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Possibilities and Constraints for the Widespread Application of Solar Cooling Integrated Façades

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Abstract
Cooling demands in buildings have drastically increased in recent decades and this trend is set to continue into the near future, due to increasing standards of living and global climate change, among the most relevant factors. Besides energy consumption, the use of refrigerants in common vapour compression cooling technologies is a source of concern because of their environmental impact. Hence, there is a need to decrease cooling demands in buildings while looking for alternative clean technologies to take over the remaining loads. Solar cooling systems have gained increased attention in recent years, for their potential to lower indoor temperatures using renewable energy under environmentally friendly cooling processes. Nonetheless, their potential for building integration has not been fully explored, with the exception of scattered prototypes and concepts. This paper aims to address these knowledge gaps by presenting the results of the PhD research project 'COOLFAÇADE: Architectural integration of solar cooling technologies in the building envelope'. The research project explored the possibilities and constraints for architectural integration of solar cooling strategies in façades, in order to support the design of climate responsive architectural products for office buildings, driven by renewable energy sources. This paper explores different aspects related to façade integration and solar cooling technologies, in order to provide a comprehensive understanding of current possibilities for façade integration, while drafting recommendations based on identified barriers and bottlenecks at different levels.

Keywords
solar cooling, integrated façades, façade design, renewables, barriers

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1 INTRODUCTION

Energy demands for cooling have increased drastically in recent decades, due to societal and economic factors such as higher standards of living and affordability of air conditioning, as well as environmental aspects such as temperature rise in cities in what is known as urban heat islands, and global climate change (Santamouris, 2016). Total energy projections for the coming decades show that energy consumption will keep rising, mostly driven by fast-growing emerging economies (BP, 2016; DOE/EIA, 2016), and cooling energy demands are expected to follow this trend (Jochem & Schade, 2009; OECD/IEA, 2015). As an example, yearly sales of room air conditioning units are expected to grow by 10-15%, going from 100 million worldwide in 2014, to an expected 1.6 billion by 2050 (Montagnino, 2017).

The first course of action in tackling this situation should always aim to reduce energy consumption through saving measures and the application of passive design strategies in buildings. Nonetheless, this is often not enough to avoid mechanical equipment altogether, particularly in the case of office buildings in warm climates, which are characterised by particularly high cooling demands (Qi, 2006). In this regard, solar cooling technologies have been increasingly explored, as an environmentally friendly alternative to harmful refrigerants used within vapour compression systems, while also being driven by solar - thus, renewable - energy. The principles behind some of these technologies have been researched for over a century, reaching mature solutions and components, and being recognised as promising alternatives to commonly-used air-conditioning units (Goetzler, Zogg, Young, & Johnson, 2014). Nonetheless, application in buildings remains mostly limited to demonstration projects and pilot experiences (Balaras et al., 2007; Henning & Döll, 2012).

Recently, façade integrated concepts have been explored as ways to promote widespread application throughout the development of multi-functional building components (Avesani, 2016; Ibañez-Puy, Martín-Gómez, Bermejo-Busto, Sacristán, & Ibañez-Puy, 2018; Prieto, Knaack, Auer, & Klein, 2017a; Xu & Van Dessel, 2008). However, while these are regarded as relevant and promising standalone concepts, further research is still needed to assess the integration potential of diverse solar cooling technologies, and identify any barriers that must be overcome, in order to promote the widespread application of solar cooling components in the built environment.

This paper aims to address these knowledge gaps by presenting the results of the PhD research project 'COOLFAÇADE: Architectural integration of solar technologies in the building envelope', carried out by the main author under the supervision of the co-authors. As the title suggests, the research project explored the possibilities and constraints for the architectural integration of solar cooling strategies in façades, in order to support the design of climate responsive architectural products for office buildings, without compromising the thermal comfort of users. The underlying hypothesis was that self-sufficient solar cooling integrated façades may be a promising alternative to conventional centralised air-conditioning systems widely used in office buildings in warm climates.

The research explored different aspects relating to façade integration and solar cooling technologies, in order to provide a comprehensive understanding of current possibilities for the development of architectural products. Hence, different types of barriers were identified, corresponding to distinct aspects that need to be considered in the development of integrated concepts. These specific findings have been presented separately and discussed in detail in previous publications. So, this article presents a collated summary of all results, focusing on the general discussion of overall possibilities after accounting for key aspects for further development, and drafting recommendations based on the identified constraints at different levels.

