Architecture
and the
Built environment

#29
2018

COOLFACADE

Architectural Integration of Solar Cooling Technologies in the Building Envelope

Alejandro Prieto Hoces

COOLFACADE

Architectural Integration of Solar Cooling Technologies in the Building Envelope

Alejandro Prieto Hoces
Delft University of Technology, Faculty of Architecture and the Built Environment,
Department of Architectural Engineering + Technology

TOC

Architecture
and the
Built environment

abe.tudelft.nl

Design: Sirene Ontwerpers, Rotterdam
Cover photo: Joyce McCown on Unsplash

ISBN 978-94-6366-098-3

ISSN 2212-3202

TOC

Offer me solutions, offer me alternatives and I decline.
It's the end of the world as we know it, and I feel fine.
R.E.M.

TOC

Preface

These are both exciting and challenging times. We are living on an age of unparalleled technological advancements, with smart gadgets, machines and systems popping up at increasing speeds. Nonetheless, we also face grave humanitarian and environmental crises, that require us to calibrate our efforts to steer and make use of these advancements for the benefit of the people and our environment. This thesis aims to shed some light in these issues, exploring the architectural integration of alternative technologies for cooling, based on solar energy and environmentally friendly processes. The book you have in your hands is the result of four years of research, but a warning seems necessary: it doesn't contain a lot of definite answers. However, it formulates several questions that will hopefully guide further developments in the field, to take us one step closer to a fully sustainable built environment.

This book has my name on the cover, but it has been developed collectively by many people who have been part of this process in a myriad of ways. First and foremost, I need to deeply thank my supervisors Prof.Dr-Ing. Ulrich Knaack, Prof.Dr-Ing. Tillmann Klein, and Prof.Ing. Thomas Auer. Thank you for both supporting and pushing me during these years, for your time, energy and sharp insights, but mostly thank you for your trust and your efforts on generating a cosy and stress-free work environment. You truly make research fun, guys! Secondly, I want to acknowledge the members of my defence committee: Prof.dr. Andy van den Dobbelsteen, Prof.dr. Anne Beim, Prof. Dr.-Ing. Norbert Fisch and Prof.ir. Thijs Asselbergs. Thanks for your interest and time invested on this manuscript. Special thanks to Dr. Claudio Vásquez, who initiated me in this field many years ago, starting a chain reaction that led me to this point.

I would like to thank the members of the European Façade Network and the COST Action 1403 - Adaptive Façades Network, for their help and support in the expert survey conducted as part of the dissertation. Also thanks to Inge Meulenberg and Henk Visscher, for their efforts to strengthen the PhD community within the Faculty; thanks to Véro Crickx for her assistance and patience with the layout of the book and Koen Mulder for the Dutch translation of the summary. I would also like to thank all my colleagues from the Department of Architectural Engineering + Technology, who contribute on making it a truly amazing and vibrant workplace. A special mention goes to all members of the Architectural Façades & Products Research Group (AF&P), particularly Thaleia Konstantinou and Juan Azcárate-Aguerre. Thanks for all the great feedback, tough love and above all, your friendship.

TOC

Four years is an important amount of time and, looking back, I can't help but be amazed by all the wonderful people I've met along the way, and whom have made this an incredible rich experience way beyond the doctorate itself. Many thanks to Phaedra, Tele, Maria, Toño, Tommi, Jandro, Peter, Jurek, Lida, Hyperion, Bernat, Nadjla, Sinem, Miren, Francesco, Stavroula, Bhavik, Karolina, Mira, Igor, Barbara, Adri and Gonza. Each one of you has made an everlasting impact in my life, with your warmth, kindness and friendship. I can confidently say that I now have family all over the world.

As I've had the opportunity to meet amazing people from several countries, I'm also deeply grateful for my fellow Chileans living in these nether lands. Thanks to César, Nati, Bego, Felipe, Francisco, Lucía, Mónica, Carmina and Javiera, whom I've had the pleasure to work with, in developing the Network of Chilean Researchers in the Netherlands (IN.NL). In that regard, special thanks to the Chilean Embassy and our Ambassador María Teresa Infante, for their strong and continuous support throughout this endeavour. Also, many thanks to the Chilean community in Delft, particularly Moisés, Nico, Dori (yes, you are one of us), Oscar(s), Maca(s), Diego, Nicole, Javier, Lore, Lucas, Chio, Nacho, Mauricio, Anande and Nicolle. Thanks for all the shared laughs, beers, piscolas, BBQs, your Chilean wit and your companionship and friendship. Chile doesn't seem that far with all of you around.

Finally, I want to thank my family. Mom, Dad, Carmen Paz, thank you for always being there for me, for supporting every decision without question and joining me along every path I've taken in life. Thanks also to my in-laws: Willy, Cecilia and Ivette, for their love and understanding; and last in the list but always first in my thoughts, special thanks to my wife. Luli, you are my own renewable and everlasting source of energy, the drive and engine behind my actions, making me want to be the best version of myself (don't worry, I'll keep trying). You have been the perfect partner throughout this adventure, and I cannot wait for the next one!

Delft, October 2018

TOC

Contents

TOC

TOC

TOC

Summary

The thesis ‘COOLFACADE – Architectural integration of solar cooling strategies in the building envelope’ aims to shed light on the possibilities and constraints for architectural integration of solar cooling systems in façades, in order to support the design of climate responsive architectural products for office buildings as self-sufficient alternatives to conventional air-conditioning systems. Increasing cooling needs in the built environment present an important and complex challenge for the design of sustainable buildings and cities. Even though the first course of action should always aim to reduce energy consumption through saving measures and passive design, this is often not enough to avoid mechanical equipment altogether, particularly in the case of office buildings in warm climate contexts.

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 common air-conditioning units. Nonetheless, building application remains mostly limited to demonstration projects and pilot experiences. Recently, façade integrated concepts have been explored, as a way to promote widespread application throughout the development of multifunctional building components. 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 barriers to overcome, in order to promote the widespread application of solar cooling components in the built environment.

The aim of this research project is to explore 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, without compromising the thermal comfort of users. The underlying hypothesis then is that self-sufficient solar cooling integrated facades may be a promising alternative to conventional centralised air-conditioning systems widely used in office buildings in warm climates. Most research efforts on solar cooling currently deal with the optimisation of the systems in terms of their performance, testing new materials and simplifying their operation to increase reported efficiencies. However, there is a lack of knowledge on the requirements and current limits for widespread façade application.

TOC

In order to achieve the research goal and comprehensively assess the façade integration potential of solar technologies and discuss current barriers, different aspects must be acknowledged. These distinct aspects are addressed through several research questions, which in turn define the different chapters of the dissertation. Introduction and conclusions aside, the research body is structured on three sequential parts, with 2-3 chapters each. The first part deals with the state-of-the-art in the field and the theoretical framework, laying the groundwork for the following sections. The second part explores different aspects required as input for façade integration; while the third part comprises the evaluation of solar cooling technologies in terms of current possibilities and constraints for the development of integrated façades, based on the inputs identified in the second part. Furthermore, all chapters were published or submitted for publication as scientific articles in peer review academic journals.

The first part considers two chapters that lay the foundations for the research project, The first chapter after the introduction expands the background of the dissertation by identifying knowledge gaps and research trends while contributing to the generation of a reference database of research experiences, throughout a systematic literature review of cooling research in office buildings during the last 25 years. On the other hand, the following chapter delves specifically in the main themes addressed within the dissertation, proposing a framework for the understanding of solar cooling integrated façades. This considers the theoretical discussion of the concept of architectural façade integration; and the identification of the main working principles and technical components from most common solar cooling technologies, based on a state-of-the-art review.

The second part explores different required inputs for façade integration. Design and construction requirements for façade integration are explored; while the response from façade design parameters to various climate conditions is assessed in parallel. The exploration of design and construction requirements is conducted through the identification of the main perceived problems for the façade integration of building services and solar technologies, by means of a survey addressed to façade professionals. On the other hand, a separate chapter explores the relation between climate conditions and cooling requirements in office buildings, evaluating the potential impact of several passive cooling strategies in various warm climates, as a first step before considering further technologies. This was conducted through the statistical analysis of reported research experiences, and dynamic energy simulations of a base scenario using specialised software.

The third part of the dissertation consists of two chapters that incorporate previous outcomes for the evaluation of selected solar cooling technologies in terms of current possibilities and constraints for the development of integrated façades. The first of

TOC

these chapters showcases a qualitative evaluation of the façade integration potential of several solar cooling technologies, based on a comprehensive review of key aspects of each technology and their prospects to overcome the identified barriers for façade integration. This is complemented by a feasibility assessment of integrated concepts in several climates, throughout numerical calculations based on climate data and building scenarios simulated with specialised software; showcased in the following and final chapter.

The driving force of the research project is the intention to test the limits of solar cooling integration in façades, showcasing current possibilities while identifying technical constrains and barriers to overcome for the widespread application of integrated façade concepts. Although interesting prospects were identified in this dissertation, important technical constraints need to be solved to conceive a façade component fail-tested for application in buildings. Furthermore, several barriers related to the façade design and development process would need to be tackled in order to introduce architectural products such as these into the building market.
The identification and discussion of these barriers, along with the definition of technology driven development paths and recommendations for the generation of distinct architectural products, are regarded as the main outcomes of this dissertation, serving as a compass to guide further explorations in the topic, under an overall environmentally conscious design approach.

TOC

TOC

Samenvatting

Het proefschrift 'COOLFACADE – Bouwkundige integratie van zonkoelingsstrategieën in de gebouwomhulling' heeft tot doel om de mogelijkheden en beperkingen in kaart te brengen van zonkoelingssystemen in de gevel, voor het ontwerpen van klimaat-responsieve bouwproducten voor kantoorgebouwen als zelfvoorzienende alternatieven voor conventionele airconditioningsystemen. De steeds groter wordende behoefte aan gebouwkoeling vormt een belangrijke en ingewikkelde uitdaging voor het ontwerpen van duurzame gebouwen en steden. Hoewel uitgangspunt moet zijn om het energiegebruik in eerste instantie te verminderen door besparingsmaatregelen en een passief gebouwontwerp, is het toch vaak onmogelijk om alle mechanische apparatuur te voorkomen, speciaal bij kantoorgebouwen in warme klimaten.

Zonkoelingstechnieken worden steeds meer onderzocht als milieuvriendelijk alternatief voor de schadelijke koelvloeistoffen die nu gebruikt worden in dampcompressiesystemen, terwijl ook zij worden aangedreven door de zon, dus door vernieuwbare energie. De principes achter deze technologie worden al meer dan een eeuw lang onderzocht. Er zijn volwassen oplossingen en bouwcomponenten ontstaan, die erkent worden als veelbelovende alternatieven voor gewone airconditioning apparaten. Toch blijft toepassing bijna altijd beperkt tot demonstratie- en proefprojecten. Recent zijn in de gevel geïntegreerde concepten onderzocht om door de ontwikkeling van multifunctionele bouwcomponenten een brede toepassing te stimuleren. Maar, hoewel deze worden beschouwd als belangrijke en veelbelovende concepten op zichzelf, is meer onderzoek nodig om het integratiepotentieel van verschillende zonkoeling technieken te kunnen vaststellen. Daarbij moeten obstakels in kaart worden gebracht die de brede toepassing van zonkoelingscomponenten nu verhinderen.

Doel van dit onderzoeksproject is de mogelijkheden en beperkingen in kaart te brengen van bouwkundige integratie van zonkoelingsstrategieën om het ontwerp te ondersteunen van klimaat-responsieve bouwproducten voor kantoorgebouwen als alternatief voor airconditioning, zonder het warmtecomfort van de gebruikers te verminderen. De onderliggende hypothese is dat in gevels waarin zelfvoorzienende zonkoeling is geïntegreerd, dit een veelbelovend alternatief voor conventionele centraal geregelde airconditioningsystemen kan zijn in commerciële gebouwen in warme klimaten. Het meeste onderzoek naar zonkoeling is op dit moment is gericht op de prestatie van systemen, waarbij nieuwe materialen worden getest en hun werking wordt vereenvoudigd om de gerapporteerde efficiëntie te verhogen. Er is echter een gebrek aan kennis met betrekking tot de voorwaarden en huidige beperkingen voor een wijdverspreide geveltoepassing.

TOC

Om het gevelintegratiepotentieel van zonnekoelingssystemen te bepalen en huidige barrières in kaart te brengen, moeten verschillende aspecten worden onderkend. Afzonderlijke onderzoeksvragen behandelen deze aspecten en vormen elk verschillende hoofdstukken van dit proefschrift. Afgezien van introductie en conclusie is de basis van het onderzoek verdeeld in drie opeenvolgende delen, die elk uit twee of drie hoofdstukken bestaan. Het eerste deel behandeld de 'state-of-the-art' stand van zaken in het onderzoeksveld en het theoretisch kader, waarmee het de basis vormt voor de volgende delen. Het tweede deel verkent de verschillende aspecten die nodig zijn voor gevelintegratie; terwijl het derde deel de evaluatie omvat van zonkoelingstechnieken, in termen van huidige mogelijkheden en beperkingen voor de ontwikkeling van geïntegreerde gevels, gebaseerd op de ingebrachte aspecten in het tweede deel.
Alle hoofdstukken zijn opgesteld als wetenschappelijke artikelen die eerder werden gepubliceerd in peer-reviewed academische tijdschriften.

Het eerste deel bevat twee hoofdstukken die het fundament voor het onderzoeksproject leggen. Het eerste hoofdstuk na de introductie ontvouwt de achtergrond van het proefschrift door kennislacunes en onderzoektrends in kaart te brengen. Het draagt bij aan het maken van een referentiedatabase van onderzoeksuitkomsten door een systematische literatuurreview van onderzoek naar koeling van kantoorgebouwen gedurende de afgelopen 25 jaar. Het erop volgende hoofdstuk richt zich op de hoofdonderwerpen van het proefschrift. Er wordt een theoretisch kader voor in gevels geïntegreerde zonkoeling voorgesteld. Het bevat ook de theoretische beschouwing van het concept bouwkundige gevelintegratie en het stelt de belangrijkste werkingsprincipes en technische componenten van de meest gebruikelijke zonkoelingstechnieken vast, gebaseerd op een state-of-the-art review.

Het tweede deel verkent de verschillende voorwaarden voor gevelintegratie. Ontwerp- en constructiebenodigdheden voor gevel integratie worden onderzocht; terwijl tegelijk wordt onderzocht wat de responsiviteit is van verschillende gevelontwerpaspecten in verschillende klimaatomstandigheden. Het onderzoek naar ontwerp en constructie benodigdheden wordt gedaan aan de hand van de meest ervaren problemen met de integratie in de gevel van gebouwinstallaties en zontechnologie. Hiertoe is een enquête onder gevelspecialisten afgenomen. In een afzonderlijk hoofdstuk wordt de relatie onderzocht tussen klimaatcondities en koelbehoeften van kantoorgebouwen. Daarbij wordt de mogelijke impact van verschillende passieve koelingsmethoden in verschillende warme klimaten onderzocht. Dit is een eerste stap voor verdere technologie moet worden overwogen. Dit is gedaan met behulp van een statistische analyse van gerapporteerde onderzoeksresultaten en een dynamische energiesimulatie van een standaard scenario met behulp van gespecialiseerde software.

TOC

Het derde deel van de dissertatie bestaat uit twee hoofdstukken die de eerdere uitkomsten van de evaluatie van de geselecteerde zonkoelingstechnieken met betrekking tot de huidige mogelijkheden en beperkingen voor de ontwikkeling van geïntegreerde gevels bijeenbrengen. Een hoofdstuk toont een kwalitatieve evaluatie van het gevelintegratiepotentieel van verschillende zonkoelingstechnieken op basis van een brede beoordeling van de belangrijkste aspecten van elke technologie. Daarbij worden ook de verwachtingen die ze scheppen met betrekking tot het slechten van de in kaart gebrachte barrières voor gevelintegratie beschouwd. Bovendien wordt de haalbaarheid onderzocht van de toepassing van geïntegreerde concepten in verschillende klimaten, met behulp van numerieke berekeningen die zijn gebaseerd op klimaatdata en op gebouwscenario's die zijn gesimuleerd met gespecialiseerde software. Een laatste hoofdstuk toont daar de resultaten van.

Drijvende kracht achter dit onderzoeksproject is de intentie om de grenzen van zonkoelingsintegratie in gevels te testen. Daarbij worden de huidige mogelijkheden getoond, terwijl technische beperkingen en barrières die wijdverspreide toepassing van integrale gevelconcepten in de weg staan, in kaart worden gebracht. Hoewel interessante vooruitzichten naar voren kwamen in dit proefschrift, geldt nog steeds dat belangrijke technische beperkingen moeten worden overwonnen om een gevelcomponent te maken die volledig getest is voor toepassing in gebouwen. Bovendien moeten nog verschillende barrières worden overwonnen in relatie tot het gevelontwerp- en ontwikkelingsproces om architectonische bouwproducten zoals deze in de markt te introduceren. De belangrijkste uitkomst van dit proefschrift betreft het in kaart brengen van deze obstakels, samen met de definitie van technologisch gedreven ontwikkelpaden en aanbevelingen voor het maken van onderscheidende architectonische bouwproducten. Het vormt een leidraad voor toekomstig onderzoek naar dit onderwerp, binnen een milieubewuste ontwerpbenadering.

TOC

TOC

1 Introduction

The thesis 'COOLFACADE – Architectural integration of solar cooling strategies in the building envelope' aims to shed light on the possibilities and constraints for architectural integration of solar cooling systems in façades, in order to support the design of climate responsive architectural products for office buildings as self-sufficient alternatives to conventional air-conditioning systems.

This first chapter introduces the topics to be addressed throughout the dissertation, stating the main research problem, aim and focus of the study. Moreover, research questions are formulated, with consequent strategy and required methods to provide comprehensive answers to the defined challenges. Finally, the impact of the thesis is discussed in terms of its scientific and societal relevance, aiming to provide new knowledge to close research gaps in the field; but most importantly striving to promote further application of environmentally friendly technologies driven by renewable energy sources in the built environment.

TOC

§ 1.1 Background

Cooling needs in the built environment present an important and complex challenge for the design of sustainable buildings and cities. Energy demands for cooling have increased drastically in the last decades, due to societal and economic factors such as higher standards of life and affordability of air conditioning; and 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 next 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 at 10-15%, going from 100 million worldwide in 2014, to over 1.6 billion by 2050 (Montagnino, 2017). These projections call for strong actions to be taken in order to minimise the impact of cooling needs in global energy consumption.

Initiatives devised to tackle this situation focus on the energy savings potential of the building sector, promoting good practices (ASHRAE, 2011; CIBSE, 2012) and enforcing regulations to reduce the operational energy demand in buildings (EP, 2010). In this regard, there is wide consensus on the application of passive cooling strategies as the first step for the design of sustainable buildings, under a climate responsive approach (Herzog, Krippner, & Lang, 2004; Lechner, 2014). This is particularly relevant in the case of office and commercial buildings, due to the relative importance of heating, ventilation and air conditioning (HVAC) equipment in their total energy consumption, which may reach over 50% in warm climates (Qi, 2006). Hence, their design should consider appropriate adaption to the local microclimate, regarding layout, solar protection, control of internal heat sources, and natural ventilation among other possibilities; before incorporating energy driven building services. Nevertheless, in most cases these systems will still be needed in order to meet comfort requirements; particularly in severe warm climate contexts such as desertic or tropical environments.

Therefore, a second recommended step for the design and operation of commercial buildings is the use of renewable energy sources to cope with the remaining demand in order to meet comfort requirements, avoiding the use of fossil fuels as much as possible (RVO, 2013). However, the quest for sustainable buildings and cities not only considers the use of clean energy sources but environmentally friendly systems as well. Conventional cooling units present an extra complication: the refrigerants used as working fluids within the cooling process have serious environmental impact. The most common refrigerants currently used in vapour compression based air-conditioning are hydrofluorocarbons (HFCs), such as R134a. This is a non-ozone-depleting substance,

TOC

but with a global warming potential (GWP) 1,430 times that of CO2 (IPCC/TEAP, 2005). Recently, an amendment to the Montreal Protocol was signed, agreeing to phase down these substances over the period of 2019-2036 and 2024-2047 in developed and developing countries respectively (UN, 2016). This represents an important landmark, breaking a vicious cycle between refrigerants that contribute to temperature rise in urban areas, thus increasing the need for them. Moreover, this is regarded as an opportunity for the development of environmentally friendly technological solutions based on alternative cooling processes.

Solar cooling technologies have gained increasing attention these last couple of decades, for their potential to lower indoor temperatures through environmentally friendly cooling processes driven by renewable energy. The principles behind some of these technologies have been researched since as far back as the 1800s, with explicit institutional support after the oil crisis of 1973, through initiatives such as the Solar Heating & Cooling Programme of the International Energy Agency (IEA-SHC, 2016) or the U.S. Department of Energy (DOE, n.d.). The maturity of certain solar cooling technologies has reached advanced levels, being recognised as promising alternatives to traditional vapour compression refrigeration (Goetzler et al., 2014). Nonetheless, building application remains mostly limited to demonstration projects and pilot experiences (Balaras et al., 2007; Henning & Döll, 2012).

In this regard, several developments in the small-scale range have been promoted through research projects, in an attempt to expand possibilities for application in residential and commercial buildings (Jaehnig, 2009). Furthermore, this has recently led to different explorations of façade integrated concepts by several researchers, as a way to promote widespread application through the development of multifunctional building components (Prieto et al., 2017a). These integrated concepts aim to seize economic and functional benefits derived from the integration of decentralised systems in the façade, while using its exposed area for direct and diffuse solar collection. Moreover, the usual match between peak solar irradiance and peak cooling demands supports harvesting that energy for cooling applications, while blocking solar heat gains under a climate responsive façade design. Nonetheless, while the development of building integrated photovoltaics (BIPV) and building integrated solar thermal collectors (BIST) has resulted in guidelines and commercial components (Escarré et al., 2015; Munari-Probst & Roecker, 2012); fully integrated solar cooling facades are not yet ready for use as architectural products. Current experiences are regarded as relevant and promising standalone concepts but further research is needed to assess their potential within façade design, and identify barriers to overcome to promote the widespread application of solar cooling components in the built environment.

TOC

§ 1.2 Problem statement

The research project deals with the integration of solar cooling systems into the building façade as a way to support the development of environmentally friendly cooling processes and the use of renewable energy sources in the built environment. Furthermore, the possibility of using the façade itself as an active heat dissipation system is seen as an opportunity for the development of self-sustaining cooling façade modules to be applied either on new buildings or refurbishment projects in the line of new 'nearly zero' energy standards. Façade integration of decentralised building services has been encouraged by several authors as a path for the development of high performing façades, based on economic and functional advantages. The former refer to construction cost savings through off-site production, and extra leasable space from avoiding complex distribution systems (Franzke et al., 2003; Knaack, Klein, Bilow, & Auer, 2007); while functional benefits range from efficient energy usage by identifying local demands, to higher perceived comfort due to personal control (Mahler & Himmler, 2008).

The underlying hypothesis behind this research project is that self-sufficient solar cooling integrated facades may be a promising alternative to conventional centralised air-conditioning systems used in commercial buildings from warm climates. The fact that experiences with integration and prototypes exist, is regarded as basic proof of the feasibility of such concepts, but they are far from commercial application, and isolated from façade design and development processes. Most research efforts on solar cooling currently deal with the optimisation of the systems in terms of their performance, testing new materials and simplifying their operation to increase reported efficiencies. However, there is a lack of knowledge on the requirements and current limits for widespread façade application.

Therefore, this thesis focuses on the suitability of solar cooling technologies in terms of their potential for façade integration, exploring current possibilities and identifying main constraints for further development of solar cooling integrated architectural products. The potential for façade integration is assessed considering both the architectural requirements for the integration of building services within the façade design and development process; and 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 (Figure 1.1).

Given that cooling needs are the main driver of the research, the assessment focuses exclusively on warm climates, ranging from temperate to extreme desertic and tropical environments. Furthermore, although a good climate responsive design should consider all comfort issues for the design of not only the façade system but the entire building; cooling is defined as the main parameter to optimise for purposes of the assessment. Similarly, discussion about design possibilities are constrained to the façade, leaving potential for further optimisation of cooling demands through building level strategies outside the scope of the present research.

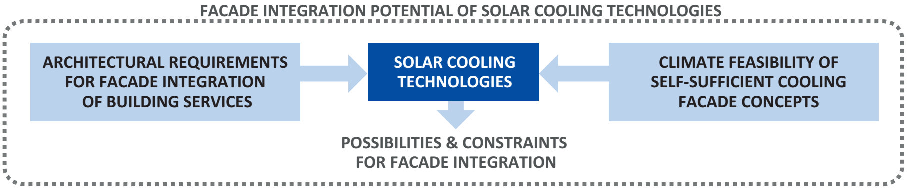


FIGURE 1.1 Main structure and focus of the research project

§ 1.3 Research objectives and questions

§ 1.3.1 Aim

The aim of the research project is to explore 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 as an alternative to conventional AC systems, without compromising the thermal comfort of users. The main outcome of the dissertation is a systematic assessment of the façade integration potential of selected solar cooling technologies, showcasing current limits for application while identifying main bottlenecks for further development of architectural products.

Furthermore, the recommendations and findings obtained from this research are expected to serve as valuable feedback to both façade professionals and cooling system developers. Thus, providing new insights for the integration of new technologies in the façade design and development process; while charting paths for the further development of each solar cooling technology considered in the assessment, based on identified requirements for new applications in the built environment.

§ 1.3.2 Research questions

The research project aims to answer the following research question, regarded as the main driver for an exploration of the current limits of the assessed technologies in terms of their façade integration potential:

To what extent can solar cooling technologies be integrated into the building envelope, in order to meet local thermal requirements through climate responsive integrated façade units, as an alternative to conventional centralised mechanical cooling in office buildings?

To be able to answer the research question, several sub-questions need to be explored. These sub-questions investigate specific aspects of the research project, addressed in different chapters throughout the present dissertation.

1. What is the available knowledge on façade related cooling strategies for office buildings? (Chapter 2)
2. What are the conceptual issues and state-of-the-art components and systems to consider for solar cooling façade integration? (Chapter 3)
3. What are the main perceived problems for building services integration in facades at different stages of the façade design process? (Chapter 4)
4. What are the main perceived barriers for façade integration of solar collection technologies? (Chapter 5)
5. What is the potential impact of the application of passive cooling strategies, on the cooling demands of office buildings in different warm climates? (Chapter 6)
6. What are the current possibilities and technical barriers for the architectural integration of solar cooling technologies in façade systems? (Chapter 7)
7. What is the potential for the application of self-sufficient solar cooling façades in different warm climate contexts, and what is the impact of the climate conditions on façade design possibilities? (Chapter 8)

TOC

§ 1.4 Research strategy and methods

In order to assess the potential for application of façade integrated solar cooling concepts, the research follows a straight forward approach, based on three sequential parts. The first part deals with the state-of-the-art in the field and the theoretical framework, laying the groundwork for the following sections. The second part explores different aspects required as input for façade integration; while the third part comprises the evaluation of solar cooling technologies in terms of current possibilities and constraints for the development of integrated façades, based on the inputs identified in the second part.

The overall strategy is shown in the scheme in Figure 1.2, comprising the main parts of the research project and the chapters in each one of them. Hence, the research strategy matches the outline of the dissertation. As stated before, the potential for façade integration of solar cooling technologies is assessed considering two main groups of aspects: architectural requirements from the façade design and development process; and the climate feasibility of self-sufficient integrated façade units. Therefore, both are assessed separately in the second part, leading to parallel explorations within that section, to then converge again in the third and final part for the evaluation of selected technologies.

Each chapter aims to respond one of the sub-questions presented above, supporting the development of the whole research by delivering specific outcomes, connected under an overall research strategy. Besides the main conclusions of the thesis, these particular outcomes are regarded as valuable contributions in each sub-field addressed in the dissertation. Hence, each chapter was conceived as a standalone exploration, using particular research methods and expanding the background related to the specific research problem at hand. Therefore, it was decided to conceive the chapters of the dissertation as scientific articles for publication in peer review academic journals. Despite some redundancy in the chapters' introductions, the benefits derived from the need to focus and clearly communicate partial results through continuous publication in scientific outlets, are regarded as an integral aspect of the research strategy.

As stated, each chapter considers different methods, to address the specific sub-questions. The particular strategy and methods are explained in detail in each chapter, but a brief overview is presented below, discussing the aim and methods from the chapters within each main part in order to understand how they relate to the others and their general role in the overall research scheme.

