Solar Cooling Integrated Façades
Towards investigating product applicability

Hamida, Hamza; Konstantinou, Thaleia; Prieto, Alejandro; Knaack, Ulrich

Publication date
2023

Document Version
Final published version

Published in
Measuring Net Zero

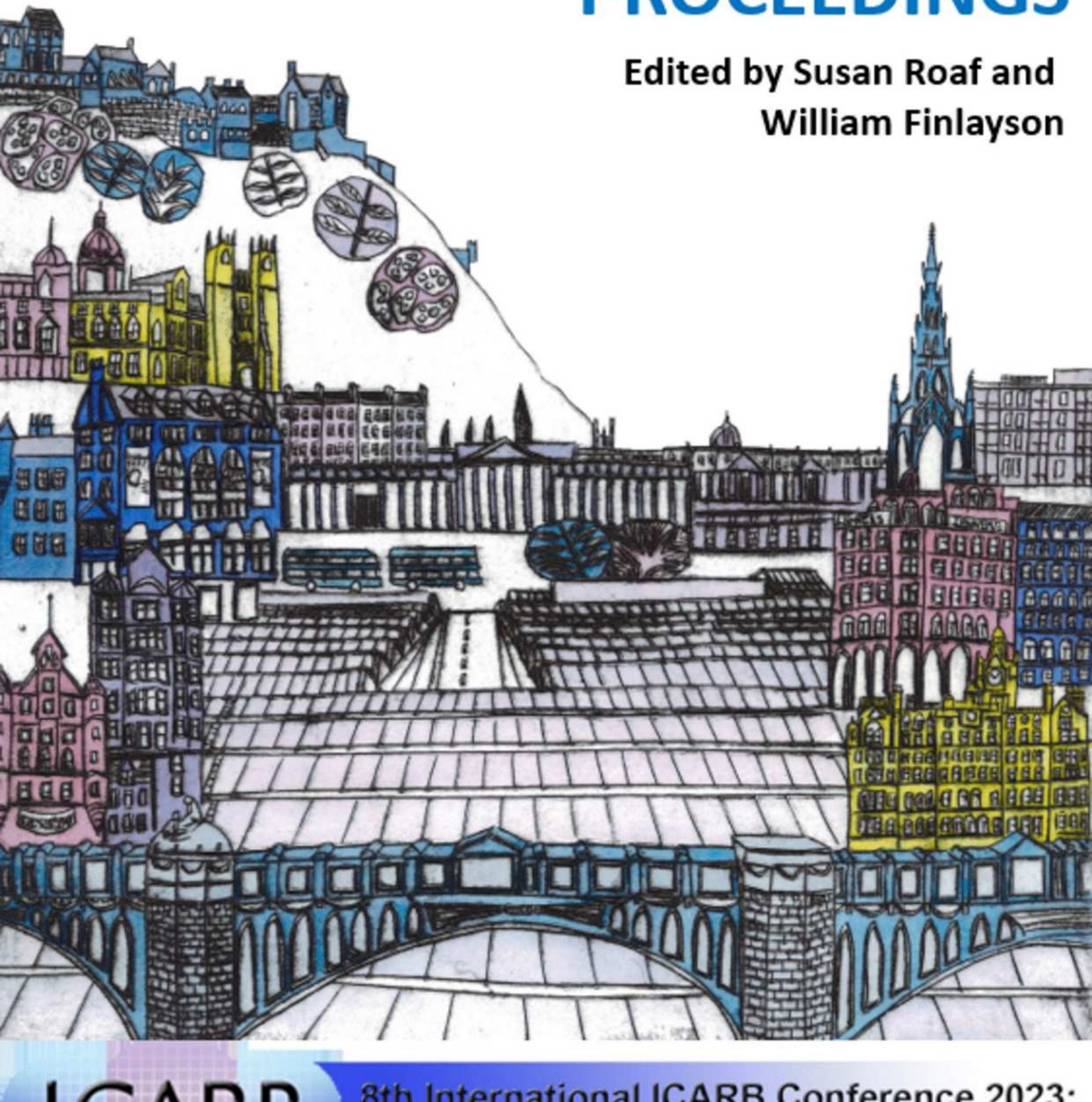
Citation (APA)
Hamida, H., Konstantinou, T., Prieto, A., & Knaack, U. (2023). Solar Cooling Integrated Façades: Towards investigating product applicability. In S. Roaf, & W. Finlayson (Eds.), *Measuring Net Zero: Carbon Accounting for Buildings and Communities* (pp. 58-70). Ecohouse Initative Ltd.

