor, since it can ensure the optimal use of the product. Such a factor has been linked to the operation phase, where actual product performance can be compared with the designed one. Furthermore, it was considered to be taken into account in building regulations to ensure that the installed technologies are used properly.
Guiding and Monitoring Users	0	0	9	9	The ability to guide and monitor users has been perceived as a key factor to be considered for the end user knowledge during the operation phase, to avoid the misuse of the technology.
Idiot–Proof and Easy to Use	1	0	7	8	Idiot–proof products that can be easily used, such as having a simple interface on a mobile phone, were perceived as a key enabling factor to be considered for the end user's knowledge during the operation phase. Furthermore, it has been identified to increase the interests of clients, designers, and developers.
Additional Skills and Training	0	0	8	8	Having additional skilled and trained labor during the production and assembly phases was identified as supporting widespread application. This can take the form of skills related to the installation of heating, ventilation, and air conditioning (HVAC) components, in addition to façade components.

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Guarantees	1	3	3	7	Providing suitable guarantees that cover the whole system for a relevant period of time, e.g., 10 to 25 years, has been perceived as a main factor to be considered for the maintenance and durability. The ability to guarantee the system performance for a certain amount of time has been identified as a financial incentive supporting the widespread application. This factor has been linked to the design phase, where designers can be aware of its availability. It has also been linked to the assembly and operation phases, where the whole system can be guaranteed by one party for a certain amount of time. Accordingly, this can address doubts about the responsible party when there are various stakeholders involved in product development.
Taxes or Fees	0	3	4	7	Taxing or charging low–efficiency buildings, such as the CO_2 cost, was identified as a financial incentive enabling the widespread application. It has been perceived to be linked to the effect of changes in energy policies in the widespread application.
Ability to Compete with Traditional Systems	0	5	2	7	The ability of façade systems integrating such technologies to compete with traditional systems in terms of cost and/or performance was perceived as a key enabling factor. Such an enabling factor was considered to be clarified to designers during early design stages. The ability to demonstrate such a factor can play a vital role in increasing the interest of clients and developers.
Circularity	0	0	7	7	The ability of façade products integrating such technologies to incorporate the concepts of circular economy has been perceived to be a key factor to be considered in both of design as well as end of life phases. However, the majority of interviewees mentioned it when discussing key aspects to consider for the end of life, such as the case of reusability and recyclability.
Fire Resistance	2	0	5	7	The ability of such façade products to be fire–resistant, such as involving the use of non–combustible materials, has been perceived to support the widespread application. Such a factor has been considered to be taken into account for building regulations as well as in standards and guidelines for stakeholders involved in early design stages.
Ability to be Combined and Interact with Other Systems	3	0	4	7	The ability of such products to be combined and interact with other systems, such as passive strategies or any other technologies, to achieve proper energy performance was perceived to be a key factor to be considered during the design phase.
Clear Design Boundaries	0	0	6	6	The possibility of having clear design boundaries for architects has been perceived to be a key enabling factor, where architects are aware of the area where they have some design freedom, such as changeable parameters, and others that have some bounds or limitations, such as fixed parameters. Such a factor has been linked to the design and production phases as well and has been perceived as an element to be considered in standards or guidelines for architects or engineers.

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
A Relevant Type of Building Ownership	0	0	6	6	A relevant type of building ownership tends to be a key factor supporting the widespread application of SCIFs. Although it depends on the nature of the project, having one client who is the building user at the same time was considered to be more relevant than having multiple owners and tenants in the buildings, as in the case of apartment buildings. This is because having multiple owners and tenants may require convincing every owner or tenant, as well as arranging separate invoices. Such an enabling factor has been linked to both of design and operation phases, since the type of building ownership and its operation should be identified from early phases.
Project Total Budget	0	3	3	6	The ability to stay within the total project budget, or specified budgets to be spent per floor area, has been perceived to be a key enabling factor. This is because it has a direct effect on the applicability as well as developing affordable and financially feasible facade products. Such a factor depends on the nature of the project, such as its size. It has been perceived to be considered during early design stages, at which various stakeholders should be involved. Higher budget projects tend to be a key motivating factor supporting the application.
Less Interactions by Users	0	0	6	6	The ability to have products requiring a minimum amount of interactions by users during the operation phase has been perceived as a key factor supporting the widespread application.
Durability and Long–Life Span of Components	3	0	3	6	The ability of façade products integrating a particular technology to have longer life spans, for example, 20 to 50 years, has been perceived to address concerns related to the potential difference in life spans of components, such as when the integrated technology has a shorter life expectancy than the main facade. Such a factor has been considered to be taken into account during the production phase, such as performing durability tests, to ensure the durability and long life span of components during the operation phase.
Design for Manufacturing and Assembly	0	1	5	6	Designing products for manufacturing and assembly has been perceived to support the development of affordable and financially feasible facade products. Such a factor takes into account various aspects that include stakeholders' welling to implement designed products, potential extra time for production and assembly, as well as potential risks related to defects or failures in products. Such a factor has been linked to the design and production phases, where different stakeholders, such as production and construction companies, can be involved so that information related to the production as assembly tools, and technologies is clear during the early stages.
Waterproofing/ tightness	4	0	2	6	Waterproofing/tightness of such façade products has been perceived to be a key factor to be considered in standards and guidelines for stakeholders involved in early design stages.
Product as a Service/Leasing Construction	0	3	2	5	Delivering façade products as a service has been perceived as a financial incentive, since it can minimize the high initial investment costs for building owners. Having a product as a service has been identified to be considered to be one of the key roles to be taken into account by system suppliers to convince other stakeholders, such as clients, during the design phase.

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TABLE C.1 Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Certified Products	0	0	5	5	Having certified products has been perceived to be a motivating factor supporting the widespread application. It has been linked to the effect of changes in building regulations in the widespread application. Furthermore, it has been identified as one of the key aspects to be available during the design phase. Although product certification has been identified as an enabling factor, interviewees 8 and 14 have some concerns that are related to the costs and potential difficulties associated with the certification process.
Ability to Upgrade	1	0	4	5	The ability to upgrade such façade products has been perceived as a key factor to be considered for maintenance and durability. It takes into account changing parts to extend the service life. This factor has been identified as be consideration during both the operation and end–of–life phases.
Similarities in systems working principles	3	0	1	4	The ability of various products to have similarities in their core working principles has been identified as an enabling factor. Such a factor can help in achieving mass customization, such as in the case of the automobile industry. It has been perceived to attract designers and clients to apply such technologies. This factor has been perceived to be considered in the production phase, so that manufacturers are able to demonstrate the working principles of different products or technologies to designers and clients.
Clear and Simple Guidance	0	0	4	4	The ability to have clear and simple guidance, such as IKEA instructions as mentioned by interviewees 10 and 21, for the required workforce during the assembly phase has been perceived to be a key enabling factor.
Low Waste	0	0	4	4	The ability of such façade products to generate a minimum amount of waste at their end–of–life phase has been a key enabling factor.
Industrialization	0	2	1	3	Having industrialized systems has been perceived to be a key factor supporting the development of affordable and financially feasible facade products. Such systems have been identified as being considered in the production phase to minimize on–site work.
Adaptable to multiple cases and conditions	1	0	2	3	The ability of such façade products to be applied in different cases, such as different building uses, has been perceived to support the widespread application. Such a factor has been linked to the design and production phase, where aspects related to the building use, climate, and ambient conditions are taken into account.
Nontoxic Materials	1	0	2	3	Avoiding the use of toxic materials in such façade products has been perceived to enable the widespread application. It has been linked to design, production, and end–of–life phases.
Weight and Structural Safety	2	0	1	3	The safety of integrating additional weight from technologies into façades, especially in existing buildings, has been perceived as a key factor to consider during the design phase.
No moving parts	2	0	1	3	Having static façade systems that do not have moving parts has been perceived as a key factor to consider in order to avoid product complexities in terms of maintenance requirements. Such a factor can support achieving low maintenance during the operation phase.
Integrated by Calculation Software Packages	0	0	2	2	The ability of such façade products to be integrated by calculation software packages used in the design phase has been perceived as a motivating factor that increases the interest in the application of such technologies.

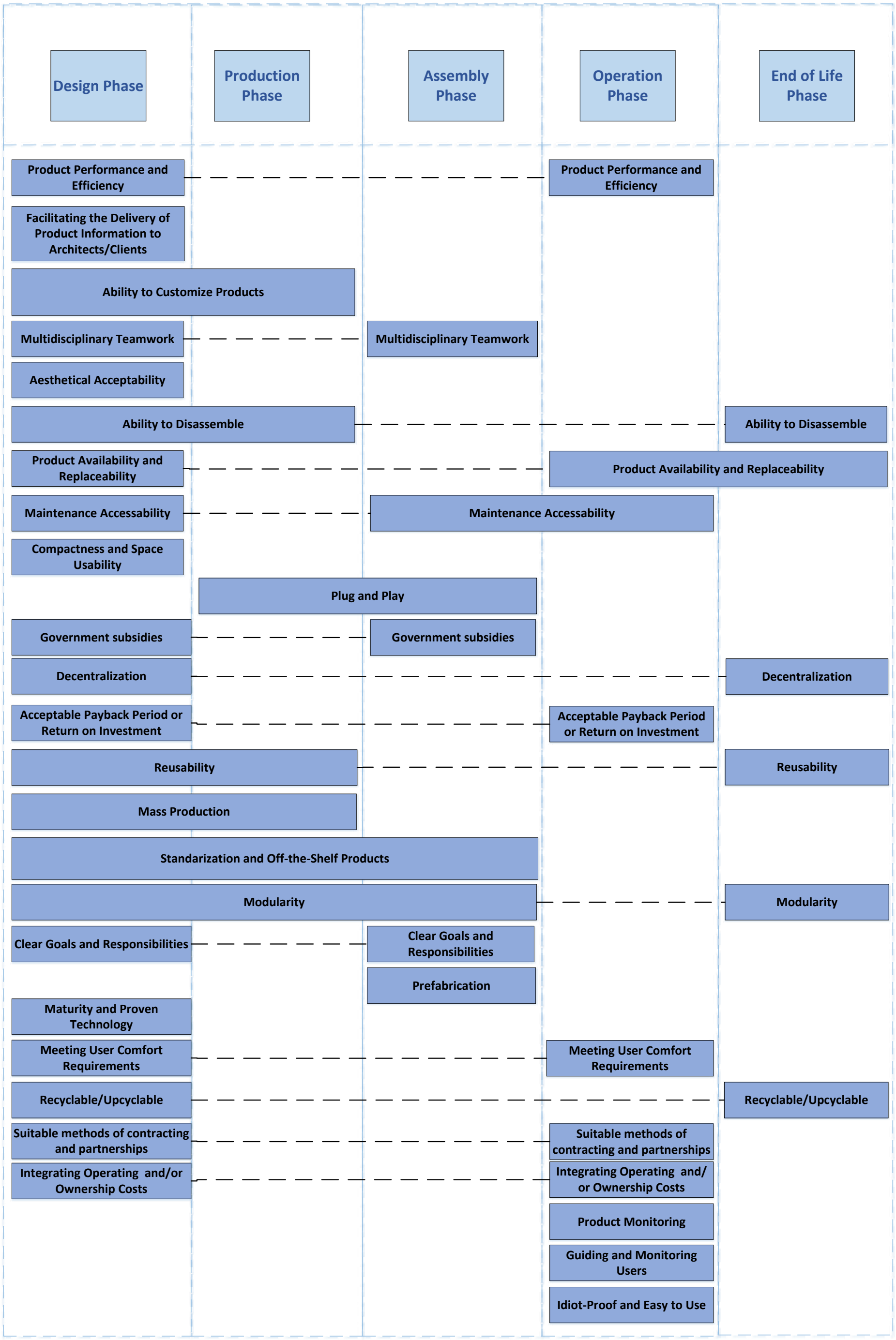

FIG. C.1 Mapping the enabling factors in the façade design and construction process (Part 1)

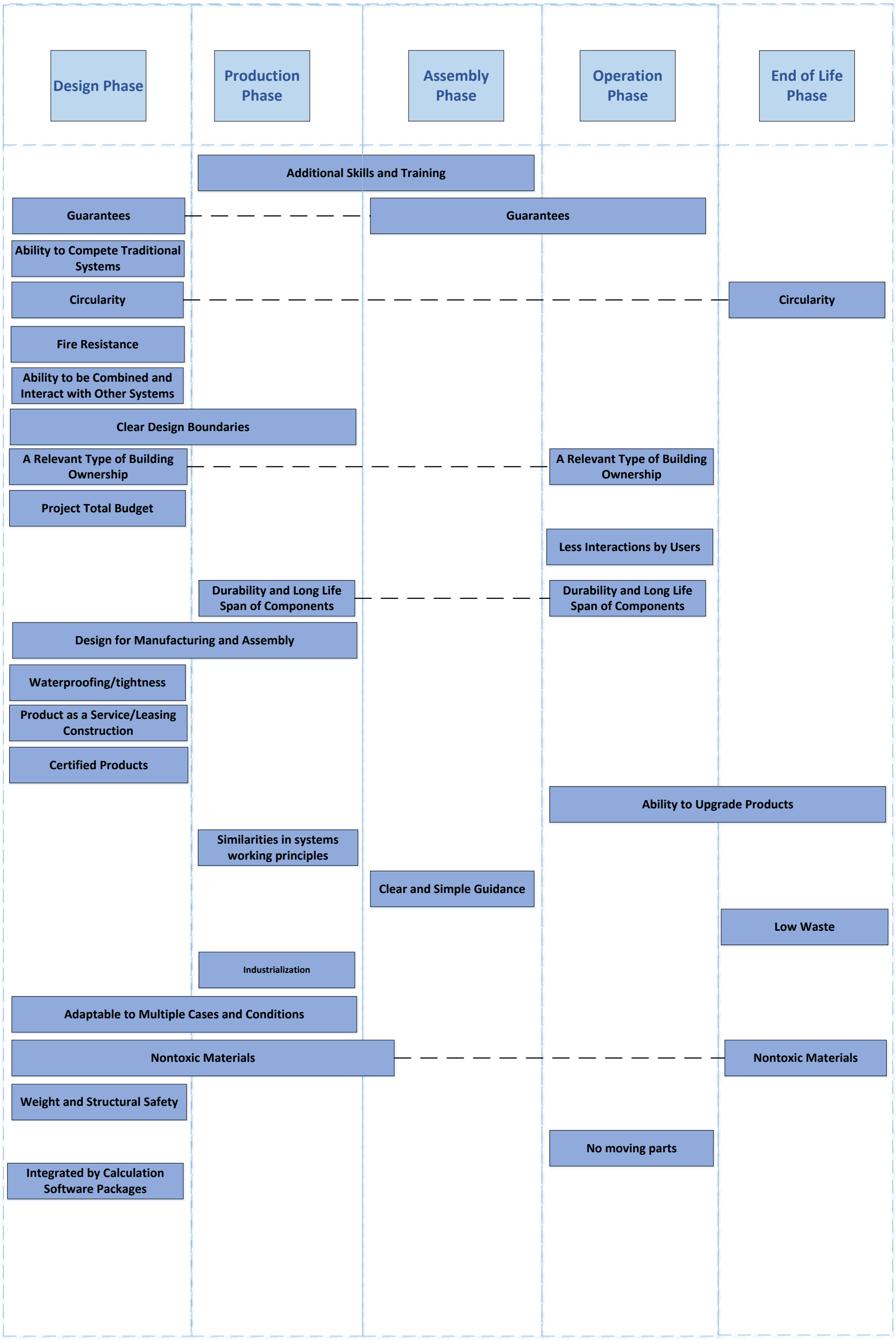

FIG. C.2 Mapping the enabling factors in the façade design and construction process (Part 2)