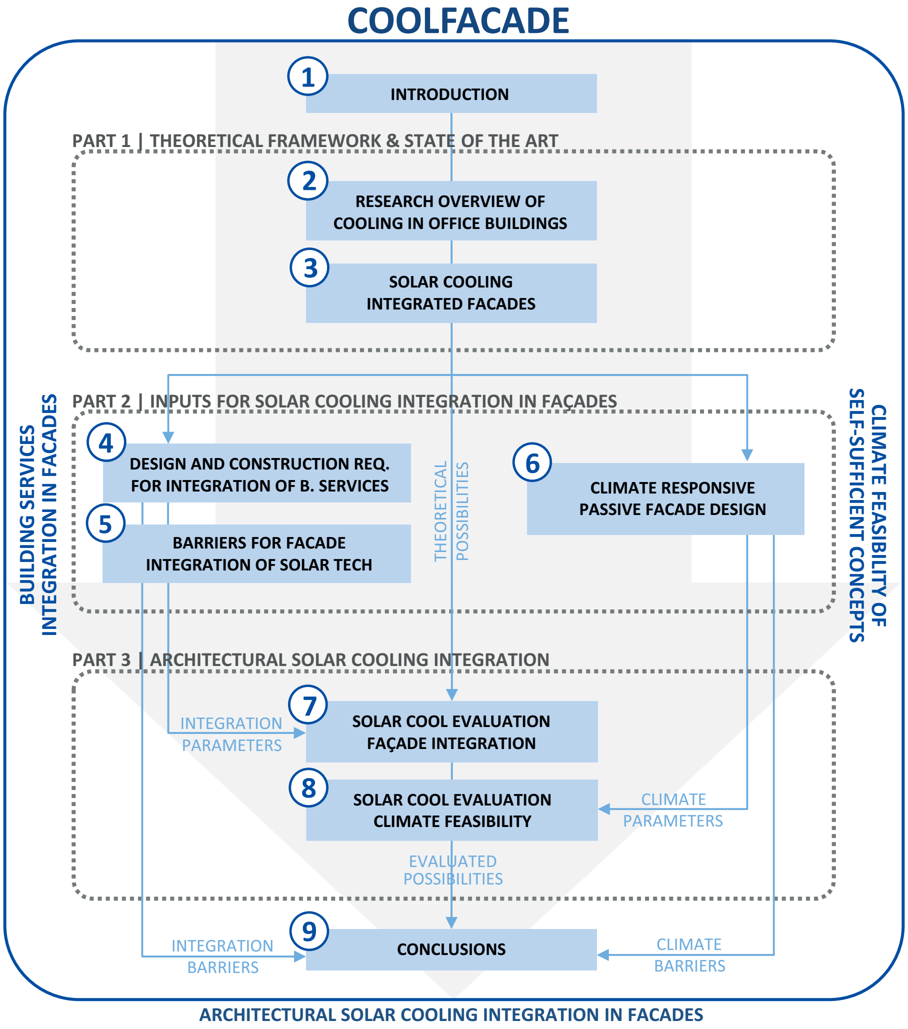


FIGURE 1.2 Research strategy scheme / dissertation outline.

Part 1: Theoretical framework and state-of-the-art

The first part considers two chapters that lay the foundations for the research project, expanding the background while exploring the state-of-the-art within the field. A systematic literature review of cooling research in office buildings is presented in Chapter 2, showcasing a panorama of the scientific knowledge in the field during the last 25 years, based on reported experiences in peer review scientific articles. This chapter is regarded as a general introduction to the topics, expanding the background of

TOC

the dissertation by identifying knowledge gaps and research trends while contributing to the generation of a reference database of research experiences. On the other hand, Chapter 3 delves specifically in the main themes addressed within the dissertation, proposing a framework for the understanding of solar cooling integrated façades. This considers the theoretical discussion of the concept of architectural façade integration; and the identification of the main working principles and technical components from most common solar cooling technologies, based on a state-of-the-art review. Reported façade concepts and prototypes are also showcased to illustrate current possibilities.

Part 2: Inputs for solar cooling integration in facades

Chapters 4-6 explore different aspects required for façade integration. Chapters 4 and 5 discuss design and construction requirements for integration, while Chapter 6 deals with the response from façade design parameters to various climate conditions. The exploration of design and construction requirements is conducted through the identification of the main perceived problems for the façade integration of building services and solar technologies, by means of a survey addressed to façade professionals. The responses from the survey are interpreted using qualitative content analysis techniques and quantitative descriptive statistics. Chapter 4 presents and discusses the main perceived barriers for the integration of building services, while Chapter 5 deals with the integration of solar collection technologies. On a parallel track, Chapter 6 explores the relation between climate conditions and cooling requirements in office buildings, evaluating the potential impact of several passive cooling strategies for the design of climate responsive façades. As stated in the background, this should be the first step when aiming to decrease cooling demands, before integrating further technology. Thus, the chapter aims to examine the performance extents from the application of passive strategies in various warm climates, through the statistical analysis of reported research experiences, and dynamic energy simulations of a base scenario using specialised software. The outcomes from the chapters in the second part lead directly to the identification of general barriers, while also providing specific input for the evaluations carried out in the third part.

Part 3: Architectural solar cooling integration

The third and final part of the dissertation incorporates the outcomes from the previous chapters for the evaluation of selected solar cooling technologies in terms of current possibilities and constraints for the development of integrated façades. Theoretical possibilities are obtained from the framework proposed in Chapter 3, which are evaluated considering parameters defined in the second part, in two sequential assessments. Chapter 7 shows the qualitative evaluation of the façade integration potential of several solar cooling technologies, based on a comprehensive review of key aspects of each technology and their prospects to overcome identified barriers for façade integration of building services. Finally, Chapter 8 explores the feasibility of the application of integrated concepts in several climates, throughout numerical calculations based on climate data and building scenarios simulated with specialised software. Base scenarios are obtained from Chapter 6, and further evaluations are conducted considering limited design variations. The outcome from the final part aims to show current possibilities and identify main limitations under a systematic assessment, drafting recommendations for the further development of façade integrated architectural products.

§ 1.5 Research impact

§ 1.5.1 Societal relevance

The foremost aspect when discussing the societal relevance of the research project refers to the aforementioned pressing need to decrease cooling demands in the built environment. Furthermore, the exploration and promotion of environmentally friendly cooling processes driven by renewable energy sources should accelerate their widespread application, with the consequent important decrease of the global warming potential of buildings.

On a building scale, energy savings comprise economic benefits in the long run. The integration of self-sufficient solar cooling modules within a climate responsive façade design considers the possibility to achieve zero or nearly-zero energy consumption from the grid. Moreover, on a more general note regarding potential economic benefits, the exploration of new technologies and their possibilities for façade integration could jumpstart the development of new architectural products and business models for new applications in the built environment. In turn, this not only would generate profit for the stakeholders, but also job opportunities and impact on the building industry.

Lastly, the use of decentralised building services has been encouraged based on health and comfort issues. The inherent possibility of direct control suited to local demands has shown improvements in the perceived indoor comfort (Mahler & Himmler, 2008); while the use of centralised equipment has been linked to indoor air quality complaints due

TOC

to lack of maintenance of coils, filters and cooling towers (Bluyssen, 2009). Moreover, the use of desiccant based solar cooling systems has been proven to enhance indoor air quality in humid environments by avoiding condensation in the cooling process and absorbing pollutants and bacteria (Sahlot & Riffat, 2016). Furthermore, the link between the well-being of workers and their productivity levels is widely accepted, translating social and health issues into economic benefits for the company (Vischer, 2007).

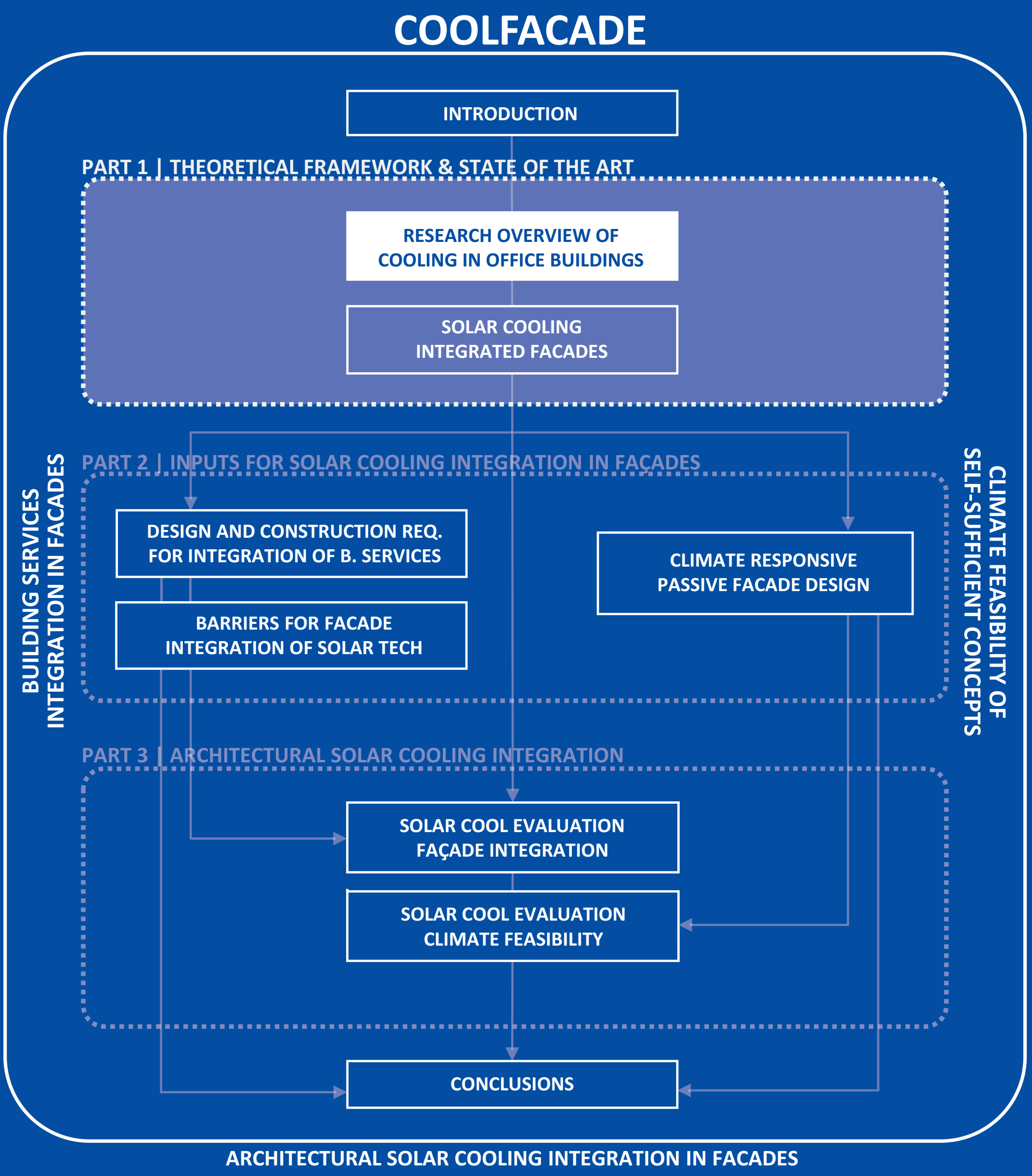
§ 1.5.2 Scientific relevance

The research project seeks to expand current knowledge in the field of façade design, focusing on the development of new architectural products based on their cooling performance, and the integration of new technologies and building services. The assessment of current possibilities and limitations for façade integration of solar cooling technologies under a systematic approach, is regarded as a relevant contribution to the field, guiding further research and development on specific technologies and façade design and construction. Furthermore, the methodology designed for the assessment may be useful not only for the case of solar cooling, but also as a path to evaluate the potential for façade integration of new technologies and innovative building systems.

Besides the central aim, the research also deals with specific research gaps, advancing the knowledge in sub-fields explored throughout the thesis. Therefore, the results from the survey presented in Chapters 4 and 5 aim to provide insights on general issues within the façade design and construction process, besides contributing to the main aim of this research project. The construction industry has been openly criticised by its poor performance and outdated production methods (Woudhuysen & Abley, 2004), so examining the façade development process itself seems relevant in the current agenda towards sustainability. Similarly, the cross-climate examination of the potential savings derived by the application of passive cooling strategies showcased in Chapter 6, is expected to serve as useful referential information in early design stages. Hence, encouraging their application in office buildings, not only as a stepping stone for solar cooling integration but as a basic aspect of all new buildings and refurbishment projects.

Finally, it is worth mentioning that throughout the dissertation, there is a conscious aspiration to make use of available scientific knowledge, based on a comprehensive panorama of the state-of-the-art on both research experiences and technical solutions within the field of study. Hence, the research project not only references and discusses previous studies, but aims to use them as valuable input for the analyses, complementing this data with new information to fill scientific gaps and defining future steps for the development of integrated façade concepts for architectural application.

TOC


COOLFACADE
INTRODUCTION
PART 1 | THEORETICAL FRAMEWORK & STATE OF THE ART
RESEARCH OVERVIEW OF COOLING IN OFFICE BUILDINGS
SOLAR COOLING INTEGRATED FACADES
PART 2 | INPUTS FOR SOLAR COOLING INTEGRATION IN FAÇADES
DESIGN AND CONSTRUCTION REQ. FOR INTEGRATION OF B. SERVICES
BARRIERS FOR FACADE INTEGRATION OF SOLAR TECH
CLIMATE RESPONSIVE PASSIVE FACADE DESIGN
BUILDING SERVICES INTEGRATION IN FACADES
CLIMATE FEASIBILITY OF SELF-SUFFICIENT CONCEPTS
PART 3 | ARCHITECTURAL SOLAR COOLING INTEGRATION
SOLAR COOL EVALUATION FAÇADE INTEGRATION
SOLAR COOL EVALUATION CLIMATE FEASIBILITY
CONCLUSIONS
ARCHITECTURAL SOLAR COOLING INTEGRATION IN FACADES

TOC

2 Research overview of cooling in office buildings

Review for the integration of cooling strategies in the building envelope.[1]

This chapter serves as a general introduction to the topics explored throughout the dissertation, presenting a panorama of the available knowledge on façade related cooling strategies in office buildings. This was carried out by categorising and discussing reported research experiences from the past 25 years in order to identify knowledge gaps and define current paths and trends for further exploration. Peer reviewed journal articles were selected as the source for the study, given the reliability of the information published under peer-review processes. Several queries were carried out throughout online journal article databases, considering published papers from 1990 onwards. The resulting article database was then explored through descriptive analysis and in-depth review of some articles to expand on specific topics in order to thoroughly visualise scientific interest and tendencies within the field of study for the last 25 years.

Results show the high current relevance of cooling research, having experienced an increase of publications under different climate contexts and varied topics ranging from passive to solar cooling, which is seen as a research field on its own. Also, in terms of research methods, software simulations seem to be the primary tool for cooling research, which makes sense for performance driven developments. On the other hand, the main knowledge gaps identified are the need for specific research regarding possibilities for application and architectural integration of cooling systems; the lack of articles addressing some specific cooling strategies, such as the use of evaporative and ground cooling; and the need for more information about the operation of cooling systems, especially taking users' perception and their behaviour into account.

---

[1] Published as: Prieto A, Knaack U, Klein T, Auer T. (2017). 25 Years of cooling research in office buildings: Review for the integration of cooling strategies into the building façade (1990–2014). Renewable and Sustainable Energy Reviews. 71: 89-102. doi: 10.1016/j.rser.2017.01.012.

§ 2.1 Introduction

Buildings have an important role in worldwide energy consumption compared to other economic sectors. According to studies performed in the EU, buildings account for 40%-45% of the total energy demand (EP, 2002). As a result, several initiatives are being put into place to reduce the operational energy demand in buildings. In Europe, the Energy Performance of Buildings Directive was approved in 2002, and then updated in 2010, considering new challenges for the building sector, and specially requesting all new buildings in the EU to consume “nearly zero” energy after 2020 (EP, 2010).

As result of the application of energy saving measures and the development of new technologies, the thermal performance of buildings during winter period has been greatly improved. However, due to a number of reasons such as increasing standards of life, affordability of air-conditioning, temperature increase in the urban environment and global climate change; the energy needs for cooling have increased drastically (Santamouris & Kolokotsa, 2013). This scenario is even more pressing considering energy projections for the next decades, which show the impact of emerging economies from outside the Organisation for Economic Cooperation and Development (OECD) on worldwide energy consumption. Estimates show that energy consumption will increase by 34% between 2014 and 2035, mostly due to demands from fast-growing emerging economies (BP, 2016). Indeed, it has been stated that just Non-OECD Asia (including India and China) will account for more than half of the world’s total increase in energy consumption between 2012 and 2040 (DOE/EIA, 2016). The fact that most emerging and growth leading economies (EAGLEs) experience warm climates (BBVA, 2016) (Figure 2.1) puts pressure on the need for buildings specifically designed to minimise cooling loads.

In this sense, the design of office buildings presents a particular challenge due to the relative importance of heating, ventilation and air-conditioning equipment in their total energy usage. Figure 2.2 shows the disaggregated energy consumption for an average high-rise office building located in USA (Wood & Salib, 2013), and for an average office building in a tropical climate (Singapore) (C. Qi, 2006). The energy used for heating and cooling in the former sums up to 33%; while it increases up to 51% in the latter, basically responding to cooling demands (Overduin, 2016). Furthermore, the widespread use of AC units in buildings has been proven to have an important impact on total energy consumption. Some studies even show that refrigeration and air conditioning are responsible for about 15% of the total electricity consumption in the world (CICA, 2002). The relevance of cooling demands in office and commercial buildings responds to high internal gains (occupation density and equipment) in general, which is aggravated by the impact of solar radiation and high external temperatures in warm climates (Bustamante, Vera, Prieto, & Vasquez, 2014; C. Vasquez, Prieto, & Aguirre, 2012).

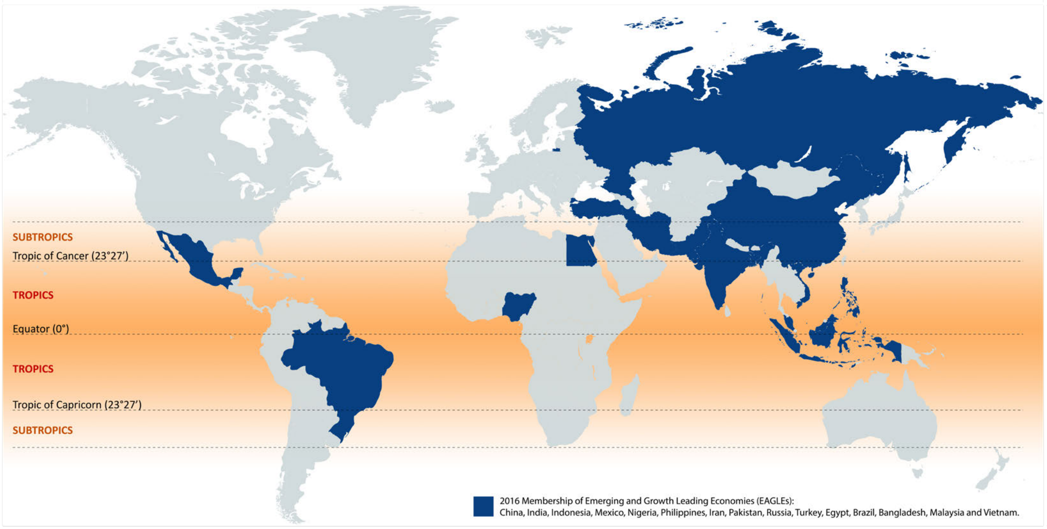


FIGURE 2.1 Emerging and Growth Leading Economies (EAGLEs) and their relative location compared to tropical and subtropical world zones.

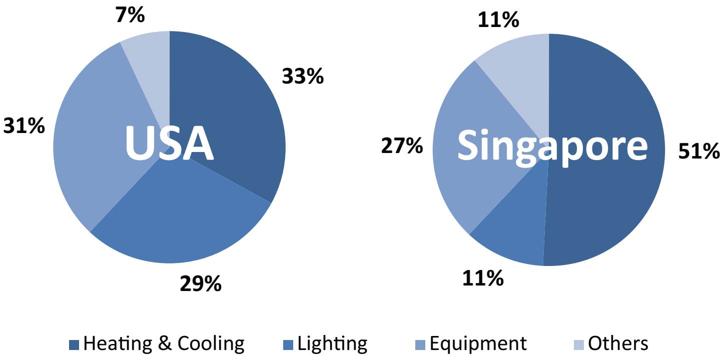


FIGURE 2.2 Disaggregated energy consumption of an average high-rise office building located in USA and Singapore.

The fact that office building designs usually favour the use of lightweight building components and high transparency in façade systems, following an international look associated with success and corporate imagery (Russell, 2003), only exacerbates the discussed problems. Indeed, these building types heavily rely on active air-conditioning equipment in order to function, replacing the traditional role of the building envelope with the application of energy driven systems to cope with the resulting demands. Opposing this widespread trend, several authors advocate for sustainable or climate responsive designs as the first step for energy efficiency. Lechner (2014) stated that a sustainable building could accomplish up to 60 percent of its heating, cooling and lighting demands by itself, compared to a reference case. Moreover, the author proposed a three-tier design approach for sustainable buildings. The first tier deals with basic building design strategies such as orientation, insulation and the use of exterior shading. If this is not enough to meet the requirements, which it is often the case in warm climates, then a second tier of passive or hybrid systems based on natural energies should follow, considering the use of evaporative cooling, earth coupling, or diurnal/nocturnal ventilation. Lastly, mechanical equipment could be incorporated into the building in the third tier, if needed, within an already passively optimised building design.

Similarly, Herzog et al. (2004) defined two sequential sets of strategies to cope with the regulatory functions of the façade. The authors considered the application of supplementary measures, such as thermal insulation, sun shading or even vegetation, as a first resource; and then suggested the use of supplementary building services such as artificial lighting and air conditioning only if needed. The authors also considered the use of thermal collectors or PV panels as supplementary services for energy generation, which relates to the hybrid use of natural energies expressed by Lechner as an alternative to the use of fossil fuels. In fact, the use of environmental heat sources and sinks as drivers for high temperature cooling systems has been reported by several researchers, supporting the use of low-exergy sources (Ala-Juusela, 2003). This definition also comprehends the heat and electrical output from solar thermal collectors and PV systems, even though solar radiation itself is regarded as a high exergy source from a technical standpoint (Hepbasli, 2012; Torío & Schmidt, 2010).

Solar cooling systems have gained increased attention these last years, for their potential to lower indoor temperatures using renewable energy (H.-M. Henning & Döll, 2012; Kohlenbach & Jakob, 2014). Several initiatives supported by private developers and public organisations such as the Solar Heating & Cooling Programme of the IEA (IEA-SHC, 2016), have been promoting the use of these technologies by showing their advantages while increasing the efficiency of the systems to allow for massive commercial application (Balaras et al., 2007; H.-M. Henning, 2007). In the current scenario of increasing cooling demands, it is highly unlikely that purely passive

TOC

strategies are enough to cope with comfort requirements, and downright impossible in the case of warm climates, so these hybrid solar based technologies are regarded as an interesting complement to bridge the gap in passively optimised office buildings.

This chapter seeks to present a panorama of cooling related research in office buildings, categorizing reported research experiences from the past 25 years in order to identify knowledge gaps and define current paths and trends for further exploration. The general goal behind this research is to support the design of sustainable office buildings in warm climates through examination of past experiences, thus the chapter focuses on strategies at building level and specially related with façade design. Although there have been important advances in strategies at larger scales, such as the use of district cooling (Gang, Wang, Xiao, & Gao, 2016; Pampuri, Cereghetti, Strepparava, & Caputo, 2016) or the concept of smart energy grids (Mathiesen et al., 2015), these are out of the scope of the present document.

Peer reviewed journal articles were selected as the source for the study, given the reliability of the information published under peer-review processes. Several systematic queries were carried out throughout three online journal article databases (Web of Science, SCOPUS and ScienceDirect), considering published papers from 1990 onwards to gather enough cooling related research experiences to detect trends and knowledge gaps. The resulting article database was then explored trough descriptive analysis and in-depth review of some articles to expand on specific topics in order to thoroughly visualise scientific interest and tendencies within the field of study for the last 25 years.

The results and discussion section of this chapter is structured in three parts: first, a general panorama of cooling related research is presented, discussing the gathered experiences in terms of main research topics, representation of different climate contexts, and tools and methods used by researchers. Then, in the second and third part, the discussion is focused on the respective assessment of two particular sets of cooling strategies: passive cooling and solar cooling. The application of passive cooling strategies was mentioned as the first step for the design of sustainable office buildings in warm climates, while solar cooling technologies are regarded as a promising alternative to provide supplementary cooling driven by renewable energy sources. These sets of strategies are explored through the literature, presenting an overview of the available information while showing examples of advances within the field.

TOC

§ 2.2 Material and methods: review of journal articles from 1990 to 2014.

§ 2.2.1 Definition of parameters for the search queries

Research experiences from peer review journal articles were considered as base material for the review. In order to gather relevant articles within the scope of the study, some parameters were defined as input for their search (Table 2.1). The constraints served the purpose of limiting the results to the most corresponding articles, and at the same time limiting the number to a manageable amount which allowed an initial review and categorization of the information.

TABLE 2.1 Parameters used for journal database searches.

TYPE OF SEARCH	TITLE / ABSTRACT / KEYWORDS	
PUBLICATION DATE	> 1989	
SEARCH KEYWORDS	AND	(PASSIVE or LOW-TECH or LOW-ENERGY or ACTIVE or MECHANICAL or SOLAR)
		(COOLING or REFRIGERATION or AIR-CONDITIONING)
		(FAÇADE or ENVELOPE or CURTAIN-WALL)
		(OFFICE or NON-RESIDENTIAL or COMMERCIAL or TERTIARY)
		(BUILDING)
		(COST or PERFORMANCE or EVALUATION or MONITORING or SIMULATION)**
	AND NOT	(HOUSE or HOUSING or DWELLING)
		(NUCLEAR or CHEM*)

** Considering only single-effect absorption chillers*
*** Extra string of parameters used to search in the ScienceDirect Database.*

The parameters shown in Table 2.1 correspond to the final query performed after an iterative process to narrow down the results to a manageable number, excluding outliers. So, the search focused on articles published from 1990 onwards considering only title, abstract and keywords match (not entire document). Besides the use of keywords that matched the declared focus, such as 'office buildings', 'cooling', and 'façade', it was decided to avoid particular keywords that conducted to misleading information. Chemical related research was discarded because of its specific focus in material science rather than building applications. Moreover, the keyword 'nuclear' was avoided, in order to rule out nuclear plant cooling systems, which considered a large number or matches but fell out of the proposed scope.

TOC

The search query was performed on three online journal article databases: Web of Science, SCOPUS and ScienceDirect obtaining the results shown in Table 2.2. However, in the case of the ScienceDirect database search, another string of parameters was added in order to narrow down the results (marked with ** in Table 2.1).

TABLE 2.2 Online journal databases consulted.

ONLINE DATABASES	MATCHES FOUND
WEB OF SCIENCE	127
SCOPUS	236
SCIENCE DIRECT	11,017 / 1,062**

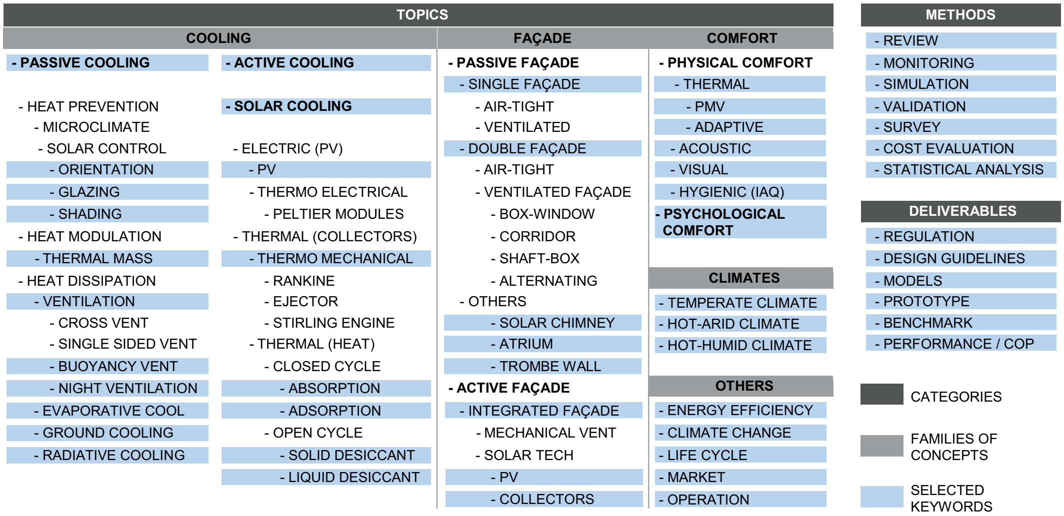
*** Results considering extra search parameters.*

After an initial review of the results, filtering outliers and avoiding repeated results, a consolidated database of journal articles was generated using a reference manager software (ENDnote). The queries were performed during September, 2014; ending up with a consolidated database of 861 journal articles at October 1st, 2014. Hence, the overview presented on this document is based on a sample of 861 research articles, considering mostly original research but also reviews conducted by other researchers. All articles' abstracts were reviewed for the evaluation, while some relevant articles were reviewed in detail to provide examples of interesting advances in the field.