Measuring Net Zero:

CARBON ACCOUNTING FOR BUILDINGS AND COMMUNITIES

PROCEEDINGS

Edited by Susan Roaf and
William Finlayson



ICARB

8th International ICARB Conference 2023:
25th - 26th September 2023 Edinburgh

PROCEEDINGS

Of the 8th International ICARB Conference on Carbon Accounting

MEASURING NET ZERO:

CARBON ACCOUNTING FOR BUILDINGS AND COMMUNITIES

Held at The Edinburgh City Chambers

25th – 26th September 2023

www.icarb.org/2023-conference/

ISBN: 978-1-9161876-5-8

COPYRIGHT:

Solar Cooling Integrated Façades: Towards investigating product applicability

Hamza Hamida[1,*], Thaleia Konstantinou[1], Alejandro Prieto[2], and Ulrich Knaack[1]

[1] Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628BL Delft, The Netherlands
[1] School of Architecture, Diego Portales University, República Av. 180, 8370074, Santiago, Chile
[*] Corresponding author: H.B.Hamida@tudelft.nl

Abstract: The application of façade products integrating solar cooling technologies tends to be one of the promising options to be considered for challenges related to the increase in global demand for cooling in the built environment. Accordingly, the technological innovation of such products represent an essential task to be taken into account for meeting the future cooling demand in buildings. However, selecting the right technology and tackling technical and product-related aspects in the context of solar cooling can be challenging, since each technology is different from one another in terms of their working principles. Furthermore, developing such building products can be a complex endeavour, due to the involvement of various components. This paper aims to propose a conceptual approach for designing and developing façade products integrating solar cooling technologies. Proposing this approach required establishing a matrix of key attributes and criteria affecting technological selection through referring to identified key perceived enabling factors by expert interviews in an earlier stage of the study. The outcomes of this study outlined various attributes, such as product performance and efficiency as well as compactness and space usability, that can be used in product development of solar thermally and electrically driven systems, in order to ensure to support the widespread application.

Keywords: renewable, building envelope, component, design, attribute

1. Introduction

The global demand for cooling in the built environment has been estimated to dramatically increase in the coming years due to climate change as well as global population growth (Enteria and Sawachi, 2020; Sahin and Ayyildiz, 2020; Santamouris, 2016). These factors have a vital role in the widespread application of air-conditioning (AC) units in order to meet thermal comfort requirements. Accordingly, the increase of such AC units represents a critical environmental challenge since most of these cooling systems depend on the electricity generated in power plans (Santamouris, 2016). Therefore, it is essential to consider the application of cooling systems that rely on renewable sources of energy to minimize greenhouse gas (GHSs) emissions resulted from the energy consumed by AC units. The application of façade products integrating solar active cooling technologies tends to be one of the potential options to be considered for reducing the use of conventional air-conditioning systems. This is due to the fact that building façade surfaces are exposed to high solar radiation, providing an opportunity to harvest solar energy for driving cooling equipment (Prieto et al., 2017). Accordingly, the technological innovation of such products represent an essential task to be taken into account for meeting the future cooling demand in buildings. 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 considering the façade integration 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 et al., 2017). 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 the façade. Accordingly, in order to provide more flexibility while considering the two aforementioned definitions of SAFs and SCIFs by (Ochs et al., 2020) and (Prieto et al., 2017), respectively, a more practical definition that can be considered is as follows:

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

The design and development of façade products integrating solar cooling technologies involve including additional functions into the façade. The inclusion of such functions represents a secondary step when the indoor requirements cannot be met by other measures, such as shading systems and/or thermal insulations (Figure 1) (Prieto et al., 2017). Current approaches that have been used to evaluate the product applicability are based on the theoretical calculation of the Solar Fraction (SF) (Noaman et al., 2022; Prieto et al., 2018). The calculation involves dividing two main parameters. The cooling effect delivered by a solar cooling system to a particular indoor environment is divided by the cooling demand of that particular indoor environment. Hence, the system is considered to be able handle the cooling demand when SF value is 100% and more. It should be noted that the development of building products with the required technical attributes is essential to support the application of SCIFs in the construction industry (Hamida et al., 2022). However, since solar active cooling technologies have different forms related to the energy conversion and working principles through producing hot water through Solar Thermal Collectors (STC) (thermally-driven technologies) or producing electricity through Photovoltaic (PV) panels (electrically-driven technologies) (Alahmer and Ajib, 2020; Alsagri et al., 2020; He et al., 2019; Karellas et al., 2019; Neyer et al., 2018; Sarbu and Sebarchievici, 2016), selecting the right technology and tackling technical and product-related aspects in the context of SCIFs can be a challenging task. This is due to the fact that each technology, electrically-driven or thermally-driven, is different from one another in terms of different aspects, including their sizes and working principles. Also developing such products can be a complex endeavour, due to the involvement of various components. Accordingly, proposing an approach to investigate product applicability through involving matrix of key attributes to be considered for designing and developing SCIFs concepts can play a vital role in enabling the widespread application.