APPENDIX D

Case Study Tables

TABLE D.1 Construction characteristics of the thermal envelope elements according to local energy saving guidelines in Spain

Construction element	Requirements			Considered materials and system to meet requirements			
	Value		Reference	System	Description	Reference	Value
Opaque façade enclosure (External walls and columns)	Thermal transmittance of external walls (U–value)	0.27 [W/m^{2}K]	DB–HE (HE 1) (Corticos & Duarte, 2022; CTE, 2022)	Ventilated Façade using Stone Wool Insulation	Multi–layered opaque external walls that can prevent heat entrance into buildings and maintain a comfortable temperature in summer	(Sánchez–Ostiz Gutiérrez & Campo Baeza, 2011; Sierra–Perez et al., 2016)	U–Value = 0.263 [W/m^{2}K]
Glazing (Openings)	Thermal transmittance of glass and frame assembly as well as windows (U–value)	1.6 [W/m^{2}K]	DB–HE (HE 1) (Corticos & Duarte, 2022; CTE, 2022)	Doble–glazing low–emissive	Double glazing of a thickness of 6 mm. An interior air chamber of 16 mm.	(Ávila–Delgado et al., 2021; Fuentes–Bargues et al., 2020)	U–Value = 1.353 [W/m^{2}K]
	Solar Heat Gain Coefficient of glazing	0.58	(Corticos & Duarte, 2022)				SHGC = 0.396
					Polyvinyl Chloride (PVC) Window Frame		U–value = 2.2 [W/m^{2}K]

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TABLE D.1 Construction characteristics of the thermal envelope elements according to local energy saving guidelines in Spain

Construction element	Requirements			Considered materials and system to meet requirements			
	Value		Reference	System	Description	Reference	Value
Roofs (Top slab)	Thermal transmit-tance of roofs (U–value)	0.22 [W/m^{2}K]	DB–HE (HE 1) (Cortiços & Duarte, 2022; CTE, 2022)	Cast concrete slab	Bitumen sheet, cement mortar, expanded polystyrene insulation (EPS), cast concrete slab, air cavity and gypsum plasterboard	(Fuentes–Bargues et al., 2020)	U–value = 0.211 [W/m^{2}K]
External floors (Floor in contact with outside air)	Thermal transmit-tance of slabs (floors in contact with outside air) (U–value)	0.27 [W/m^{2}K]	DB–HE (HE 1) (Cortiços & Duarte, 2022; CTE, 2022)	Cast concrete slab	Stoneware tiles, cement mortar, expanded polystyrene insulation (EPS), cast concrete slab, air cavity, and gypsum plastered board	–	U–value = 0.240 [W/m^{2}K]
Ground Floor (GF) Slabs (floors in contact with ground)	Thermal transmit-tance of slabs (floors in contact with ground) (U–value)	0.48 [W/m^{2}K]	DB–HE (HE 1) (Cortiços & Duarte, 2022; CTE, 2022)	Cast concrete slab	Stoneware tiles, cement mortar, Cast concrete slab, expanded polystyrene insulation (EPS), water proof membrane, and sand and gravel	(Fuentes–Bargues et al., 2020)	U–value = 0.301 [W/m^{2}K]

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

Parameter			Description	Considerations and Values	Reference
Climate Context			Madrid: Köppen–Geiger climate classification: BSk – a cold semi–arid climate	EnergyPlus weather file (Madrid 082210 (IWEC))	(EnergyPlus, n.d.)
Internal Heat Loads	**Appliances**		Plug and equipment's power density	18.04 W/m^2 Schedule: Monday to Friday from 9:00 to 19:00	(Cortiços & Duarte, 2022)
	Lighting	Average illumination	Average illumination in the horizontal plane	600 lux	(CTE, 2022)
		Power	Power of the installed lighting	10 W/m^2 Schedule: Monday to Friday from 9:00 to 19:00	(CTE, 2022; Pérez–Carramiñana et al., 2023)
	Occupancy	Number of occupants	Number of people per square meter (m^2)	0.13 people/m^2	(Pérez–Carramiñana et al., 2023)
		Occupancy hours	The period at which the building is occupied and operated	Overall occupancy schedule: Monday to Friday from 9:00 to 19:00, except Dining and drinking areas which have an occupancy schedule: Monday to Friday from 13:30 to 15:30	(Sánchez–garcía et al., 2019, 2020)
		Holidays	Labour holidays in the Community of Madrid in 2024 that include 12 days	January 1^{st}, January 6^{th}, March 28^{th}, March 29^{th}, May 1^{st}, May 2^{nd}, July 25^{th}, August 15^{th}, October 12^{th}, November 1^{st}, December 6^{th}, and December 25^{th}	(BOCM, 2023)

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

Parameter			Description	Considerations and Values	Reference
Heating, Cooling, and Air Conditioning (HVAC) – Variable Air Volume (VAV)	**Heating (Gas–fired boiler)**	Set–point	Schedule: Monday to Friday from 9:00 to 19:00 Use end use default: Heating demand	20 ºC	(Corticos & Duarte, 2022)
		Set–back		17 ºC	
		Efficiency	Efficiency of the boiler, heating system seasonal CoP	0.9	
	Cooling	Set–point	Schedule: Monday to Friday from 9:00 to 19:00 Use end use default: Cooling demand	25 ºC	(Corticos & Duarte, 2022)
		Set–back		27 ºC	
		Efficiency	Efficiency of the chiller, cooling system seasonal CoP	2.6	(Corticos & Duarte, 2022; CTE, 2022)
	Mechanical Ventilation	Fresh air (person)	Outdoor air rate (person)	2.5 l/s Schedule: Monday to Friday from 9:00 to 19:00	(ANSI/ASHRAE Standard 62.1–2019, 2019; Corticos & Duarte, 2022)
		Fresh air (area)	Outdoor air (area m^2)	0.43 l/s Schedule: Monday to Friday from 9:00 to 19:00	(Corticos & Duarte, 2022)
Air infiltration			Air Change Units	0.15 ACH	(Costanzo & Donn, 2017)

TABLE D.3 Simulation outcomes as well as the key features associated with different orientations

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

TABLE D.4 Framework of technical possibilities of integrating solar absorption cooling technologies into facades (Prieto et al., 2019; Prieto, Knaack, et al., 2017a)

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

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TABLE D.5 Evaluation of compactness and space usability, assembly and connections, and maintenance requirements for DE absorption chillers with ETCs (Rooftops & Façades) (Alahmer & Ajib, 2020; Chelmer heating solutions, 2014; Prieto et al., 2019)

C_n	Aspects Considered	Relevant information related to the aspects	Level (Status): Score
Compactness and Space Usability	• Amount of used area and space by solar collection devices and their compactness	Rooftops & Façades Thickness = 100 mm: Relatively compact collection devices (100 mm ≤ Panel thinness <150 mm)	**Level C (Somehow acceptable)**
	• Structural support requirements based on the weight density (Kg/m2)	24 to 24.7 kg/m2: Relatively simple structural support requirements to install components (20 Kg/m2≤ weight density < 30 Kg/m2)	
Assembly and Connections	• Use of hydraulic components based on pipe lengths and their amounts • Number of connections	• Rooftops and façades • High use of hydraulic components among the cooling system components • Use of hydraulic components through the façade	**Level D (Difficult to be acceptable)**
Maintenance Requirements	• Working materials and periodic maintenance	• Some periodic maintenance complexity: ○ Some preventive maintenance requirements: Preventive maintenance is required for pumps and heat exchangers, requires a twice shutdown every year for diluting the lithium bromide solution, and requires replacement of the absorbent every 5 years ○ Some corrosive materials	**Level D (Difficult to be acceptable)**
	• Complexity of product cleaning	• Some cleaning complexity of solar collection devices: Medium cleaning complexity	
	• Complexity of product accessibility	• Some accessibility complexity: Both rooftops and façades or façades only	

TABLE D.6 Evaluation of compactness and space usability, assembly and connections, and maintenance requirements for water-cooled VCC and PV panels (Rooftops & Façades) (Alahmer & Ajib, 2020; SolarWorld, 2014)

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

TABLE D.7 Key information required to investigate cost-effectiveness (Dehwah et al., 2020; ENF Solar – Solar Companies and Products, n.d.-a, n.d.-c, n.d.-d, n.d.-b; Gabbrielli et al., 2016; IEA, 2022; Martínez Jaimes, 2022; Mugnier et al., 2017; Neyer et al., 2015; Saez et al., 2023)

Item		Thermally-Driven Technology	Electrically-Driven Technology
		DE absorption chillers with ETCs	Water–cooled VCC and PV panels
Investment cost (I)	I_{SCD}	• **Specific cost of ETCs [€/m^2] = 760.59*(ETCs area in m^2)$^{-0.135}$** Based on the collector area in m^2, the scenario has, the aforementioned equation gives the estimated specific costs of ETCs [€/m^2], taking into account the economies of scale **Investment cost of ETCs = Specific cost of ETCs [€/m^2]*Size of collectors (m^2)**	• Electricity generation of common PV solar panels = 400 W_p/m^2 • Typical price of a standard module crystalline silicon = 0.22 €/Wp • Specific cost of PV panels = (Electricity generation of common PV solar panels)*(Typical price of a standard module crystalline silicon)= 88 €/m^2 • **Investment cost PV panels = Specific cost of PV panels [€/m^2]*Size of PV panels (m^2)**
		• **Specific cost of ETCs auxiliaries [€/m^2] = 5500*(ETCs area in m^2)$^{-0.696}$** Based on the collector area in m^2, the scenario has, the aforementioned equation gives the estimated specific costs of ETCs auxiliaries [€/m^2], taking into account the economies of scale **Investment cost of ETCs auxiliaries = Specific cost of ETCs auxiliaries [€/m^2] *Size of collectors (m^2)**	• Electricity generation of common PV solar panels = 400 W_p/m^2 • Typical price solar mounting system = AVG (0.0263, 0.0279, 0.022, 0.0201) = 0.0241 €/Wp • Specific cost of solar mounting system = (Electricity generation of common PV solar panels)*(Typical price of solar mounting system)= 9.64 €/m^2 • **Investment cost of solar mounting system = Specific cost of solar mounting system [€/m^2]*Size of PV panels (m^2)**
	$I_{chiller}$	• **Specific cost of DE absorption chillers [€/kW_c] = 4300*(nominal capacity in kW)$^{-0.46}$** Based on the chiller nominal capacity in kW, the scenario has, the aforementioned equation gives the estimated specific costs of SE absorption chillers [€/kW_c], taking into account the economy of scale • **Investment cost of DE absorption chillers = Specific cost of DE absorption chillers [€/kW_c] *Size chiller (kW)**	**Specific cost of Water–cooled VCC [€/kW_c] = 6543*(nominal capacity in kW)$^{-0.534}$** Based on the chiller nominal capacity in kW, the scenario has, the aforementioned equation gives the estimated specific costs of SE absorption chillers [€/kW_c], taking into account the economies of scale • **Investment cost of Water–cooled VCC = Specific cost of Water–cooled VCC [€/kW_c] *Size chiller (kW)**
O&M Costs	$O\&M_{SCD}$	• **O&M cost of ETCs = 1.5% of the Investment cost of ETCs** • **O&M cost of ETCs auxiliaries = 2.5% of the Investment cost of ETCs auxiliaries**	• **O&M cost of PV panels = 1.0% of the Investment cost of PV panels and solar mounting system**
	$O\&M_{chiller}$	• **O&M cost of DE absorption chillers = 3.0% of the Investment cost of DE absorption chillers**	• **O&M cost of Water–cooled VCC = 3.0% of the Investment cost of Water–cooled VCC**

APPENDIX E

Case Study Figures

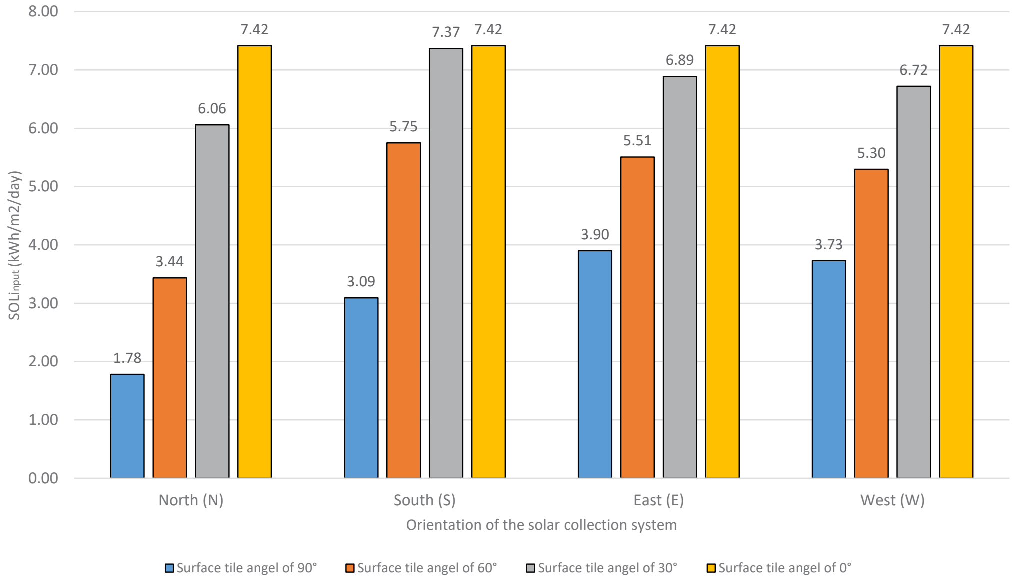

FIG. E.1 Daily average solar irradiance SOLinput at different orientations of the solar collection system considering the month of summer design week