2 RESEARCH STRATEGY AND METHODS

The evaluation of the façade integration potential of solar cooling technologies was carried out considering two main families of parameters, targeting particular key aspects for the development and application of integrated façade concepts. Therefore, selected solar cooling technologies were assessed in terms of (a) architectural requirements for the integration of building services within the façade design and development process, and (b) the potential climate feasibility of self-sufficient integrated concepts, matching current technical possibilities with cooling requirements from several climates under an holistic approach to climate responsive façade design. The basic strategy behind the research project is summarised in Fig. 1.

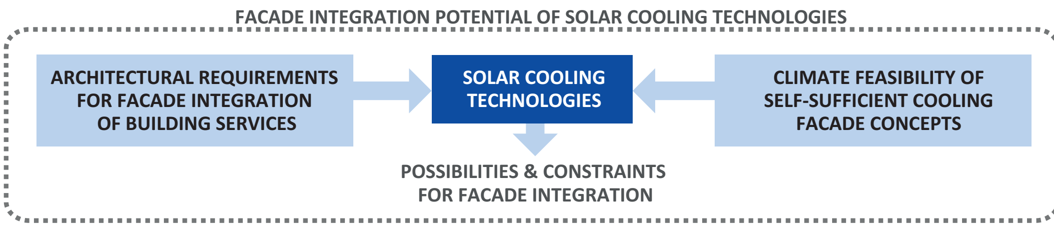

FIG. 1 Research strategy and parameters for the assessment

On the one hand, the response of the technologies to architectural requirements for façade integration was assessed qualitatively, based on a comprehensive review of the key aspects of each technology and their potential to overcome the main identified barriers for façade integration of building services. These barriers were previously identified and discussed by means of a survey addressed to experienced professionals in the fields of façade design and construction. The survey aimed to identify the main perceived problems relating to the façade integration of building services (Prieto, Klein, Knaack, & Auer, 2017), and the integration of solar collection technologies (photovoltaic panels and solar thermal collectors) (Prieto, Knaack, Auer, & Klein, 2017b), discussing specific barriers separately. The responses from the survey were interpreted using qualitative content analysis techniques and quantitative descriptive statistics, defining barriers relating to the design and construction process, as well as barriers relating to the products themselves.

On the other hand, the feasibility of applying integrated façade concepts in several climates was evaluated through numerical calculations based on climate data and building scenarios simulated with specialised software (EnergyPlus). The goal of this assessment was to check the theoretical feasibility of solar cooling façades as self-sufficient cooling units, matching solar availability at different orientations and locations, with the cooling requirements of a base scenario that consisted of a single office room in different climate contexts (Prieto, Knaack, Auer, & Klein, 2018). These scenarios considered several passive cooling strategies, such as shading, window-to-wall ratio, glazing type, and ventilation, as the first step of the assessment, obtaining optimised base scenarios for each orientation before integrating solar cooling technologies (Prieto, Knaack, Klein, & Auer, 2018).

The assessment focused on five main solar electric and solar thermal technologies, based on widespread categorisations: thermoelectric, absorption, adsorption, solid desiccant, and liquid desiccant cooling (Henning, 2007; Prieto, Knaack, et al., 2017a). Given that cooling needs are the main driver of the research, the assessment focused exclusively on warm climates, ranging from temperate to extreme desertic and tropical environments. Furthermore, discussion about design possibilities is constrained to the façade, leaving potential for further optimisation of cooling demands throughout building level strategies, which is outside the scope of the research project.