This paper aims to propose a conceptual approach for designing and developing façade products integrating solar cooling technologies, including both of solar thermally and electrically systems. Proposing this approach required having a matrix of key attributes and criteria affecting technological selection through referring to identified key perceived enabling factors by expert interviews in an earlier stage of the study (Hamida et al., 2023). The research materials and methods section (Section 2) presents the steps required to propose the aforementioned approach. Then section 3 provides a theoretical background about solar cooling technologies, whereas section 4 presents and discusses the proposed approach. Finally, the paper ends with the conclusion section (Section 5) that states future research scope.

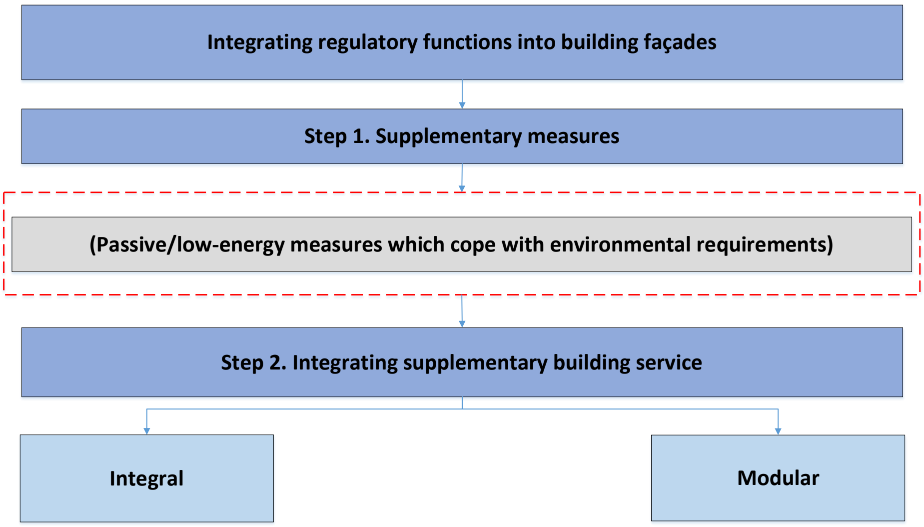


Figure 1. Decision-making process for façade integration of regulatory functions (Prieto et al., 2017)

2. Materials and Methods

To propose a conceptual approach for designing and developing façade products integrating solar cooling technologies, the research materials and methods are as follow:

1. Determining key attributes that can be considered in the process of designing and developing facade products integrating solar cooling technologies. The determination of these attributes was obtained through considering potential quantifiable key enabling factors that were identified by expert interviews in an earlier stage of the study (Hamida et al., 2023). These enabling factors were perceived to enable the widespread application of SCIFs. The scope and criteria considered for determining the attributes to be taken into account in the matrix consider that the attribute can potentially be measured during the design phase, such as dynamic energy simulations and life cycle cost analysis (LCC).
2. Determining criteria affecting the technological selection of solar cooling technologies. The determination of these criteria was obtained from aspects identified to affect the perception of the status of current technologies that were obtained from the expert interviews (Hamida et al., 2023).
3. Proposing a conceptual approach to investigate product applicability through combining the outcomes of the aforementioned steps. Proposing the approach involves a sequential steps covering a matrix of key measurable attributes to be considered for designing and developing, as well as the criteria affecting technological selection.

3. Theoretical Background

As indicated in Figure 2, there are different types of solar active thermally and electrically-driven solar cooling technologies (Alsagri et al., 2020).

3.1. Thermally-Driven Technologies

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

- Generators of sorption cooling systems are powered by the thermal energy.
- Thermal energy is converted to mechanical energy which is therefore is used for producing cooling effects.

Table 1 summarizes technological options for the thermal solar sorption cooling that consist of mature components (Mugnier et al., 2017). The solar collectors are the fundamental components needed for all installations of solar thermal energy systems. Their main function is to capture and convert sun radiations 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 in the market. The flat plate collector, evacuated tube collector, and parabolic through collector are the main types of collectors. The utilization of different solar collectors based on temperature variations and their applications is illustrated Figure 3 (Alahmer and Ajib, 2020).

Solar thermal cooling technologies can be categorized into closed sorption cycles, open sorption cycles, and the 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).

Table 1. Technological options for the thermal solar sorption cooling (Mugnier et al., 2017).