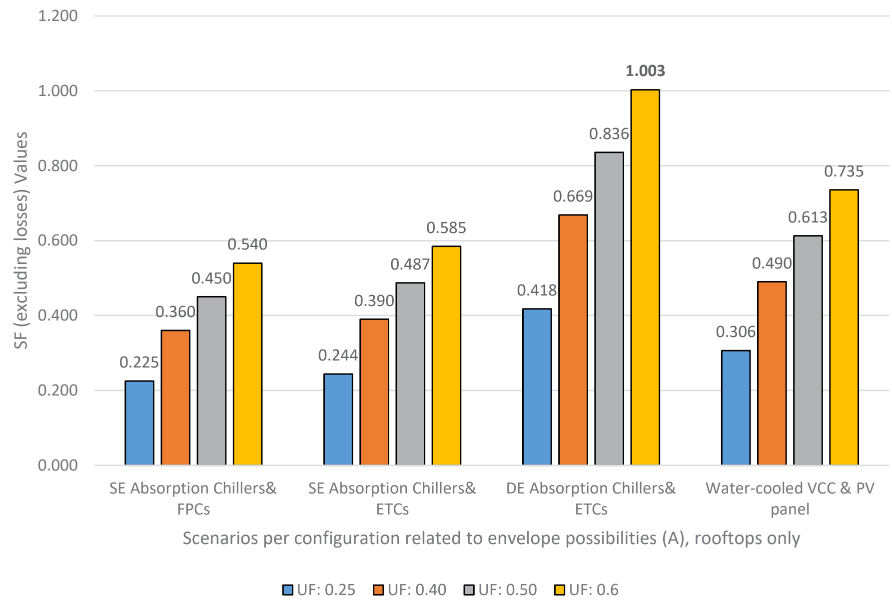

FIG. E.2 SF values (excluding losses) for scenarios related to envelope possibilities (A), rooftops only.

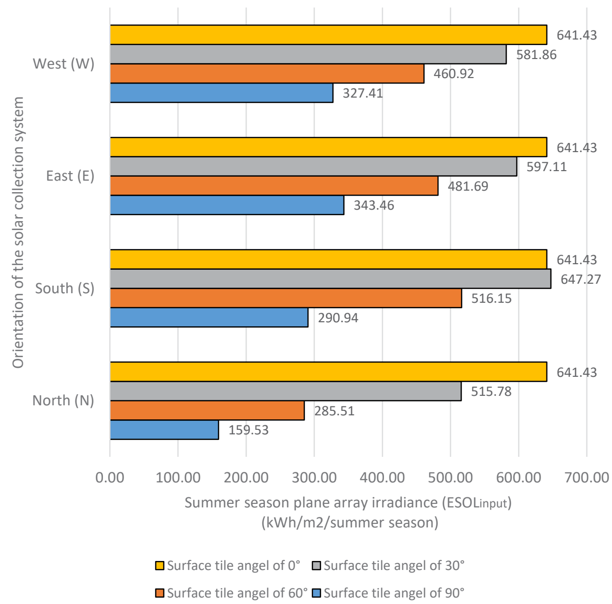

FIG. E.3 Plane array irradiance available on a particular location/orientation considering whole summer as the time frame ESOLinput

APPENDIX F

Desk Research and Analyzed Relevant Publications

TABLE F.1 Summary of analysed relevant publications

Reference		Stages	Stakeholders
RIBA, 2020	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
Oliveira & Melhado, 2011	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
Oliveira & Melhado, 2011	Integrated design and construction processes for renovation projects	1. Conception 2. Design	• Project owner • Design coordinator • Architectural designer • Façade designer
Prieto et al., 2023	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

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TABLE F.1 Summary of analysed relevant publications

Reference		Stages	Stakeholders
Klein, 2013	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
Hamida et al., 2025b	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	–

TABLE F.2 Workplan for all disciplines in the construction industry, considering (RIBA, 2020)

Process	Inputs	Outputs and information exchanges at the end of the process	Requirements or considerations	Tasks/Tools	Stakeholders	Others
0. Strategic definition	–	• Suitable means to achieve client requirements • Appointed client team	• Client require-ments •Business case	• Preparations of client require-ments • Development of a business case considering project budget and risks for fea-sibility options • Ratification of an option delivering client require-ments • Review feedback considering pre-vious projects • Evaluation of site conditions • Evaluation of planning consid-erations	• Client	• The output of process 0 can be the decision of project initiation • Design team is not required • Advisors of the client might be determined to approve strategic advice to the client

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TABLE F.2 Workplan for all disciplines in the construction industry, considering (RIBA, 2020)

Process	Inputs	Outputs and information exchanges at the end of the process	Requirements or considerations	Tasks/Tools	Stakeholders	Others
1. Preparation and briefing	• The decision of project initiation	• Approved project brief confirming the ability to accommodate the project on site • Appointed design team • Project budget • Site information • Information requirements • Project program • Matrix of responsibilities • Procurement strategy	–	• Preparations of project brief covering project and sustainability outcomes, quality ambitions, spatial requirements • Conduction of feasibility studies • Agreement on project budget • Collection of site information • Preparation of project program and execution plan • Determination of pre–application planning advice • Initiation of preconstruction data collection regarding health and safety	• Client team	• Processes 1 to 6 represent the project span • Design team is not required • Advisors of the client might be determined to approve strategic advice to the client

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TABLE F.2 Workplan for all disciplines in the construction industry, considering (RIBA, 2020)

Process	Inputs	Outputs and information exchanges at the end of the process	Requirements or considerations	Tasks/Tools	Stakeholders	Others
2. Concept design	•Pre–application planning advice	• Approved architectural concept by the client • Appointed contractor in case of Management Contract/ Construction Management procurement route • Cost plan • Brief derogation of the project	• Approved project brief confirming the ability to accommodate the project on site (ensure the alignment) • Employer's requirements in case of Design & Build 2 Stage or Contractor–led procurement routes • Strategic engineering requirements • Cost plan • Project strategies and specifications • Compliance with building regulations • Signed off on stage report	• Preparation of architectural concept • Design reviews • Preparation of stage design program	• Client team • Design team	• Processes 1 to 6 represent the project span

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TABLE F.2 Workplan for all disciplines in the construction industry, considering (RIBA, 2020)

Process	Inputs	Outputs and information exchanges at the end of the process	Requirements or considerations	Tasks/Tools	Stakeholders	Others
3. Spatial coordination	• Approved architectural concept by the client	• Spatial co-ordination of architectural and engineering information • Preferred bidder in case of or Contractor–led procurement route	• Cost plan • Project strategies and specifications • Compliance with building regulations • Signed off on stage report	• Architectural concept test through engineering analysis, design studies, and cost estimations • Initiation of change control procedures • Preparation of stage design program • Preparation and submission of planning application • Agreement on the pre–contract services in the case of Design & Build 2 Stage procurement route	–	• Processes 1 to 6 represent the project span

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TABLE F.2 Workplan for all disciplines in the construction industry, considering (RIBA, 2020)

Process	Inputs	Outputs and information exchanges at the end of the process	Requirements or considerations	Tasks/Tools	Stakeholders	Others
4. Technical design	• Contractor's proposals in case of Design & Build 1 Stage, Design & Build 2 Stage, and Contractor–led procurement routes	• Design information for manufacturing and constructing the project • Appointed contractor in case of Traditional, Design & Build 1 Stage, Design & Build 2 Stage, and Contractor–led procurement routes	• Employer's requirements in case of Design & Build 1 Stage • Project strategies and specifications	• Development of architectural and engineering design • Preparation and coordination of design tram • Preparation and integration of specialist subcontractor • Preparation of stage design program • Submission of building regulations application • Tendering in case of the traditional procurement route • Preparation of the construction phase plan	–	• Processes 1 to 6 represent the project span • Processes 4 and 5 can overlap in many cases

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TABLE F.2 Workplan for all disciplines in the construction industry, considering (RIBA, 2020)

Process	Inputs	Outputs and information exchanges at the end of the process	Requirements or considerations	Tasks/Tools	Stakeholders	Others
5. Manufacturing and construction	–	• Completion of project manufacturing, constructing, and commissioning • Building a manual covering fire safety information and health and safety files • Asset information • Practical completion certificate considering the list of defects	• Compliance with planning conditions associated with construction	• Finalization of site logistics and carrying out the construction phase • Production of building systems and construction of the building • Progress monitoring with respect to the construction program • Inspection of construction quality • Resolution of sit queries • Building commissioning and preparation of building manual	–	• Processes 1 to 6 represent the project span • Processes 4 and 5 can overlap in many cases • Design works are not present in process 5, except for the response to the site queries. • Processes 5 and 6 are bridged by building handover tasks considered in the plans for building use
6. Handover	–	• Initiated aftercare • Concluded building contract • Final certificate • Project performance • Feedback from Post Occupancy Evaluation (POE)	• Compliance with planning conditions	• Building handover • Project performance review • Seasonal commissioning • Rectification of defects • Completion of initial aftercare tasks, considering light touch POE	–	• Processes 1 to 6 represent the project span • Process 7 begins simultaneously with process 6 and lasts for the building's life • Processes 5 and 6 are bridged by building handover tasks considered in the plans for building

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TABLE F.2 Workplan for all disciplines in the construction industry, considering (RIBA, 2020)

Process	Inputs	Outputs and information exchanges at the end of the process	Requirements or considerations	Tasks/Tools	Stakeholders	Others
7. Use	–	• Efficiently used, operated, and maintained the building • Feedback from POE • Appointed Facilities and Asset Management teams and/or strategic advisers • Updated building manual covering fire safety information and health and safety files	• Compliance with planning conditions	• Implementation of Facilities and Asset Management • POE of building performance during use phase • Verification of project outcomes	–	• The ongoing building use • Process 7 begins simultaneously with process 6 and lasts for the building's life • Building adaptation at the end of life may result in a new process 0

TABLE F.3 Integrated design and construction processes for new building construction, considering (Oliveira and Melhado, 2011)

Stage	Phase (Processes)	Inputs	Outputs	Requirements or considerations	Tasks/Tools	Stakeholders	Others
1. Building conception	Determination of possibilities and restrictions	Legal and technical data	• Technical and legal restrictions • Possibilities to establish the façade product	–	Data collection	• Project owner • Architectural Designer • Design coordinator	–
	Preliminary definitions and briefing	• Possibilities to establish the façade product	• Building objective, project size, and geometric aspects • Intended standards & performance requirement (aesthetics, structural, fire, acoustics, and energy efficiency) • Defined Finishing	• Technical and legal restrictions	–		The following two outputs influence the façade design: •Intended standards & performance requirement (aesthetics, structural, fire, acoustics, and energy efficiency) • Defined Finishing
	Technical visibility study	Intended standards & performance requirements (aesthetics, structural, fire, acoustics, and energy efficiency)	Viability to meet the priority requirements program	• Technical and legal restrictions	Technical evaluation		–
	Developing documents with technical and administrative definitions	–	• Stakeholders' responsibilities • Process schedule • Guarantees			• Project owner • Design coordinator	Used for developing notebooks for each particular contract

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TABLE F.3 Integrated design and construction processes for new building construction, considering (Oliveira and Melhado, 2011)

Stage	Phase (Processes)	Inputs	Outputs	Requirements or considerations	Tasks/Tools	Stakeholders	Others
2. Design	Preliminary design	• Building objective, project size, and geometric aspects • Intended standards & performance requirement (aesthetics, structural, fire, acoustics, and energy efficiency) • Defined Finishing	• Technical functions of façade elements and components • Optimal architectural position • Pre–evaluated costs	–	• Feedback dossier analysis • Evaluation of architectural options • Cost estimation	• Project owner • Design coordinator • Architectural designer	–
	Façade technological selection	• Optimal architectural position	• Architectural façade technology	• Project owner requirements •Cost, technical, and risk benefit criteria	–		–
	Pre–design	• Intended standards & performance requirement (aesthetics, structural, fire, acoustics, and energy efficiency) • Architectural façade technology	• Quantitative parameters for the characteristics of façade elements • General façade composition • List of interfaces • Graphical representation of the adopted solution • Estimated life–cycle costs, including maintenance costs • Preliminary schedule	–	• Determination of element characteristics • Graphic designs • Cost analysis • Scheduling	• Façade designer • Design coordinator	–

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TABLE F.3 Integrated design and construction processes for new building construction, considering (Oliveira and Melhado, 2011)

Stage	Phase (Processes)	Inputs	Outputs	Requirements or considerations	Tasks/Tools	Stakeholders	Others
2. Design (cont.)	Executive design	• Architectural façade technology • General façade composition • Graphical representation of the adopted solution	• Defined façade element modulation • Defined manufacturing and assembly tolerances • List of technical and operational interfaces covering components, elements, and systems • Formulated documents indicating structural calculations and compliance with safety criteria, such as fire, structural, and maintenance • Documents covering the installation techniques of the faced system	• Intended standards & performance requirement (aesthetics, structural, fire, acoustics, and energy efficiency)	• Comparing the designed façade with the intended standards • Evaluating interfaces related to façade use and maintenance, cleaning equipment, and inspection accessibility. • Studying geometric tolerances • Providing technical installation definitions.	• Architectural designer • Façade designer • Design coordinator	–

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TABLE F.3 Integrated design and construction processes for new building construction, considering (Oliveira and Melhado, 2011)