§ 2.2.2 Building a reference database: assignment of new keywords for categorization

The second step after gathering relevant journal articles was to categorise them for further exploration of the information. To accomplish this, new keywords were assigned to each article within the database. This was done through a review of the abstracts, considering topics, methods and focus of each article. All 861 abstracts were checked and categorised according to the newly defined keywords. This categorisation fulfilled two goals: it structured the information in an accessible manner, generating a organised reference database; while at the same time it provided the means to explore the information through descriptive analysis.

The new keywords used for categorization are shown in Figure 2.3 grouped into topics, methods and deliverables addressed in each article. The definition of the new keywords was carried out by developing families of concepts relevant to the field of study after an initial review of reference articles and books. As it was stated before, the review explicitly addressed some specific topics in more depth, such as passive strategies and solar cooling systems due to their potential for achieving low-energy cooling in office buildings. Thus, their families of concepts are larger than other topics.



TOPICS

COOLING

- PASSIVE COOLING
- HEAT PREVENTION
  - MICROCLIMATE
  - SOLAR CONTROL
    - ORIENTATION
    - GLAZING
    - SHADING
- HEAT MODULATION
  - THERMAL MASS
- HEAT DISSIPATION
  - VENTILATION
    - CROSS VENT
    - SINGLE SIDED VENT
    - BUOYANCY VENT
    - NIGHT VENTILATION
  - EVAPORATIVE COOL
  - GROUND COOLING
  - RADIATIVE COOLING

- ACTIVE COOLING
- SOLAR COOLING
- ELECTRIC (PV)
  - PV
  - THERMO ELECTRICAL
    - PELTIER MODULES
- THERMAL (COLLECTORS)
  - THERMO MECHANICAL
    - RANKINE
    - EJECTOR
    - STIRLING ENGINE
  - THERMAL (HEAT)
    - CLOSED CYCLE
      - ABSORPTION
      - ADSORPTION
    - OPEN CYCLE
      - SOLID DESICCANT
      - LIQUID DESICCANT

FAÇADE

- PASSIVE FAÇADE
  - SINGLE FAÇADE
    - AIR-TIGHT
    - VENTILATED
  - DOUBLE FAÇADE
    - AIR-TIGHT
    - VENTILATED FAÇADE
      - BOX-WINDOW
      - CORRIDOR
      - SHAFT-BOX
      - ALTERNATING
  - OTHERS
    - SOLAR CHIMNEY
    - ATRIUM
    - TROMBE WALL
- ACTIVE FAÇADE
  - INTEGRATED FAÇADE
    - MECHANICAL VENT
    - SOLAR TECH
      - PV
      - COLLECTORS

COMFORT

- PHYSICAL COMFORT
  - THERMAL
    - PMV
    - ADAPTIVE
  - ACOUSTIC
  - VISUAL
  - HYGIENIC (IAQ)
- PSYCHOLOGICAL COMFORT

CLIMATES

- TEMPERATE CLIMATE
- HOT-ARID CLIMATE
- HOT-HUMID CLIMATE

OTHERS

- ENERGY EFFICIENCY
- CLIMATE CHANGE
- LIFE CYCLE
- MARKET
- OPERATION

METHODS

- REVIEW
- MONITORING
- SIMULATION
- VALIDATION
- SURVEY
- COST EVALUATION
- STATISTICAL ANALYSIS

DELIVERABLES

- REGULATION
- DESIGN GUIDELINES
- MODELS
- PROTOTYPE
- BENCHMARK
- PERFORMANCE / COP

CATEGORIES

FAMILIES OF CONCEPTS

SELECTED KEYWORDS

FIGURE 2.3 Selected keywords within the families of concepts.

Afterwards, some of the concepts were selected as new keywords for categorisation (highlighted in Figure 2.3), trying to avoid over specification in issues out of the main scope (such as the specific type of double façade), or to avoid redundancy in the categories (to state that an article addresses absorption chillers also implies that it considers closed cycle thermally driven solar cooling).

Finally, these new keywords were used as main input for a descriptive analysis of the database. The keywords represent the information contained in each article, thus they are presented as a valid mechanism for the generation of an overview and the evaluation of research trends over time. It is important to point out though, that all conclusions should lie within the scope of the search queries and the defined categorization method in order to be valid. This of course means that it is only possible to analyse and state valid conclusions about topics and concepts specifically addressed in the database.

TOC

§ 2.3 Results and discussion: descriptive analysis and article review

The database was explored through descriptive analysis, to generate a panorama of the field of study for the last 24 years. This analysis was complemented with an in-depth review of some articles in order to understand certain topics in a more detailed way. The main topic addressed on the query was the use of façade related cooling strategies in office buildings, thus all interpretation of the results must consider this specific focus.

Figure 2.4 shows an initial approach to the matter, by counting the number of articles that consider each keyword (the size of the word expresses the number of articles). Therefore, the figure shows the weight of each concept within the database, showing also the direction of the scientific interest on the subjects for the past couple of decades.

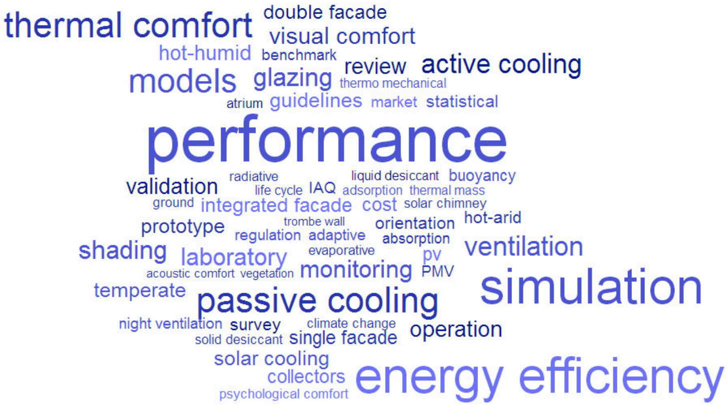


FIGURE 2.4 Word cloud of the assigned keywords. Size of the word equals the number of articles that contain it.

Research about performance of cooling strategies and systems has the higher results (577 matches), which makes sense by also stating the fact that "energy efficiency" is the second most repeated topic (417). Overall, cooling related research is focused on developing energy efficient systems and strategies. Therefore, performance assessment of existing technologies as well as performance evaluation of new cooling systems are key aspects for the improvement of the technical possibilities.

Besides energy aspects, the performance of cooling systems and strategies has to take thermal comfort into account. While some of the studies specifically focus on this subject (258), it is indeed a subject at least indirectly considered while discussing thermal control of indoor spaces.

TOC

In terms of the methods used for research purposes, simulation seems to be the leading one (407). The continuous development of energy simulation software during the last two decades has improved both the accuracy of the results and the speed of the calculation processes, which has made possible their widespread use. Nonetheless, there is an important number of articles that seek to develop new energy consumption prediction models (239) to be used in early design stages, simplifying energy calculations even more for easier application.

Specific analyses of the database were carried out focusing on particular topics, in order to understand their relevance and explore their evolution over time. The results are presented organized into three topics: an overall assessment of cooling research, and two particular explorations into the state of research in passive cooling and solar cooling technologies.

§ 2.3.1 Cooling research: general overview of gathered experiences

First of all, a general panorama of cooling research in office buildings is presented. Figure 2.5 shows that passive cooling strategies have been studied more than active and solar cooling. However, all three strategies have experienced increased scientific interest over the years (Figure 2.6). This is especially true in the case of solar cooling research, which became noticeable in the turn of the century due mostly to the support of several initiatives developed by the Solar Heating & Cooling programme of the International Energy Agency.

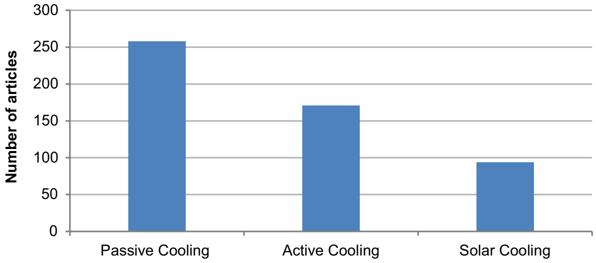


FIGURE 2.5 Different types of cooling articles between 1990 and 2014

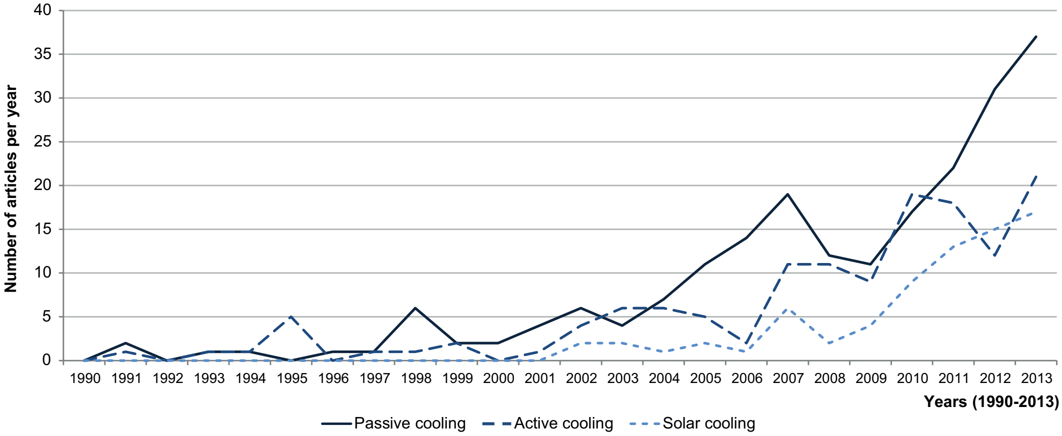


FIGURE 2.6 Cooling articles between 1990 and 2013

When considering cooling research focused on a particular climate, results vary. In general terms, there is less recognizable research focused on hot-arid contexts (Figure 2.7), but Figure 2.8 shows that this is currently changing due to research projects being carried out in middle eastern countries such as Bahrain, Saudi Arabia, Kuwait and United Arab Emirates. Topics being researched consider mostly the evaluation of passive cooling strategies, like the energy performance of shading systems (Aldawoud, 2013a; Freewan, 2014), evaluation of glazing properties (Bahaj, James, & Jentsch, 2008), or possibilities for the application of multi-façade systems in hot-arid climates (Hamza, 2008; Radhi, Sharples, & Fikiry, 2013).

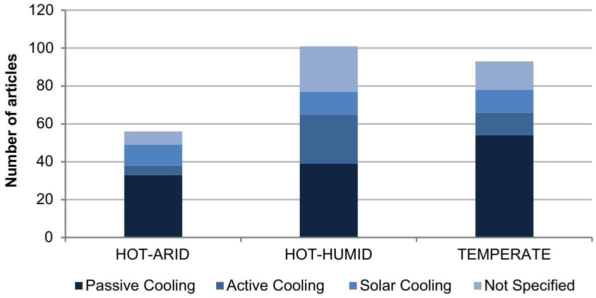


FIGURE 2.7 Cooling research considering specific climates

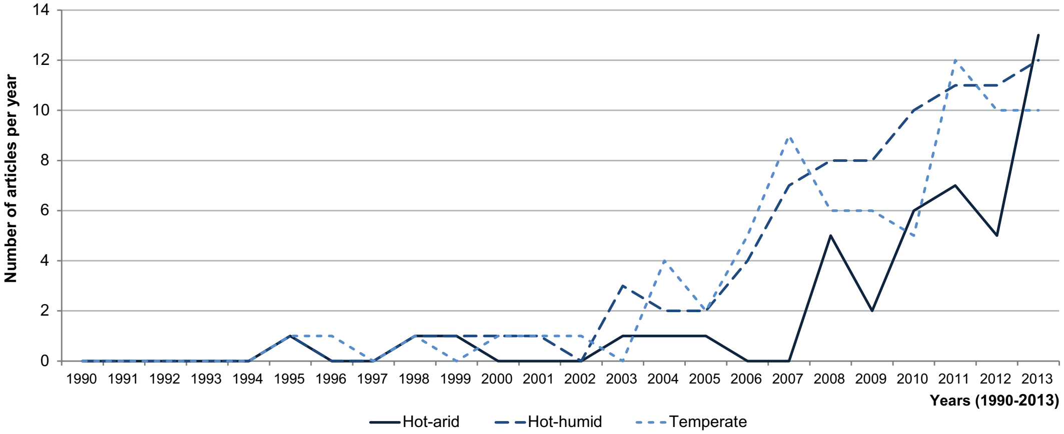


FIGURE 2.8 Cooling articles on specific climates

Also in temperate climate contexts passive cooling research has leaded scientific interest. Among relevant experiences in this subject it is possible to highlight the studies carried out by Santamouris and Kolokotsa (2013) about passive heat-dissipation techniques, the research done on night ventilation performance by Pfafferott (2004) and Kolokotroni (1998) and the extensive studies carried out by Gratia and De Herde on the potential for natural ventilation on double-skin facades (Gratia & De Herde, 2004a, 2007b).

In the case of hot-humid climate cooling research, there is also a big number of passive driven studies related to the design of naturally ventilated façades (Haase & Amato, 2006; Thirakomen, 2007; Zhou & Chen, 2010), evaluation of atrium performance (Abdullah et al., 2009; Wang et al., 2014) and the assessment of adaptive thermal comfort levels in hot-humid conditions (Cândido, de Dear, & Lamberts, 2011; Hwang et al., 2009; Makaremi et al., 2012). However, unlike other climate specific research discussed, there is a considerable amount of experiences focused on active cooling technologies.

Topics of interest concerning active technologies are the development of energy use estimation models for the design of HVAC systems (Huang & Lin, 2007; Lam & Hui, 1995; Lam, Li, & Cheung, 2003), analyses of current policy related with the design and operation of air-conditioned offices (Wong & Mui, 2009) and the evaluation of specific systems and prototypes such as decentralised AC units (Yau & Pean, 2014) or mechanical ventilation units (Kim, Leibundgut, & Choi, 2014; Yang, Sekhar, & Melikov, 2010). In terms of solar cooling research, it is worth mentioning that it is possible to encounter experiences on all three specific climate regions, which is evidence that there is scientific interest and potential for application in all these contexts.

Besides the initiatives supported by the Solar Heating & Cooling Programme, and research projects carried out by organisations such as Fraunhofer, to promote solar cooling technologies (Henning, 2007; Henning & Döll, 2012), there are other analyses on the performance and economic aspects of these systems, like the studies carried out in the Stuttgart University of Applied Sciences (HFT) on thermal and photovoltaic solar cooling (Eicker, Colmenar-Santos, Teran, Cotrado, & Borge-Diez, 2014; Eicker & Dalibard, 2011) or the generation of a technology roadmap for future development of these technologies by the Austrian Institute of Technology (AIT) (Preisler et al., 2012).

Among solar cooling experiences in hot-humid climates, it is possible to recognize the studies carried out in Australia by Baniyounes, Liu, Rasul, and Khan (2013) and experimental testing of solar desiccant technologies for application in office buildings of Hong Kong (Fong et al., 2010b, 2011). On the other hand, concerning hot-arid climate experiences, studies are concentrated either in middle east, such as assessments of possibilities for implementation in Jordan (Fasfous et al., 2013) and Qatar (Sim, 2014); or in Spain. Among Spanish experiences in the subject, there are studies concerning about the development of new models and simulation tools (López-Villada et al., 2014; Ortiz et al., 2010) and studies focused on optimization of existing technologies considering the overall system (Sanjuan, Soutullo, & Heras, 2010) or components, such as air handling units (Cejudo et al., 2013).

The methods used in the documented experiences are also noteworthy. As it was stated before, simulation is the preferred alternative in order to assess the performance of different cooling strategies or systems (Figure 2.9). This seems to be the case for all types of strategies, given the possibility of easily testing different alternatives within a cheap and controlled experimental setup when compared with built prototypes and field studies.

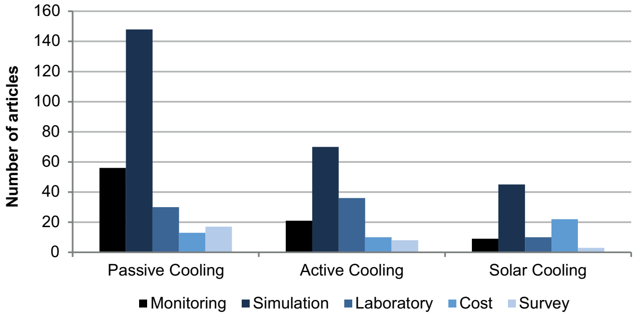


FIGURE 2.9 Cooling articles considering diverse research methods

Monitoring is also seen as a relevant method, especially in the case of passive cooling studies, however the lack of existence of a great number of built projects using solar cooling is probably the main cause for the low number of studies that consider this approach as main input. Furthermore, the existence of studies relying in experiments being conducted in laboratories is relevant for the development of new technologies and systems not yet used on buildings. This approach seems to be relevant in the case of active cooling systems development, building prototypes for the evaluation of new solutions.

Finally, it is possible to see that cost analyses have particular importance in solar cooling evaluation. This of course shows that cost is a relevant issue for the current development of these technologies, aiming to generate not just high-performance solutions, but also cost-effective ones.

§ 2.3.2 Passive cooling: building design strategies

Passive cooling strategies for buildings are categorised into three types: (a) heat prevention, (b) heat modulation and (c) heat dissipation. Heat prevention strategies are mostly related with solar radiation control, avoiding the entrance of heat from the external environment. Heat modulation strategies consider heat storage techniques in order to control heat flux indoor, also working as a complement for heat dissipation strategies, which seek to remove indoor heat releasing it into a natural reservoir (air, water, ground).

Figure 2.10 shows the amount of experiences that address different passive cooling strategies considering diverse methods for evaluation. It can be seen that solar control strategies (orientation, glazing and shading) are the most evaluated passive strategies, and particularly shading analysis have the highest results among them.

It is commonly stated that the best method for solar radiation control is to apply proper external sunshade, intercepting direct solar radiation before it falls over the window of a given wall (Ralegaonkar & Gupta, 2010). Sun shading systems have been studied since the 60s, establishing criteria for the proper design of the shadow according to the latitude of a given location (Olgyay & Olgyay, 1963). By the end of the 20th century, sun shading systems have been properly classified and described in existing literature. One common initial distinction is made regarding control possibilities of the system, separating them between movable or fixed systems (Paricio, 2000). The first ones give more possibilities for the users but have high maintenance costs, while the second ones are seen as more efficient (if well designed) but consider no possibility of control from the user and could have varying performance during the day.

TOC

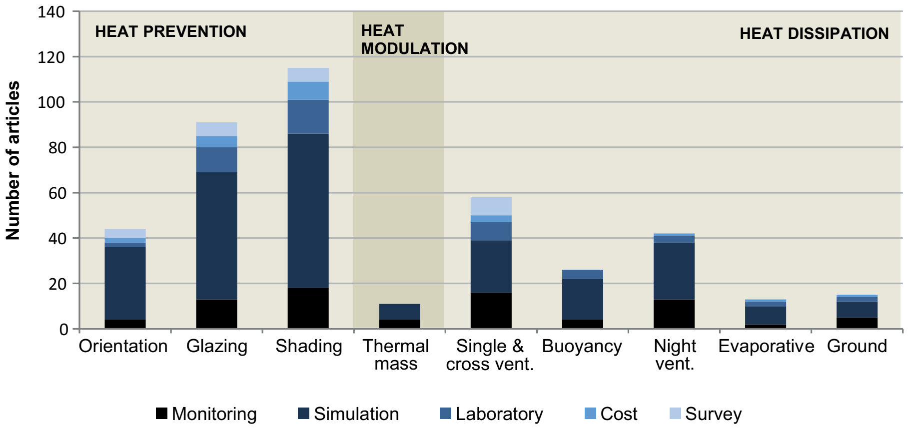


FIGURE 2.10 Passive cooling strategies in articles considering diverse research methods

Studies regarding sun shading systems have focused on optimisation of the design of the components to improve its performance, along with the development of software for multi-variable analysis and parametric design (Ahmed & Wongpanyathaworn, 2012; Gratia & De Herde, 2007c; Manzan, 2014). The reported performance of sun shading systems greatly varies among the reviewed experiences, encountering cooling demand reduction values ranging from 10 to 50% compared to reference cases. Hwang and Shu (2011) showed the impact of overhangs of different lengths on the cooling demands of a south facing office in a lightweight office building located in Taiwan, with 72% window-to-wall ratio. Their results showed a reduction of cooling loads between 7% and 11%. Ferrari and Zanotto (2012) reported cooling reduction values ranging from 10% to 27% by using external venetian blinds in different south facing offices located in several Italian cities. The worst values correspond to office buildings with low window-to-wall ratio, due to the limited action of sun shading on an already optimised façade, and vice versa. Manzan (2014) evaluated the impact of the application of flat screens parallel to the window in south facing offices in Italy, obtaining cooling savings ranging from 49% to 56% in the case of Trieste and from 30% to 46% in the case of Rome. Similarly, Pino et al., (2012) reported cooling savings of up to 54% following the application of louvres at north, east and west orientations of a fully glazed office building located in Santiago, Chile.

Besides energy performance, comfort levels of occupants have been a growing issue of concern, regarding mostly daylighting and glare problems reported on office buildings with facades with high window-to-wall ratio (Chan & Tzempelikos, 2013; Konis, 2013). Recently, research focused on occupant comfort has expanded its area of interest, considering the interaction of the user with shading systems. Occupancy patterns are seen as relevant input for the assessment of both performance of the shading system and comfort of the user, improving the knowledge regarding indoor comfort (considering not just thermal or lighting inputs, but actual human response to the environment) and at the same time refining predictive methods such as software simulation by giving real information (Van Den Wymelenberg, 2012).

It is usual to find studies that address both shading and glazing solar strategies considering also different orientations. Some experiences seek to address the overall performance of entire fenestration systems, like the monitoring campaigns conducted in Chile by Bustamante et al. (2014), or the studies carried out through simulations in USA (Tzempelikos, Bessoudo, Athienitis, & Zmeureanu, 2010) and South Korea (Yoon, Kim, & Lee, 2014); while others seek to establish comparisons between the resulting performance of the application of glazing or shading technologies (Aste, Compostella, & Mazzon, 2012).

Studies focused specifically in glazing performance seek to understand the influence of glazing in the indoor thermal conditions and energy consumption, considering both the type of glazing used (Gasparella, Cappelletti, Pernigotto, & Romagnonj, 2012; Pérez-Grande, Meseguer, & Alonso, 2005) and the window-size or window-to-wall ratio of a specific façade system (Amos-Abanyie, Akuffo, & Kutin-Sanwu, 2011; Melendo & La Roche, 2008). Eskin and Türkmen (2008) reported cooling demand savings of up to 16% by using low-e double glazing instead of clear double glazing in a simulated office building located in several cities in Turkey, while Hamza (2008) found a reduction of 13% by using reflective glazing instead of clear single glass in a south facing office located in Egypt. Regarding the impact of window-to-wall ratio, J. W. Lee, Jung, Park, Lee, and Yoon (2013) stated savings of 27-30% in buildings 50% glazed and between 41 and 44% in buildings with a window-to-wall ratio of 0.25, compared with a fully glazed reference case located in China and The Philippines.

On the other hand, there is also a considerable amount of research focused on developing and testing new technologies. Among them, it is possible to highlight the evaluation of solar film coatings (Danny H. W. Li, Lam, Lau, & Huan, 2004; Danny H. W. Li, Lam, Wong, & Tsang, 2008; Yin, Xu, & Shen, 2012), vacuum glazing (Eames, 2008) and “smart” adaptive glass, such as electrochromic or aerogel glazing (Bahaj et al., 2008; James & Bahaj, 2005; Lorenz, 1998). Aldawoud (2013a) evaluated the use of electrochromic glass in a building located in Phoenix, USA; obtaining solar heat gain values 57% lower than a reference building with double clear glazing. Similarly, Bahaj et al. (2008) reported a cooling demand reduction of 45-49% by using different electrochromic glass panes instead of a low-e double glass unit in a simulated office building located in Dubai, United Arab Emirates.

TOC

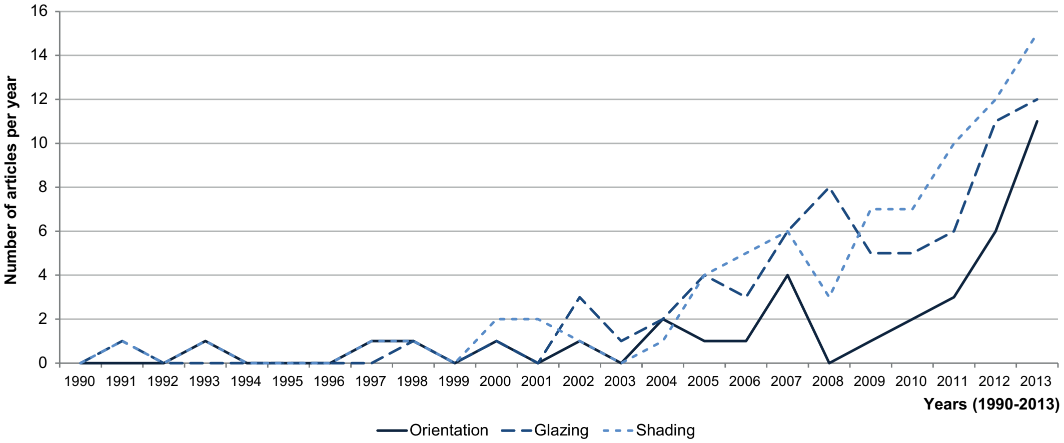


FIGURE 2.11 Heat prevention strategies in journal articles.

Passive heat dissipation strategies have also been researched in the recent years, focusing on natural ventilation. Besides research on single and cross-ventilation in office buildings (Belleri, Lollini, & Dutton, 2014; Stavrakakis et al., 2008; Wei et al., 2010), continuous research regarding buoyancy-driven stack ventilation has been carried out by several authors, considering the performance of multi-layered facades (Gratia & De Herde, 2004a; Jiru, Tao, & Haghighat, 2011) or whole-building scale strategies such as atriums and solar chimneys (Aldawoud, 2013b). Radhi et al. (2013) stated that the use of a ventilated double skin façade could lower cooling demands by up to 17% through the simulation of a real university building located in the United Arab Emirates. Nevertheless, Gratia and De Herde have claimed that even if the use of double skin facades may be beneficial in some cases, they need to be carefully designed according to ventilating patterns to avoid overheating in the cavity (Gratia & De Herde, 2004b, 2007a).

Within ventilation strategies, night ventilation has been consistently researched as a specific subject for the last 15 years. Some early experiences dealt with the evaluation of these strategies via on-site measurements (Geros, 1999; Kolokotroni et al., 1998; Pfafferott et al., 2004), while others used simulations to assess the energy saving potential of their application (Campaniço, Hollmuller, & Soares, 2014; Roach, Bruno, & Belusko, 2013), even discussing possibilities for implementation in different climate contexts (Artmann, Manz, & Heiselberg, 2007; Ramponi, Angelotti, & Blocken, 2014). Campaniço et al. (2014) evaluated the application of several night cooling strategies in an office building located in Geneva, obtaining cooling savings between 41% and 66% compared to a non-ventilated reference. Similarly, Ferrari and Zanotto (2012) found cooling savings of up to 64% after simulating the impact of 5 air changes per hour (ach) from 23:00 to 07:00 in office buildings located in several Italian cities. Better results were reported by Roach et al. (2013) for night ventilation application in the Australian context. The authors claimed cooling savings ranging from 69% to 83%, depending on the air change rate in a simulated entire floor of an office building located in Adelaide.

Besides energy assessments, some studies focus in specific aspects in an attempt to understand the impact of different variables in the overall performance, such as surface convection during night cooling (Leenknegt et al., 2012) or window-use patterns (Yun & Steemers, 2010). In terms of optimisation, it has been stated that night ventilation effectiveness is greatly improved when it is combined with heat modulation strategies like the use of exposed thermal mass, storing heat to be released into the ambient during night time (Corgnati & Kindinis, 2007; L. Yang & Li, 2008).