Type of Temperature Application	Type of Collector	Cooling Device
Low Temperature **(<100°C)**	**• Air collectors** **• Flat plate collectors** **• Evacuated tube collectors**	**• Absorption chiller (Single-effect)** **• Adsorption chiller** **• Solid desiccant cooling** **• Liquid desiccant cooling**
High Temperature **(>100°C)**	**• Compound parabolic collectors** **• Single axis tracking concentrating collectors**	**• Absorption chiller (Double or triple effect)** **• Low-temperature refrigeration**

Closed sorption cycles have two main divisions, according to the sorption material, which are the liquid sorption and solid sorption. The absorption is referred to liquid sorption whereas the adsorption is referred to 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 and Ajib, 2020). It requires dissolving liquids or gases in the bulk of a sorbent in one process 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 a combination with adsorption (He et al., 2019). It is a solid sorption process that involve an 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 and 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 adsorption cooling equipment process (He et al., 2019).

Open sorption cycles are commonly known as the desiccant cooling due to the use of sorbent for humidifying air (Sarbu and 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 and Ajib, 2020). Solid desiccant cooling systems use rotary adsorption wheels as sorption materials, such as the 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 and Sebarchievici, 2016). The achievement of 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 a dehumidifiers and a 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 and 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 resulted by pistons that change both of temperature and pressure of gas. However, this technology has practical limitations related to the 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.

3.2. Electrically-Driven Technologies

The solar energy associated with such technologies are considered as a Photovoltaic (PV)-based systems, which involves an initial conversion of solar energy into electrical energy that is then used to produce cooling effect that is similar to conventional systems, or through thermoelectric processes (Sarbu and Sebarchievici, 2016). The utilization of PV for cooling through coupling it with conventional vapor-compression units is considered to provide advantages related construction simplicity and high efficacy (Sarbu and Sebarchievici, 2016). An example for such electric systems is the solar electric chillers that comprises 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 term Building-Attached Photovoltaics (BAPV) has been defined when PV modules are mounted directly on a building envelop. On the other hand, Building-Integrated Photovoltaics (BIPV) has been considered in case when conventional building materials are replaced by PV modules (Singh et al., 2021). Figure 4 summarizes the technologies and applications of BAPV and PIPV, including the façade. The consideration of vapor-compression air-conditioning equipment was identified as a relevant option due to the decrease in PV prices (Montagnino, 2017).

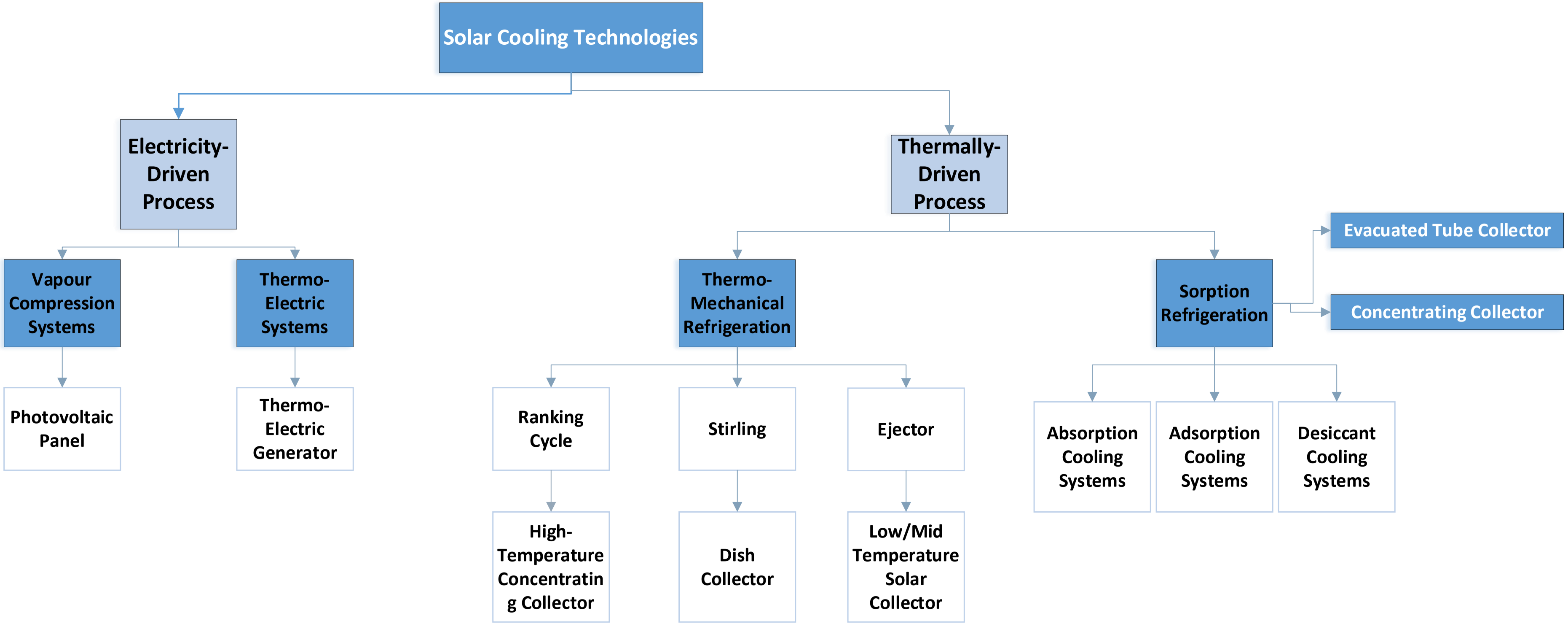


Figure 2. Solar Cooling Technologies (Alsagri et al., 2020)