Stage	Phase (Processes)	Inputs	Outputs	Requirements or considerations	Tasks/Tools	Stakeholders	Others
3. Construction preparation	Hiring suppliers/façade assemblers	• Documents covering the installation techniques of the faced system	• Selected suppliers/façade assemblers	• Stakeholders' responsibilities • Process schedule • Guarantees	• Supporting project owner	• Façade designer • Design coordinator	–
	Contracting	• Selected suppliers/façade assemblers	• Established rules to be adopted by selected suppliers/façade assemblers regarding the construction	–	–	• Façade designer • Design coordinator • Suppliers/ façade assemblers	–
	Detailed Design	• List of technical and operational interfaces covering components, elements, and systems • Documents covering the installation techniques of the faced system	• Detailed design • Construction design • Façade interface with construction • Assembly procedure	• Product characteristics of selected suppliers/façade assemblers	–	• Façade designer • Design coordinator • Suppliers/ façade assemblers • Contractor	–
	Construction planning	• List of technical and operational interfaces covering components, elements, and systems • Façade interface with construction	• Physical and financial schedules	–	–	• Façade designer • Design coordinator • Suppliers/ façade assemblers • Contractor	–

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TABLE F.3 Integrated design and construction processes for new building construction, considering (Oliveira and Melhado, 2011)

Stage	Phase (Processes)	Inputs	Outputs	Requirements or considerations	Tasks/Tools	Stakeholders	Others
4. Façade construction/ assembly	–	• Physical and financial schedules	• Coordinated construction companies and activities	–	Construction management	• Façade designer • Suppliers/ façade assemblers • Contractor	–
5. Construction delivery and facilities management	Building delivery	–	• Documents, including as–built drawings, demonstrating the construction completion according to contractual requirements.	–	Reviewing the design process and construction phase	• Façade designer • Design coordinator • Suppliers/ façade assemblers • Contractor	–
	Maintenance plan	–	• Preventive and corrective maintenance plans	–	–		–
	Building use	• Façade performance during building operation	• Feedback document	–	• Performance analysis	• Contractor • Project owner	–

TABLE F.4 Integrated design and construction processes for renovation projects, considering (Oliveira and Melhado, 2011)

Stage	Phase (Processes)	Inputs	Outputs	Requirements or considerations	Tasks/Tools	Stakeholders
1. Conception	–	Performance issues related to thermal performance, watertightness, maintenance, or structural security	• Renovation aim	–	–	• Project owner • Design coordinator
2. Design	Preliminary studies	• Building design at the original construction time • Designs of any interventions • Façade performance conditions • Sketches of design alternatives	• Building a historical dossier • Created building design before building renovation • Technical and economic viability of the building renovation process	•Technical and architectural issues •Laws related to architectural modifications of the façade	• Studying building history • Architectural design • Building conservation diagnosis • Feasibility study	• Design coordinator • Façade designer • Architectural designer
	Façade technological selection	• Building a historical dossier • Created building design before building renovation • Technical and economic viability of the building renovation process	• Architectural façade technology	• Project owner requirements •Cost, technical, and risk benefit criteria	–	

TABLE F.5 Key phases associated with zero-energy residential building renovation, considering (Prieto et al., 2023)

Process	Outputs	Tasks/Tools	Stakeholders
1. Pre–project	• Defined project needs, problems, and ambition • Approved project brief • Confirmed feasibility • Appointed design team	• Determination of project objectives and criteria • Diagnosis of the building conditions • Definition of the client requirements • Initial cost estimation • Definition of the client requirements • Design team selection	• Client team
2. Concept design	• Approved renovation strategy	• Identifying and comparing strategies, interventions, as also design principles • Identifying renovation measures • Consideration of design concepts involving industrialized components • Evaluation and optimization • Preparing building permit application	• Client team • Design team • Consultants
3. Final design	• Design information required for manufacturing and constructing the project	• Detailed designs for the industrialized renovations • Surveying the existing building • Component engineering • Tendering and product specification	• Design and/or construction team • Subcontractors
4. Execution and handover	• Completion of manufacturing, construction, and commissioning • Project handover	• Manufacturing • Transportation • Installation and site construction • Quality control	• Construction team • Subcontractors
5. Post–construction	• Efficient use, operation, and maintenance of the building	• Optimization of building operation • Monitoring and POE	• Client • Facility management team • Consultants

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TABLE F.6 Façade design and construction processes associated with the curtain wall industry, considering (Klein, 2013)

Processes	Subprocess-es	Inputs	Outputs	Require-ments and consider-ations	Tasks/Tools	Stakeholders	Others
1. System Design	–	• External factors: ◊Society's interest, or ◊Sustainabil-ity in the built environment	Developed system.	• Anticipated market re-quirements: ◊Legal re-quirements ◊Architec-tural design requirements • External factors, such as the social interest in sustainabil-ity in the built envi-ronment.	System de-velopment	System supplier/de-veloper	•Project inde-pendent • The design of a façade system is carried out before the actual design
2. Pre–design/ Development	–	Buildings' type, size, and location	• Building basic re-quirements • Functional require-ments of façades	• Legal re-quirements	Feasibility studies and market surveys	•Investors/ developers •Architects •Consultants	• Project dependent
3. Architectural Design	–	• Functional require-ments of façades	• Construc-tion techni-cal details &working drawings • Tender doc-uments • Estimated façade cost	• Building permit re-quirements • Mutual agreement on costs with clients	Agree on products	•Investors/ developers	• Project dependent • Can differ from one country to another • An iterative process that may require feedback on the outcomes of previous steps.
					Support	• System supplier/ developer	
					Design	• Architect	
						• Consultants	
					Design sup-port	• Façade builder	

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TABLE F.6 Façade design and construction processes associated with the curtain wall industry, considering (Klein, 2013)

Processes	Subprocesses	Inputs	Outputs	Requirements and considerations	Tasks/Tools	Stakeholders	Others
4. Execution Design	Overall	• Construction technical details &working drawings	Finalized decision about the system to be used	Guaranteeing the thermal performance, wind/water tightness	Design	• Façade builder	• Project dependent • Various internal design steps are performed by façade builders during the execution phase, which ensure the ability to carry out the job.
					Supervision	• Architect	
					Sales	• System supplier/ developer	
					–	• Consultants	
					–	•Investors/ developers	
	Development of the basic product	Architectural design outcomes: • Construction technical details &working drawings • Tender documents • Estimated façade cost	Developed a basic system	–	•Identifying potential missing elements in tendering documents	Façade builder	
	Design elaboration and completion	–	–	–	•Sending related designs to architects/ consultants for obtaining approval.		
	Production and Assembly design	–	–	–	• Ordering all necessary components • Support	• Façade builder • System supplier/ developer	

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TABLE F.6 Façade design and construction processes associated with the curtain wall industry, considering (Klein, 2013)

Processes	Subprocess-es	Inputs	Outputs	Require-ments and consider-ations	Tasks/Tools	Stakeholders	Others
5. Production	–	Profiles and fittings	Manufactured and/or pre–assembled curtain walls	• Façade builders' production facilities • External factors, such as the social interest in sustainable production	Cutting, milling, and coating received profiles and fittings	Façade builder	• Project dependent
					Supporting façade builders with Profiles and fittings	• System supplier/ developer	
					Supervision	• Architect	
					Monitoring	• Consultants	
					–	•Investors/ developers	
6. Assembly	–	Manufactured and/or pre–assembled curtain walls	Finished installing façade system	•Time schedule. •Weather conditions • Primary structure status • Façade quality requirements • External factors, such as societal interest in minimal transport	–	Façade builder	• Project dependent
					Supervision	Architect	
					Monitoring	Consultants	
					–	• System supplier/ developer	
7. Use (building operation)	–	• Energy bill and building performance	–	• External factors, such as societal interest in low energy consumption	Maintaining and/or repairing the façade	Façade builder	• Dependent on the business model
					–	•Investors/ developers	
					Management	Facility management team	
					Inhabitation	User	
					Monitoring	–	

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TABLE F.6 Façade design and construction processes associated with the curtain wall industry, considering (Klein, 2013)

Processes	Subprocesses	Inputs	Outputs	Requirements and considerations	Tasks/Tools	Stakeholders	Others
8. End of Life	–	–	–	• External factors, such as societal interest in reducing waste or CO_2 impact	Promoting the second lives of building components. Reuse or recycle of building components	–	–

APPENDIX G

Pre-Workshop Survey Form (MS Forms) and Results

G.1 Pre-Workshop Survey

G.1.1 Introduction

Dear Participant,

It is my pleasure to invite you to take part in this study. The study is a part of an ongoing PhD project entitled “Solar Active Cooling Integrated Facades”. It is conducted by Hamza Hamida, a doctoral researcher at the Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands.

This research project is supervised by Dr. Ing. Thaleia Konstantinou, Prof. Dr.-Ing. Ulrich Knaack und Dr. Alejandro Prieto.

What is the purpose?

This survey aims to obtain the perspective of different stakeholders regarding the roles and responsibilities in designing and developing solar cooling integrated facades. The targeted group of stakeholders includes the following:

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

The survey will take 15 to 20 minutes, and it has the following three parts:

- **Section (A):** Informed Consent Form
- **Section (B):** General Information of the Participants
- **Section (C):** Main Questions

On behalf of the Architectural Facades and Products research group at TU Delft.

Kind regards,

Hamza Hamida
PhD Candidate
Architectural Façades & Products (AF&P) Research Group
Department of Architectural Engineering + Technology (AE+T)
Faculty of Architecture and the Built Environment (A+BE)
Delft University of Technology (TU Delft)
Email: H.B.Hamida@tudelft.nl

G.1.2 Survey Informed Consent Form (Section A)

- I have read and understood the study information. I have been able to ask questions about the study, and my questions have been answered to my satisfaction.
- I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason.
- I understand that taking part in the study involves filling out an online survey.
- I understand that the study will end within 15 to 20 minutes.

- I understand that risks related to maintaining the confidentiality and privacy, including names of participants and their organizations, will be mitigated by the following actions:
  1. Storing survey data on the TU Delft storage drive, where it will have restricted access only among the study team.
  2. Names will be deleted after anonymization.
  3. The use of the Microsoft Forms platform provided by TU Delft will be used as much as possible.
- I understand that personal information collected about me that can identify me, such as emails, consent forms, and names, will not be shared beyond the study team.
- I understand that the (identifiable) personal data I provide will be destroyed at the end of the PhD project.
- I understand that after the research study, the de-identified information I provide will be used for publications and academic purposes.
- I agree that my responses, views, or other input can be quoted anonymously in research outputs.
- I give permission for the de-identified, anonymized transcripts that I provide to be archived in 4TU.Research Data repository so it can be used for future research and learning.
- I understand that access to this repository is unrestricted.
- **I agree to all of the aforementioned points**

G.1.3 General Information of the Participants (Section B)

1 **First Name**

____

2 **Last Name**

____

3 **What is your main educational and technical background? (You can choose more than one option)**

- ☐ Architecture
- ☐ Building Physics
- ☐ Civil Engineering
- ☐ Mechanical Engineering
- ☐ Electrical Engineering
- ☐ Others: ______________________________

4 **What is your field of professional experience in the building industry?**

- ☐ 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 facade consulting).
- ☐ Construction Team: Contractor, subcontractor, supplier/manufacturer, and/or façade builder/assembler.

5 **Based on the selected previous answer (client, design, or construction team), could you please provide your specific role within the selected team?**

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6 **Professional years of experience**

- ☐ Less than 5 years
- ☐ 5 to 10 years
- ☐ 11 to 15 years
- ☐ 16 to 20 years
- ☐ More than 20 years

7 **In which countries have most of the projects you have worked on been located? (You can name between 1 and 4 countries)**

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8 **Have you been involved in the design and/or construction of building facades?**

- ☐ Yes
- ☐ No

9 **Which of the following phases have you been involved in during the design or construction of building façades? (You can choose more than one option)**

- ☐ Design
- ☐ Production
- ☐ None of the above, as I have not been involved in the design or construction of building façades
- ☐ Installation (Assembly)
- ☐ Maintenance/operation

10 **Have you worked on projects involving the application of solar technologies in buildings?**

- ☐ Yes
- ☐ No

11 **Which of the following technologies were used in projects that applied solar technologies in buildings? (You can choose more than one option)**

- ☐ Photovoltaics (PV)
- ☐ Solar Thermal Collectors (STC)
- ☐ Photovoltaic Thermal Collectors (PVT)
- ☐ Others: ______________________________
- ☐ None of the above, as I have not been involved in projects that applied solar technologies in buildings

12 **Have you worked on projects involving the application of solar cooling technologies in buildings?**

- ☐ Yes
- ☐ No

13 **Which of the following technologies were used in projects that applied solar cooling technologies in buildings? (You can choose more than one option)**

- ☐ Electrically-driven systems (Photovoltaic (PV)-assisted vapor-compression air-conditioning equipment or Thermoelectric technologies)
- ☐ Thermally-driven systems (Absorption, Adsorption, Desiccant, or Thermomechanical technologies)
- ☐ Others: ______________________________
- ☐ None of the above, as I have not been involved in projects that applied solar cooling technologies in buildings

14 **Have you worked on projects involving façade integration of solar or solar cooling technologies?**

- ☐ Yes
- ☐ No

15 **Which of the following technologies were used in projects that integrated solar or solar cooling technologies into facades? (You can choose more than one option)**

- ☐ Photovoltaics (PV)
- ☐ Solar Thermal Collectors (STC)
- ☐ Photovoltaic Thermal Collectors (PVT)
- ☐ Electrically-driven systems (Photovoltaic (PV)-assisted vapor-compression air-conditioning equipment or Thermoelectric technologies)
- ☐ Thermally-driven systems (Absorption, Adsorption, Desiccant, or Thermomechanical technologies)
- ☐ Others: ______________________________
- ☐ None of the above, as I have not been involved in projects that integrated solar or solar cooling technologies into facades

G.1.4 Main Questions (Section C)

Solar cooling technologies utilize solar energy to produce either conditioned air or chilled water. These technologies are divided into two primary categories: those that generate hot water using Solar Thermal Collectors (STCs) and those that produce electricity using Photovoltaic (PV) panels. These categories represent two key approaches for converting solar energy into cooling effects: thermally driven processes and electrically driven processes. Electrically driven systems include PV-assisted vapor-compression air conditioners or thermoelectric systems, while thermally driven systems encompass methods such as absorption, adsorption, desiccant cooling, and thermomechanical processes.
Integrating components of solar cooling technologies into 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 a cooling effect in a particular indoor environment.

