Solar Cooling Integrated Façades: Main Challenges in Product Development for Widespread Application

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Abstract. The global attention to solar cooling systems has increased during 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 the sun radiation. However, there are different challenges affecting the widespread application of solar cooling integrated façades. This paper aims to identify and categorize these challenges through conducting a comprehensive literature review. A literature review was conducted on scientific papers published in conference proceeding 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 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 widespread application in the built environment.

Keywords. Solar cooling, façade, challenges, widespread, product development
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1. Introduction

The global need for space cooling in buildings is expected to increase in the coming future for various factors, such as climate change and the associated temperature increase (1,2). Other factors comprise the population and economic growth with the subsequent increase in the quality of life, and the affordability of air-conditioning units (2,3). It has been demonstrated that the global energy demand for the building space cooling may increase by 50% in 2030 if no considerable improvements take place in efficiency of cooling equipment (4).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 (5). 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 (6). It employs cooling strategies such as the window-to-wall ratio, insulation and shading devices (7,8). The potential impact for implementing such strategies has been found to be 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 the energy consumption, since their effectiveness is influenced by the climatic harshness and other various building parameters (8). Furthermore, their potential is expected to decrease due to the increase in ambient temperatures resulted from the global warming (2).

Therefore, active cooling, representing a secondary approach, is still needed in many conditions, especially in warm regions such as hot and humid climates (3,9). Such approach employs complementary mechanical cooling systems to meet required cooling demands in buildings (6). According to Neyer *et al* (10), the estimated total global room air-conditioning units sold in 2016 exceeded 100 million unit. The increase in the use of such active cooling systems depends on electricity consumption, which therefore affects peak energy demand negatively due to their dependency on power plants (2).

The production of 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 (11,12). 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 friendly to the environment and have no ozone depletion effects (12). The concept of solar cooling technologies, which started in the seventies, is based on generating conditioned air or chilled water from solar energy (13). The technologies can be in a form of producing hot water through Solar Thermal Collectors (STC) or producing electricity through Photovoltaic (PV) panels (14). 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 (10,13–17). Some of these technologies are mature enough for building application, such as the solar absorption cooling technologies (15,18).

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 ability to provide external surfaces exposed to solar radiation (19). 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 (20–22). It should be noted that such integration represent 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 (22,23). The integration can be achieved through two different design approaches, namely integral or modular paths (**Figure 1**)(23). The functions and components associated 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 is required 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 (24).

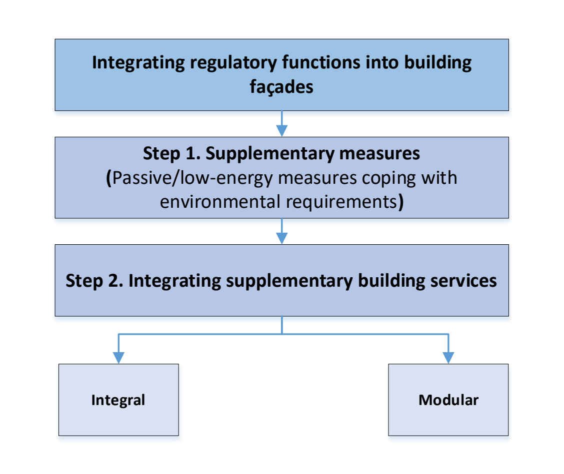
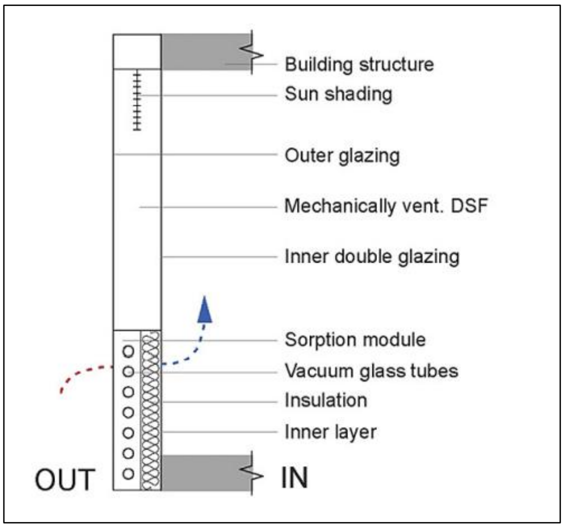


Fig. 1 – Decision-making process for integrating regulatory functions into building façades (23)