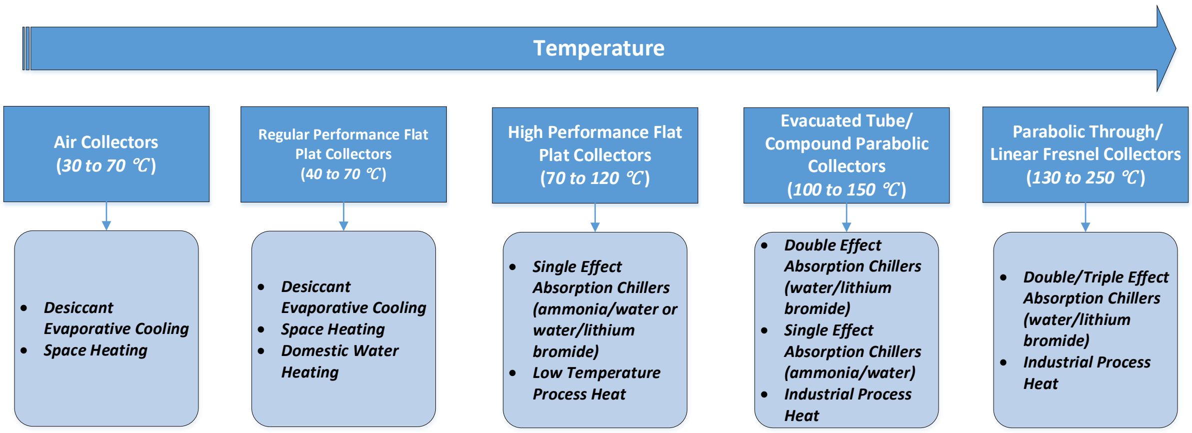


Figure 3. Use of solar collectors based on temperature variations and their applications (Alahmer and Ajib, 2020)

Solar thermoelectric systems involve a conversion of solar radiations 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 that however have the ability to produce high electric currents. It provides benefits related to lowering the operational level of 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 generator run (Sarbu and Sebarchievici, 2016).

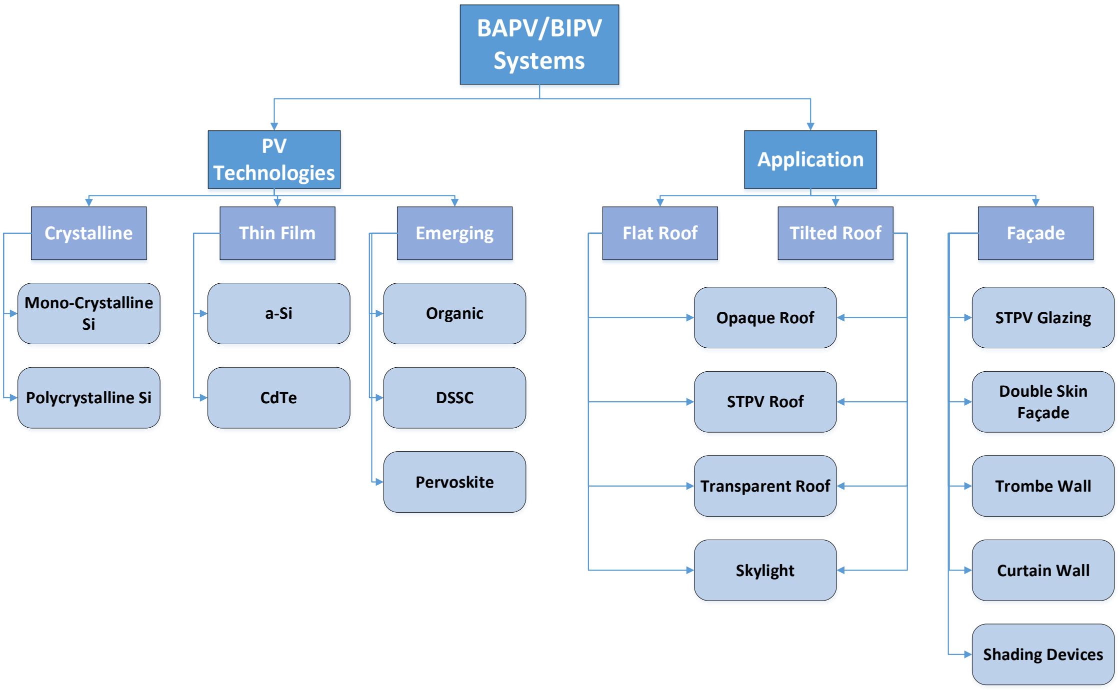


Figure 4. Technologies and applications of BAPV and BIPV (Singh et al, 2021)