In this research, a total of five main stages have been defined for designing and developing building façades that integrate solar cooling technologies. The following picture illustrates the main stages involved in designing and developing façade products that incorporate solar cooling technologies for office buildings. It highlights each stage along with its purpose and outcomes. Please note that these stages specifically relate to the design and development of façade products integrating solar cooling technologies for office buildings.

In the following section, you will give your opinion on the roles and responsibilities of stakeholders within these stages.

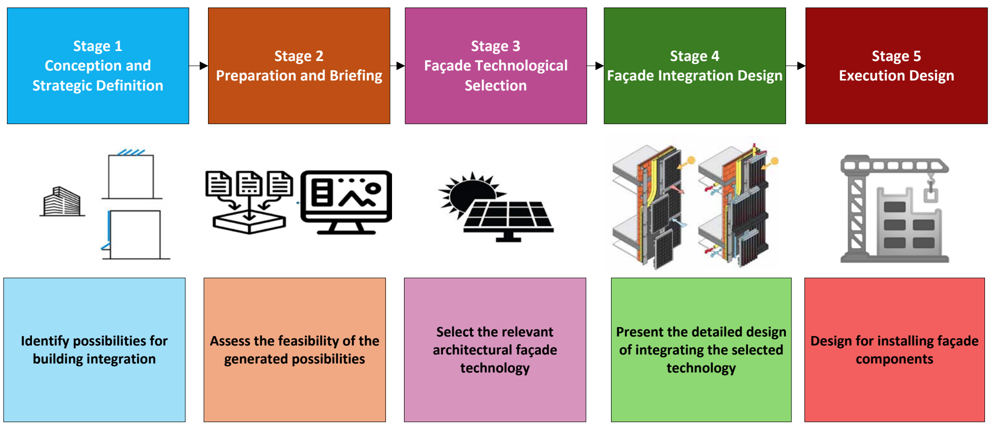

FIG. G.1 Design and development stages

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
- ☐ Others: ____________________
- ☐ I have no role

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)
- ☐ Others: ____________________
- ☐ I do not interact with stakeholders because I have no role

Stage 2

Preparation and Briefing: Assess the feasibility of the generated possibilities.

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

- ☐ Assessment of pre-technical feasibility by determine available envelope possibilities meeting cooling demand
- ☐ Evaluation of how the technology can be integrated and operated
- ☐ Assessment of economic viability
- ☐ Others: ____________________
- ☐ I have no role

Preparation and Briefing: Assess the feasibility of the generated possibilities.

Based on the role you chose for Stage 2 (Preparation and Briefing), 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)
- ☐ Others: ____________________
- ☐ I do not interact with stakeholders because I have no role

Stage 3

Façade Technological Selection: Select the relevant architectural façade technology.

Based on your expertise, what role do you play in the façade technological selection stage? (You can choose more than one option)

- ☐ Summarization of techno-economic feasibilities
- ☐ Selection of architectural façade technology and agreement on products
- ☐ Others: ____________________
- ☐ I have no role

Façade Technological Selection: Select the relevant architectural façade technology.

Based on the role you chose for Stage 3 (Façade Technological Selection), 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)
- ☐ Others: ____________________
- ☐ I do not interact with stakeholders because I have no role

Stage 4

Façade Integration Design: Present the detailed design of integrating the selected technology.

Based on your expertise, what role do you play in the façade integration design stage? (You can choose more than one option)

- ☐ Determination of characteristics of key elements
- ☐ Identification of means of connections according to the standards
- ☐ Demonstration of detailed design
- ☐ Others: ____
- ☐ I have no role

Façade Integration Design: Present the detailed design of integrating the selected technology.

Based on the role you chose for Stage 4 (Façade Integration Design), 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)
- ☐ Others: ____
- ☐ I do not interact with stakeholders because I have no role

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Stage 5

Execution Design: Design for installing façade components.

Based on your expertise, what role do you play in the execution stage? (You can choose more than one option)

- ☐ Identifying potential missing elements in tendering documents
- ☐ Spatial coordination of architectural and engineering information
- ☐ Approve the final design
- ☐ Production and assembly design
- ☐ Determine installation techniques of the façade system
- ☐ Project planning and scheduling
- ☐ Others: ____________________
- ☐ I have no role

Execution Design: Design for installing façade components.

Based on the role you chose for Stage 5 (Execution), 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)
- ☐ Others: ____________________
- ☐ I do not interact with stakeholders because I have no role

G.2 Participants' Profile

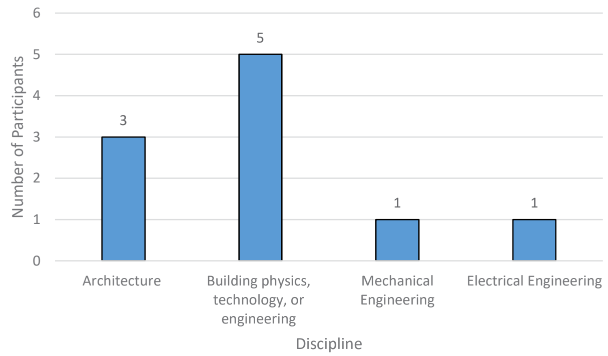


FIG. G.2 Main educational and technical background

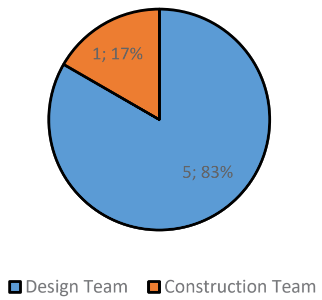


FIG. G.3 Field of professional experiences in the building industry

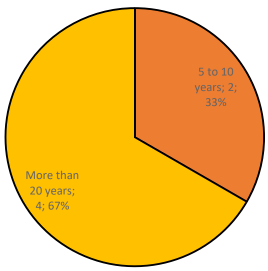


FIG. G.4 Years of professional experience

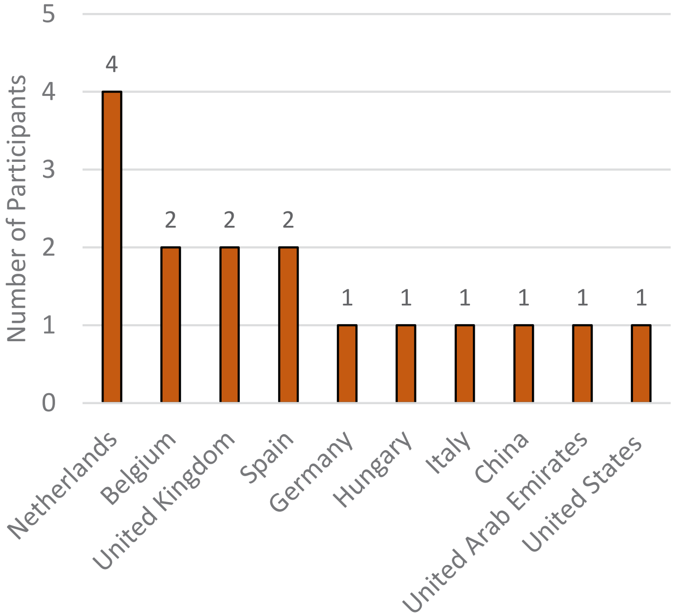


FIG. G.5 Countries where most of the project participants had worked

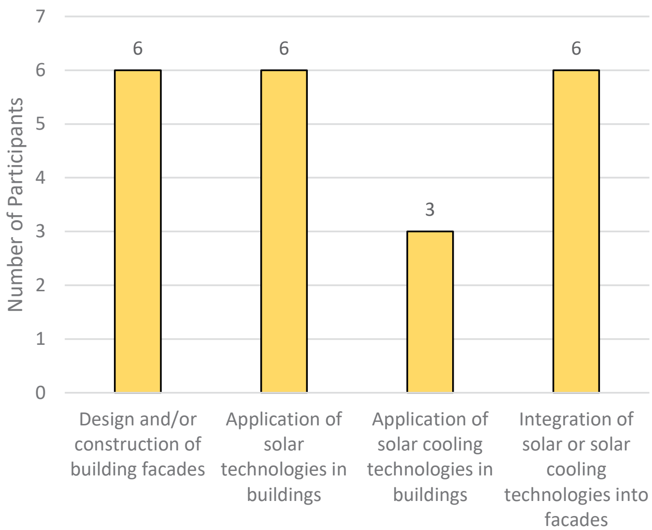


FIG. G.6 Involvement of participants in different types of projects

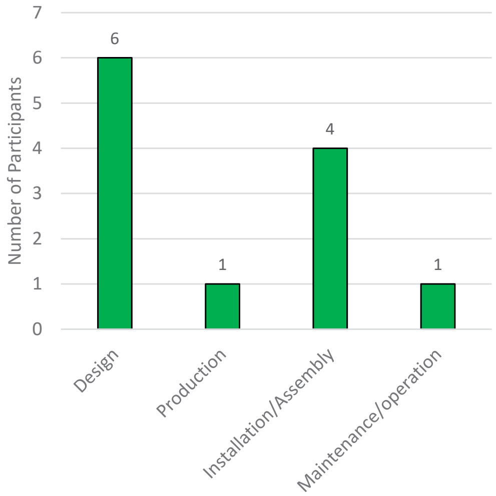


FIG. G.7 Phases in which participants were involved during the design or construction of building façades

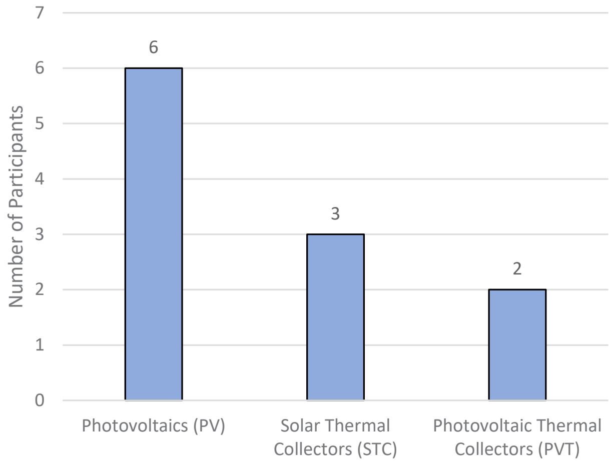


FIG. G.8 Technologies used in projects that applied solar technologies in which participants have been involved

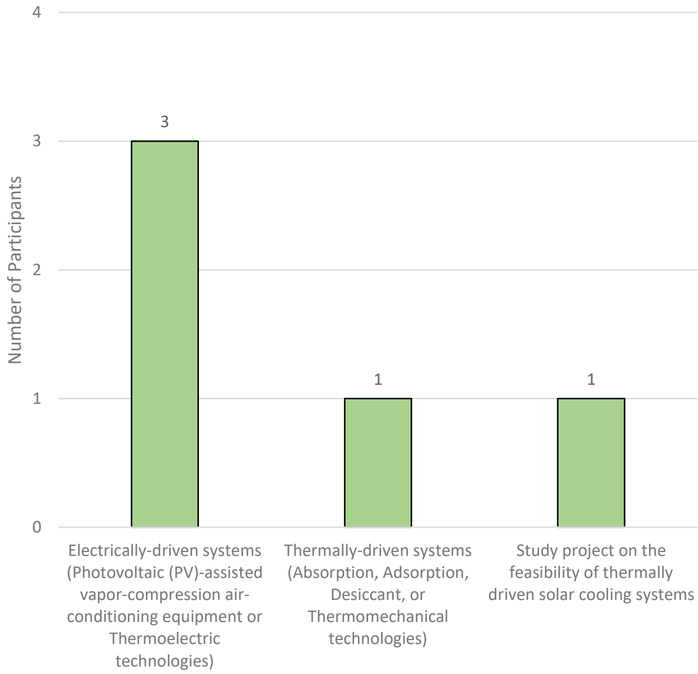


FIG. G.9 Technologies used in projects that applied solar cooling technologies in which participants have been involved

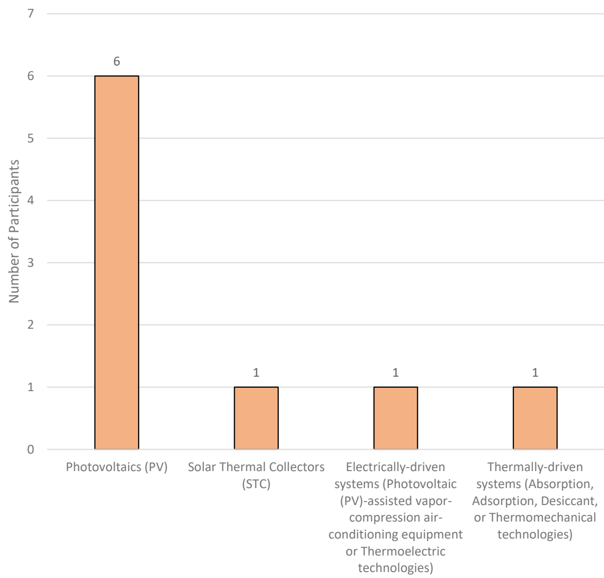


FIG. G.10 Technologies used in projects that integrated solar or solar cooling technologies into façades, in which participants have been involved

APPENDIX H

Virtual Workshop Guide Protocol (MS Teams and MS Whiteboard) and Results

H.1 Workshop Guide

H.1.1 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

H.1.2 Research background (PowerPoint Slides)

- A short presentation about the research background, including providing an overview of previous findings as well as relevant definitions.