Additionally to ventilation strategies, studies about evaporative and ground cooling strategies are worth mentioning due to the current interest on alternative cooling systems. The application of these strategies in office buildings falls into the definition of hybrid systems based on passive environmental heat sinks discussed in the introduction, due to the incorporation of low energy equipment such as fans and small size pumps. Although these strategies have not been studied as much as the others mentioned, it is possible to see that scientific interest on both subjects has increased during the last years (Figure 2.12) probably as a result of efforts to find new cost-effective strategies for cooling.

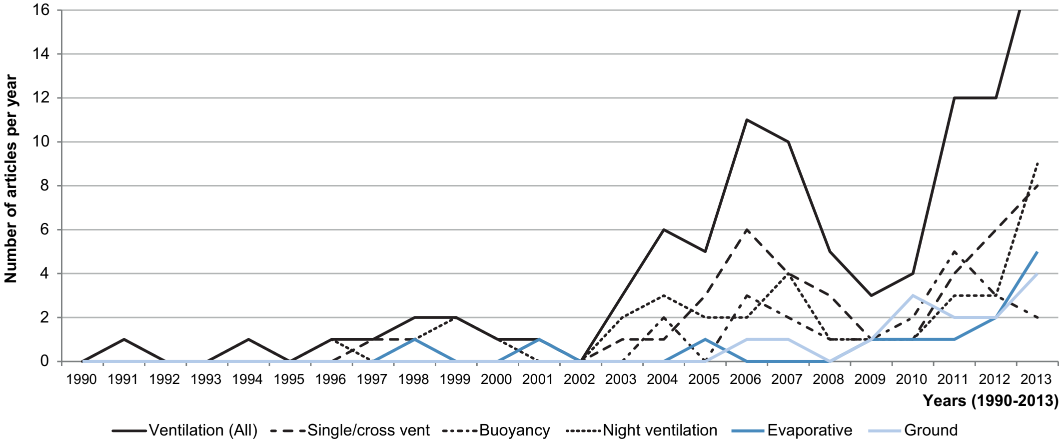


FIGURE 2.12 Heat dissipation passive cooling strategies in journal articles.

Evaporative cooling techniques have been researched mostly for hot-arid climate applications, considering them along with ventilation strategies in order to bring pre-cooled fresh air into the buildings. Experimental applications have been developed and tested, either integrated in façade modules (Abu Khadra & Chalfoun, 2014) or integrated in larger structures like solar chimneys (Abdallah et al., 2013). Also, the efficiency of evaporative cooling is being analysed under different climate contexts, in order to explore the potential for implementation in other regions (Hanby & Smith, 2012; Morgado et al., 2011). Ezzeldin and Rees (2013) studied total energy savings related to the use of evaporative cooling combined with ventilation in several hot arid locations (Australia, Bahrain, Egypt and Saudi Arabia). Their results showed energy savings ranging from 43% to 60% and from 52% to 66% considering high and low internal gains respectively.

Regarding ground cooling techniques, the studies are focused on the development of heat exchangers, either for stand-alone application (Hollmuller & Lachal, 2014; Sagia, Rakopoulos, & Kakaras, 2012), or coupled with other strategies such as thermal storage (Pardo et al., 2010), evaporative cooling (Bansal et al., 2012) or ventilation through the use of solar chimneys (H. Li et al., 2014; Maerefat & Haghighi, 2010; Yu et al., 2014). Pardo et al. (2010) encountered energy savings in electrical consumption of up to 40% by comparing the application of several combinations of ground coupled heat pumps and thermal storage devices, to a referential HVAC system driven by an air to water heat pump in the Mediterranean coast. H.Li et al. (2014) proposed a coupled system consisting of a solar collector enhanced solar chimney and an earth-to-air heat exchanger, and measured its performance in Omaha, USA. The results showed that the system was capable to maintain indoor air temperatures between 21.3 and 25.1 °C, with a maximum cooling capacity of 2,582 W, which almost covered the building design cooling load. The discussed findings related to these hybrid technologies are regarded as promising, achieving relevant energy savings as complement to the building design strategies previously mentioned. Nonetheless, further research is needed in order to promote their development as competing alternatives to conventional vapour based cooling technologies.

§ 2.3.3 Solar cooling: renewable sources for complementary cooling

Solar cooling systems may be classified according to their energy input into two main groups: solar electric process systems (using PV cells to transform solar radiation into electric energy) and solar thermal process systems (using heat transformation process as base for cooling purposes). Furthermore, solar thermal process systems may be classified into solar thermo-mechanical systems, thus transforming thermal energy into mechanical power; and solar thermal systems, using the stored heat directly in sorption based cooling technologies (Henning, 2007).

Figure 2.13 shows the amount of studies within the database that address each type of the mentioned solar cooling systems. Thermal cooling systems appear to be much more researched than the rest, however it is important to state that all studies grouped under 'Electric' only consider the application of PV cells used explicitly for solar cooling purposes, given the explained search parameters. PV cells are used to generate energy, and cooling is only one of the possibilities for using this energy. So, research related with the integration of PV cells in the façade is not restricted nor specifically related to the development of solar electric cooling systems.

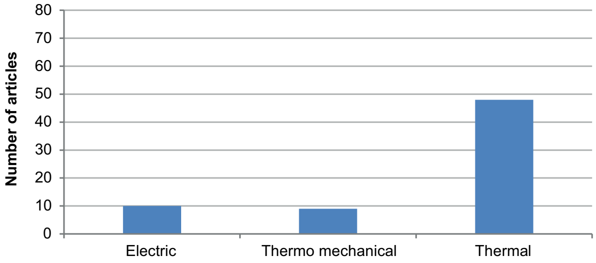


FIGURE 2.13 Solar cooling systems in journal articles.

Evidence of this is the fact that all specific solar electric cooling studies reviewed also addressed thermal solar cooling. These studies consist either of the development of a PV/thermal mixed-mode solar cooling system (He et al., 2014; Liu, Zhang, & Gong, 2014; Mei et al., 2006) or comparative analyses between electric and thermal driven solar cooling considering both energy performance and economic assessment (Eicker, Colmenar-Santos, et al., 2014; Lazzarin, 2014; Noro & Lazzarin, 2014; Otanicar, Taylor, & Phelan, 2012).

On a side note, besides specific cooling application, the integration of PV cells in facades has been driven by the development and evaluation of new façade concepts such as photovoltaic double-skin façades (Peng, Lu, & Yang, 2013; Qiu et al., 2009), semi-transparent PV glazing (Fung & Yang, 2008; D.H.W. Li et al., 2009) or PV integrated shading devices (Frontini, 2011; Mandalaki et al., 2012; Yoo & Manz, 2011). Furthermore, there are studies carried out on laboratories focused on specific aspects for PV application and operation, such as the technical development of new optimized concentrators (Mallick et al., 2004) or studies about the effect of overheating in PV cell efficiency and the use of ventilation alternatives to avoid it (Kaiser et al., 2014; Mirzaei, Paterna, & Carmeliet, 2014).

Regarding thermo-mechanical cooling systems, most of them are mentioned in review articles that address different possibilities for solar cooling (Anand, Gupta, & Tyagi, 2015; Brown & Domanski, 2014; Sarbu & Sebarchievici, 2013). However, there are also research experiences concerned with the development of cooling systems based on these principles. Main examples of this are the studies on solar ejector refrigerating (Buyadgie, Nichenko, & Schenyh, 2010; Chunnanond & Aphornratana, 2004; Yapıcı & Ersoy, 2005) and the exploration of Rankine cycle systems for cooling application (Quoilin et al., 2011; Zandian & Ashjaee, 2013). Huang et al. (1998) measured COP values of 0.22 on a prototype of a solar ejector system at a temperature of 88 °C and solar radiation levels of 700 W/m^2, while Buyadgie et al. (2010) stated that even though COP values of 0.25-0.3 were considered high years ago, nowadays it is common to obtain COP values of 0.5 or higher using ejector based technologies. Regarding the application of rankine cycles, Wu et al. (2012) simulated the performance of a façade integrated prototype, being able to cope with cooling requirements from a hot and humid climate, with an annual solar fraction of about 13%. The thermal efficiency of steam rankine cycles was studied by Zandian and Ashjaee (2013), recombining a dry cooling tower with a solar chimney. CFD simulation results showed an increase of up to 37% in the thermal efficiency of a power plant located in Iran, selected as case study.

As mentioned before, solar thermal systems are most studied within solar cooling related articles. Even built examples have been evaluated as part of research projects such as SACE and SOLAIR. Solar thermal systems are generally divided into two categories: closed and open cycles. Closed-cycle systems are based mainly on the absorption cycle, considering absorption and adsorption; while open-cycle systems consider desiccant materials in either solid or liquid state (Balaras et al., 2007).

Absorption systems are the most studied among solar thermal cooling technologies (Figure 2.14). Energy performance of these systems is assessed either via numerical simulations and modelling (Argiriou et al., 2005; Labus, Bruno, & Coronas, 2013; Marc et al., 2011) or via empirical validation through monitoring of built examples (Monné et al., 2011; Rosiek & Batlles, 2009). Also, there are documented experiences considering all three selected climates: hot-humid (Li, Ye, & Liu, 2014), hot-arid (López-Villada et al., 2014; Sanjuan et al., 2010) and temperate (Desideri, Proietti, & Sdringola, 2009; Tamasauskas, Kegel, & Sunye, 2014), which shows scientific interest on the development and application of these systems on diverse contexts. Pando et al. (2014) simulated the performance of an hybrid solar-gas absorption heat pump of 17.6 kW of cooling capacity in Mexico, showing a reduction in gas consumption of 24%

during the evaluated period. Qu et al. (2010) used monitoring and simulation tools to assess the performance of a LiBr/H_2O absorption chiller with a cooling capacity of 16 kW in Pittsburgh, USA. It was found that the system could potentially supply 39% of the cooling demands, if it included properly sized storage tanks and low diameter connecting pipes. Rosiek and Batlles (2009) also monitored the performance of a LiBr/H_2O absorption chiller in a building located at Spain, under different operation modes. Experimental results showed that in practice it is highly possible to obtain COP values around 0.6.

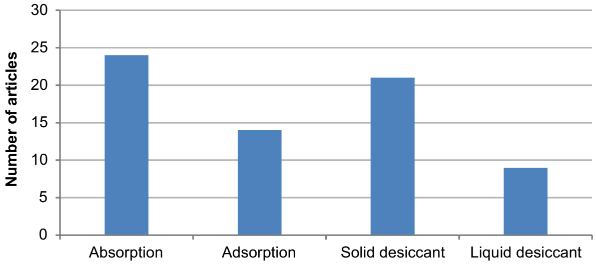


FIGURE 2.14 Solar thermal cooling strategies by type in journal articles

During the last years, there has been increasing interest on adsorption systems as well. Besides some studies carried out to evaluate their performance considering materials such as activated carbon and ammonia (Louajari, Mimet, & Ouammi, 2011; Yeo, Tan, & Abdullah, 2012); there are also studies focused on the development of compact units with small range capacity in order to promote widespread use of adsorption driven solar cooling systems (Weber et al., 2014). This seems relevant for further exploration on the possibilities of architectural integration of solar driven systems. Fadar et al. (2009) simulated the performance of a Carbon/ammonia adsorption chiller, obtaining a refrigeration cycle COP of 0.43 by producing a daily useful cooling effect of 2,515 kJ per 0.8 m2 of thermal collector area; while Sim (2014) evaluated the performance of a small size adsorption system of 4.5 kW cooling capacity in Doha, Qatar. The results from numerical models showed that the system could reduce the electricity consumption by 47% compared to a compression cooling system, being labelled as promising for further development.

On the other hand, open-cycle systems have been studied as well, focusing either on monitoring some built experiences (Angrisani et al., 2010; Eicker et al., 2010), or performance optimisation via simulation of new concepts (Cejudo et al., 2013; Zhang & Niu, 2003). The use of evaporative cooling as complement of desiccant systems also has been studied given its impact on the cooling performance of the systems (Bongs, Morgenstern, & Henning, 2012; Vitte et al., 2008). Mei et al. (2006) reported an average COP of 0.52 over summer season with a solar fraction of 75% for a solar powered desiccant cooling system coupled with evaporative cooling in Barcelona. Similarly, Cejudo et al. (2013) studied the energy performance of solar desiccant air handling units, finding up to 35% savings in two warm climates in Spain. A solid desiccant system was also monitored by Eicker et al. (2010) in Stuttgart, reporting an average seasonal COP close to 1.0 and an electric COP between 1.7 and 4.6, with a dehumidification efficiency of 80%.

Lately, liquid desiccant systems have gained attention, because of their lower heat requirements. Furthermore, these systems can work with temperatures below 80 °C, which makes them more effective than solid desiccant systems in terms of heat input (Sarbu & Sebarchievici, 2013). Research is being done in order to develop commercial cooling systems mostly through experimental evaluation of prototypes (Audah, Ghaddar, & Ghali, 2011; Ge, Xiao, & Xu, 2011; Zhang et al., 2013). Qi et al. (2014) studied the cost-effectiveness of a liquid desiccant system coupled to an air handling unit for cooling for application in hot-humid climates (Houston and Singapore). The results showed that the system could reduce up to 40% of the total energy consumption during cooling seasons, with a calculated cost payback period of approximately 7 years. A similar payback period (7 years and 8 months) was calculated by Keniar et al. (2015) for the use of a liquid desiccant unit in Beirut, compared to investment costs of vapour compressor units.

Table 2.3 shows cooling capacities and coefficients of performance (COP) of market ready solar thermal technologies, reported by several research projects (Balaras et al., 2007; ClimaSol, 2002; Jaehnig, 2009; KeepCool, 2005; Kohlenbach & Jakob, 2014; SOLAIR, 2009). It is possible to observe that even though COP values have remained stable for commercial applications over time, the ranges of cooling capacity have been expanded, particularly in the case of absorption and adsorption heat pumps. The fact that smaller capacities have been pursued seems especially promising regarding possibilities for integration in building components, and widespread application at lower implementation costs (Jaehnig, 2009).

Given that solar thermal collectors play a fundamental role in the application of solar thermal cooling technologies, there is also research that deals specifically with their development and evaluation. As it was stated when discussing PV related research, also in this case the point is to explore specific issues regarding solar collectors which can be used (or not) for cooling purposes. It is possible to see studies focused on evaluating the performance of different types of collectors, such as flat plate (Deng et al., 2013), evacuated tube heat pipe (Fiaschi & Manfrida, 2013; Nkwetta & Smyth, 2012) and unglazed transpired solar air collectors (Badache et al., 2013).

TOC

TABLE 2.3 Cooling capacities and Coefficients of performance (COP) of market ready solar thermal technologies reported by several research projects over time.

REFRIGERANT CYCLE	COOLING PRINCIPLE	TYPICAL COOLING CAPACITY					
		SACE (2002-2004)	ClimaSol (2002-2005)	KEEPCOOL (2005-2007)	SOLAIR (2007-2009)	SHC IEA Task 38** (2006-2010)	Kohlenbach & Jakob (2014)
CLOSED CYCLE	ABSORPTION*	-	15 - 5,000kW	15 - 5,000kW	4.5 - 5,000kW	4.5- kW	10 – 20,500 kW
	ADSORPTION	-	50- 430 kW	50- 430 kW	5.5- 500 kW	2.5- kW	19 – 1,000 kW
OPEN CYCLE	SOLID DESICCANT	-	20- 350 kW	20- 350 kW	20- 350 kW	-	6 - 300 kW
	LIQUID DESICCANT	-	-	-	-	-	-
		TYPICAL COEFFICIENT OF PERFORMANCE (COP)					
CLOSED CYCLE	ABSORPTION*	0.6-0.7	0.6-0.75	0.6-0.75	0.6-0.75	0.6-0.78	0.5-0.7
	ADSORPTION	0.55-0.65	0.5-0.7	0.5-0.7	0.5-0.7	0.5-0.6	0.5-0.65
OPEN CYCLE	SOLID DESICCANT	-	0.5- >1	0.5- >1	0.5- >1	-	0.5-1
	LIQUID DESICCANT	0.5	>1	-	>1	-	1

** Considering only single-effect absorption chillers*

*** Review focused on market available systems with cooling capacity below 20kW*

Nevertheless, it is also possible to see studies that address aesthetical aspects of solar collectors, that is of course, without compromising performance issues. Examples of these are the studies carried out by Andreas Schüler to develop coloured glazed thermal collectors through the use of multilayer films (Schüler et al., 2005; Schüler et al., 2004) or the development of selective paint coatings (Joly et al., 2013; Orel et al., 2007). Furthermore, the so called 'architectural quality' of thermal collectors has been explored in research projects conducted by the IEA, understanding its importance in achieving a successful architectural integration in buildings (Munari Probst & Roecker, 2007).

The mentioned studies show that there have been advances on the architectural integration of solar collectors, even proposing façade design concepts using curved collectors (Rodríguez-Sánchez et al., 2014), integrating evacuated tubes into fenestration systems (Maurer et al., 2012) or even using shading devices as solar thermal collectors (Palmero-Marrero & Oliveira, 2006). However, there is little research about façade integration of solar cooling systems, except for some scattered experiences.

TOC

Among some interesting examples it is possible to mention the experiences conducted by Wu (2012) and Chan (2012) in the University of Melbourne and the National University of Malaysia respectively. The first one considers the use of evacuated tube collectors within the cavity of a double-skin façade, coupled with an organic Rankine cycle turbine (ORC) which drives the compressor of a vapour compression cycle (VCC) chiller. Although a chiller is used, it is an interesting exploration on the role of the façade as part of an ORC-VCC coupled cooling system.

The second example is a 3-layered façade system that consists of: an external aluminium transpired plate (solar collector), an intermediate sand tile wall (evaporative pad) and the internal building wall. The operation of the system is based on the use of indirect evaporative cooling, that is cooling the air without adding moisture to it. This system was evaluated via mathematical models and experimental setup obtaining similar energy performance than other solar indirect evaporative cooling and desiccant cooling systems (Chan et al., 2012).

Given the presented overview, it is possible to state that there is potential for the design of solar cooling integrated façade systems. However, there are various issues, either technical requirements (size and performance of the components and systems), or the so-called 'architectural' aspects (design and operation of integrated façades), that need to be further studied in order to conceive a roadmap for the development of new architectural façade products.

§ 2.4 Conclusions

The main purpose of this chapter was to promote the development of façade related strategies and systems for low-energy cooling in office buildings, by presenting a panorama of research experiences from the last twenty five years. Given the nature of the chapter, it is possible to state conclusions about both the methods used in the review and the content of the discussion itself.

The analysis of the information was done through a review of journal articles from three online databases. The amount of available information called for the use of a systematic approach, from the definition of search parameters and new keywords to the use of descriptive analysis in order to explore the data. The proposed method was successful in its attempt to categorise and visualise high amounts of information in broad levels, while providing examples through in-depth reviews of some of the

TOC

experiences. However, there are also limitations in this approach. The most important one is that the analysis of the database, and thus, the main findings of the chapter are inherently linked to the defined parameters and keywords. As mentioned before, it is only possible to perform an analysis and state valid conclusions about topics and concepts specifically addressed as keywords and search parameters.

In terms of the content, the presented review sought to visualise existing knowledge concerning cooling strategies and systems for office building application, in order to detect research trends and discover knowledge gaps for further development. Thus, main findings may be classified following the same logic.

§ 2.4.1 Research trends

Cooling research: high relevance and increasing interest. It is relevant to state that cooling research is currently a very active field, having experienced an important increase of related publications up to date, especially since the last ten years. There is interest in cooling research not only in warm climates, but temperate climates as well, which seems to be true for passive, active and solar cooling systems. In that aspect, solar cooling research is seen as a particular field on its own, dealing with specific issues while gathering special attention from researchers.

Research methods: simulating performance. Software simulations seem to be the primary tool for cooling research, which makes sense for performance driven developments. However, there is also an increasing number of monitoring campaigns which may present invaluable information about the actual performance of strategies and systems under operation. This allows for feedback in a very clear performance driven research field.

Passive cooling: solar control and ventilation. There are clearly two main sub fields within passive cooling research: research about solar control strategies (shading, glazing and building orientation), and research on ventilation strategies (single-sided and cross ventilation, buoyancy effect and nocturnal ventilation). There is substantial information and specialized interest in these areas to identity them as particular and differentiated research fields.

TOC

§ 2.4.2 Knowledge gaps

Cooling systems: application and architectural integration in the built environment. Even though there is an increasing amount of cooling research, there is need for specific research regarding possibilities for application and architectural integration of cooling systems, without neglecting performance issues, of course. This need for practical information is particularly true in the case of low-energy active technologies and solar cooling, in order to promote accessible guidelines for a wide spread use of these systems by architects and building professionals.

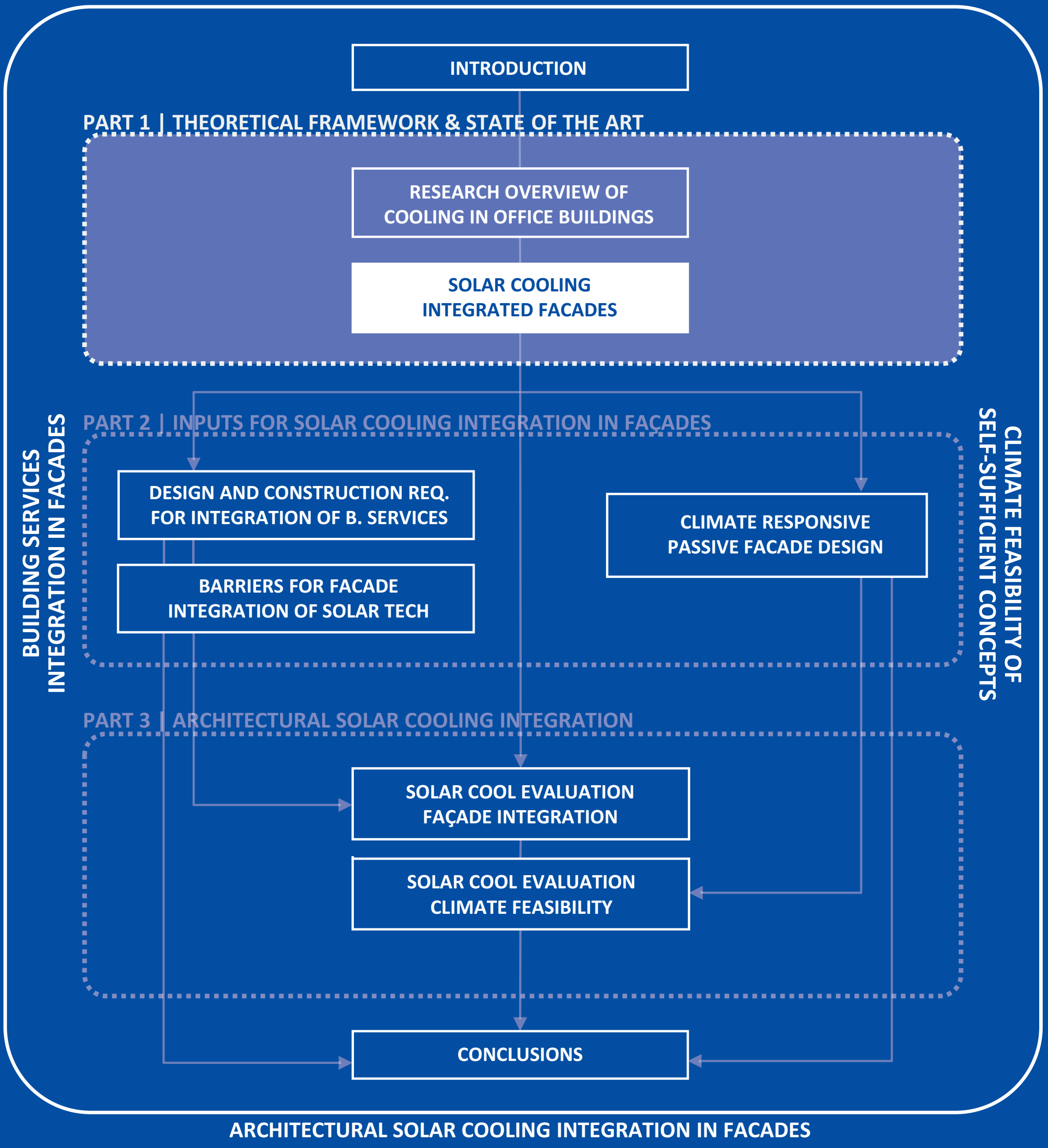
Technological development: performance and application of less explored systems. An obvious gap is seen in the lack of articles addressing some specific cooling strategies, such as the use of thermal mass, evaporative and ground cooling, when comparing with sun shading or ventilation strategies. Even though these strategies have also experienced an increase in terms of number of related articles, there is room for much more growth regarding both performance and application issues. The same could be said for solar cooling systems. There is room for exploration of thermomechanical systems, along with research about compact sized adsorption chillers and liquid desiccant based technologies. Furthermore, the smaller potential sizes of these systems present favourable possibilities for architectural integration in office buildings.

Feedback: operation and implementation data. As stated, cooling research has mostly relied on software simulation methods and monitoring in a lesser extent. While monitoring provides invaluable information about the actual performance of running systems, there is need for more information about their operation, especially taking users' perception and their behaviour into account. Survey based studies should be promoted along with studies about implementation and maintenance costs for new cooling technologies. Clear information about costs would facilitate the decision making process related with building systems design and operation, for both clients and architects.

As a final remark, it is important to reaffirm that even though there is increasing scientific interest in cooling research, much more information is needed to facilitate a wide spread use of low-energy cooling technologies in office buildings. Issues such as the performance limits of passive strategies in hot climates, the use of renewable sources of energy for cooling, or the energy efficiency of low-energy active systems are tasks which, without being knowledge gaps, still require further attention to achieve the goals of nearly zero energy consumption in office buildings.

TOC

COOLFACADE



TOC

3 Solar cooling integrated facades

Framework for the integration of solar cooling technologies in the building envelope[2]

Solar cooling systems have gained increased attention these last years, for their potential to lower indoor temperatures using renewable energy. However, architectural integration of these systems in buildings has not been fully explored. Current developments such as small scale solar driven heat pumps and solar cooling kits commercially available for application raise questions about how to successfully integrate these systems into buildings, while present interesting opportunities for the development of new performance based façade components or even self-sustaining cooling façade modules for high-performing commercial buildings. So, *what are the conceptual issues and state-of-the-art components and systems to consider for solar cooling façade integration?*

This chapter discusses current possibilities for façade integration of solar cooling systems, generating a framework for the understanding and further development of solar cooling façade systems. The proposed framework was made by means of a review of solar cooling technologies and solar cooling façade concepts reported by several researchers. The outcomes of the chapter are a matrix outlining the possibilities for the integration of several components and subsystems from the entire cooling process (cooling generation, distribution and delivery), and an early assessment of the development level of state-of-the-art experiences within the field considering examples from current research projects and working prototypes, for the development of solar cooling integrated façade concepts.

---

[2] Published as: 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. doi: 10.1016/j.energy.2017.04.141

§ 3.1 Introduction

The energy utilised for the cooling of buildings is an important aspect of the current public agenda towards sustainability. Buildings account for almost a third of the global energy consumption (Gea, 2012), while studies show that refrigeration and air conditioning are responsible for about 15% of the total electricity consumption in the world (CICA, 2002). Furthermore, research projects supported by the European Union, show that energy needs for cooling are increasing and are expected to maintain that trend during the coming years (ECOHEATCOOL, 2006; Jochem & Schade, 2009; Weiss & Biermayr, 2009). On a global scale, energy projections for the next decades show that energy consumption will increase by 34% between 2014 and 2035, mostly due to demands from fast-growing emerging economies (BP, 2016). It has been stated that just Non-OECD Asia (including India and China) will account for more than half of the world's total energy consumption increase between 2012 and 2040 (DOE/EIA, 2016). On the one hand, this means that implementing energy saving measures will not be enough to cope with increasing energy consumption, hence renewable energy sources will need to be promoted to drive long term economic growth. On the other hand, the fact that most emerging and growth leading economies (EAGLEs) experience warm climates (BBVA, 2016), demands a special focus on the development of novel cooling solutions for the built environment.

Solar cooling systems have gained increasing attention these last years, for their potential to lower indoor temperatures using renewable energy (Prieto, Knaack, Klein, & Auer, 2017). Several research projects have contributed to the understanding and development of solar cooling systems, mostly referring to thermally driven technologies (Balaras et al., 2007; ClimaSol, 2002; SOLAIR, 2009), while the use of PV panels as main driver of electric based cooling has also been advocated as solar driven processes (Fong et al., 2010a; Otanicar et al., 2012). Nonetheless, these systems have not been largely implemented in the built environment due to several barriers ranging from economic aspects to product related issues. Regarding the integration of solar thermal collectors and PV panels in buildings, research shows that besides economic issues; lack of knowledge and suitable products for architectural integration are among the most pressing barriers for widespread application (Farkas & Horvat, 2012; Prieto et al., 2017b). Hence, it seems reasonable to expand current knowledge on solar cooling, focusing on application possibilities, to promote the development of new architectural products.