4. Towards Investigating Product Applicability

In order to understand key aspects enabling the product applicability of SCIFs in the construction industry, a total of 23 interviews were conducted with various experts in the European building industry (Hamida et al., 2023). The interviews were conducted between May and September 2022, and involved experts from different fields. The fields included façade design and construction, application/façade integration of solar (or solar cooling) technologies, and research and development in multifunctional façades. The outcomes of these interviews have been adopted in this paper to propose the conceptual approach, which included determining key attributes and criteria affecting technological selection. The findings included key factors enabling the product applicability which are related to the technical & product (T&P)-related, financial (F)-related, as well as process and stakeholder (P&S) aspects. These findings were obtained from a deductive analysis focusing on the three aforementioned aspects. The results also included findings related perceptions of the status of current technologies, which were obtained from an inductive data analysis. Taken into account the scope and criteria considered for determining attributes involved in designing and developing SCIFs concept (section 2), Table 3 summarizes the attributes identified from the key enabling factors. Regarding the determination of criteria affecting the technological selection of solar cooling technologies, the interviews outcomes revealed various perceived aspects influencing the perception of the status of current technologies, for both of electrically-driven as well as thermally-driven. Some of these aspects were also related to the enabling factors identified enabling factors, as indicted in Table 3.

Table 3. Matrix of key attributes and criteria affecting technological selection.

Item	Attribute as a Key Enabling Factor			Selection Criteria as an Aspect Influencing the Perception of the Status of Technologies	
	Related Aspect			Related Technology	
	T&P	F	P&S	Electrically-Driven	Thermally-Driven
Product performance and efficiency	×	×	×	×	×
Compactness and Space Usability (Size)	×	×	×	×	×
Meeting user comfort requirements	×	-	×	-	-
Durability and long life span	×	-	×	-	×

Table 3. Matrix of key attributes and criteria affecting technological selection (cont.).

Item		Attribute as a Key Enabling Factor			Selection Criteria as an Aspect Influencing the Perception of the Status of Technologies	
		Related Aspect			Related Technology	
		T&P	F	P&S	Electrically-Driven	Thermally-Driven
Financial and life-cycle costs	Project Budget	-	×	×	-	-
	Initial Cost	-	-	-	×	-
	Government Subsidies	-	×	×	-	-
	Taxes and Fees	-	×	×	-	-
	High Energy Prices	-	×	×	-	-
	Operating/Ownership Cost	-	×	×	-	-
	Return on Investment (Payback Period)	-	×	×	-	-
	Ability to Compete Traditional Systems	-	×	×	-	-

Table 3. Matrix of key attributes and criteria affecting technological selection (cont.).

Item	Attribute as a Key Enabling Factor			Selection Criteria as an Aspect Influencing the Perception of the Status of Technologies	
	Related Aspect			Related Technology	
	T&P	F	P&S	Electrically-Driven	Thermally-Driven
Aesthetical Acceptability	×	-	×	×	-
Applicability at Different Climate Conditions (Adaptability in Multiple Cases)	×	-	×	-	-
Plug and Play (Assembly and Connections)	×	×	×	×	×
Waste and Product End of Life	-	-	×	×	×
Fire Resistance (Safety)	×	-	×	×	-
Maturity and Advancement (Proven Technology)	×	-	×	×	×
Periodic Maintenance	-	-	-	×	×
Working Principle	-	-	-	×	×

Based on the established matrix of key attributes and criteria affecting technological selection, a conceptual approach to investigate product applicability is proposed. As indicated in Figure 5, investigating the product applicability requires determining particular technologies. Selecting the technology can involve different criteria such as the availability, size, and maturity. After that, design and development of façade concepts can be carried out through considering the attributes, which are related to the three main aspects. Designing and developing façade concepts should take into account particular boundary conditions, such as the following:

- Focusing on façade products to be used in a particular building vintage, such as considering new building construction projects or existing buildings.
- Considering a particular building typology, such as office buildings, due to the considerable amount of heat gains resulted from the building occupants, lighting systems, and office equipment (Konstantinou and Prieto, 2018).
- Focusing on premises located in particular warm climate conditions (considering the Koppen–Geiger climate zones), where the use of mechanical equipment is still needed.