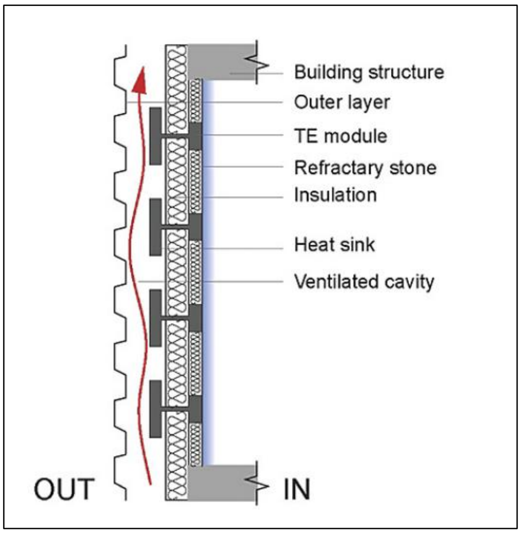
When having an insight into the consideration of solar cooling technologies, solar cooling integrated façades have been previously defined as *"façade systems which comprise all necessary equipment to self-sufficiently provide solar driven cooling to a particular indoor environment"*, which indicates that the necessary equipment needed at least for cooling generation and distribution should be integrated by façade systems (23). **Figure 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 paper aims to identify and categorize those challenges through conducting a comprehensive literature review in order to propose main potential dimensions that should be tackled and integrated for supporting the product widespread application of solar cooling integrated façades.

2. Research Approach and Methods

A literature review was conducted on scientific papers published in conference proceeding and scientific journals. The review includes a literature search, using the concepts indicated in **Table 1**, through considering two databases, namely Scopus and Web of Science. The assessment of a particular article's relevance involved different criteria, that include the scope of the journal and the article novelty (from 2015 to 2021). Such criteria were set in order to narrow down the amount of documents to be reviewed and also ensure 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



(a) Solar-thermal sorption cooling façade



(b) Solar solid-based cooling thermoelectric facades

Fig. 2 – Concepts of solar cooling integrated facades (23)

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 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 conducting experiments or preforming 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 were found to provide no information regarding the issues affecting the widespread of solar technologies in the built environment. Based on that, total of thirteen relevant references were found to be provide reliable information regarding the main challenges affecting the widespread of solar cooling integrated façades. All of the information obtained from the 13 articles are presented and discussed in section 3.

3. Results and Discussion

The results obtained from the literature search 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 of having an insight to them. 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 the technology type.
- Specific product-related challenges precisely linked to different solar cooling technologies, which varies from one technology to another.

Regarding the general challenges, a categorization to them was adapted from (25). It includes total of six main groups, namely financial, product-related, knowledge, information, processes, and interest. **Table 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 due to the fact that various solar cooling

Tab. 1 - Concepts included in the literature search

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

technologies have different barriers and attributes related to the performance and sizes. These product-related challenges associated with different solar cooling technologies were analysed by Prieto *et al.* (9).

Tab. 2 - Challenges affecting product development and widespread application of solar technologies integrated façades.

Category	Issues related to the such challenges	References
Product-Related Challenges	Performance and efficiency	(25–31)
	Technical considerations (complexities, space availability, and interrupting other building services)	(25,27,28,32)
	Availability of products appropriate for quality integration	(25)
	Maintenance and Durability	(25,26,33)
	Aesthetics	(25,26,28)
Financial Challenges	High Costs (Initial, operation, and maintenance)	(25,27,28,30,32–35)
	Long payback period	(25,28,34)
	Current energy prices are low	(25)
	Lack of incentives/subsidies to execute such technologies	(18,25,30,32)
Challenges Related to the Knowledge	Lack of technical knowledge and experience of architects/engineers about technical aspects related to solar technologies	(25,28)
	End users' lack of knowledge associated with operating the systems	(25,35)
	Required workforce experience for installing the products	(25,32,35)

Tab. 2 - Challenges affecting product development and widespread application of solar technologies integrated façades (cont.).