In this line, a small but increasing number of researchers have explored integration potential of these technologies in the building envelope, developing façade components or systems which integrate solar cooling equipment. Façade integration

TOC

of building services in general, has been reported to have advantages not only in terms of performance, but also from a constructional point of view, considering benefits associated with prefabrication and the resulting high quality of factory assembled components, besides potentially reducing time needed for building on-site (Knaack et al., 2007). Furthermore, the possibility of using the façade itself as a heat dissipation system is seen as an opportunity for the development of self-sustaining cooling façade modules to be applied either on new buildings or refurbishment projects, avoiding energy intensive cooling equipment whatsoever in the line of new 'nearly zero' energy standards.

This article seeks to discuss the integration of solar cooling systems into the building envelope, by proposing a framework for the understanding of solar cooling integrated façade systems. This is regarded as a necessary step to assess facade integration feasibility of existing technologies, while providing a systematic approach for the categorisation of current and future solar cooling integrated façade concepts.
The chapter focuses on the identification of the working principles and physical components and connections to be considered for façade integration of different solar cooling technologies, along with documented façade concepts to illustrate existing possibilities. The comparison of the performance of particular systems is out of the defined scope, being regarded as a matter to be further discussed in following articles, due to the complexity and variety of technical solutions associated with each cooling principle. Nevertheless, general performance indexes were included for referential purposes in the most mature technologies.

The article is structured in three sections: façade integration, solar cooling technologies, and solar cooling integrated facades. In the first section, the concept of facade integration is discussed, describing possibilities and boundaries for its understanding and application. A review of existing solar cooling principles is presented in the second section, considering technical components to be integrated and common relations among them for application. Finally, the third section deals with solar cooling integrated facades, defining the proposed concept and reviewing several façade systems in different development stages, that integrate the solar cooling principles previously discussed, in order to present the state of the art of related experiences in the field.

§ 3.2 Integration in architecture and façade design

The word integration has been generally used within the field of architectural design to advocate for an holistic design process, combining different variables in an efficient manner under an interdisciplinary integrated approach (Lechner, 2014; Schuler, 2002). In constructional terms, this integrated approach has promoted the development of multifunctional building components, striving for a more efficient use of available resources. Thus, several functions have to be combined into one element, which usually considers the assimilation of 'new' functions that were otherwise fulfilled by separate building components or building services.

The idea to combine several functions into one particular element has encountered interest among façade designers, due to the multiple requirements that have to be fulfilled by the building enclosure. Herzog et al. (2004) provided a basic theoretical frame for the understanding of all basic façade functions, categorising them in two main groups: protective and regulatory. Protective functions are fulfilled by the main facade component, that is, considering elements such as structure, cladding and seals to successfully protect an internal space against the dangers of the external environment.

Regulatory functions comprehend all necessary functions to provide a comfortable inner space, allowing for a controlled exchange between inside and outside.
Thus, understanding the façade not only as a limit but also as a filter, by means of supplementary measures and supplementary building services. Supplementary measures refer to constructive elements that fulfil their regulatory function without using additional energy. Some examples are sun shading systems, extra thermal insulation, and anti–glare protection. Supplementary building services are technically complex systems, driven by energy to cope with particular requirements. Examples are air conditioning units, artificial lighting and energy generation systems, such as photovoltaics or thermal collectors. Several authors (Herzog et al., 2004; Lechner, 2014) have argued that the use of these 'supplements' should always follow a hierarchical order. This means that the installation of building services should only be considered after the application of supplementary construction measures, given the additional energy consumption and maintenance costs of building services.

The development of façade concepts driven by regulatory functions and environmental performance has been explored by several authors. This line of research has been fuelled by the desire to develop new façade concepts that fulfil comfort requirements throughout an efficient use of available resources, integrating new functionalities in new 'high-performance' (E. Lee et al., 2002) 'intelligent' (Compagno, 2002; Wigginton

& Harris, 2002), ‘advanced’ (Selkowitz, 2001; Warren, 2003), or ‘adaptive’ facades (Knaack et al., 2007). Among examples of façade concepts based on the integration of specific functions are exhaust-air facades (Knaack et al., 2007), heat extraction double-skin facades (E. Lee et al., 2002) and ventilated double facades (Loncour et al., 2004).

If supplementary measures are not enough to fulfil indoor requirements, building services must be considered. The potential use of building services as architectural elements was early addressed by Banham in the late 60s, instigating architects to adopt the possibilities given by new technologies in the field of environmental control (Banham, 2013). Herzog et al. (2004) referred to the integration of building services in the façade as ‘decentralised façade services’, to name the cases when required equipment is not installed in a central plant but is rather decentralised in façade components. Indubitably façade designs that consider decentralised services may be grouped under concepts such as high-performance or adaptive façades, but the particular integration of building services is recognised as a specific trend within the field.

This distinction was also evidenced by Knaack et al. (2007) while discussing the different possibilities grouped under the definition of ‘adaptive’ façades. In an effort to categorise and differentiate several façade systems the authors distinguished a particular type resulting from the integration of functions such as air-conditioning or energy generation. The application of these ‘hybrid’ or ‘integrated’ façades present advantages both in terms of performance and construction. However, the authors stated that close collaboration between different disciplines is a main condition for the development of ‘integrated’ façades, under an efficient and coordinated design.

Klein (2013) addressed this issue by adding another level into the understanding of building services integrated facades. As part of his PhD dissertation, the author established the difference between ‘integral’ and ‘modular’ construction as two ways to integrate functions into the building envelope. The former considers the fulfilment of the functions by one element, while the latter is presented as the sum of different parts connected to form a whole. Even though the use of the word ‘integral’ may seem redundant, this distinction adds an important characteristic for the conception of integrated façade systems in early design stages. Furthermore, the author claimed that the choice for each type of construction has an influence on both the material side and the immaterial side of a product, pointing out that the design of an ‘integral’ product requires a different design strategy with a much closer collaboration of all involved parties, whereas ‘modular architecture’ needs a better management of the systems and their interfaces (Klein, 2013).

TOC

§ 3.2.1 Façade integration of regulatory functions

Figure 3.1 shows a summary of the discussion presented above, organising the information gathered from the literature to define the basis for façade integration of environmental control methods (regulatory functions). On the left side, a flowchart shows the hierarchical decision-making process for façade integration. Following the conducted review, the use of passive or low-energy supplementary measures should always be the first step to cope with environmental requirements. Then, the second step is the integration of active building services, following either an integral or a modular design approach.

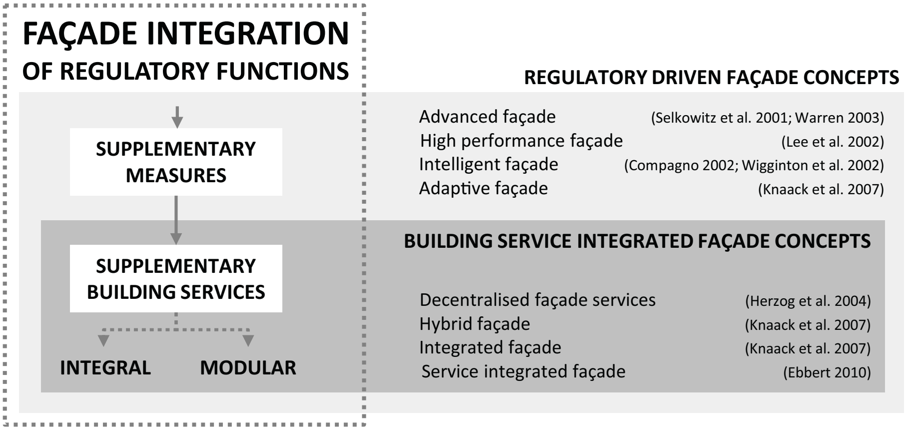


FIGURE 3.1 Scheme for façade integration of regulatory functions

On the right side, several façade concepts found in the literature are presented, organised in two groups: a broad group considering regulatory driven façade concepts, and a specific sub-group within the first one, which contains building service integrated façade concepts. Therefore, the first group comprehends all reviewed concepts; integrating either supplementary measures, building services, or both. The second group, or rather sub-group, particularly addresses the integration of building services into the façade, being established as a specific trend within the field.

This chapter seeks to explore integration possibilities of solar cooling systems, so it focuses on the identified sub-group of building service integrated façade concepts. Although supplementary measures are recognised as a necessary first step to cope with indoor comfort requirements, the description of passive strategies or supplementary measures for cooling is out of the scope of the present document. Hence, the chapter explores current solar cooling principles and associated technical components to generate an overview of possibilities for the further development of solar cooling integrated facades.

§ 3.3 Solar cooling technologies for façade integration

A review of solar cooling technologies was conducted to generate an overview of current technical possibilities to consider for façade integration. The technologies are described and presented in an orderly way, following a categorisation system proposed in the chapter. This categorisation aims to be useful during early design stages, not only showing existing technologies or components, but also stating potential relationships between them for their application.

This overview seeks to explore technological possibilities for the development of self-sustaining solar cooling façade modules. Thus, the review also considered complementary components not exclusively defined as solar cooling technologies, but fundamental for the overall operation of any cooling system to be integrated in the building envelope. A cooling system basically comprehends five elements/stages: the room to be conditioned, heat transfer equipment, the refrigeration machine, heat rejection equipment, and the external heat sink (Daniels, 2003; Lechner, 2014). While solar cooling technologies account for cooling generation, conventional equipment needs to be coupled with the refrigeration machine for heat transfer and rejection.

§ 3.3.1 Review of classification criteria

There are different alternatives for the classification of cooling systems. A list of available low-exergy technologies for heating and cooling was compiled as an outcome of IEA Project Annex 37, based mainly on their primary function (Ala-Juusela, 2003). Thus, the technologies were categorized under five main groups: surface heating and cooling, air heating and cooling, generation / conversion of cold and heat, thermal storage, and finally, distribution. The first two groups have more impact on architectural design while the rest are more related to energy issues (Hepbasli, 2012).

Additionally, the list considered a brief evaluation providing an overview of these technologies in terms of their suitability, level of development, costs, and operational temperature ranges for cooling and heating.

A different approach was used by Kalz and Pfafferott (2014) to establish a categorisation of cooling systems for non-residential buildings. They proposed a broad distinction between five groups: Passive Low-Exergy cooling, Active Low-Exergy Cooling, Mechanical Cooling, Thermally driven cooling, and District cooling. With the exception of district cooling, the categorisation proposed by Kalz and Pfafferott is driven by energy input. In broad terms, the groups comprehend low-exergy sources (passive and active), high-exergy sources (electricity driven mechanical cooling) and solar thermally driven cooling systems.

Besides the main energy input criteria for classification, the authors proposed two other layers of criteria for further categorisation of cooling systems. The first one addressed the main heat transfer medium (whether is an air-based or a water-based cooling system) while the second layer deals with the operation of the system within the building, differentiating central and decentral applications. Several technologies were presented within each subgroup, considering possibilities for cooling generation, distribution and delivery. Furthermore, the authors included an evaluation of the systems in terms of temperatures at heat sink and delivery level, final energy value, and estimated efficiency and costs. It is worth mentioning that even though the list compiled by Ala-Juusela (Ala-Juusela, 2003) is more thorough regarding available technologies, the categorisation proposed by Kalz and Pfafferott (2014) allows to establish relationships between different technologies for cooling generation, distribution and delivery, which could represent relevant information for the integration of cooling systems at early design stages.

The categorisation of cooling systems based primarily on heat transfer medium is widespread among the literature, being used extensively as main parameter to present and describe mechanical cooling systems and their components. Both Daniels (2003) and Lechner (2014) defined four types of active cooling systems: All-air systems, All-water systems, Air and water systems, and Direct refrigerant systems. In all-air systems, air is directly cooled and delivered by ducts, while in all-water systems water (or another liquid such as glycol) is chilled and then delivered through pipes. Air and water systems refer to the combined use of both systems in order to fulfil cooling requirements, usually relying on an all-water system to handle the bulk of the cooling. Finally, direct refrigerant systems simply consist of refrigeration machines and two fans to deliver cool air indoors and to reject heat to the external ambient. In practical terms, these could be regarded as all-air systems as well, with the only difference that they are decentral units.

TOC

§ 3.3.2 Design driven categorisation for façade integration

An alternative categorisation of cooling technologies is proposed, based on reviewed examples. This classification seeks to present available technologies and systems in an organised manner to assess possibilities for façade integration during early design stages.

The first categorisation level considers an initial distinction of technologies based on their function within a cooling system. Three main functions were identified: generation, distribution and delivery, based on the applications defined by Kalz & Pfafferott (2014). Cooling generation refers to the main mechanism utilised to cool the indoor space, namely the refrigeration machine. Distribution deals with the necessary equipment to transfer heat from the indoor space to the refrigeration machine and then to the heat sink, while cooling delivery comprehends the components needed to discharge cold (remove heat) at room level. Heat rejection was not distinguished as a function, but discussed under each solar cooling generation principle instead, in case it corresponds. Each group of components is addressed separately to then discuss the possible relationships between them.

§ 3.3.2.1 Cooling generation

Cooling generation is based on thermodynamic cycles. The most frequently used is the vapour compression cycle, which represents over 90% of all installed systems (Daniels, 2003). Researchers have explored alternative systems for space cooling, in order to potentially replace vapour compression technologies, thus eliminating the need for harmful substances used as refrigerants (Fischer, Tomlinson, & Hughes, 1994). Some explored alternatives are sorption, desiccant, magnetic, thermoacoustic, thermoelectric and transcritical CO2 cooling (Brown & Domanski, 2014). All these technologies consider specific components and could be promising alternatives in the future through further development. However, this chapter will focus purely on solar driven cooling technologies as main cooling generation systems.

Solar cooling systems use solar radiation as main energy input. The way this input is used defines two major types of technologies involved: solar electric processes, using electricity from PV panels, and solar thermal processes, using heat from thermal collectors (Henning, 2007). The necessity to convert solar radiation into usable energy (electricity or heat) implies that the converter is a central part of the solar cooling process. Therefore, in practice, a solar cooling system consists of two main

TOC

components: the 'cooling generator' which provides cooling based on thermodynamic principles, and the 'energy converter', which provides the generator with the primary energy it needs to perform.

Table 3.1 shows technological possibilities derived from solar electric (PV based) and solar thermal (collector based) processes. On the one hand, common PV cells are mostly composed of crystalline silicon cells, either formed in a single or multi-crystalline structure. This traditional PV technology accounts for about 85% of PV cells used worldwide (Munari-Probst & Roecker, 2012; Szokolay & Brisbin, 2004). The second generation of PV cells consisted of thin-film cells, made from different semiconductor materials; while novel developments such as organic solar cells or polymer cells have been branded as emerging technologies or 'third generation' cells. These refer to technologies which have been developed passed the 'proof-of-concept' phase, but further research is still needed to allow for widespread commercial application (Munari-Probst & Roecker, 2012). In terms of façade integration, experiences have been driven by the evaluation of new concepts such as photovoltaic double-skin façades (Qiu et al., 2009) and PV integrated shading devices (Frontini, 2011; Mandalaki et al., 2012; Yoo & Manz, 2011), or the exploration of specific attributes such as semi-transparent PV glazing (Fung & Yang, 2008; D.H.W. Li et al., 2009), or colour customisation possibilities for solar modules (Escarré et al., 2015).

TABLE 3.1 Available solar technologies for energy conversion (electric and thermal).

COOLING GENERATION			
ENERGY INPUT	**ENERGY CONVERSION TECHNOLOGIES**		
SOLAR ELECTRIC PROCESSES - ELECTRICITY	PV CELLS	Wafer based crystalline silicon cells (1st generation)	Single crystalline
			Multi-crystalline
		Thin-film cells (2nd generation)	Amorphous silicon
			Cooper Indium Gallium Selenide (CIS or CIGS)
			Cadmium Telluride (CdTe)
		Novel PV Technologies (3rd generation)	Organic solar cells
			Polymer cells
SOLAR THERMAL PROCESSES - HEAT	SOLAR COLLECTORS	Hydraulic collector systems	Unglazed flat plate collectors
			Glazed flat plate collectors
			Evacuated / vacuum tube collectors
		Air systems	Flat plate collectors

TOC

On the other hand, solar collector technologies are mostly defined by their heat transfer medium. Air systems are characterised by low costs, but also low efficiency because of the low thermal capacity of air. In these systems, heated air is usually used immediately, without heat storage, by means of introducing warm air into the building. On the contrary, hydraulic collectors are more efficient and allow for easy storage of solar gains, which makes them more versatile for their use in buildings. There are three types of hydraulic collectors: flat plate (glazed and unglazed) and evacuated tube collectors. These systems have different appearances, levels of efficiency and working temperatures, which have to be taken into account when deciding on the most suitable technology for a specific requirement (Munari-Probst, Roecker, & Schueler, 2005).

Regarding façade integration, research experiences have been driven by the need for more flexibility. While some experiences focus on the development of new materials, such as selective paint coatings (Orel et al., 2007) or thin film multilayer filters (Schüler et al., 2006) to provide colour variation for collectors; others focus on the design of new components to be easily integrated into building façades, such as sun shading devices (Palmero-Marrero & Oliveira, 2006) or cladding panels (Munari Probst & Roecker, 2007). Furthermore, whole façade components have been developed using evacuated tubes within a window system to provide fully transparent façade collectors for architectural integration (Maurer et al., 2014).

In terms of cooling generation, the main solar driven cooling principles are shown in Table 3.2, categorised according to their energy input. Additionally, the table considers some common technologies associated to each cooling principle. The use of a vapour compression heat pump for air conditioning was considered under electric driven processes for the sake of completeness, provided that it is coupled with PV panels to supply its electric input. Nevertheless, it will not be further discussed in the text to focus on alternative solar driven cooling processes.

Thermoelectric cooling

Thermoelectric cooling is based on the Peltier effect, which describes the temperature change in a circuit consisting of two different metallic conductors when direct current voltage is applied (Daniels, 2003). Peltier modules consist of P-type and N-type blocks of semiconductors. When direct current is passed through them, the temperature from one side decreases, allowing heat absorption, while temperature on the other side increases, dissipating heat into the environment (Figure.3.2). Both heating and cooling can be achieved by controlling the direction of the current (Liu et al., 2015).

TABLE 3.2 Available cooling generation technologies based on solar electric and solar thermal processes.

COOLING GENERATION			
ENERGY INPUT	COOLING PRINCIPLE	COOLING TECHNOLOGIES	WORKING MATERIALS
SOLAR ELECTRIC PROCESSES - ELECTRICITY	Vapour compression cooling	Compression heat pump	Refrigerants: chloro/hydro-chloro/hydro-fluorocarbons (CFCs/HCFCs/HFCs), ammonia, carbon dioxide, water, among others
	Thermoelectric cooling	Peltier modules	P-type & N-type Semiconductors
SOLAR THERMAL PROCESSES - HEAT	Sorption cooling	Absorption heat pump	Lithium-Bromide/water, Lithium-Chloride/water
		Adsorption heat pump	Silica gel, zeolites
	Desiccant cooling	Solid desiccant	Silica gel, zeolites
		Liquid desiccant	Lithium-Bromide/water, Lithium-Chloride/water
	Thermomechanical cooling	Steam ejector system	Water
		Stirling engine	Water
		Rankine cycle heat pump	Organic fluids, water

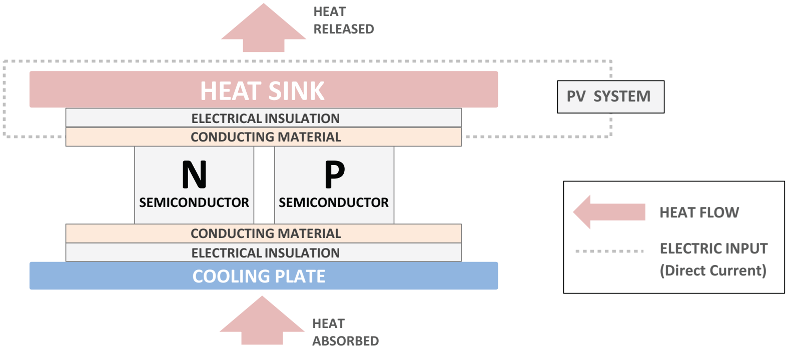


FIGURE 3.2 Functioning scheme of a thermoelectric cooling module

Besides the use of PV cells to convert solar radiation into electrical current, the essential components are the thermoelectric (TE) modules and heat sinks for heat absorption/dissipation. Although the performance of these systems is lower than conventional compressor based air-conditioning, they present interesting advantages such as the use of solid materials (no liquids or gases), and the lack of moving parts (noiseless operation), besides the use of renewable energy as main input. Facade integration experiences have

TOC

been carried out, using thermal mass as main conductor in active building walls (Khire, Messac, & Van Dessel, 2005) and windows (Xu & Van Dessel, 2008b; Xu, Van Dessel, & Messac, 2007). Nevertheless, commercial application of thermoelectric modules has been mostly constrained to small size consumer goods, such as portable camping coolers, and specialised cooling devices for electronic equipment and microprocessors.

Sorption cooling

Similarly to vapour compression systems, sorption cooling is based on the basic refrigeration cycle which results from the continuous evaporation and condensation of a particular refrigerant. However, in sorption cooling, the mechanical compressor unit is replaced by a thermal compressor unit which drives the cycle using heat from an external source (Henning, 2007). The cooling effect is obtained with a working pair of refrigerant and sorbent. The refrigerant evaporates in the evaporator, extracting indoor heat. Then it is mixed with the sorbent and consecutively separated, to end up being condensed again, rejecting the extracted heat outside. In solar driven sorption cooling, solar radiation is used as external heat source for the regeneration of the sorbent (Figure 3.3).

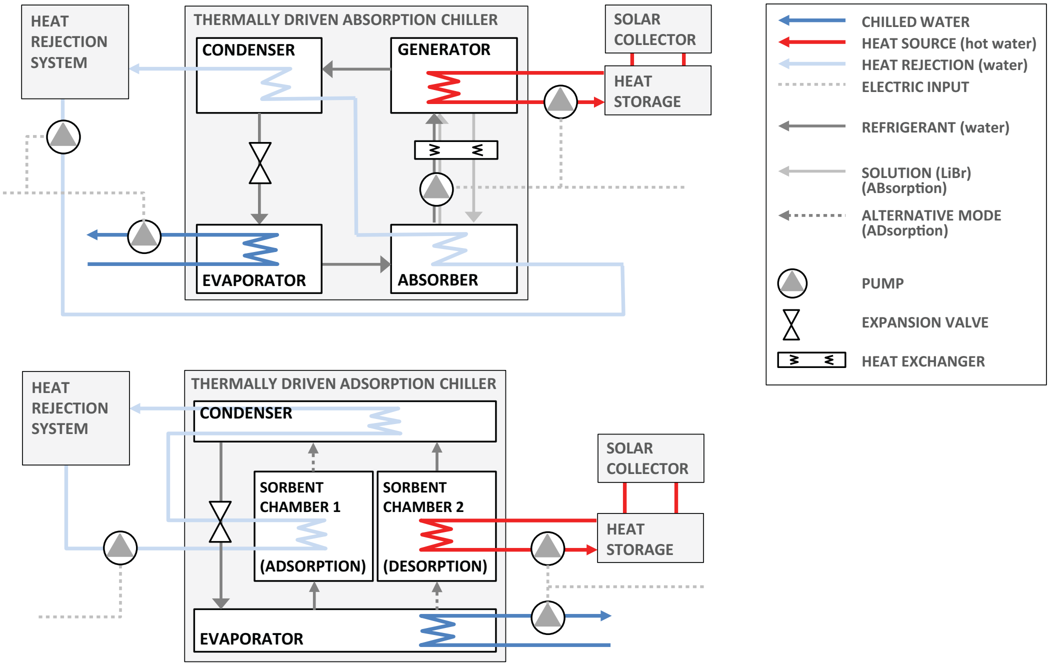


FIGURE 3.3 Required components for the operation of solar driven absorption and adsorption chillers.

TOC

There are two distinct technologies under this basic principle, defined by the type of sorbent used. Absorption heat pumps use a liquid solution as sorbent, while adsorption heat pumps use solid sorption materials (Table 3.2). Both technologies commonly use water as main refrigerant, and also as heat transfer medium for cooling distribution on a closed cycle. Therefore, complementary distribution and heat rejection components must be considered besides the heat pump itself. Absorption chillers represent a mature technology (OECD/IEA, 2012), commercially available over a wide range of cooling capacities from 4.5 to over 20,500 kW, and coefficients of performance (COP) from 0.6 to 0.8 for single-effect and around 1.2 for double-effect absorption chillers (Balaras et al., 2007; Kohlenbach & Jakob, 2014; SOLAIR, 2009). Adsorption systems are less used due to lower efficiencies and intermittent operation. However, they do not consider moving parts in their working cycle, which simplifies maintenance and provides noiseless operation. Hence, there is an increasing amount of research being conducted about small scale adsorption chillers for widespread use in buildings, in the range of 2.5-500 kW with reported COP of 0.5-0.7 (Jaehnig, 2009; SOLAIR, 2009; Weber, Mehling, et al., 2014).

Desiccant cooling

Desiccant cooling technologies are also sorption based, using a working pair of refrigerant and sorbent materials. However, while sorption cooling works in closed systems, desiccant systems provide conditioned air directly into the building, under an open ended process. Therefore, internal heat is removed through airflows of conditioned fresh air, providing not only temperature control for indoor spaces, but also ventilation (Kohlenbach & Jakob, 2014).

The cooling effect is achieved through the combination of dehumidification and adiabatic cooling of the incoming airflow, which is why these technologies are known as desiccant-evaporative cooling systems (DEC). At the beginning of the cycle, external air is dehumidified by direct contact with a desiccant, and then cooled using indirect or direct evaporative coolers. Heat exchangers are commonly used to pre-cool the incoming air to enhance the efficiency of the system. Within this cycle, solar energy is used as heat source for desiccant regeneration (Figure 3.4).

There are two main technologies following this principle, based on different desiccant types. Solid DEC uses a solid hygroscopic adsorption material, commonly placed on a rotary bed referred to as a ‘desiccant wheel’. Liquid DEC uses a hygroscopic solution, which may be applied onto a carrier or directly sprayed into the incoming air stream (Kohlenbach & Jakob, 2014). Some advantages of desiccant technologies are the integration of ventilation requirements, direct heat rejection system with exhaust air flow, lower working temperatures compared with sorption cooling, and potential higher

TOC

efficiencies, especially considering liquid-based technologies, which have reported COP values over 1 (ClimaSol, 2002; SOLAIR, 2009). Some disadvantages are the need for an additional cooling source coupled to the system, and the use of corrosive materials in open cycles in the case of liquid-based technologies. Solid desiccant cooling systems are commercially available, predominantly in large sizes for centralised operation coupled with air handling units; while smaller units are being developed and tested for application (Finocchiaro et al., 2015). Liquid desiccant cooling technology is still largely in development, with scattered examples of air-conditioning systems applied in buildings; but several research experiences and prototypes of liquid desiccant dehumidifiers, standalone cooling systems, and hybrid vapour compression/liquid desiccant systems to enhance the efficiency of existing heat pumps (Abdel-Salam, Ge, & Simonson, 2013; Bergero & Chiari, 2011; Qi et al., 2014; Zhang et al., 2013).

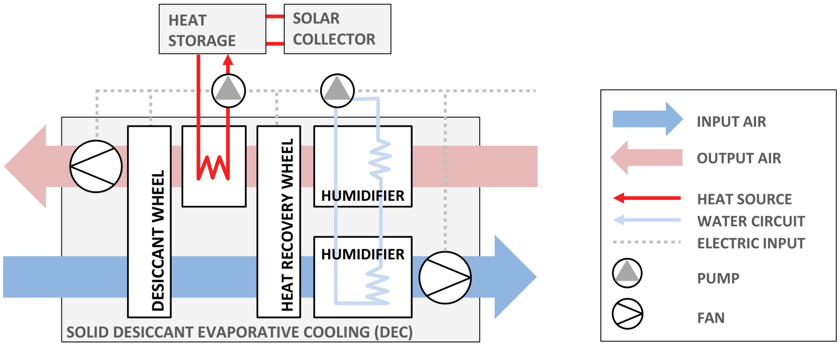


FIGURE 3.4 Operation of a solid desiccant cooling system (DEC).