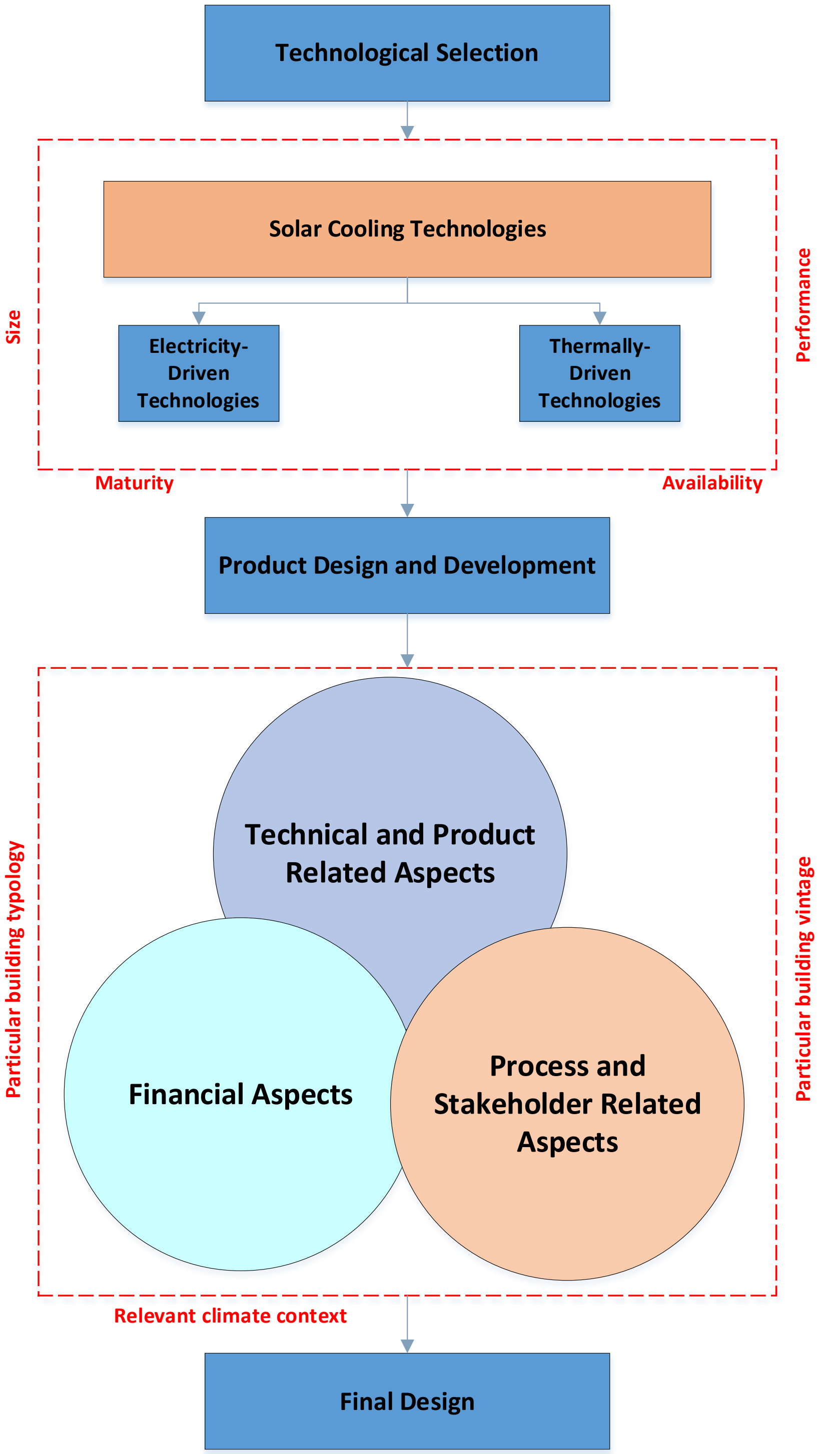


Figure 5. A conceptual approach to investigate product applicability

It should be noted that the proposed approach is considered to a secondary step after taking into account the supplementary measures needed to minimize cooling demands in buildings, as indicated in Figure 1. The approach is still also in the conceptual level and represents a basic foundation for further developments. This require a movement towards a more practical and detailed level, such as considering operational level as well as process flow charts (Rahman Abdul Rahim and Shariff Nabi Baksh, 2003).

5. Conclusion

The application of façade products integrating solar cooling technologies tends to be one of the promising options to be considered for challenges related to the increase in global demand for cooling in the built environment. Accordingly, the technological innovation of such products represent an essential task to be taken into account for meeting the future cooling demand in buildings. However, selecting the right technology and tackling technical and product-related aspects in the context of solar cooling is challenging, since each technology is different from one another in terms of their working principles. Furthermore, developing such building products can be a complex endeavour, due to the involvement of various components. This paper aimed to propose a conceptual approach for designing and developing façade products integrating solar cooling technologies, including both of solar thermally and electrically systems. Proposing this approach required establishing a matrix of key attributes and criteria affecting technological selection through referring to identified key perceived enabling factors by expert interviews in an earlier stage of the study. The outcomes of this study outlined various attributes, such as product performance and efficiency as well as compactness and space usability, that can be used in product development of solar thermally and electrically driven systems, in order to ensure to support the widespread application. Future work should take into account transforming the presented conceptual approach into a product development framework combining various technical, financial, and stakeholder related aspects while considering investigating the applicability of particular technologies in relevant contexts.