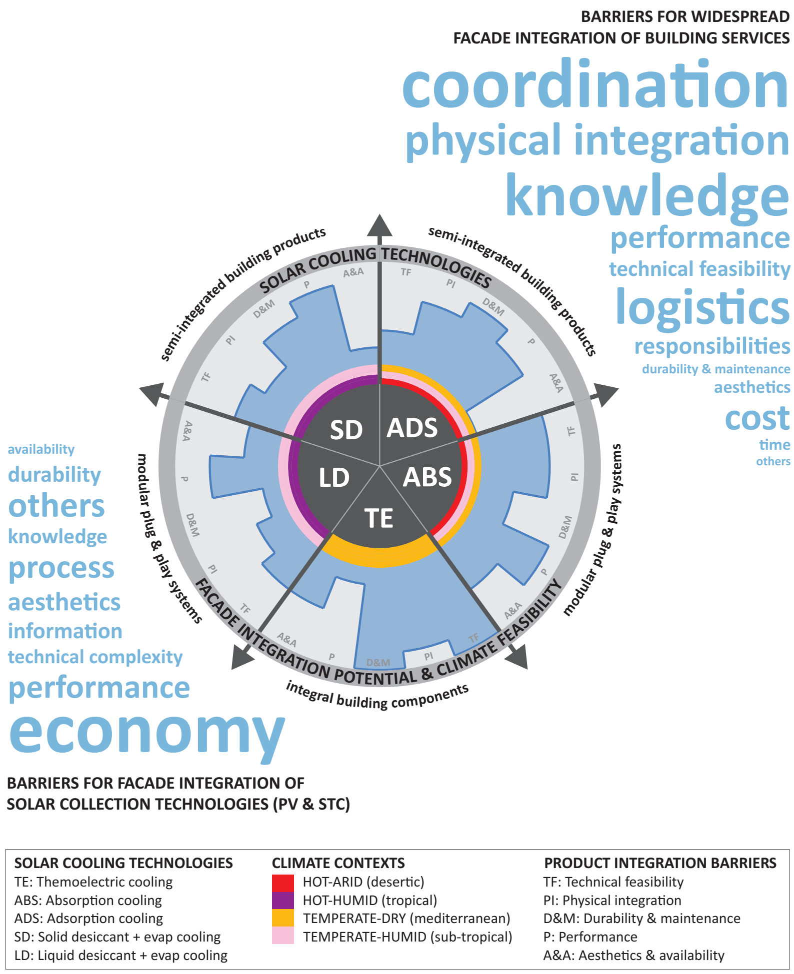

FIG. 2 Chart of current possibilities and identified barriers for the development of solar cooling integrated façades

3 RESULTS AND DISCUSSION

The driving force behind the research project was the intention to test the limits of solar cooling integration in façades, showcasing current possibilities while identifying technical constraints and barriers to be overcome to achieve a widespread application of integrated façade concepts. In response to this task, an overview of the main outcomes of the research project is presented in Fig. 2. This chart is regarded as a summarised panorama of the identified strengths and shortcomings of the assessed technologies in terms of façade integration; serving as a compass to guide further explorations and developments in the field.

The chart comprises several types of barriers acting at different levels, around a core composed of the solar cooling technologies assessed throughout the research project. The widespread application of integrated solar cooling façades will therefore depend on successfully overcoming each particular set of barriers. The ring around the core of solar cooling technologies consists of the threshold for façade integration of these systems, under self-sufficient operation in different climate contexts. Therefore, this ring shows distinct possibilities and constraints for each assessed technology, allowing them to be compared against each other. On the contrary, the barriers depicted outside of the circle are identified barriers for the development of solar cooling integrated concepts in general, applicable to all technologies; these consider barriers for further façade integration of solar collection technologies, namely photovoltaics and solar thermal collectors (lower left corner), and barriers for widespread façade integration of building services in general. The font size alludes to the perceived relevance of each barrier, based on how often it was mentioned by respondents of the survey (Prieto, Klein, et al., 2017). This comparative relevance only applies within each group of barriers separately, due to the nature of the assessment tool.

3.1 FAÇADE INTEGRATION POTENTIAL OF SOLAR COOLING TECHNOLOGIES

The potential for façade integration of each solar technology is represented by the shaded area around the inner core of solar technologies, summarising the qualitative evaluation conduced in terms of their ability to overcome product related key issues derived from the façade integration of building services. Technical feasibility, physical integration, durability & maintenance, performance, and aesthetics & availability were defined as these key issues, following analysis of the aforementioned expert survey conducted during the project.

First, it is clear that, although some technologies fare better than others, no technology currently meets all criteria in all required aspects for the development of self-sufficient integrated façade products, so further research and development is needed, targeting specific aspects. Table 1 shows the final recommendations for each technology in order to overcome current key barriers for façade integration. These were obtained from a qualitative evaluation that was presented in detail and discussed in a scientific article currently under review for publication (Prieto, Knaack, Auer, & Klein, n.d.). Recommendations that are marked in bold within particular aspects were identified as having particular shortcomings in relation to each technology, advocating for more pressing efforts on those matters.