Thermomechanical cooling

In thermo-mechanical solar cooling systems, thermal energy is converted directly into mechanical energy, then used as an input for cooling generation. Technologies that fall into this category are steam ejector systems, Rankine cycle based heat pumps, and Stirling engines. Steam ejector systems use steam produced by solar collectors as the driving force of the refrigerating cycle. Steam passes through a jet ejector, reducing the pressure in the evaporator and thus enabling water vaporisation by absorbing the heat from a cold water supply (Figure 3.5) (Daniels, 2003; Sarbu & Sebarchievici, 2013). The principle behind steam ejector cooling is basically the same as vapour compression cooling, with the only difference being that the mechanical compressor is replaced with an ejector, considered as a thermally driven compressor (Pollerberg, Ali, & Dötsch, 2009; Zeyghami, Goswami, & Stefanakos, 2015).

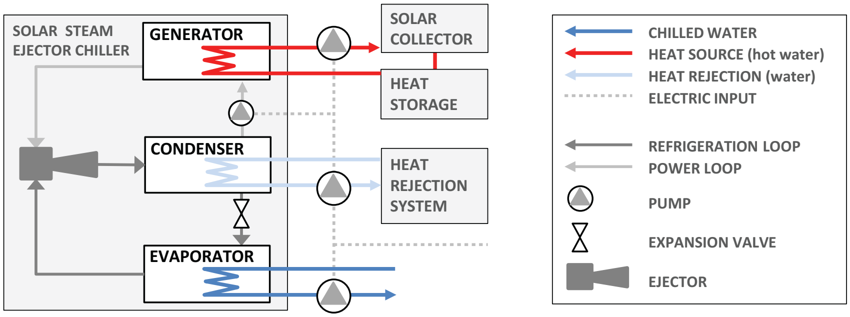


FIGURE 3.5 Operation of a solar steam ejector chiller.

Rankine cycles are also driven by the vaporisation of a working fluid. There are experiences coupling vapour compression heat pumps with organic Rankine cycles (ORC), which use organic fluids instead of water with the benefit of lower working temperatures (H. Wang et al., 2011). Under this operation, the vapour expands in the ORC turbine, producing mechanical work to drive the compressor, avoiding the use of electricity (Wu et al., 2012).

Finally, Stirling engines are heat engines that sequentially compress and expand a working fluid in a closed system. The pressure differential caused by an external heat source moves an inside displacer which in turns drives a piston, generating mechanical work (Streefkerk, 2011). Stirling engines have reported higher efficiencies compared to steam driven engines, which make them interesting for small scale application. Thermomechanical systems are interesting alternatives for specific applications, however, they are barely used in space air-conditioning, mostly due to their low cooling capacities, large irreversibilities, and high costs (Brown & Domanski, 2014). Further research is needed in order to develop competitive systems against mature technologies in the field.

§ 3.3.2.2 Cooling distribution

Cooling distribution systems basically address how cold is distributed within the building, or, more precisely, how heat is removed from indoors. Generally, these systems are classified according to their heat transfer medium, defining water-based and air-based distribution systems (Table 3.3).

TABLE 3.3 Available cooling distribution technologies.

COOLING DISTRIBUTION		
TRANSFER MEDIUM	COMPONENTS - TRANSPORT	COMPONENTS - DRIVER
AIR-BASED SYSTEM	Air ducts	Fans
WATER-BASED SYSTEM	Hydronic system	Pumps

Water-based systems use a fluid on liquid state as heat transfer medium. The most commonly used is water, but glycol has also been used for some applications (Ala-Juusela, 2003). The essential components of a water-based distribution system are pipes within a closed loop hydronic system driven by pumps. The most important advantage of water-based systems, is their efficiency given the high specific heat capacity of water. In practical terms, this means smaller pipe diameters and overall size of the entire distribution system compared to air-based systems, which also implies lower implementation costs (Kohlenbach & Jakob, 2014).

Air-based systems use air as heat transfer medium, distributed through ducts powered by fans. Although component sizes are larger compared to water-based systems, the main advantage is the integration of ventilation requirements in an open cycle. Basically, air-based systems are differentiated into single-duct and two-duct systems. The former transport supply air into the building from a central AC unit, while the latter consider two parallel ducts carrying cold air and warm air streams, to be mixed according to local demands. Given the higher complexity of two-duct systems, their use is mostly limited for buildings with different loads and demand distribution, which inner thermal conditions must be thoroughly controlled, such as laboratories and production sites (Daniels, 2003).

§ 3.3.2.3 Cooling delivery

As explained before, 'Cooling delivery' addresses the components needed to discharge cold (remove heat) at room level. These systems may be primarily classified by their delivery medium, either by surface cooling or air cooling (Ala-Juusela, 2003). This classification is relevant from an architectural point of view, because it comprehends an initial distinction based on whether the cooling effect is embedded in a building element, such as a wall or slab/ceiling (surface cooling), or is delivered by means of a supplementary device incorporated into the room (air cooling). As stated before, design approaches for architectural integration range from 'integral' to 'modular' (Klein, 2013). This becomes especially evident for cooling delivery, where surface cooling systems tend to be integrated under an ‘integral’ approach, while air cooling systems tend to follow ‘modular’ design for their architectural integration.

A second level for the classification of these technologies is proposed, based on heat transfer medium: water-based or air-based delivery cooling. Table 3.4 shows several cooling delivery technologies classified according to their delivery medium, and the heat transfer medium that they employ. Surface cooling systems basically operate as radiators, while air cooling systems operate as heat exchangers. Both families of systems may work using a water or air-based cold distribution network, which drives the development of different cooling delivery technologies.

TABLE 3.4 Available cooling delivery technologies.

COOLING DELIVERY		
DELIVERY MEDIUM	DELIVERY TECHNOLOGIES	
SURFACE COOLING	WATER BASED RADIANT COOLING	Embedded pipes / Core cooled
		Mounted pipes / Panel system
		Capillary tubes
	AIR BASED RADIANT COOLING	Double walls
AIR COOLING	AIR-AIR HEAT EXCHANGERS	Diffusers
	WATER-AIR HEAT EXCHANGERS	Induction units
		Fan-coils

Surface cooling

Commonly, surface cooling technologies are water-based, due to the higher heat transfer efficiency of water compared to air. Nonetheless, the use of mechanically ventilated double walls is considered as an alternative for surface cooling based on air movement, when the cavity is not used for ventilation purposes (Ala-Juusela, 2003). There are several studies about air-movement patterns in ventilated cavities, operation, and alternatives for their classification based on constructional or functional characteristics (Loncour et al., 2004). However, they will not be further described in the present chapter due to their limited use as a purely surface cooling device.

Water-based surface cooling systems operate by circulating chilled water through a coil placed within a building surface. Three types of technologies may be identified according to the integration level of the circulating coil within the building structure: embedded pipes, capillary tubes, and panel systems (Figure 3.6).

TOC

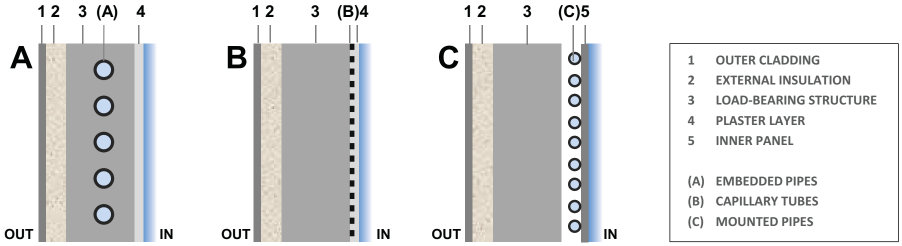


FIGURE 3.6 Water-based surface cooling systems: embedded pipes (A), capillary tubes (B) and panel systems (C)

In embedded pipes (Ala-Juusela, 2003), or core cooled (Daniels, 2003; Lechner, 2014) systems, circulating water pipes are embedded in the centre of a slab or wall, usually made of concrete, delivering cooling effect by using the thermal storage capacity of the building component itself. These systems are also commonly known as 'thermally activated building systems' (TABS), describing a completely integrated building component. The use of thermal mass is a relevant advantage in terms of performance; however, having embedded pipes present a disadvantage in the case of malfunctions, making repairs difficult without mayor interventions on site.

Capillary tubes are a grid of thin propylene tubes, placed in the outer layer of a building component. Given their dimensions (2-6 mm of diameter), the tubes are embedded in the plaster used as finishing layer on walls, ceilings, or the topping slab for floor applications. Therefore, their use does not compromise the inner section of structural elements; which simplifies installation and maintenance activities. Mounted pipes or panel systems (Lechner, 2014) use a secondary surface as cooling delivery medium, placed in front of a structural element. Chilled ceilings are common examples of commercially available systems based on this principle, where chilled water circulates through coils placed on a suspended ceiling.

Air cooling

Air cooling delivery systems are generally less invasive than surface cooling systems, having limited impact on the design of surrounding building elements. In air-air delivery systems, inlet air is treated and then distributed by ducts throughout the building, to be discharged into the rooms by diffusers (Wang, 2001). A direct advantage of these systems is the integration of functions to cope with ventilation and thermal requirements at the same time.

Water-based air cooling uses water circulating in pipes to cool down indoor air using water-air heat exchangers, such as induction units or fan-coils. In induction units, air is cooled down by contact with a chilled coil and distributed in the room by convective

TOC

flows. Chilled beams are common available products based on this principle, where water pipes pass through a beam, suspended at short distance from the ceiling (Daniels, 2003). Alternatively, in fan-coils, air is forced to pass through a chilled coil by fans, to be delivered into the room. Cooled air may consist of recirculated indoor air, outdoor air, or a mixture of both. Fan-coils represent a vastly mature technology, used in centralised HVAC systems worldwide (Wang, 2001).

§ 3.3.2.4 Design driven categorisation of cooling systems and technologies.

Figure 3.7 shows the reviewed technologies categorised according to their main function within a cooling system, defining groups of components under generation, distribution, or delivery. As stated before, cooling generation systems discussed in this chapter only consider solar driven cooling technologies; however, this same categorisation scheme could be further extended to consider other alternative cooling technologies.

All groups of components are presented according to the sub categories discussed above, differentiating energy conversion from cooling generation technologies, electric based from thermal based cooling generation, and air-based from water-based cooling technologies among other distinctions. In the case of cooling distribution systems, a third previously unmentioned group was included: solid-based heat transfer. Although it is not commonly used and therefore not usually addressed in the literature, some reviewed experiences use the mass of particular components as heat medium transfer, so it was included in the chart for the sake of completeness. Additionally, as it was mentioned before, conventional vapour compression cooling was included as a possibility, provided that is driven by the use of PV cells. However, its specific components and relations among them will not be further discussed, to focus on application possibilities of alternative cooling technologies.

The chart shows the reviewed technologies and possible relationships between them based on common applications. The connections are mostly determined by the compatibility between components and cooling working principles. This becomes clear with the evident compatibility between air-based distribution systems and air-based delivery technologies, to name an example. The connections shown in the chart do not pretend to be definitive nor exhaustive; moreover, they seek to provide an overview of current possibilities for the combination of cooling components as referential input during design stages. In addition, other connections not considered may be further explored for the development of innovative products and integrated cooling systems.

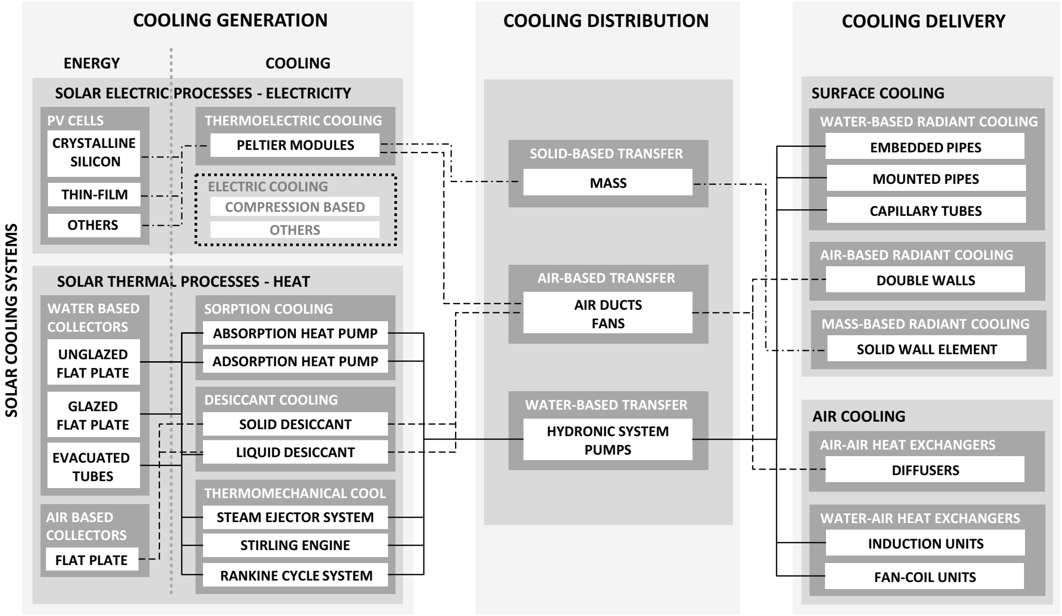


FIGURE 3.7 Chart for the categorisation of cooling technologies for façade integration purposes.

§ 3.4 Solar cooling integrated facades

The categorisation discussed above seeks to present available technologies and referential guidelines for their combination under an integrated design. The most simple approach for facade integration may consider one functionally defined group of components, such as the discussed examples of cooling delivery integration in thermally activated building systems (TABS). Nonetheless, the integration of some components may not be sufficient if the goal is to explore and promote the development of self-supporting solar cooling façade systems, as opposition to the use of centralised cooling in office buildings.

With this in mind, solar cooling integrated facades are defined for purposes of this study as *façade systems which comprise all necessary equipment to self-sufficiently provide solar driven cooling to a particular indoor environment*. This means that these façade systems should integrate the necessary equipment to handle at least cooling generation and distribution. The integration of cooling delivery in façade modules is not regarded as essential for the definition, considering that delivery could be handled by complementary systems such as chilled ceilings or beams, in order to reach areas distant from the façade.

§ 3.4.1 Review of façade concepts: Description and overview

A review of façade concepts that fit this definition was carried out, in order to discuss state-of-the-art experiences in the field and show possibilities for the development of solar cooling integrated façades. The concepts were briefly described and categorised according to the proposed chart, to test the framework, and also provide an initial assessment of the integration possibilities explored by researchers and designers.
The review focused on the integrated cooling components and façade systems from a constructional standpoint, succinctly explaining the principles behind their operation. Nonetheless, the performance of the systems will not be discussed in detail during this initial assessment.

Table 3.5 shows the reviewed experiences, considering consulted references, the name of the façade concept, and cooling principles and technologies integrated into the façade systems, categorised under generation, distribution and delivery. Additionally, the table shows other functions covered by the concepts and the integration approach followed. The experiences are listed chronologically, based on the publication year of the first available reference. The list does not presume to be exhaustive, although it is regarded for its referential value in showing current examples for the formulation of a state-of-the-art panorama within the field.

It is interesting to point out that all reviewed experiences consider façade functions other than cooling, such as providing thermal insulation, heating, dehumidification and ventilation, among others. The development level of these experiences varies, but the inclusion of several façade functions is worth mentioning when addressing integrated concepts. Moreover, the reviewed concepts were developed following both integral and modular approaches, which holds true for different technologies. This fact supports the variety of the sample, promoting a wide array of possibilities for integration.

Regarding cooling technologies, five solar electric and four solar thermal generation processes were considered, operating under different modes of cooling distribution and delivery. Additionally, the review included two concepts which do not entirely fall under the solar cooling principles discussed above, but use solar thermal energy to assist the operation of a vapour compression heat pump (Ruschenburg et al., 2011), and an indirect evaporative cooling system (Chan et al., 2012), both integrated into façade units.

TABLE 3.5 Review of solar cooling integrated façade concepts.

#	AUTHORS / REFERENCES	FAÇADE CONCEPT	COOLING GENERATION PRINCIPLE	COOLING DISTRIBUTION	COOLING DELIVERY	OTHER FAÇADE FUNCTIONS	INTEGRATION APPROACH
1	Xu et al. (2007) Xu & Van Dessel (2008) Xu & Van Dessel (2008)	Thermoelectric modules for active building envelopes (ABE)	Thermoelectric cooling	Water-based transfer	Surface cooling (Mounted pipe)	-Visual contact (window) -Heating -Heat storage	MODULAR
2	Gibson (2008)	Active thermoelectric manifold double façade	Thermoelectric cooling	Air-based transfer	Air cooling (Diffusers)	-Heating -Visual contact -Ventilation	MODULAR
3	Ruschenburg et al. (2011) Kuhn (2013)	Solar-assisted heat pump for decentral applications	Vapour compression heat pump (Solar assisted)	Water-based transfer	Air cooling (Induction Unit)	-Heating -Visual contact (window) -Sun shading	INTEGRAL
4	Streefkerk (2011)	Stirling solar cooling for office facades	Thermo-mechanical cooling (duplex stirling engine)	Water-based transfer	NO	-Heating -Visual contact (window) -Sun shading -Power generation	MODULAR
5	Chan et al. (2012)	Solar façade for space cooling	Indirect evaporative cooling	Air-based transfer	NO	-Heating -Ventilation -Insulation (external wall)	INTEGRAL
6	Ibanez-Puy et al. (2013) Ibanez-Puy et al. (2014)	Active façade envelope with Peltier cells	Thermoelectric cooling	Air-based transfer	Air cooling (Diffusers)	-Heating -Ventilation -Insulation	INTEGRAL
7	Avesani et al. (2014) Hallstrom et al. (2014) Hallstrom et al. (2015) Blackman et al. (2014)	Metal-glass façade + Sorption collector (FP7 EU iNSPiRe Project)	Absorption cycle	Air-based transfer	Air cooling (Diffusers)	-Heating -Visual contact (window) -Sun shading -Insulation	MODULAR
8	Fernandez-Hernandez et al. (2015)	Desiccant channel façade	Solid desiccant	Air-based transfer	NO	-Insulation	INTEGRAL
9	Ibanez-Puy et al. (2015)	ThEEn: Adaptive Thermoelectric vent. facade	Thermoelectric cooling	Solid-based transfer	Surface cooling (Radiative wall)	-Heating -Ventilation -Insulation	INTEGRAL

>>>

TABLE 3.5 Review of solar cooling integrated façade concepts.

#	AUTHORS / REFERENCES	FAÇADE CONCEPT	COOLING GENERATION PRINCIPLE	COOLING DISTRIBUTION	COOLING DELIVERY	OTHER FAÇADE FUNCTIONS	INTEGRATION APPROACH
10	Liu et al. (2015)	Active solar thermoelectric radiant wall	Thermoelectric cooling	Solid-based transfer	Surface cooling (Radiative wall)	-Insulation -Heating mode	INTEGRAL
11	Tanuharja (2015)	Integrated Monsoon façade system for tropical climates	Liquid desiccant & Indirect evaporative cooling	Air-based transfer	Air cooling (Diffusers)	-Dehumidification -Visual contact (window) -Sun shading -Insulation	MODULAR

§ 3.4.1.1 Solar electric cooling integrated façade concepts

Solar electric processes rely on the thermoelectric effect. Small component sizes and the simplicity of its operation, have been regarded as important advantages for façade integration purposes. Therefore, it does not come as a surprise to realise that five out of eleven reviewed experiences are based on this cooling generation technology. Among the façade concepts identified, there are examples of all heat transfer mediums (water, air, solid), and both main groups of cooling delivery technologies (surface and air cooling), which proves the flexibility and potential for diversity associated with thermoelectric cooling technology.

Solid-based experiences are regarded as the most simple use of the thermoelectric principle, basically attaching a solid conductive material to the cold end of a TE (thermoelectric) module. In turn, this solid material delivers cooling into the room. In the façade concept developed by Liu et al. (2015), distribution/delivery is fulfilled by an aluminium radiant panel embedded in the inner layer of the building wall, thus directly facing the indoor environment. The facade component consists of two layers, separated by an externally ventilated cavity, working as a mechanically ventilated opaque wall from a constructional standpoint. The TE modules are directly attached to the aluminium panel, considering external insulation to minimise heat loses. Heat sinks are connected to the TE modules, with fans to enhance heat rejection through the cavity. Finally, the outer layer consists of a PV module, which drives the system (Figure 3.8a).

TOC

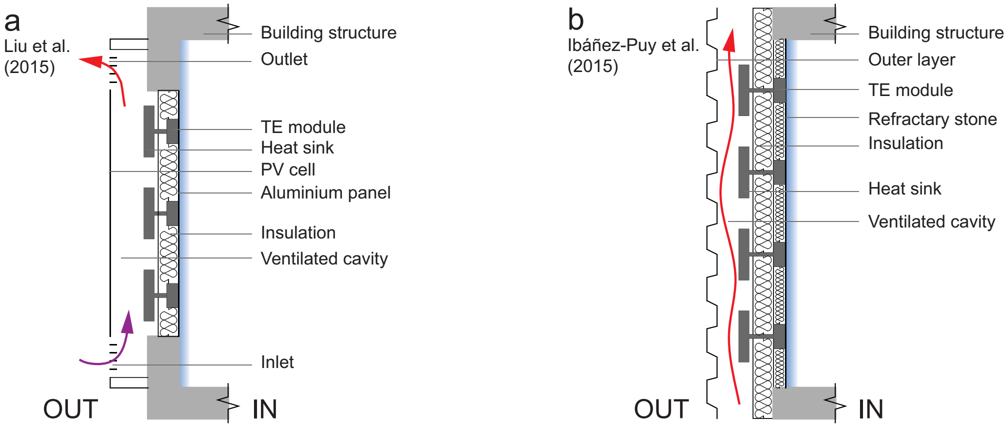


FIGURE 3.8 Solid-based thermoelectric facades. Schemes based on Liu et al. (2015) and Ibanez-Puy et al. (2015).

The working principle of the concept developed by Ibanez-Puy et al. (2015) follows the same principle explored by Liu et al. (2015). However, they further advanced in the design of the building element, developing a complete façade module instead of a component embedded in a wall. The façade module is conceived as a shaft-box system, naturally ventilated to the exterior for heat rejection (Figure 3.8b). Similarly to the concept above, TE modules are directly attached to the inner layer, and connected to heat sinks placed in the air cavity, with insulation in between. In this case, the inner layer was a refractory stone of 14 mm. This concept was numerically and experimentally tested, although it was not possible to incorporate PV panels in the experimental setup due to economic reasons (Ibáñez-Puy et al., 2015). Instead, a trapezoidal steel sheet was used as outer layer for the testing.

The concept presented above was an evolution from an earlier concept developed by the same authors (Ibáñez-Puy et al., 2014; Ibáñez-Puy, Sacristán-Fernández, & Martín-Gómez, 2013). This employed an air-based distribution system instead of the solid-based system discussed above. The main difference was the inclusion of a second air cavity, placed indoors. Hence, the TE modules cool the indoor air within the second cavity, to deliver it to the room through diffusers placed in an inner layer composed of laminate gypsum boards. Both air cavities (internal and external) may be opened and closed to take advantage of buoyancy ventilation if necessary (Figure 3.9a).

Another concept for an air-based thermoelectric cooling façade was developed by Gibson (2008), basically being a double-skin façade with TE modules placed in its outer layer (Figure 3.9b). Inner and outer layers were floor to ceiling glass panes, with air inlets in the inner glazing to allow air exchange between the room and the cavity. Thus, the air in the cavity is cooled down by means of heat sinks attached to TE modules, using fans to enhance air movement besides natural convection currents. After initial testing, it was discovered that the solar heat gain was a serious challenge against the limited capacity of the TE modules. So, the cavity was subdivided in order to restrict the action of each TE module to a smaller volume, while limiting its direct exposure to the exterior by means of the geometry of the cavity partition. This partitioning was generated by inserting a manifold structure (double wall extruded polycarbonate) into the air cavity. The façade concept has been numerically and experimentally tested, both with the use of models and full-scale prototypes (Gibson, 2008).

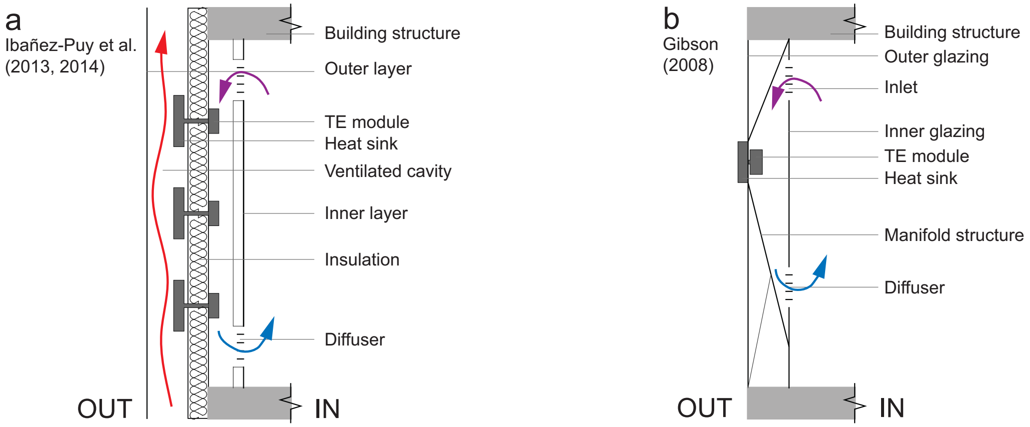


FIGURE 3.9 Air-based thermoelectric facades. Schemes based on Ibanez-Puy et al. (2013, 2014) and Gibson (2008).

Finally, a façade concept using water as heat transfer medium, was proposed by Xu et al. (2008a; 2008b; 2007). The façade component is a window system, consisting of two parts: a transparent module, operating as a window; and two opaque modules placed at each side of the window, in charge of the cooling process (Figure 3.10). An external transparent PV layer was designed to be in front of the window, to act as energy input without blocking the view. However, experimental tests were conducted using a regular opaque PV panel isolated from the façade unit, in order to assess the overall performance of the system. Each opaque cooling module consists of four TE units connected to external heat sinks for heat dissipation, and to an aluminium tube filled with water for indoor cooling delivery. The aluminium tube is thermally insulated on all sides except for the side facing the indoor environment, while the water acts as thermal bank to slow down cooling delivery. Both the active building envelope (ABE) system and its separated components have been numerically and experimentally tested (Xu et al., 2007).

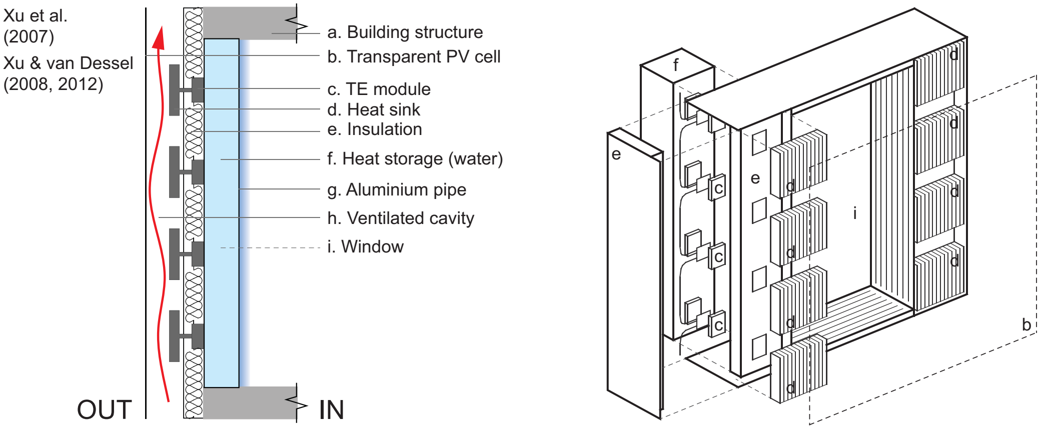


FIGURE 3.10 Water-based thermoelectric facade. Schemes based on Xu et al. (2007, 2008a, 2008b).

§ 3.4.1.2 Solar thermal cooling integrated façade concepts

Regarding solar thermal processes, it was possible to find examples of all three relevant technology sub-groups in the reviewed experiences: sorption, desiccant, and thermomechanical cooling. Two experiences consider cooling delivery systems integrated within the façade (Avesani, Hallstrom, & Fuldner, 2014; Tanuharja, 2015), while the other two only deal with cooling generation and distribution to serve a secondary delivery unit (Fernández-Hernández et al., 2015; Streefkerk, 2011).