6. References

Alahmer, A., Ajib, S., 2020. Solar cooling technologies: State of art and perspectives. Energy Convers. Manag. 214, 112896.

Alsagri, A.S., Alrobaian, A.A., Almohaimeed, S.A., 2020. Concentrating solar collectors in absorption and adsorption cooling cycles : An overview. Energy Convers. Manag. 223, 113420.

Enteria, N., Sawachi, T., 2020. Air Conditioning and Ventilation Systems in Hot and Humid Regions. In: Enteria, N., Awbi, H., Santamouris, M. (Eds.), Building in Hot and Humid Regions: Historical Perspective and Technological Advances. Springer Nature Singapore Pte Ltd., pp. 205–219.

Hamida, H., Konstantinou, T., Prieto, A., Klein, T., 2023. Solar Cooling Integrated Façades: Key perceived enabling factors and prospects of future applications. J. Build. Eng. 76, 107355.

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: The 14th REHVA HVAC World Congress. Rotterdam, the Netherlands.

He, W., Zhang, Xinghui, Zhang, Xingxing, 2019. Solar Heating, Cooling and Power Generation—Current Profiles and Future Potentials. In: Zhao, X., Ma, X. (Eds.), Advanced Energy Efficiency Technologies for Solar Heating, Cooling and Power Generation. Springer Nature Switzerland AG, pp. 31–78.

Karellas, S., Roumpedakis, T.C., Tzouganatos, N., Braimakis, K., 2019. Solar Cooling Technologies. CRC Press.

Konstantinou, T., Prieto, A., 2018. Environmental Design Principles for the Building Envelope and More _: Passive and Active Measures. In: Konstantinou, T., Ćuković, N., Zbašnik, M. (Eds.), Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design. TU Delft Open, pp. 147–180.

Montagnino, F.M., 2017. Solar cooling technologies. Design , application and performance of existing projects. Sol. Energy 154, 144–157.

Mugnier, D., Neyer, D., White, S.D., 2017. The Solar Cooling Design Guide: Case Studies of Successful Solar Air Conditioning Design. Ernst & Sohn.

Neyer, D., Mugnier, D., Thür, A., Fedrizzi, R., Vicente Quiles, P.G., 2018. Solar Heating and Cooling & Solar Air-

Conditioning. IEA Solar Heating and Cooling Technology Collaboration Programme.

Noaman, D.S., Moneer, S.A., Megahed, N.A., El-ghafour, S.A., 2022. Integration of active solar cooling technology into passively designed facade in hot climates. J. Build. Eng. 56, 104658.

Ochs, F., Magni, M., Venturi, E., de Vries, S., Hauer, M., Bonato, P., Taveres- Cachat, E., Venus, D., Geisler-Moroder, D., Abdelnour, N., 2020. Design Guidelines: Deliverable DC. 3, IEA SHC TASK 56 | Building Integrated Solar Envelope Systems for HVAC and Lighting.

Prieto, A., Knaack, U., Auer, T., Klein, T., 2017. Solar Coolfacades: Framework for the Integration of Solar Cooling Technologies in the Building Envelope. Energy 137, 353–368.

Prieto, A., Knaack, U., Auer, T., Klein, T., 2018. Feasibility study of self-sufficient solar cooling fa ade applications in different warm regions. Energies 11, 121693718.

Rahman Abdul Rahim, A., Shariff Nabi Baksh, M., 2003. The need for a new product development framework for engineer-to-order products. Eur. J. Innov. Manag. 6, 182–196.

Sahin, G., Ayyildiz, F.V., 2020. Chapter 14: Climate Change and Energy Policies: European Union-Scale Approach to a Global Problem. In: Qudrat-Ullah, H., Asif, M. (Eds.), Dynamics of Energy, Environment and Economy: A Sustainability Perspective. Springer Nature Switzerland AG, pp. 295 – 320.

Santamouris, M., 2016. Cooling the buildings – past, present and future. Energy Build. 128, 617–638.

Sarbu, I., Sebarchievici, C., 2016. Solar Heating and Cooling Systems: Fundamentals, Experiments and Applications. Academic Press.

Singh, D., Chaudhary, R., Karthick, A., 2021. Review on the progress of building-applied integrated photovoltaic system. Environ. Sci. Pollut. Res. 28, 47689–47724.

Copyright Notice