H.1.3 Interactive session and activities (PowerPoint Slides and MS Whiteboard)

- Describing the moderation principles and rules related to the behaviour of participants and expectations. This included the setup and tools that participants could use during the virtual workshop, which included the main tools of Microsoft Teams and Microsoft Whiteboard
- Overview of hypothetical building case and activities

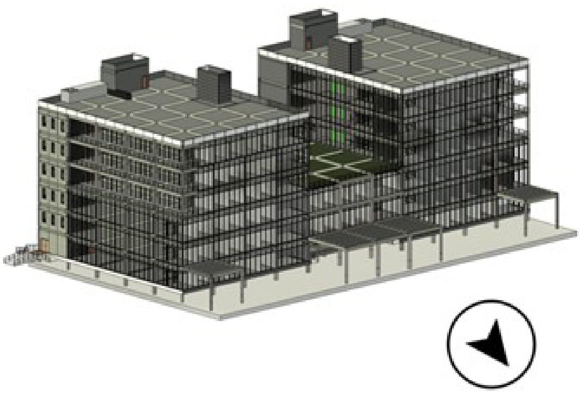


FIG. H.1 Overview of hypothetical building case

TABLE H.1 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	The ground floor has its own layout	2695.68 m^2
Window–to–wall ratio (WWR)	Proportion of exterior glazed walls	55%

TABLE H.2 Construction characteristics of the thermal envelope elements according to local energy saving guidelines in Spain

Construction Element	Considered Materials and Systems 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]

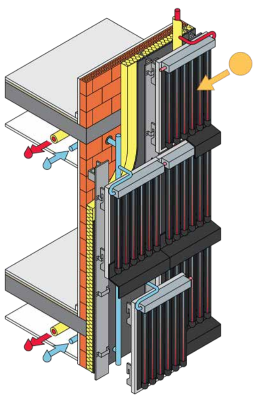
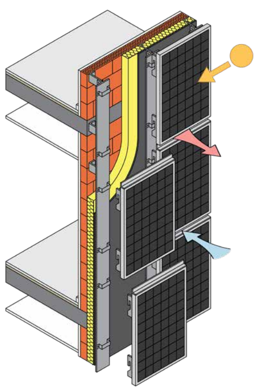
TABLE H.3 Energy performance of the building

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 the summer design week	9805.58 [kWh/day]

TABLE H.4 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 owner-ship and use	A single company owns the whole building
	The owner is the building user

TABLE H.5 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		

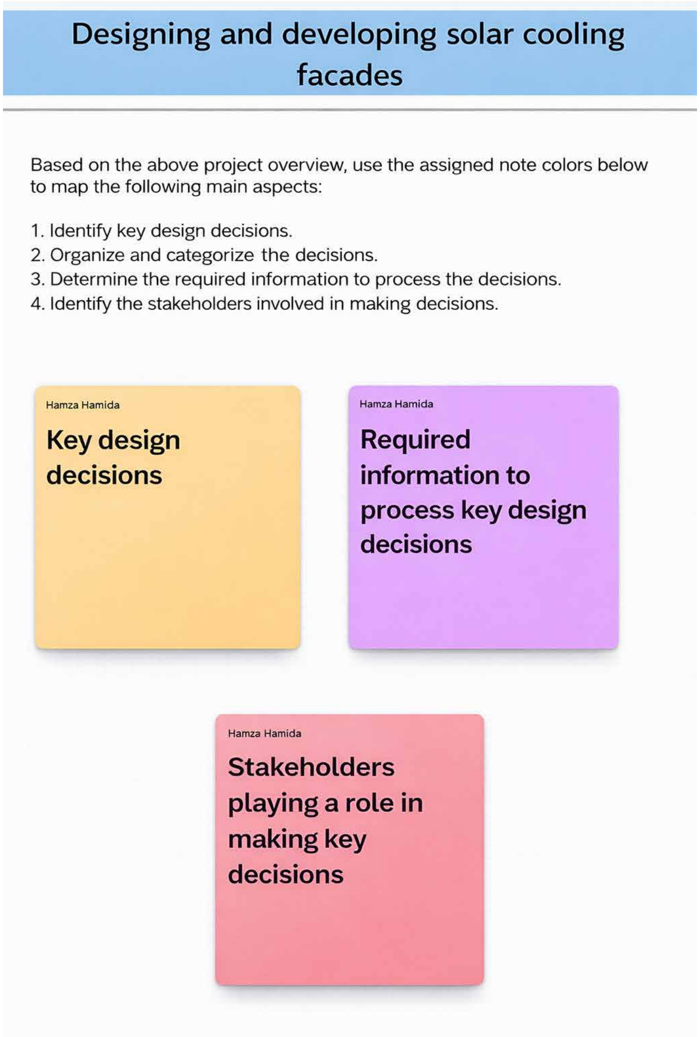


FIG. H.2 Assigned note colours

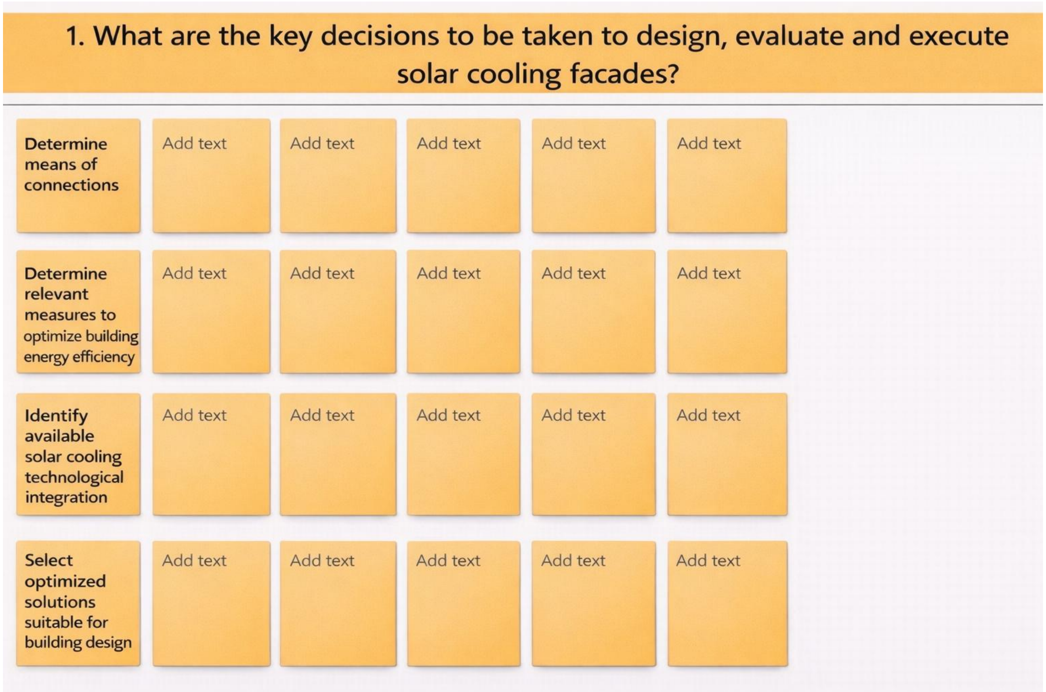


FIG. H.3 Identification of design decisions

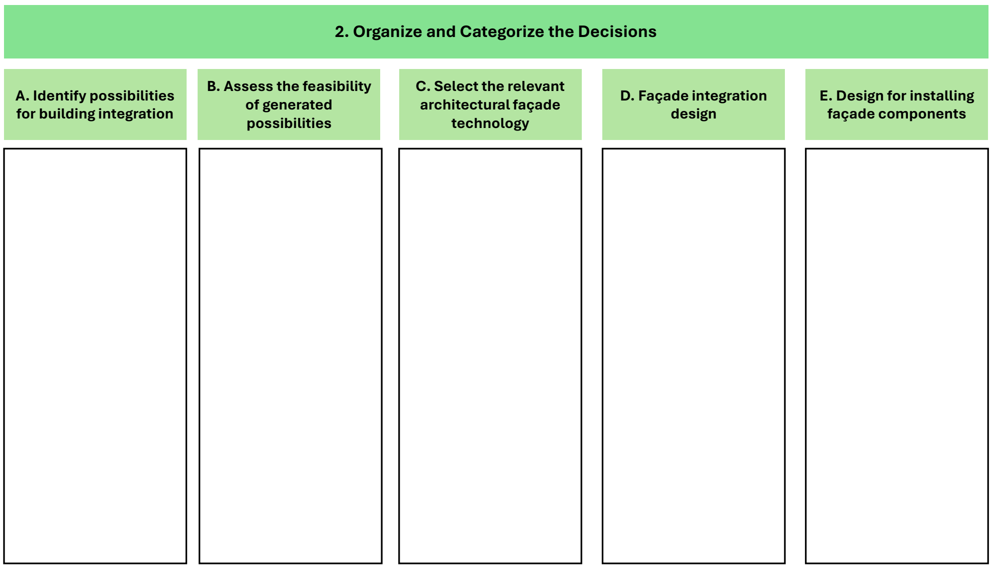


FIG. H.4 Main canvas

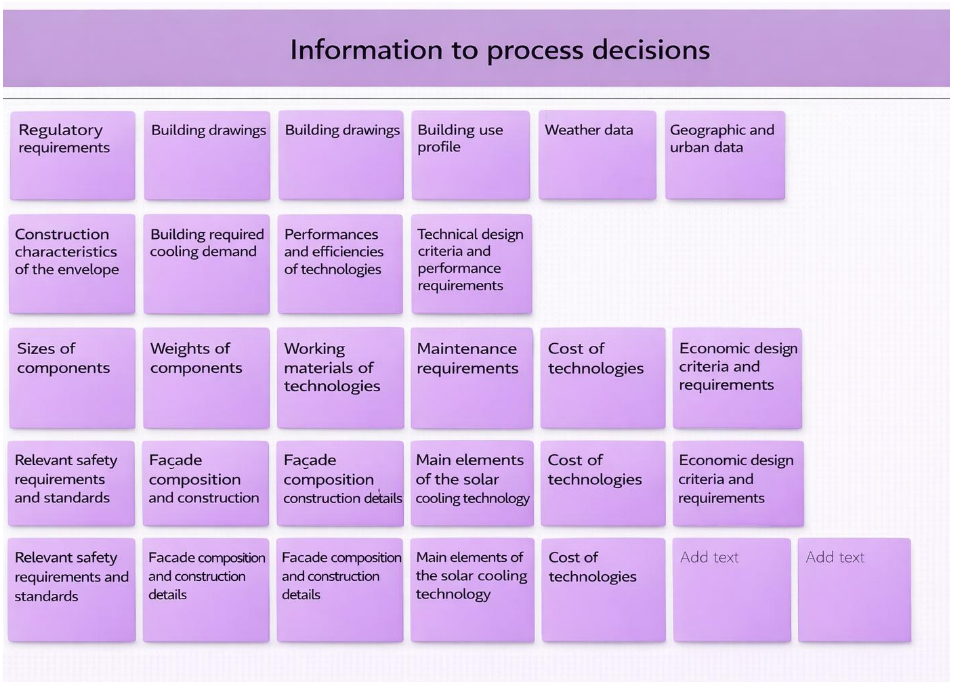


FIG. H.5 Identification of information

FIG. H.6 Identification of main stakeholders

H.1.4 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.)

H.1.5 Conclusion

- Summarization of key points and themes, and reflecting on their thoughts, obtaining some perspectives regarding future developments.

H.2 Summary of main outcomes

TABLE H.6 Summary of the workshop's main outcomes

Item	Stage				
	Conception and Strategic Definition	Preparation and Briefing	Façade Technological Selection	Façade Integration Design	Execution Design
Purpose and Main Outcomes	Identify possibilities for building integration	Assess the feasibility of the generated possibilities	Select the relevant architectural façade technology	Present the detailed design of integrating the selected technology	Design for installing façade components

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TABLE H.6 Summary of the workshop's main outcomes

Item	Stage				
	Conception and Strategic Definition	Preparation and Briefing	Façade Technological Selection	Façade Integration Design	Execution Design
Decision Aspects Linked to the Stage	• Assessing and reducing building preliminary energy consumption in relation to energy demand • Determining the potential of having modular, industrialized, or plug–and–play solutions • Analysing the sequence of construction activities • Considering building orientation, architectural elements, and available envelope possibilities to integrate the technology • Identifying life expectancy and replacement requirements of components • Amortization (payback period/cost–effectiveness)	• Assessing the feasibility in terms of demand and cost: Assess whether the system makes sense based on energy demand and financial feasibility. • Determining component weight and Structural Impact: Heavy components may require structural reinforcements, increasing costs. • Ensuring the fire safety of materials	• Prefabrication types of system components (storage, evaporation, electrical–driven heat pump) • Sizes of components for façade integration and checking how much space is available in the façade • Maintenance accessibility requirements	• Ease of installation, considering the potential of having a prefabricated and plug–and–play solution • Maintenance accessibility requirements	• Analysing the installation process, considering auxiliary elements, and avoiding conflicts with other activities • A company providing guarantees and having sufficient expertise to maintain the installation

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TABLE H.6 Summary of the workshop's main outcomes

Item	Stage				
	Conception and Strategic Definition	Preparation and Briefing	Façade Technological Selection	Façade Integration Design	Execution Design
Determined Required Information to Process Decisions	• Technical design criteria and performance requirements • Working materials of technologies • Performances and efficiencies of technologies • Cost of technologies • Maintenance requirements	• Technical design criteria and performance requirements • Working materials of technologies	• Regulatory requirements • Safety, fire resistance, thermal performance • CE marking for existing products. Architectural elements • Detailed cost calculation data	• Information on the components, size, way of connection, etc. How can it be connected	• Warranties • Order of construction activities not to damage the active systems • Information about installation
Identified stakeholders playing a role in making decisions	• Owner, investor, and/or real estate/property developer • Façade suppliers/ manufacturers • Architectural designer (As responsible for the design)	• HVAC suppliers/ manufacturers • Consultants (Mechanical, Electrical and Plumbing (MEP), building physics, or facade consulting) • Architectural designer (As responsible for the design)	• Architectural designer • Consultants (Mechanical, Electrical and Plumbing (MEP), building physics, or facade consulting) • Suppliers/ manufacturers	• Façade designer • Suppliers/ manufacturers	• Contractors • Suppliers/ manufacturers

APPENDIX I

Framework Validation Instrument (MS Forms) and Results

I.1 Validation Instrument (MS Forms)

I.1.1 Introduction

Integrating components of solar cooling technologies into 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 a cooling effect in a particular indoor environment.

In this exercise, you will go through the process of designing and developing solar cooling integrated façades to understand how the aspects considered can support design decisions. The exercise will take approximately 5 to 10 minutes.