The only sorption based cooling façade concept reviewed was proposed by Avesani et al. (2014). As explained before, the size of the required systems, and the need for heat rejection components in a closed loop system are seen as disadvantages for façade integration. Nonetheless, the authors were able to bypass these disadvantages, by designing a sorption-based concept, working on open cycles by using air as heat transfer medium (Hallstrom & Füldner, 2015; Hallström et al., 2014). The basis of the system is a novel thermal heat pump component previously developed for rooftop applications (Blackman, Hallstrom, & Bales, 2014; Hallstrom & Füldner, 2015). This component consisted of small size sorption modules integrated within evacuated tube solar collectors. The sorption modules are vacuum glass tubes with two connected compartments: a reactor and a evaporator/condenser. The reactor compartment is then attached to a solar absorber, while the evaporator/condenser is shielded from direct solar radiation, providing the cooling effect (Figure 3.11).

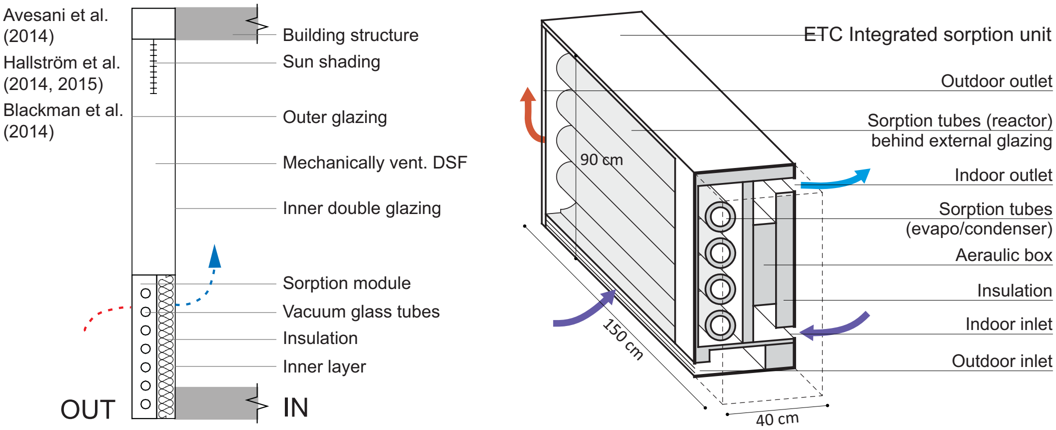


FIGURE 3.11 Sorption based facade. Scheme based on Avesani et al.(2014), Hallström et al.(2015) and Blackman et al.(2014).

While the existing component works in closed cycles, the proposed component operates with air as heat transfer medium, making façade integration feasible. The cooling component was developed as a 'plug and play' independent element to be placed in the sill of a prefabricated façade module, with a mechanically ventilated double window on top, considering double glazing as inner layer, venetian blinds in the air cavity and single glazing as outer layer. The cooling component has been numerically and experimentally tested showing promising results (Avesani et al., 2014; Hallström et al., 2014). The main disadvantage is that it operates under day/night cycles, releasing cooling during night time, and charging during the day. The authors stated that due to this reason, the performance of the system should be further studied considering additional thermal storage strategies, and particularly the thermal mass of the building, combining passive strategies for an holistic design.

Desiccant cooling façade concepts reviewed consider both the use of solid and liquid desiccants. Fernandez-Hernandez et al. (2015) proposed a desiccant channel for façade integration, applying a layer of silica gel in the cavity of an opaque ventilated wall system, to dehumidify incoming external air for ventilation purposes (Figure 3.12a). The cavity is divided vertically in two parts: the bottom part houses a solar collector, while the upper part carries the desiccant material, allowing for intermittent operation modes. During desiccant operation, the bottom part is sealed by a damper, and air intake occurs in the upper part, providing treated air indoors through ducts connected to the upper end of the façade module. Contrarily, during regeneration mode, air intake occurs at the lower end of the façade, heating the air stream while it flows through the solar collector, to then pass through the desiccant channel to evaporate the moisture previously absorbed by the silica gel layer. Finally, the warm and moist air is rejected to the exterior through an air outlet placed at the upper end of the façade. Numerical calculations and dynamic simulations have proven the potential of the façade concept to take care of the latent heat, however, it must be coupled to an additional cooling component to cope with sensible loads.

A liquid desiccant based facade system for hot-humid climates was proposed by Tanuharja (2015) as the outcome of a master thesis (Figure 3.12b). The system consists of three prefabricated modules, coupled to each other to allow for the overall operation: an opaque component, a transparent component, and the solar collector, for desiccant regeneration. The opaque component incorporates a dehumidifier and an indirect evaporative cooler, to treat incoming air in an open cycle. The window component is a sealed double glass unit, while the regenerator consists of evacuated tubes placed in an overhang over the window, to receive direct solar radiation while acting as sun shading system for the transparent areas. The liquid desiccant (Calcium Chloride), is distributed in microporous polypropylene tubes, permeable to water vapour, but impervious to the desiccant solution (Tanuharja, 2015). The concept was only tested numerically, so further studies would be needed to unequivocally assess its performance and technical feasibility. Nonetheless, it is an interesting example of design possibilities tied to the use of these technologies.

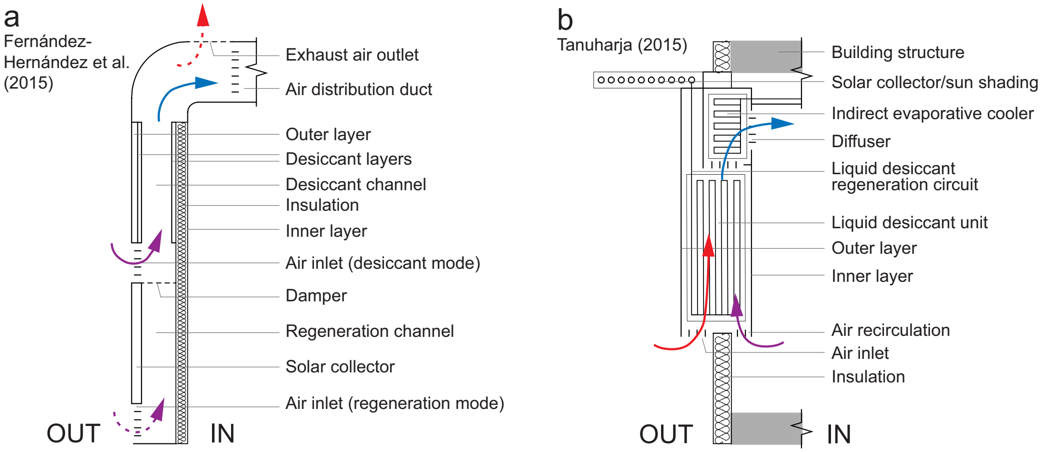


FIGURE 3.12 Desiccant facades. Schemes based on Fernandez-Hernandez et al. (2015) and Tanuharja (2015).

TOC

The façade concept proposed by Streefkerk (2011), was also the outcome of a master thesis, which sought to design a solar cooling façade component, driven by a duplex Stirling machine placed at the edge of the building slab. The proposed façade system consists of a window component, a solar collector placed in the sill, and the aforementioned Stirling engine (Figure 3.13). In order to reach the high temperatures required to drive the engine, Fresnel lenses were used as solar concentrator devices instead of a regular solar thermal collector. Water is used as heat transfer medium, while chilled ceilings were proposed as cooling delivery system. This concept was only tested numerically, being recognised as a potential alternative for future developments. Nonetheless, problems related to the high temperatures required by the system should be considered in more detail (Streefkerk, 2011).

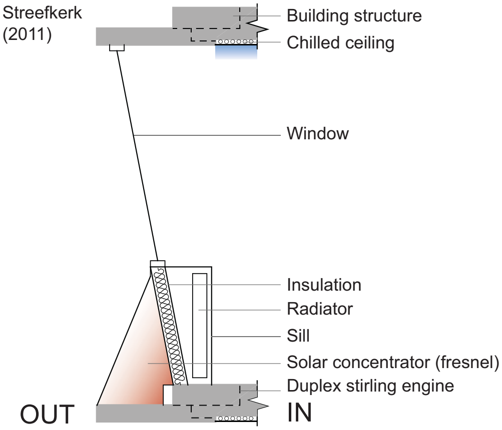


FIGURE 3.13 Stirling solar cooling facade. Scheme based on Streefkerk (2011).

§ 3.4.1.3 Other solar assisted cooling integrated façade concepts

The two remaining experiences considered in the review use solar thermal energy to assist processes outside of commonly defined solar cooling systems. These façade concepts were included for the sake of completeness, due to the fact that they are referred as 'solar facades' or 'façade-integrated solar systems' by the authors.

A façade-integrated solar heat pump system was developed as one of the outcomes of the project "Resource- and cost-effective integration of renewables in existing high-rise buildings", supported by the Seventh Framework Programme of the European Union (Kuhn, 2013). The system consists of a specially designed small scale vapour compression heat pump, coupled with an unglazed solar collector for sill integration (Figure 3.14a). A capillary mat embedded in the external plaster layer of the sill was used as solar collector, while a glycol solution was used as heat transfer medium from the collector to a storage tank, to then be used as input for the heat pump. The system has been mostly tested for heating operation (Ruschenburg et al., 2011), so further research is needed to assess its performance under cooling operation.

Finally, Chan et al. (2012) proposed a 'solar façade for space cooling', basically as an opaque mechanically ventilated façade coupled with an indirect evaporative cooler (Figure 3.14b). The ventilated façade consists of two air cavities: the inner layer is an insulated wall; the outer layer is a black aluminium transpired plate, and the intermediate layer is a sand tile wall, which acts as an indirect evaporative cooler. Pumps are used to moist the sand tile wall, while air is drawn by fans into each cavity through differentiated inlets. The system was numerically and experimentally tested, obtaining similar results to other solar indirect evaporative coolers and desiccant cooling systems (Chan et al., 2012). However, it was found that the cooling effect was enhanced when there was no solar radiation. Hence, it is the author's opinion that further testing and research is needed in this case to fully advocate for the use of solar energy as the main driver of this façade concept.

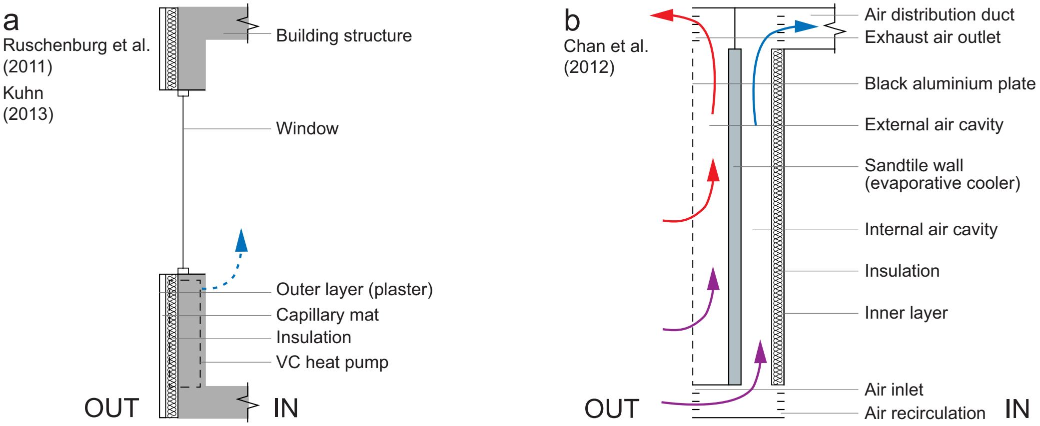


FIGURE 3.14 Other solar assisted cooling façades. Schemes based on Ruschenburg et al. (2011) and Chan et al. (2012).

§ 3.4.2 Solar cooling integrated façade concepts: categorisation and assessment of state-of-the-art experiences

The façade concepts were categorised following the proposed chart (Figure 3.15), in order to graphically show the relationships between different components explored by the researchers. At first glance, it seems interesting to point out the variety of possibilities encountered, recognizing 9 different combinations among 11 presented cases. Most combinations follow common relationships discussed above; however, some concepts explore uncommon combinations, either through novel applications of established technologies (Xu et al., 2007), or the development of new cooling generation technologies (under established principles), to be used under different distribution mediums (Avesani et al., 2014). Additionally, extra components were included in the chart to comprehensibly exhibit the technologies being integrated into the façade, such as the evaporative cooling system used by Chan et al. (2012) and the solar concentrators considered by Streefkerk (2011).

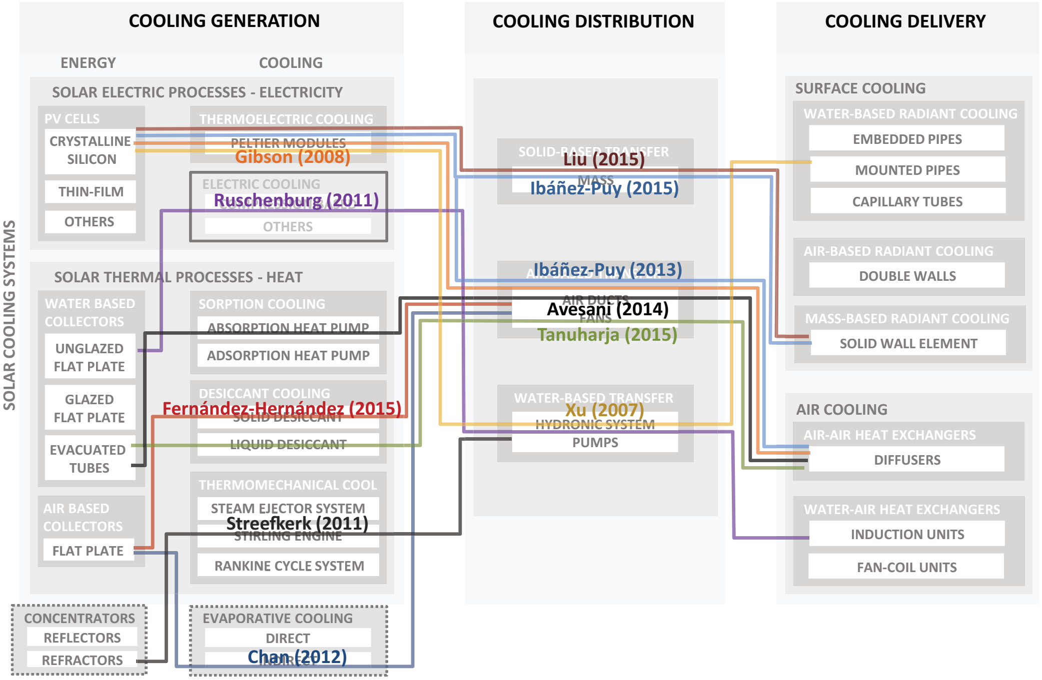


FIGURE 3.15 Categorisation of the reviewed integrated façade concepts in the proposed chart.

Regarding cooling distribution technologies, most façade concepts employ air as heat transfer medium (6 out of 11). This decision makes sense in the context of façade integration, due to several functional and constructional issues. On the one hand, intake air treatment considers the possibility to respond to ventilation needs together with cooling, which addresses multi-functional requirements of the building envelope. On the other hand, the fact that distribution works without liquids, simplifies the required systems, in terms of number of components for delivery and distribution. Overall, air-based systems seem to be more suitable for decentral operation.

In relation to cooling delivery, again the most used option seems to be the most simple one, using diffusers to directly inject cooled air into the room. This direct approach to air cooling is useful to supply instant cooling, at any given moment, provided that there is availability at the source. However, if the cooling effect needs to be delayed, thermal storage strategies would be needed, which may be a factor for choosing water as main heat transfer medium.

Table 3.6 shows the level of development of the different experiences, in order to assess the state of the art in the field. This assessment aimed to estimate the development stage of each experience considering the execution of performance evaluations and the level of detail presented for the façade concepts. Four categories were defined regarding performance evaluation, considering different possible tools employed by the researchers: static calculations, dynamic simulation, component testing and full scale prototypes of the entire façade system. In terms of design level, two categories were considered: façade concept and façade system design. The first refers to a concept not yet fully developed, considering detailed information about some components but a general layout of the overall façade, shown by schemes of operation and partial plans. The second category considers more detailed designs of the integrated façade systems, shown in plans, 3D images, and photos (for built cases). It is important to mention that this assessment is based on currently available information, so there could be more data from unpublished sources. Nonetheless, the information presented is regarded as a baseline for further developments within the field.

The table shows that all experiences have been numerically tested, while other tools have been used in some of them for further evaluation. The experiences with less information about their performance correspond to Master thesis projects (Streefkerk, 2011; Tanuharja, 2015), possibly due to time constraints and the focus of the research. Contrarily, six experiences have been tested using prototypes while four of them have been tested under all defined evaluation tools (Avesani et al., 2014; Ibáñez-Puy et al., 2014; Ibáñez-Puy et al., 2015; Xu et al., 2007).

TOC

TABLE 3.6 Level of development of the reviewed façade concepts.

#	AUTHORS	PERFORMANCE EVALUATION				FAÇADE DESIGN LEVEL	
		STATIC LOAD CALCULATIONS	DYNAMIC SIMULATION	COMPONENT TESTING	1:1 PROTOTYPE MONITORING	FAÇADE CONCEPT	FAÇADE SYSTEM DESIGN
1	Xu et al. (2007, 2008)	✓	✓	✓	✓		●
2	Gibson (2008)	✓	✖	✓	✓		●
3	Ruschenburg et al. (2011)	✓	✓	✓	✖	●	
4	Streefkerk (2011)	✓	✖	✖	✖		●
5	Chan et al. (2012)	✓	✖	✓	✖	●	
6	Ibanez-Puy et al. (2013, 2014)	✓	✓	✓	✓	●	
7	Avesani et al. (2014)	✓	✓	✓	✓		●
8	Fernandez-Hernandez et al. (2015)	✓	✓	✖	✖	●	
9	Ibanez-Puy et al. (2015)	✓	✓	✓	✓		●
10	Liu et al. (2015)	✓	✖	✖	✓	●	
11	Tanuharja (2015)	✓	✖	✖	✖		●

In terms of façade design, five experiences are classified as 'façade concepts', and six as 'façade system designs'. Among the second group, four have been tested using three or four evaluation tools (Avesani et al., 2014; Gibson, 2008; Ibáñez-Puy et al., 2015; Xu et al., 2007), while the remaining two are the Master projects already mentioned (Streefkerk, 2011; Tanuharja, 2015). The four alluded experiences (highlighted in the table) are regarded as the most developed cases of the sample, considering testing and level of design; hence, they represent the forefront in terms of possibilities for façade integration of solar cooling technologies.

Three out of the four most developed experiences integrate thermoelectric cooling components (Gibson, 2008; Ibáñez-Puy et al., 2015; Xu et al., 2007), while the remaining one employs sorption cooling (Avesani et al., 2014). Additionally, three

TOC

followed a modular approach for integration (Avesani et al., 2014; Gibson, 2008; Xu et al., 2007), while one was designed as an integral system (Ibáñez-Puy et al., 2015). Evidence seems to show that thermoelectric cooling is a more suitable technology for façade integration, mostly due to sizes/number of components and simple operating principles. However, the resulting performance of the systems has to be considered in order to properly establish limitations for their operation. In a similar fashion, a modular approach to façade integration seems to provide more flexibility to organise several façade functions within one system. Nonetheless, the logics behind façade design and construction processes must be further explored to allow for façade integration of solar cooling systems under coordinated actions from all involved stockholders.

§ 3.5 Conclusions

This chapter discussed the potential integration of solar cooling technologies in façades, proposing a framework for its understanding and the promotion of future developments, based on a state-of-the-art review. The framework consisted of three main sections: façade integration, solar cooling technologies, and solar cooling integrated facades.

The concept of façade integration was briefly discussed, exploring its meaning and conceptual boundaries for its application. Two sets of sequential measures were defined for the façade integration of regulatory functions: supplementary measures (constructive elements that use low or no energy) and supplementary building services (technically complex systems, driven by energy). The integration of the latter was defined as the focus of the chapter; nonetheless, previous integration of supplementary measures was regarded as essential to cope with comfort requirements efficiently using available resources.

Commercially available solar cooling technologies were reviewed and categorised, particularly noting possible relationships among different generation, distribution and delivery cooling systems. The proposed connections are regarded as relevant referential information during early design stages, however, it is necessary to expand on the possibilities given by each particular cooling principle to fully assess the boundaries for application. Finally, a state-of-the-art panorama on solar cooling integrated façades was presented, considering current experiences from researchers and designers. Solar cooling integrated façades were defined for purposes of this study as façade systems which comprise all necessary equipment to self-sufficiently provide solar driven cooling to a particular indoor environment, thus, functioning under decentral operation.

TOC

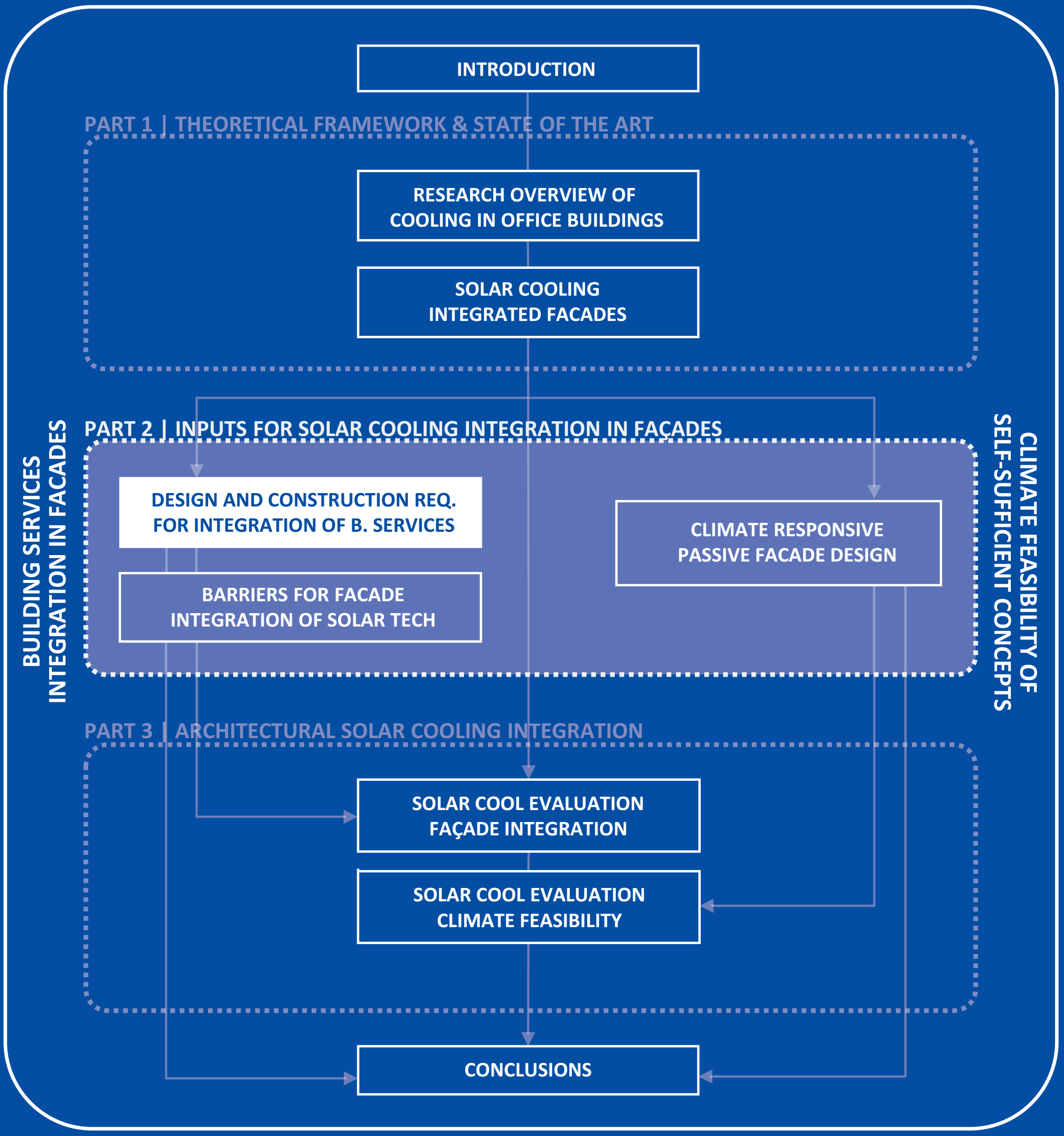
Eleven façade concepts were reviewed to discuss and show existing possibilities for the development of solar cooling integrated façade systems. Several possibilities for integration were found, either following proposed connections between components, or exploring new ones based on novel applications of common technologies or the development of new components. It was possible to find examples of façade concepts using all four solar cooling principles discussed in the chapter. However, the façade systems judged as more advanced, with a higher development level, considered almost exclusively thermoelectric cooling components, with one exemption which considered sorption cooling. Even though the performance of the systems was not discussed, the sorption-based concept seems to be a promising alternative compared to thermoelectric-based façade systems. Additionally, a modular approach for integration was preferred in the most developed cases, which seems to grant more flexibility during design and construction stages. Nonetheless, further studies are needed to unequivocally state this.

Overall, the information presented in this chapter configures a comprehensive framework for the understanding of solar cooling integrated facades, and an initial assessment of state-of-the-art experiences to show the current level of development within the field. Nonetheless, more information is needed to determine the full range of possibilities and constraints for widespread application. Further studies should consider the implications of building services integration during façade design and construction processes; and the performance of the solar cooling technologies addressed, both as stand-alone systems, and considering the use of supplementary measures under an overall integrated design.

TOC

TOC

COOLFACADE



INTRODUCTION

PART 1 | THEORETICAL FRAMEWORK & STATE OF THE ART

RESEARCH OVERVIEW OF COOLING IN OFFICE BUILDINGS

SOLAR COOLING INTEGRATED FACADES

PART 2 | INPUTS FOR SOLAR COOLING INTEGRATION IN FAÇADES

DESIGN AND CONSTRUCTION REQ. FOR INTEGRATION OF B. SERVICES

BARRIERS FOR FACADE INTEGRATION OF SOLAR TECH

CLIMATE RESPONSIVE PASSIVE FACADE DESIGN

PART 3 | ARCHITECTURAL SOLAR COOLING INTEGRATION

SOLAR COOL EVALUATION FAÇADE INTEGRATION

SOLAR COOL EVALUATION CLIMATE FEASIBILITY

CONCLUSIONS

BUILDING SERVICES INTEGRATION IN FACADES

CLIMATE FEASIBILITY OF SELF-SUFFICIENT CONCEPTS

ARCHITECTURAL SOLAR COOLING INTEGRATION IN FACADES

TOC

4 Design and construction requirements for façade integration of building services

Discussion of main perceived barriers from an exploratory expert survey[3]

The integration of decentralised building services into façade components presents advantages from functional and constructional standpoints. However, this integrated approach has not been massively implemented, having only stand-alone buildings and façade concepts as examples. This chapter delves into the requirements for integration within the façade development process, aiming to *identify the main perceived problems for building services integration in facades at design, production and assembly stages*.

The employed method was an exploratory survey addressed to professionals involved in the development of façade systems for office buildings, at different stages, in order to generate new knowledge based on practical experience. The survey was conducted from mid-September to mid-November, 2015 and was distributed both as an online form and in printed format among several professional networks. Results show that the main problems refer to the overall process, particularly regarding coordination issues among different disciplines and stakeholders, while other problems such as costs and lack of knowledge, while still relevant, have more impact on particular stages. Among relevant problems related to the products themselves, the results show physical integration issues during production and assembly stages, and barriers derived from unreliable performance and technical limitations of current products to be integrated in façade systems.

---

[3] Published as: Prieto A, Klein T, Knaack U, Auer T. (2017). Main perceived barriers for the development of building service integrated facades: Results from an exploratory expert survey. Journal of Building Engineering; 13: 96-106. doi: 10.1016/j.jobe.2017.07.008.

§ 4.1 Introduction

The building industry is facing relevant challenges in the current agenda towards sustainability. On the one hand, more strict building codes and regulations are being enforced in an effort to decrease current energy consumption levels, as evidenced by the request for all buildings in the EU to consume 'nearly zero' energy after 2020 (EP, 2010). This of course impacts the overall design of new buildings, but also considers particular challenges for the building façade, as the filtering layer between outside and inside conditions (Herzog et al., 2004), pushing for the application of climate responsive façade systems on both new and refurbishment projects. On the other hand, the construction industry itself has been criticised by its poor performance and outdated craft-based production methods (Egan, 1998; Woudhuysen & Abley, 2004), besides the environmental impact associated with common construction processes and building related activities (Dimoudi & Tompa, 2008; Ortiz, Castells, & Sonnemann, 2009). Therefore, not only there is a need for new performance driven façade products, but also new production processes that ensure high quality results and an efficient use of resources throughout the entire life cycle of the product.