Category	Issues related to the such challenges	References
Challenges Related to the Information	Need for documenting the properties of technologies appropriately	(25)
	Lack of standards/guidelines related to the technology, such as the ones related to building integration	(25,28)
	Uncertainties associated with changes in legal legislations	(28)
Challenges Related to the Design and Construction Processes	Need to consider integration during early stages of the project (considering close collaboration among various disciplines)	(25,28)
	Need for design-oriented tools so that (A/E)s are involved in technical issues during early design stages	(25)
	Ability to provide varieties forms of products for attracting customers	(28)
Challenges Related to the Interest	Lack of interest in the field of solar designs by designers, developers, and clients	(25)

Having such various forms of challenges illustrates the complexity for 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 for supporting the widespread application of a particular technology. Accordingly, to minimize the problem complexity, the study suggested three main potential dimensions that should be tackled and integrated when supporting the widespread application of the façade integration a particular solar cooling technology (**Figure 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 widespread application in the built environment.

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 to the construction market. Technical challenges related to current products, such as technical complexities and aesthetics, result in challenges related to the interest as well as financial aspects. The resulted 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 lack of considering the integration during early design stages of buildings.

Accordingly, technical developments of building products needs 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 the specific aspects related to selected cooling technology (9). This is due to the fact that such aspects varies from one technology to another. In addition to that, understanding the definition of products and how it is linked to building façades is needed for tackling such aspects. Products can be defined as tangible and quantifiable goods that are produced for customers, which can be end items in themselves or component items (36,37). Additionally, they do have a scope that indicate their features and functions (37). 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 (38). Since products can be end items in themselves or component items (37), façades have been identified to have different product levels that ranges from the material (base ingredients) to the building (24). Therefore, it essential to have a well-defined product scope of functionalities and level for an integration of particular solar cooling technology into the building façade.

3.2 Financial Aspects

High initial costs of solar cooling systems and the low energy prices can result in challenges related to the 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 market. It should be noted that not only the initial cost is the only parameter to be considered. Other parameters are should be included, which may include the maintenance cost as well as potentials for energy savings. Accordingly, considering the life cycle cost can aid in investigating cost-effectiveness for an integration of particular solar cooling technology into the building façade.

3.3 Process and Stakeholder Related Aspects

Products are developed through having a process consisting of a sequential set of activities aiming to cause particular end results (37). Having an insight into façade products, they were traditionally identified to have various processes contributing their design and development in built environment, which start from the system design till the assembly, use, and end of life. Moreover, the role of different stakeholders have been identified in façade processes, which include suppliers, façade builders, general contractors, architects, consultants, and clients (24). 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 an achievable construction and assure the overall façade performance. They also work on integrating various subcomponents which require putting efforts on planning and logistical arrangements. Such stakeholder take into account the necessity of establishing relationships with architects and general contractors.

Therefore, it is essential to shed the light on processes and stakeholders, when considering an integration of particular solar cooling technology into the building façade. Tackling such dimension can consider identifying the potential integrated roles and responsibilities of various stakeholders during the product life cycle. Such identification can contribute to address issues affecting the interest and provide stakeholders with required knowledge of information supporting the product development and use.

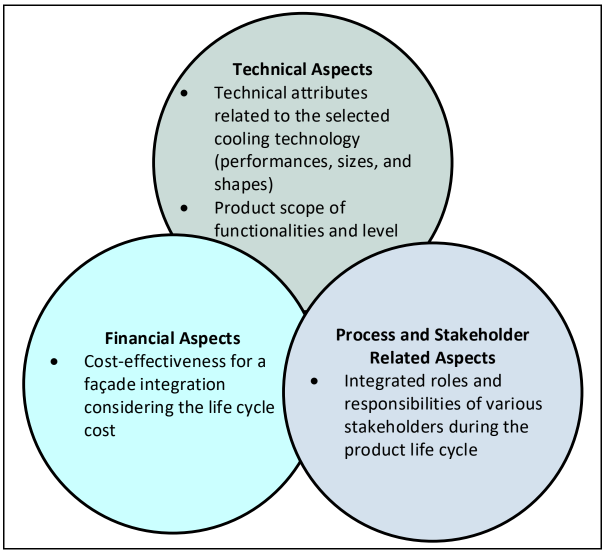


Fig. 3 – Proposed main potential dimensions to be tackled for supporting the application of a façade integration of solar cooling technologies

4. Conclusion

This paper 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 the type of technology. The second from covered specific product-related challenges precisely linked to different solar cooling technologies, which varies from one technology to another. Taken into account that having various forms of challenges illustrate 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 widespread application in the built environment. Based on the identified three main dimensions to be tacked, future work should consider investigating a further breakdown of the aspects to a 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 framework would tackle and combine the three main aspects.

5. Acknowledgement

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Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.