Kind regards,
Hamza Hamida
PhD Candidate
Architectural Façades & Products (AF&P) Research Group
Delft University of Technology (TU Delft)
Email: H.B.Hamida@tudelft.nl

I.1.2 Survey Informed Consent Form (Section A)

- I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason.
- I understand that taking part in the study involves filling out an online survey.
- I understand that the study will end within 5 to 10 minutes.
- I understand that risks related to maintaining the confidentiality and privacy will be mitigated by the following actions:
  1. Storing survey data on the TU Delft storage drive, where it will have restricted access only among the study team.
  2. Names of participants are not required.
  3. The use of the Microsoft Forms platform provided by TU Delft is used as much as possible.
- I understand that the survey does not collect personal information about participants that can identify them, such as names or emails.
- I understand that after the research study, the de-identified information I provide will be used for publications and academic purposes.
- I agree that my responses, views, or other input can be quoted anonymously in research outputs.
- I give permission for the de-identified, anonymized transcripts that I provide to be archived in 4TU.Research Data repository so it can be used for future research and learning.
- I understand that access to this repository is unrestricted.
- **I agree to all of the aforementioned points**

I.1.3 General Information of the Participants (Section B)

1 **What is your main educational and technical background? (You can choose more than one option)**

☐ Architecture
☐ Building Physics
☐ Civil Engineering
☐ Mechanical Engineering
☐ Electrical Engineering
☐ Others: ______________________________

2 **What is your field of professional experience in the building industry? (You may select more than one option.)**

- ☐ 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 facade consulting).
- ☐ Construction Team: Contractor, subcontractor, supplier/manufacturer, and/or façade builder/assembler.
- ☐ Others: ____________________

3 **Professional years of experience**

- ☐ Less than 5 years
- ☐ 5 to 10 years
- ☐ 11 to 15 years
- ☐ 16 to 20 years
- ☐ More than 20 years

4 **In which countries have most of the projects you have worked on been located? (You may select more than one option.)**

- ☐ Europe
- ☐ North America (USA/Canada)
- ☐ Middle-East
- ☐ East Asia (E.g., China)
- ☐ Others: ____________________

5 **Which of the following types of projects have you worked on? (You can choose more than one option)**

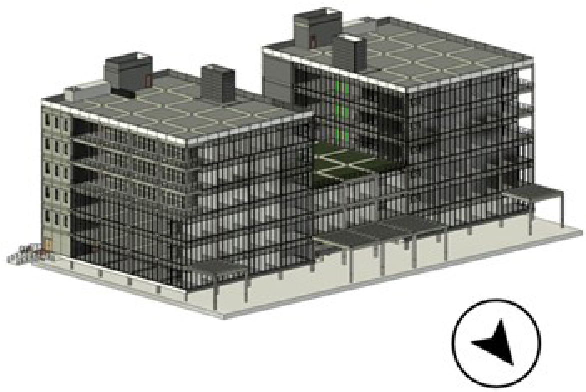
- ☐ Design and/or construction of building facades (Design, production, installation, and/or maintenance/operation).
- ☐ Application of solar technologies in buildings (Photovoltaics (PV), Solar Thermal Collectors (STC), and/or Photovoltaic Thermal Collectors (PVT))
- ☐ Application of solar cooling technologies in buildings (Photovoltaic (PV)-assisted vapor-compression air-conditioning equipment, thermoelectric, absorption, adsorption, desiccant, or thermomechanical technologies).
- ☐ Façade integration of solar or solar cooling technologies
- ☐ Others: ____________________

I.1.4 Façade Design and Development Process (Section C)

In this section, you will go through the design and development process of solar cooling integrated façades.
Based on your background, you will assume the role of a design or construction team to explore how this process can support the application of the technology.
Please consider the following conceptual design for a new office building in Madrid. The project client is a private investor. The building has the following features:

- **Function:** Office building (5-story building)
- **Project:** New construction
- **Location:** Madrid, Spain
- **Window-to-Wall Ratio (WWR):** 55%
- **Opaque façade:** Ventilated Façade-Multi-layered opaque external walls (U-Value = 0.263 [W/m^{2}K])
- **Glazing (Openings):** Doble-glazing low-emissive (U-Value = 1.35 [W/m^{2}K])
- **Roofs (Top slab):** Cast concrete slab (U-value = 0.21 [W/m^{2}K])
- **Building annual energy use intensity:** 227.02 [kWh/m^2/year]
- **Building annual cooling demand intensity:** 53.61 [kWh/m^2/year]
- **Building average daily cooling demand in Summer Design Week:** 9805.58 [kWh/day]

FIG. I.1 Reference Building



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1 **Consider the following five façade design and development stages. At which stage can the integration of solar cooling technologies (or other solar technologies) into the façade be considered?**

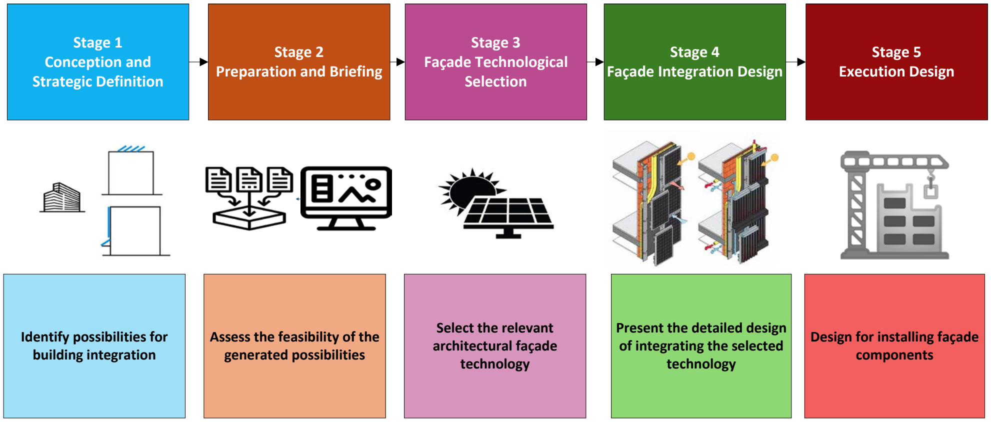


FIG. I.2 Design and development stages

- ☐ Stage 1: Conception and Strategic Definition
- ☐ Stage 2: Preparation and Briefing
- ☐ Stage 3: Façade Technological Selection
- ☐ Stage 4: Façade Integration Design
- ☐ Stage 5: Execution Design

2 **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
- ☐ Others: ______________________________
- ☐ Façade designer
- ☐ Building physics consultant
- ☐ Suppliers

3 **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.)**

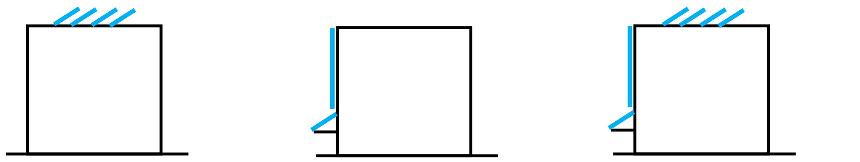


FIG. I.3 Envelope integration possibilities

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

4 **Based on your expertise and the information provided about the office case, please rank the decisions in the order they should be made, from the first to the last. (Drag and drop the boxes vertically to arrange them accordingly.)**

– Determine available envelope possibilities meeting cooling demand
– Determine installation techniques for the façade system and identify the required construction equipment
– Determine relevant measures to optimize building design

5 **Based on your expertise, please rank the technical design criteria in the order they could be considered, from the first to the last. (Drag and drop the boxes vertically to arrange them accordingly.)**

– **Assembly and connections** (connection of components, physical integration, and the nature of the working principle of applied components)
– **Compactness and space usability** (amount of used area and space by solar cooling components, bulkiness of products, and structural support requirements)
– **Product performance and efficiency** (the ability to meet cooling requirements)
– **Maintenance requirements** (periodic maintenance, product cleaning, and product accessibility)

6 **If you would determine a suitable solar cooling technology to develop design solutions, what key information is required to support or process these decisions? (You may select more than one option.)**

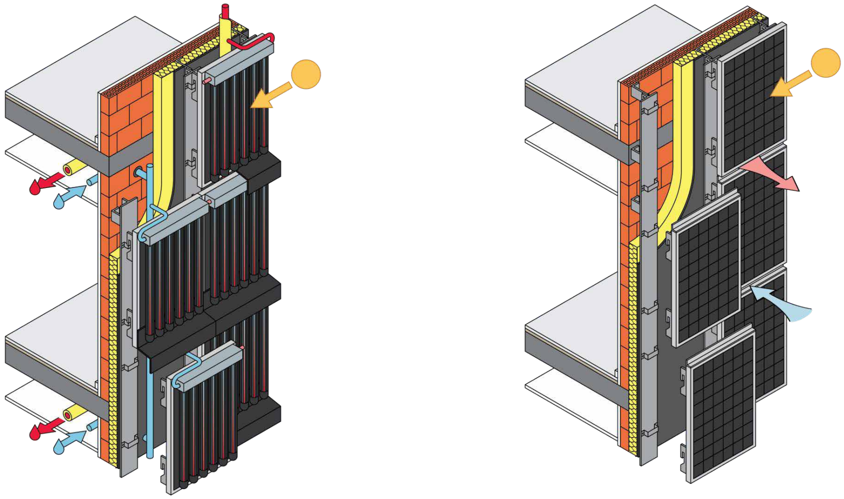
Thermally-Driven Systems
(Absorption, Adsorption, Desiccant, or Thermomechanical technologies)

Electrically-Driven Systems
(Photovoltaic (PV)-assisted vapor-compression air-conditioning equipment of Thermoelectric technologies)

FIG. I.4 Types of solar cooling technologies

- ☐ Building drawings
- ☐ Weather, geographic, and urban data
- ☐ Performances and efficiencies of technologies
- ☐ Working materials of technologies
- ☐ Construction characteristics of the envelope
- ☐ Others: ______________________________

7 **Based on your expertise, what financial factors should be considered to evaluate the following design solutions?**



Thermally-Driven Systems
(Absorption, Adsorption, Desiccant, or Thermomechanical technologies)

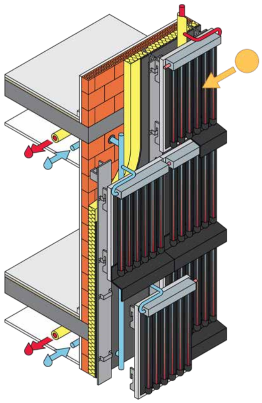
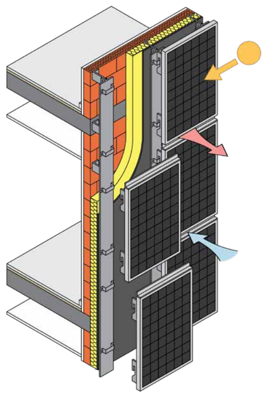
Electrically-Driven Systems
(Photovoltaic (PV)-assisted vapor-compression air-conditioning equipment of Thermoelectric technologies)

FIG. I.5 Design solutions

- ☐ Initial Investment Cost
- ☐ Government Subsidies
- ☐ Energy Prices
- ☐ Return on Investment (Payback Period)
- ☐ Annual solar renewable energy produced by the technology
- ☐ Total life cycle cost
- ☐ Project Budget
- ☐ Others: ____________________

8 **Which of the following design solutions might be relevant based on the provided information?**

TABLE I.1 Design solutions

Design Solution	Thermally–Driven Systems (Double–Effect Adsorption Chiller and Evacuated Tubes Collectors)	Electrically–Driven Systems (Water–Cooled Vapor Compression Chiller and PV Panels)
		
Efficiency of the solar collection system	65%	22%
Coefficient of performance (COP) of the cooling technology	1.2	2.6
Solar Fraction (Cooling effect delivered by the technology/ cooling demand)	1.394	1.022
Life Cycle Cost in Annual Worth (20 years) [€/year]	111,800	52,800
Levelized Cost of Cooling [€/ kWh/year]	0.095	0.059

- ☐ Thermally-Driven Systems (Double-Effect Adsorption Chiller and Evacuated Tubes Collectors)
- ☐ Electrically-Driven Systems (Water-Cooled Vapor Compression Chiller and PV Panels)

9 **What were the main factors that influenced your selection of this solution? (You can choose up to two options)**

- ☐ Efficiency of the solar collection system
- ☐ Coefficient of performance (COP) of the cooling technology
- ☐ Solar Fraction (Cooling effect delivered by the technology /cooling demand)
- ☐ Life Cycle Cost in Annual Worth
- ☐ Levelized Cost of Cooling

I.1.5 Reflection (Section D)

1 **Based on the provided information, would you integrate solar cooling technologies into the office building?**

- ☐ Yes
- ☐ I am not sure
- ☐ No

2 **How did the information presented during the process of designing and developing solar cooling integrated façades help you make decisions?**

- ☐ To a great extent – they provide comprehensive guidance across all design stages
- ☐ To a moderate extent – they support certain key phases but not all
- ☐ To a limited extent – they offer only general direction
- ☐ Not at all – they are not applicable or relevant to the design process
- ☐ I am not sure / I need more information to assess

3 **Based on the previous case, what were the key struggles you faced when making decisions?**

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4 **Reflecting on the previous case, what information or support do you feel was lacking?**