Further developments and exploration focused on the generation of integrated building products, or plug & play compact systems, are needed for all assessed technologies. At the same time, the fact that liquid desiccant cooling technologies have only been explored recently, as opposed to other thermally-driven systems about which there is more knowledge, puts them at a disadvantage in both the level of development and technical maturity, needing further research in most aspects to be up to date. For adsorption and solid desiccant cooling, the main current bottlenecks are related to the size of components and the generation of compact integrated systems. This also holds true for some compact desiccant units currently being developed, which still need to be field tested and thoroughly validated under different working conditions (Finocchiaro, Beccali, Brano, & Gentile, 2016; SolarInvent, n.d.). Finally, thermoelectric modules are regarded as a promising technology for the development of integral building components, and absorption-based compact units present interesting prospects for modular plug & play systems for façade integration. Nevertheless, important performance barriers remain in the former, while further exploration of alternative working materials and testing of compact modular units are the main challenges for the latter.

KEY PRODUCT RELATED ISSUES FOR FAÇADE INTEGRATION	THERMOELECTRIC COOLING	ABSORPTION COOLING	ADSORPTION COOLING	SOLID DESICCANT COOLING	LIQUID DESICCANT COOLING
Technical feasibility	Prototype testing and experimental measurement of façade integrated concepts.	Further exploration and development of compact systems for façade integration.	**Size reduction of components and exploration of alternative processes.**	**Development and validation of compact systems for façade integration.**	**Development and testing of compact units.**
Physical integration	Standardize connections and components for development of architectural products.	Further exploration of plug & play integrated approaches to system design.	Exploration of integrated systems.	**Exploration of integrated compact systems.**	**Exploration of alternative processes to simplify connections and increase compatibility.**
Durability & maintenance	Testing of durability of TE modules applied in building components over time and different climate conditions.	**Exploration of non-corrosive working pairs and vacuum sealed compact systems.**	Testing of compact adsorption systems over time and different climate conditions.	Testing of compact solid desiccant systems over time and different climate conditions.	**Exploration and testing of alternative non-corrosive materials.**
Performance	**Increase cooling power of peltier modules, balancing adequate COP values. Explore up-scaled components.**	Further development and testing of compact systems below 3kW.	Increase COP values of small scale systems.	Further development and testing of compact systems below 3kW for reliability of COP values.	Further development and testing of compact systems below 3kW for reliability of COP values.
Aesthetics & availability	**Development of architectural products and integrated building components.**	**Development of plug & play systems for façade integration.**	**Size reduction of components for development of plug & play systems.**	**Size reduction and simplification of connections for development of decentralised ventilation systems.**	**Development and validation of compact integrated systems for future product development.**

TABLE 1 Recommendations for further development of solar cooling technologies for façade integration purposes

3.2 THEORETICAL CLIMATE FEASIBILITY OF SELF-SUFFICIENT SOLAR COOLING FAÇADES

The inner ring shows the climate contexts where self-sufficient application could be theoretically feasible, based on the development of integrated concepts based on specific technologies. Results from numerical calculations showed that the application of these concepts could be feasible on virtually all orientations, from every assessed location (Prieto et al., 2018). Even though these outcomes followed a theoretical approach, based on several assumptions and referential values, this fact is regarded as evidence that the application of self-sufficient solar cooling façades is not a far-fetched concept and could indeed be promoted following further technical developments to overcome previously identified barriers for façade integration. Nevertheless, the self-sufficiency of these concepts is conditioned by important restrictions for façade design in most cases, seeking to optimise the solar input throughout lower panel tilt and bigger dimensions of photovoltaic/thermal collector solar arrays in the building façade. These design constraints are more persistent in south and north façades, making east and west orientations more generally suited to solar cooling applications.

With regard to the climatic application potential of the assessed technologies, there are clear research and development paths. Although solar electric processes present advantages for façade integration, as previously discussed, their overall performance is a significant barrier, allowing for application in mild temperate dry climates, as a best case scenario, under medium to strong design constraints. Solar thermal offers more possibilities, further research is recommended for the application of sorption-based concepts in temperate and hot-arid contexts with minor to medium constraints, depending on orientation and climate severity. Finally, desiccant based units are recommended for warm-humid environments, both due to higher efficiencies associated with the technology, and particular general suitability to handle larger latent loads. In Hong Kong and Singapore, west, east, and north applications are theoretically feasible with medium design constraints, but south applications are heavily hindered.