I.2 Respondents' Profile

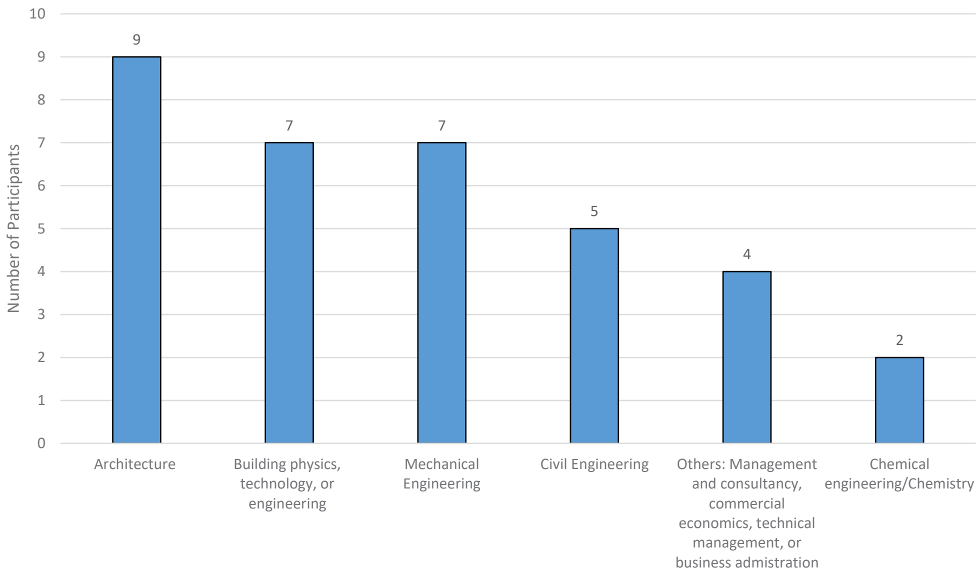

FIG. I.6 Main educational and technical background of respondents

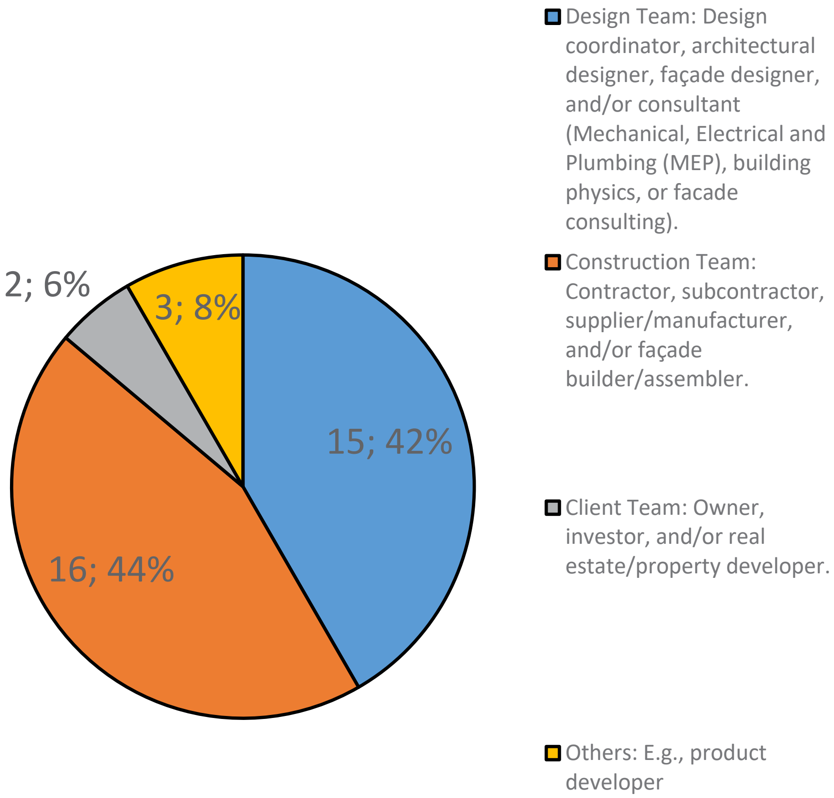

FIG. I.7 Respondents' fields of professional experiences in the building industry

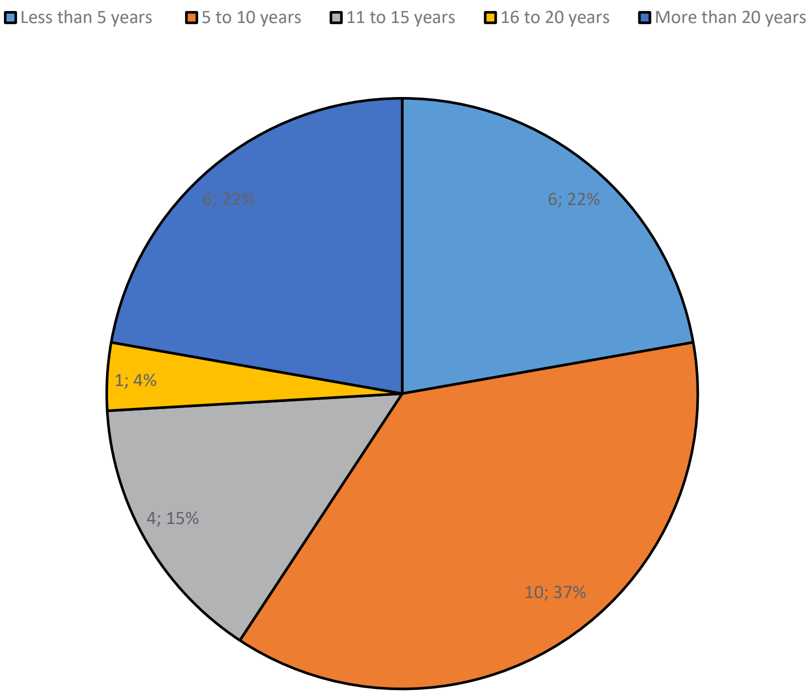

FIG. I.8 Respondents' professional years of experience

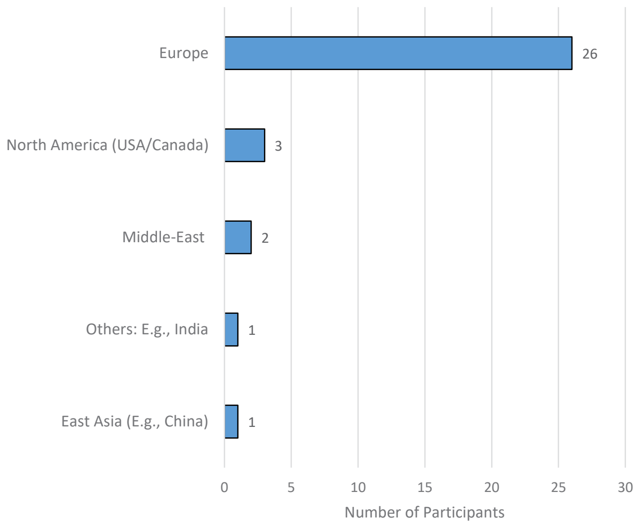

FIG. I.9 Countries where most of the project respondents have worked

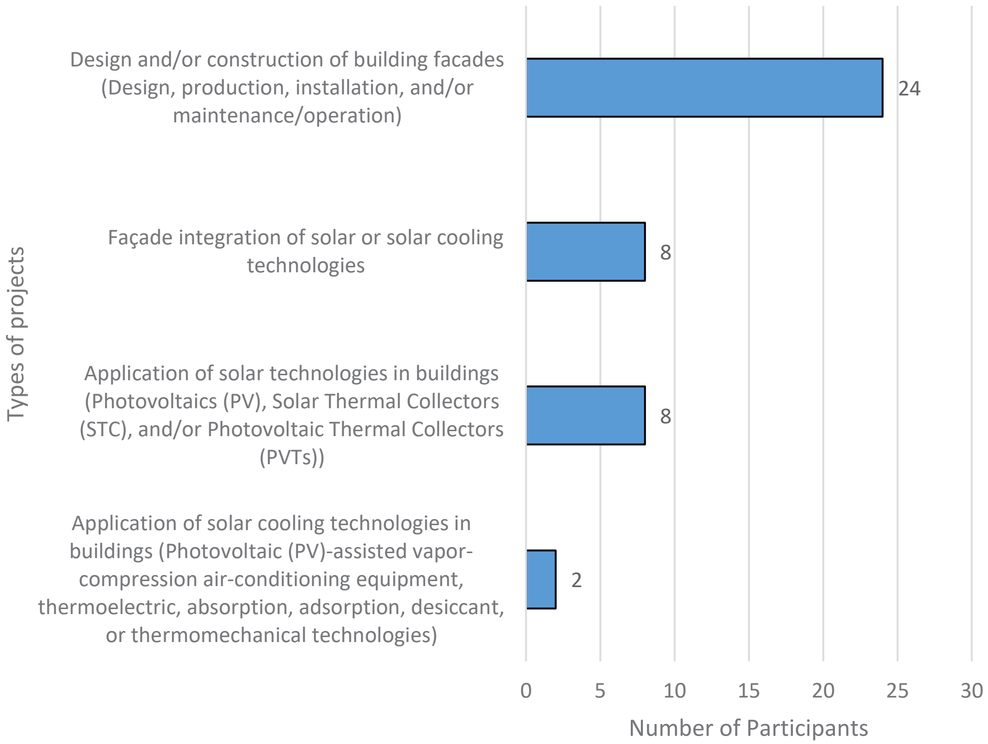

FIG. I.10 Types of projects respondents worked on

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APPENDIX J

Data Availability

Chapter 1
Data sharing is not applicable to this chapter as no datasets were generated or analyzed.

Chapter 2
Data sharing is not applicable to this chapter as no datasets were generated or analyzed.

Chapter 3
The data supporting these research findings are openly available in 4TU. ResearchData at this link:

https://doi.org/10.4121/bead775f-2674-477a-85b5-cf8446291348

Chapter 4
The data supporting these research findings are openly available in 4TU. ResearchData at this link:

https://doi.org/10.4121/ce64c708-8347-4eb3-9d9c-91a2d5e0c96d

Chapter 5
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

Chapter 6
Data sharing is not applicable to this chapter as no datasets were generated or analyzed.

Chapter 7
Data sharing is not applicable to this chapter as no datasets were generated or analyzed.

Curriculum Vitæ

Education

January 2021 – April 2026

Doctor of Philosophy (PhD) in Architectural Engineering and Technology

– Department of Architectural Engineering and Technology, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft (TU Delft), The Netherlands

January 2018 – May 2020

Master of Science (MS) in Construction Engineering and Management

– Department of Construction Engineering and Management, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia

September 2012 – January 2018

Bachelor of Science (BS) in Civil Engineering with Second Class Honors

– Department of Civil and Environmental Engineering, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia

Academic Experience

Lecturer–Researcher A, Hanze University of Applied Sciences (Hanzehogeschool Groningen), Groningen, The Netherlands

December 2025 – present

– Part-time Researcher — NWO-funded project: Accelerating Building Renovation and Decarbonization through Data Integration (RenoDat)

PhD Researcher, Delft University of Technology

January 2021– April 2026

– Architectural Facades and Products Research Group,
Department of Architectural Engineering and Technology (AE+T),
Faculty of Architecture and the Built Environment

January 2023 – September 2024

– BK-PhD Council member from AE+T Department

– Faculty of Architecture and the Built Environment (A+BE)

June 2023 – December 2023

– Member of TUD Ethics Review Board, Human Research Ethics Committee (HREC)

Grader, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

September 2019 – December 2019

– Course title: CEM 530-Construction Engineering (Graduate Course)

– Responsibilities: Grading homework assignments and proctoring exams

September 2018 – December 2018 and January 2019-April 2019

– Course title: CEM 510-Project Planning and Scheduling (Graduate Course)

– Responsibilities: Grading homework assignments and proctoring exams

September 2017 – December 2017

– Course title: CE 318-Numerical and Statistical Methods in Civil Engineering (Undergraduate Course)

– Responsibilities: Grading homework assignments and quizzes

Professional Experience

7thJune – 24th August, 2017

– Trainee Civil Engineer, Maeen Engineering Consultancy, Jubail Industrial Area, Saudi Arabia

Awards and Honors

2018

Awarded the *Second Class Honors* in the BS degree from KFUPM

2017

Awarded the *First Rank Certificate* among all senior design projects in the Civil Engineering department during KFUPM Senior Design Expo 171

List of Publications

Journal Papers

Hamida, H., Prieto, A., Konstantinou, T., & Knaack, U. (2025). Supporting the Design and Development of Solar Cooling Integrated Façades: A Framework of Decisions, Information, and Stakeholder Involvement. *Sustainability*, 17(17), Article 7745. https://doi.org/10.3390/su17177745.

Hamida, H., Prieto, A., Beneito, L., Konstantinou, T., & Knaack, U. (2025). Design and Evaluation Strategies for Solar Cooling Integrated Façades: A case study in a Southern European office building. *Journal of Building Engineering*, 105, Article 112440. https://doi.org/10.1016/j.jobe.2025.112440

Hamida, H., Konstantinou, T., Prieto, A., & Klein, T. (2023). Solar Cooling Integrated Façades: Key perceived enabling factors and prospects of future applications. *Journal of Building Engineering*, 76, Article 107355. https://doi.org/10.1016/j.jobe.2023.107355

Conference Papers

Hamida, H., Prieto, A., Beneito, L., Konstantinou, T., & Knaack, U. (2024). Towards designing and evaluating solar cooling integrated façades in office buildings. In *Proceedings of EuroSun 2024* International Solar Energy Society. https://doi.org/10.18086/eurosun.2024.08.02.

Hamida, H., Konstantinou, T., Prieto, A., & Knaack, U. (2023). Solar Cooling Integrated Façades: Towards investigating product applicability. In S. Roaf, & W. Finlayson (Eds.), Measuring Net Zero: Carbon Accounting for Buildings and Communities (pp. 58-70). Ecohouse Initative Ltd.

Hamida, H., Konstantinou, T., Prieto, A., Klein, T., & Knaack, U. (2022). Solar Cooling Integrated Façades: Main Challenges in Product Development for Widespread Application. In *CLIMA 2022 - 14th REHVA HVAC World Congress: Eye on 2030, Towards digitalized, healthy, circular and energy efficient HVAC* Article 1294 TU Delft OPEN Publishing. https://doi.org/10.34641/clima.2022.353.

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Solar Active Facade Design and Development

A Framework for designing and developing building envelopes integrating solar cooling technologies

Hamza Basel Hamida

The global demand for cooling in the built environment is expected to increase in the near future due to factors such as climate change and rising temperatures. Solar cooling technologies offer a promising option to address the environmental challenges associated with the growing demand for space cooling. These technologies are based on producing conditioned air or chilled water using solar energy.

Building façades have significant potential for integrating solar cooling technologies and are increasingly evolving into multifunctional components that actively contribute to building energy systems. Through the integration of energy-related services, façades can support energy savings while enhancing occupant comfort. Despite this potential, the widespread application of solar cooling integrated façades remains limited. This is largely due to various technical, economic, and process-related challenges that hinder broader adoption. Providing clear guidance to relevant stakeholders to assess current levels of technology adoption and address existing challenges can play a key role in enabling successful implementation. Accordingly, the main research question of this dissertation is as follows:

How can the design and development of solar cooling integrated façades be guided to support their widespread application?

The research project aimed to provide a product design and development framework for solar cooling integrated façades to support their widespread application. Developing such a framework required several steps, including identifying key challenges and critical aspects to be considered; determining enabling factors and future application prospects; developing strategies to guide façade design and evaluation; and identifying, outlining, and validating key decisions, required information, and involved stakeholders.

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