The design constraints discussed refer to requirements for the optimisation of the solar array. However, basic design constraints remain for the application of all concepts, based on the collection technology needed to achieve the reference efficiencies used in the calculations. Presently, building integrated solar thermal (BIST) and photovoltaic (BIPV) products such as coloured thermal collectors or transparent PV cells, especially designed to appeal to architects, have lower efficiencies than state-of-the-art basic systems with no 'aesthetical considerations'. Hence, further development of these technologies is needed to expand the general range of façade design possibilities. Furthermore, the self-sufficiency of integrated concepts is conditioned to the use of passive strategies to lower cooling demands to a manageable amount. If these concepts are theoretically possible under important design constraints, their feasibility is downright impossible without being embedded within a climate responsive approach to façade design.

3.3 GENERAL BARRIERS FOR FAÇADE INTEGRATION OF BUILDING SERVICES AND SOLAR COLLECTION TECHNOLOGIES

In general, barriers related to the overall process are perceived as more critical issues to solve than issues relating to the end product itself, to allow for widespread façade integration of building services. In particular, problems related to coordination of different professional areas are perceived to be the most relevant, which holds true in all three defined stages of façade development (design, production, and assembly). In terms of other frequently mentioned process related problems, lack of technical knowledge seems to be especially relevant during design and assembly stages, and less so during production. Nonetheless, several logistical issues were identified in production and assembly stages, focusing on the lack of flexibility within the production chain, together with economic barriers during production for the construction of high quality components, aggravated by a common underestimation of cost projections during design phases. Finally, other mentioned problems, which are minor in comparison, refer to undefined responsibilities and warranties throughout the overall process.

In terms of product related problems, the physical integration of components seems to be the most relevant issue during both production and assembly stages. Additionally, the inaccuracy of long term performance estimations and operational limitations of currently available systems were stated as relevant problems in the design stage. Furthermore, other product related barriers that were identified, albeit with fewer mentions across all stages, are: the technical feasibility of integrated concepts; durability and maintenance; and aesthetics and lack of variety of available building services for integration. Even though these problems do not seem to hold the same importance as process related aspects, they represent basic requirements and relevant challenges that must be overcome on the development path of components and systems for façade integration.

Regarding the particular integration of solar collection technologies in façades, economic issues were declared as the most pressing barrier to overcome. The cost of current systems, energy prices, and the lack of economic incentives were mentioned among key aspects within this barrier. Secondly, grouped product related issues were perceived as a highly relevant barrier, based on the total amount of mentions. The disaggregated exploration of product related issues refers to performance, technical complexity of the systems, aesthetics, durability, and product availability. Besides performance, aesthetics is a relevant perceived issue to be overcome, which makes sense considering the strong impact of solar collectors and PV panels on the external finish of the façade and thus, the outward appearance of buildings.

4 CONCLUSIONS

General results based on the assessment of current possibilities show that self-sufficient integrated façade concepts based on solar cooling technologies are still far from achieving widespread application. However, there is clear potential for further development of distinct integrated concepts, based on specific technologies, provided that we manage to overcome existing barriers and technical bottlenecks. The main recommendations for further research and development in the field follow the different types of barriers discussed in the paper, posing specific challenges for diverse disciplines.

First, there is a need for further research on small-scale solar cooling systems and components, aiming to increase current efficiencies and simplify their operation. Fundamental research on new working materials and alternative cooling processes derived from the main addressed principles would enhance the potential for application at a base technological level. Furthermore, experimental and applied research at a system level is encouraged for all cooling technologies, in order to develop integrated building components, or modular compact plug & play units for façade integration purposes. Fundamental research needs to be carried out by specialists, but the development of systems conceived for architectural integration would greatly benefit from a multidisciplinary approach, in order to tackle technology-specific challenges.

Similarly, the integration of solar collection technologies in façades needs to be further promoted. The technical optimisation of these systems is currently well on track, steadily achieving performance goals set by different technological roadmaps, whilst there is an increasing number of products conceived with 'aesthetical considerations' in mind. Nonetheless, important economic restrictions remain in order to promote widespread application. Recommended actions to mitigate this include the further manufacturing of cost-effective products for integration by system developers, technical improvements in electricity and heat storage technologies, and the exploration of new business models and subsidy schemes to incentivise their application.

Finally, further parallel actions are needed to push for the integration of building services and new technologies for high-performing façades in general. Building technologies should be a central part of façade design education, striving for a basic understanding of technical aspects of building systems and façade requirements under an integrated design approach. Moreover, the façade manufacturing industry should take the lead in the exploration of new production processes, simplifying logistical and coordination issues derived from the integration of several systems, under an integrated supply chain. Furthermore, research on innovative business models for the management of façade systems could change the current value chain, generating new incentives for the development and application of high-performing façades under an environmentally conscious design approach.

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