The façade industry has responded to these challenges by promoting the development of multifunctional building components, striving for a more efficient use of available resources. Hence, besides basic protective functions, also regulatory functions have been considered in the design of building envelopes to mediate between interior comfort requirements and exterior stimuli, by means of integrating supplementary measures and supplementary building services (Herzog et al., 2004). Supplementary measures refer to the use of constructive elements such as sun shading systems or extra thermal insulation, to cope with comfort requirements using nearly zero extra energy. In some cases, a small amount of energy is needed for movable mechanical components, to improve the performance of the system allowing for dynamic responses in intelligent, advanced, or climate adaptive building envelopes (Compagno, 2002; Knaack et al., 2007; Loonen et al., 2013; Selkowitz, 2001; Wigginton & Harris, 2002). The most common façade concepts in this regard are related to the development of double-skin facades considering different combinations of layers, static or fixed building elements and multiple ventilation modes (E. Lee et al., 2002; Loncour et al., 2004).

The integration of supplementary building services into the façade has been promoted as a next step, if the aforementioned measures are not enough to meet indoor requirements, exploiting the possibility to include extra functions under standardised manufacturing processes based on prefabrication. Hence, besides providing daylight, heat or noise protection; façade components may integrate active heating, ventilation and air-conditioning systems (HVAC), artificial lighting, energy storage, and even

TOC

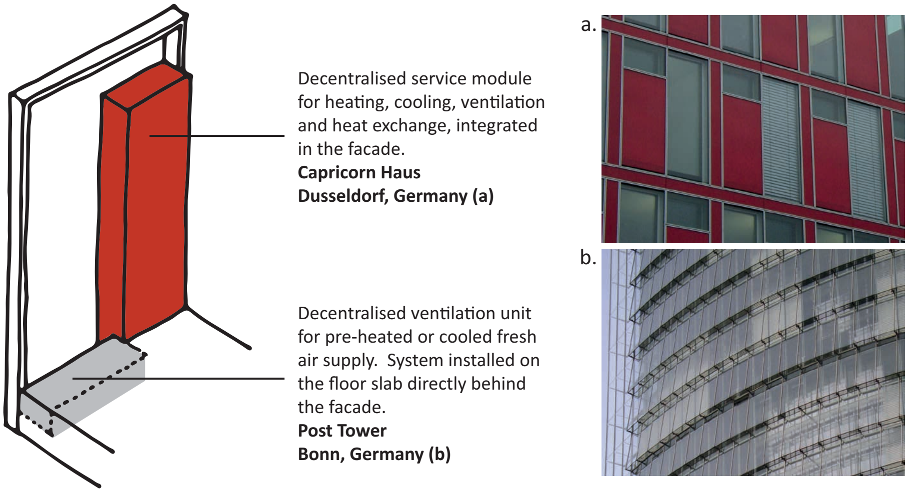
energy generation through photovoltaic panels or solar thermal collectors. These façade concepts have been discussed in the literature as 'decentralised façade services', 'service integrated facades', or simply 'integrated facades' (Ebbert, 2010; Herzog et al., 2004; Knaack et al., 2007), presenting benefits on several fronts ranging from users' comfort to cost savings for the main stockholders. The present article focuses on these 'integrated façades', understanding them as a specific product within the development of high-performance building envelopes.

Daniels (2003) addressed the benefits derived from integration when discussing design and construction of building services, focusing on potential cost and energy savings associated with the application of integrated planning concepts. Moreover, the flexibility and local control associated with decentralised units mean potential improvements in the perceived indoor comfort and a more efficient energy usage by identifying local demands (Mahler & Himmler, 2008). Similarly, Knaack et al. (2007) supported advantages from a constructional point of view, stating that the industrial manufacturing of integrated façade modules could decrease building times during assembly stages, while limiting the occurrence of construction mistakes on site by dealing with prefabricated components. Furthermore, decentralised units do not need distribution systems nor space for large equipment, which generates more leasable floor area for any given commercial building (Franzke et al., 2003).

Regardless of the mentioned advantages, this integrated approach has not been massively implemented, having stand-alone examples instead of understanding it as a promising path to follow for the development of high-performance buildings. Besides the development of façade concepts such as TE,motion, E^2, and SmartBox, from Wicona, Schueco, and ECN respectively (ECN, n.d.; Schüco, 2009; WICONA), built examples such as Capricorn Haus in Dusseldorf, and Post Tower in Bonn (Figure 4.1) have been recognised by their sustainable features, demonstrating the environmental potential of technically integrated buildings (Klein, 2013; Wood, Henry, & Safarik, 2014).

The main goal of this chapter is to identify and discuss perceived barriers for the integration of building services in façade systems, as a way to promote the application of new cost-effective multifunctional façade products for high-performance office buildings. The method chosen for this was an exploratory survey addressed to professionals with practical experience in the development of façade systems for office buildings, situated at any stage of the design and construction process. Hence, the information gathered by the survey relies on empirical knowledge, adding new insights to previous experiences in the subject. It is important to point out that the research centred around perceived problems based on practical experience, considering the role of perception in decision-making processes related to façade design and development.

TOC



Decentralised service module for heating, cooling, ventilation and heat exchange, integrated in the facade.
Capricorn Haus
Dusseldorf, Germany (a)

Decentralised ventilation unit for pre-heated or cooled fresh air supply. System installed on the floor slab directly behind the facade.
Post Tower
Bonn, Germany (b)

FIGURE 4.1 Integrated façades: Capricorn Haus, Dusseldorf (a) and Post Tower, Bonn (b). Pictures from the author

Several authors have discussed barriers for integration of building services, with focuses ranging from potential introduction into specific markets to the integration of particular active systems into the façade such as decentralised ventilation units or solar components for energy generation. Haase et al. (2009) declared a series of issues that need to be addressed for the development of advanced integrated facades, considering the application of 'reactive building elements' together with building services. The authors mentioned aesthetics, functionality, economy (initial and operational) and flexibility as relevant issues for integration, without delving into details. Ledbetter (2001) stated problems during the design stage of façade systems while discussing the need for holistic design of building services and façades. In general terms, he discussed the lack of knowledge of designers and the limited action of specialists during early design stages. Furthermore, he described problems indirectly caused by the package separation of components, such as responsibilities for interfaces between components, warranties in case of malfunction, or lack of feedback between contractors. Even though some technical issues such as air leakage and heat transfer were also mentioned, the attention given to aspects related to the design process itself was far greater in the paper, highlighting their relevance.

The perceived importance of barriers related to the design process was shared by Klein (2013). As part of his doctoral dissertation, Klein conducted a limited series of in-depth interviews in order to characterise the façade construction process and determine driving factors and barriers for innovation. Fifteen professionals with practical experience in façades were interviewed, considering designers, consultants, system suppliers, developers and façade builders. Regarding building services integration, it was found that decisions about the contracting strategy are essential, defining the roles and influence of the involved parties beforehand. Furthermore, the responses showed that internal processes for each party are rather optimised, so a successful project does not depend on the ability of individual stakeholders, but on their coordination and interaction during the design and construction process (Klein, 2013).

Zelenay et al. (2011) also used interviews with experts as the main source of information to identify design strategies and practical considerations for the development of high-performance facades in general, focusing on barriers for implementation in the U.S. Around forty professionals from North America and Northern Europe were interviewed, counting architects, façade and energy consultants, researchers, manufacturers and building managers. The study identified particular barriers related to different stages of the development process: design, construction and operation. Firstly, during the design stage, it was found that additional risk for the involved professionals, client acceptance and economic issues (higher design fees, construction costs and few incentives) present the main barriers to overcome. Barriers during construction stage were focused on the need for properly trained installers and several undeclared installation issues. Finally, issues discussed during operation were the cost-effectiveness of systems, continuous performance, and the need for monitoring and maintenance activities to assure occupant comfort over time (Zelenay et al., 2011).

Besides the discussed examples, the application of surveys has been used as a valuable tool to evaluate possibilities for façade integration of particular technologies such as decentralised ventilation units, or building integrated solar thermal panels (BIST). Operational issues related to the use of decentralised ventilation units were discussed by Mahler and Himmler (2008) as a result of a monitoring campaign conducted in ten buildings. It was found that the maintenance effort for these technologies was about 2-3 times higher compared to centralised ventilation systems. Nevertheless, the reported satisfaction of the users was high, being rated either 'good' or 'very good' by 75% of the surveyed building managers. Cappel et al. (2014) identified economic factors and lack of knowledge as the main barriers for solar thermal market penetration after conducting a series of interviews among forty planners, contractors, manufacturers and customers, mostly from Germany. Similarly, Munari-Probst et al. (2005) used a multiple choice web survey, addressed to architects, engineers and façade manufacturers in order to identify patterns for the aesthetical evaluation of solar thermal components for integration. It was found that general architectural rules do apply when integrating solar collectors into buildings, favouring customisation and variety of shapes and colours to ease acceptability.

This chapter contributes to the general knowledge in the field, presenting the results from an exploratory survey and discussing the findings considering previous research. The survey addressed several development stages separately in order to distinguish particular issues to overcome during design, production and assembly of building services integrated façades. Furthermore, the findings were categorised and discussed in terms of process and product related barriers, generating an information matrix with specific issues to solve for each category and development stage, considering their perceived importance based on a qualitative and quantitative assessment of the gathered responses.

§ 4.2 Strategy and methods

The assessment was based on data gathered through an exploratory survey addressed to professionals involved in any stage of the façade development process. Hence, architects, façade consultants, façade engineers and suppliers were considered as the target group. The survey sought to bring new knowledge in the field of façade design and construction, discussing barriers for the specific implementation of building service integrated facades, being understood as a particular façade product.

The assessment and discussion centred around the identification of the main perceived problems in distinct façade development stages, so the questionnaire consisted mostly of open-ended questions. The respondents were asked to state up to three main problems, in order of relevance, that they perceive as key issues during design, production and assembly stages, separately. Later, all gathered responses were examined using conventional content analysis techniques. Content analysis is a widely used tool for qualitative analysis, to interpret meaning from the content of text data. The conventional approach is used when coding categories are obtained directly from the observation of the data (Hsieh & Shannon, 2005; Mayring, 2014). Thus, main perceived problems were categorised in relevant nodes or general topics, for the discussion and prioritisation of main barriers to overcome. The chosen approach allowed for the use of mixed evaluation methods, to address different aspects of the assessment.

On the one hand, a quantitative evaluation was conducted through descriptive statistical analysis, exploring the information in terms of the frequency of each identified node for the definition of the main barriers. Hence, it was possible to discuss and compare the perceived relevance of the different key topics within each development stage, establishing priorities. On the other hand, qualitative evaluation was the basis of the assessment, considering the exact responses for the discussion of detailed problems to state recommendations for further development. The exact non-formatted responses were used for an early assessment and are presented in the form of frequency based word maps in Section § 4.3, for each defined stage. The word maps were made using the

TOC

exact words from the responses, and considered all words mentioned at least two times, after filtering connectors and other auxiliary words without standalone meaning. Word frequency count and the use of word clouds as graphical representations are commonly used as valid tools in content analysis of exploratory surveys or interviews, assisting in the identification of relevant trends, concepts or topics (SAGE, n.d.).

§ 4.2.1 Questionnaire and survey

The questionnaire was structured in three main sections: (I) Basic Information, (II) Design process of building services integrated facades, and (III) Integration of solar technologies in the building façade [Appendix A]. The first section dealt with basic information to assess the background and experience of the respondents. The second section focused on the development of building services integrated facades, seeking to identify the main problems encountered during design, production and assembly stages. Finally, the third section sought to assess the potential for integration of solar technologies in façade systems, identifying specific barriers to overcome for those particular technologies. The results presented in this chapter cover the first and second sections of the questionnaire, while the results from the third section (barriers for façade integration of solar technologies) will be discussed on Chapter 5.

The survey was conducted from mid-September to mid-November, 2015 and was distributed both as an online form and in printed format among several professional and research networks related to façade design and construction. It is unclear how many people were reached, however, the number is estimated to be between 250 and 300. At the end of the campaign, 133 questionnaires were received, comprising a final number of 79 valid questionnaires after filtering empty (40) and half empty forms (14). The response rate of the survey was 59.4% considering only the received questionnaires, and around 25-30% taking into account the estimated total universe reached. These results fall in line with similar research experiences that have used surveys in the construction field, with response rates ranging from 25.3 to 32% (Blismas et al., 2005; Nadim & Goulding, 2009). It is relevant to point out that the analysis does not pretend to be exhaustive nor completely representative of façade design and construction issues, but it is regarded as valuable referential information to understand perceived barriers and problems encountered during the development process of building services integrated façades. The assessment of perceived issues from façade professionals is considered relevant due to the role that they play in the decision-making process particularly at early design stages, having an impact on early integration of particular technologies or building services into façade concepts.

TOC

§ 4.2.2 The sample

The first section of the questionnaire aimed to characterise the sample, in order to provide context for the responses that followed. The characteristics of the respondents were defined in terms of background, role in the design/construction process, years of experience, location of projects, and experience with building services integration in facades.

In terms of the background of the respondents (n=79), the large majority corresponded to engineers (44%) and architects (39%). Only 5% declared that they have a background in material sciences while 12% stated that their background corresponds to other disciplines, such as physics, management, or others not specified (Figure 4.2). Regarding the role of the respondents within façade design and construction processes (n=79), 53% declared that they mostly have a design related role, either as architects or façade consultants, while 8% of the sample worked as system suppliers and 9% as façade builders. The remaining 30% stated that their roles were not covered by those three alternatives, filing themselves under other roles such as researchers, managers, or consultants in specific issues like energy performance, materials or structural analysis (Figure 4.3).

Regarding experience in the field (n=79), 67% of the respondents stated that they have between 5 and 20 years of experience in façade design or/and construction, and 18% claimed to have more than 20 years. Only 15% of the professionals approached for the survey had less than 5 years of experience (Figure 4.4). Furthermore, 66% of the total respondents declared to have specific experience dealing with integration of building services into façade systems. The type of experience referred was not further detailed (Figure 4.5).

The respondents were also asked to declare up to three main countries for the location of the projects they have been involved with. The locations are shown in Figure 4.6. All mentioned countries are included on the map, with different name sizes according to the amount of mentions. This map is relevant for the description of the sample because it accounts for externalities related to the professional and cultural background of the respondents, so the results also have to be studied taking this information into consideration. As it is clearly shown, the vast majority of the respondents have worked in Europe, particularly in Germany, The Netherlands and UK. There is also a relevant amount of experiences in USA and the middle east (especially UAE) and some scattered responses from the western coast of Africa, Asia and South America. This of course responds to the fact that the survey was distributed along professional networks mostly based in Central Europe, so the results must be judged accordingly.

TOC

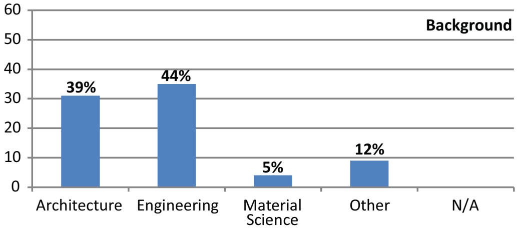


FIGURE 4.2 Sample characterisation according to the background of the respondents.

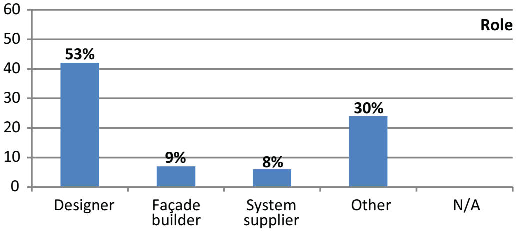


FIGURE 4.3 Sample characterisation according to the role of the respondents in the façade development process.

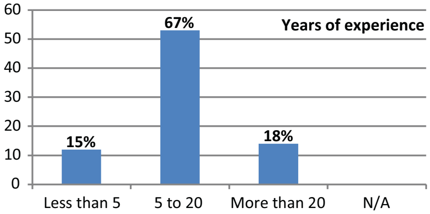


FIGURE 4.4 Sample characterisation according to years of experience.

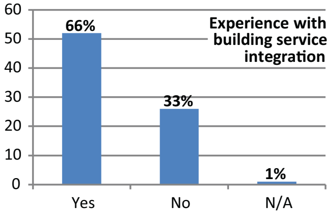


FIGURE 4.5 Experience with building services integration in facades.

FIGURE 4.6 Main location of projects from the respondents. Word sizes illustrate the amount of mentions.

§ 4.3 Results and discussion

§ 4.3.1 Early assessment and categorisation of the responses into general topics

The results discussed in this chapter aim to identify relevant problems associated with the integration of building services in façades from the perspective of experienced professionals, considering three main stages: design, production, and assembly. Detailed steps for the understanding of these stages are described in Figure 4.7, based on a scheme previously developed by Klein (2013). The questions were open ended, to allow for an exploratory entry to the subject; therefore, the responses were processed and categorised under topics for the evaluation, using content analysis techniques. This step was necessary in order to overcome false conclusions created by different phrasing or word choice by the respondents. However, detailed information from the original answers was preserved and used when discussing the results, to add depth to the analysis. Table 4.1 shows the complete list of topics recognised during the initial review, organised under two main groups to distinguish and discuss perceived problems related to either the process or the product itself.

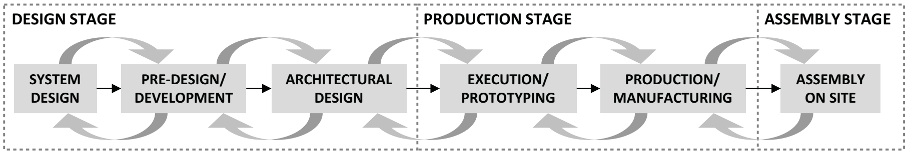


FIGURE 4.7 Stages of development process for façade products (based on scheme in Klein, T. 2013).

Several topics or nodes were identified as process related barriers. Some topics, such as coordination between trades, technical knowledge of professionals, logistics and responsibilities, mostly depend on the professionals involved in the design and construction, or are directly related to internal management of the process. Meanwhile, topics such as the existence of regulation and standards, or public acceptance are regarded as externalities that may affect the process at different stages, compromising the final result.

TOC

TABLE 4.1 List of identified topics for the categorisation of the responses.

GROUPS	TOPICS
PROCESS	Coordination
	Knowledge
	Logistics
	Time
	Cost
	Responsibilities
	Acceptance
	Regulation
	Environmental Impact
PRODUCT	Technical feasibility
	Physical integration
	Durability & Maintenance
	Performance
	Aesthetics
	Availability

Regarding the product itself identified topics considered technical feasibility, physical integration, durability, performance, aesthetics and availability of the required components and systems to be integrated. It is relevant to point out that these categories were devised for this particular analysis, based on the responses gathered through the survey, so they are not presented as definitive categories for a general understanding of the matter at hand. Furthermore, this categorisation does not change the original information in any aspect, allowing for alternative points of view to conduct further analyses of the basic unformatted dataset.

Figure 4.8 shows the number of total mentions for each particular topic, considering all three development stages within the process (design, production and assembly). Two points are worth mentioning: first of all, some topics, although mentioned in the responses, do not seem to be perceived as relevant as other groups. This is clearly noticeable in the cases of 'acceptance', 'regulation', 'environmental impact', and 'availability'. For this reason, it was decided to combine the process related topics into an 'others' category for further evaluation and discussion of the results. Secondly, there seem to be topics with high perceived relevance on all three stages, such as coordination between professionals, or physical integration of the required components in the façade module; while some others are particularly relevant in a specific stage, such as aesthetical and performance concerns during the design stage.

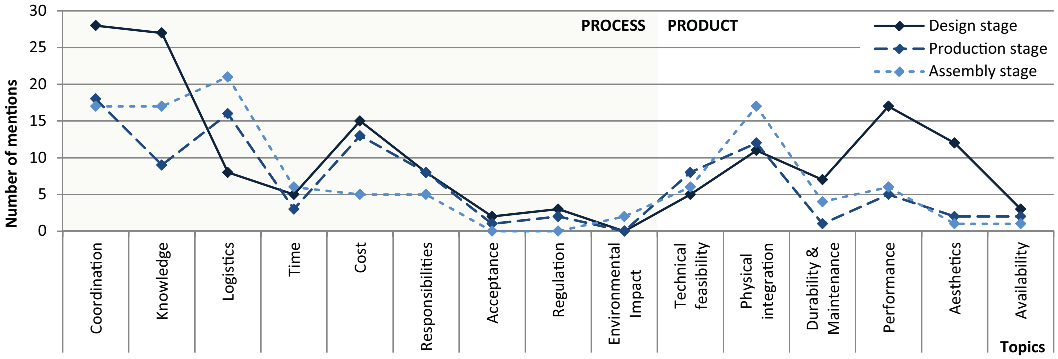


FIGURE 4.8 Number of mentions per each identified topic.

This initial assessment presented an overview of the formatted responses, establishing general trends for the defined categories in each development stage. Nonetheless, each category has different connotations and impacts on each stage, resulting on specific problems to be addressed. Consequentially, a detailed analysis of the responses from the questionnaire was performed, evaluating each stage separately to address particularities mentioned by the respondents. Furthermore, the mention order stated in the responses was taken into account to discuss perceived priorities within each defined category.

§ 4.3.2 Main identified problems during the DESIGN STAGE (n=151)

Figure 4.9 shows a word map composed with all the responses from the respondents when asked about the main perceived problems during the design stage. Complementarily, Figure 4.10 shows all formatted responses categorised according to the topics mentioned above. The respondents were asked to mention up to three main problems related with each stage, in order of relevance. Therefore, the analysis considered this when assessing the results, as shown in the graph.

By looking at the word map, it is clearly noticeable that there are topics that particularly stand out, illustrated by the use of words such as cost, knowledge, design and performance. The presence of these words does not seem surprising, given that these are indeed common relevant topics within the field of façade design and overall building technologies. However, the graph shows differences on the perceived relevance of the problems, after reviewing and formatting the responses. For instance,

TOC

‘cost’ is indeed mentioned extensively, but it represents the fourth most relevant group of problems considering the total of mentions, while it drops to the sixth place, along with ‘aesthetics’ and ‘logistics’ if we consider just the first mentioned problem. This means that even though ‘cost’ is without a doubt a relevant issue during the design stage, was not perceived as relevant as others such as ‘knowledge’ or ‘coordination’ among the respondents.

FIGURE 4.9 Word map of main perceived problems during design stage.

In terms of total number of mentions, problems about ‘coordination’ and ‘knowledge’ seem to be perceived as the most relevant within the design process, followed by ‘performance’, ‘cost’, ‘aesthetics’ and ‘physical integration’. The specific problems identified by the respondents are discussed below, according to each one of the main topics.

Among problems regarding coordination issues, the most cited ones addressed difficulties on the communication between professionals from different areas. Specifically there seems to be a widespread lack of coordination between designers/façade consultants and building services specialists, which may result in redundancies, and overall inefficiency within the design process. Furthermore, the respondents declared that there is no integral vision ruling the development process, but all professionals are concentrated on solving specific sectorial problems instead. This adds to the fact that common targets are not usually defined, which may lead to deviations from core issues.

TOC

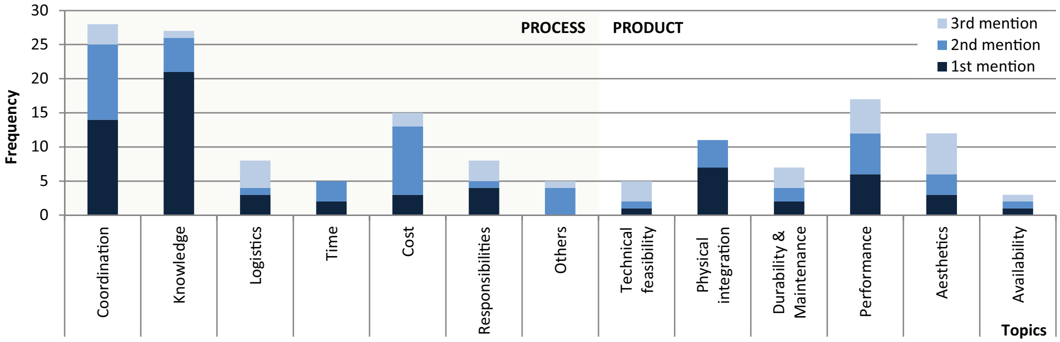


FIGURE 4.10 Main problems during design stage categorised on identified topics.

In terms of knowledge, the main complaint was the widespread lack of knowledge of designers and façade consultants. Moreover, this situation becomes more relevant considering a perceived lack of technical experience from suppliers and the communication issues discussed above. Besides the direct impact of the lack of technical knowledge on the design of building services integrated façade systems, there are indirect impacts declared by the respondents that influence the decision to develop these systems, such as the presence of prejudices or misguided expectations based on unrealistic aims.

Problems about performance fall under two types. Foremost, the main number of mentions follows problems related with the lack of tools for the accurate prediction of long term performance during early design stages. Several respondents declared that there is need for more empirical information to validate theoretical or numerical simulations for the assessment of integrated technologies, considering diverse climates and particularities from regional contexts. Secondly, some problems were identified concerning technical limitations of current systems, in terms of their achieved performance. This is perceived as particularly relevant at comparing the energy performance of compact units against the energy performance of centralised systems that cannot be fully integrated in the building façade. Besides the necessary optimisation of current systems in terms of their own performance, some identified problems discussed the expected performance of the entire façade component, considering an extra technical complexity to properly fulfil functions such as secure air tightness or provide thermal resistance. In this aspect, the performance assessment of an integrated façade component should consider the multi functionality character of the building enclosure.

Regarding cost issues, the evident problem was the perception that integrated facades would cost more, along with the difficulty for the designer to undoubtedly prove that these higher costs would in turn generate a return of the investment on the long term. Nonetheless, some respondents declared that even if it increases the cost, the main issue is about the budget structure of the development process which is segmented on different trades, making an integrated approach difficult to assimilate under current budgetary conditions.

Aesthetical aspects were not particularly explained among the responses, besides the main concern that the aesthetical quality of the façade concept should have more relevance during the discussion in early design stages. Nonetheless, some respondents declared some detailed problems related to aesthetical concerns, such as the lack of variety in terms of design solutions and available building systems, and the size of the components that need to be integrated.

Lastly, regarding problems categorised under ‘physical integration’, three main issues were identified: one general aspect and two specific issues to solve. The first one was the added complexity by having to integrate building physics aspects and building services into existing construction principles, requiring a clear identification of the structural system of the façade component. The specific issues identified by the respondents were related to the available space for service integration in façades, and the compatibility of the integrated technologies in terms of connections to be solved. The main concern expressed regarding the lack of space was referred to the depth of curtain-wall facades, which presents a major limitation for integration of conventional building systems.

§ 4.3.3 Main identified problems during the PRODUCTION STAGE (n=101)

Figure 4.11 shows the word map for the identified problems during the production stage, which includes prototyping and manufacturing of the required components. As expected, the use of words mostly respond to technical issues from the manufacturing and construction process, as seen by the prominent use of words such as ‘production’, ‘cost’, ‘feasibility’, ‘components’, ‘materials’ and ‘technical’ itself.

By looking at the total amount of categorised mentions shown in Figure 4.12, ‘coordination’ related problems again are perceived as the most relevant, followed by ‘logistics’, and then on a third level, ‘cost’ and ‘physical integration’. This trend slightly changes by solely focusing on the first mentioned problem, showing a rise of ‘cost’ and ‘physical integration’ over ‘logistics’. Even though logistics related issues remain relevant, it seems that ‘cost’ and ‘physical integration’ are perceived as a more pressing source of problems during the production stage. At the same time, although mentioned, the frequency of knowledge related problems is particularly low, especially considering only first mentions. This seems to point out that while more knowledge is clearly needed during design stages, it does not seem to be a major concern during production, hinting at a mature and trained industry.

FIGURE 4.11 Word map of main perceived problems during production stage..

Regarding particular problems associated with the mentioned categories, most problems grouped under ‘coordination’, are related to the lack of communication between professionals from different areas. Following problems encountered under the design stage, there seem to be lingering concerns about the lack of proper communication channels between designers and manufacturers during production stages. In turn, this may result in mismatches between design and built concept, and hinder the possibility to allow feedback to/from the design team. A second relevant aspect regarding communication among professionals is the perceived difficulty associated with the coordination of subcontractors and sub-suppliers. This holds true both in terms of extra time and associated costs of a disaggregated process and in terms of the distribution of responsibilities among the professionals for achieving the expected goals.

The main problem regarding cost was again the increased costs associated with integration of building services. Furthermore, it was mentioned by some respondents that the required ‘high quality’ of the building solutions would imply higher costs when compared with conventional façade components. Other relevant issue identified by the respondents was the occasional mismatch between initial costs predicted during design

TOC

stages and the real cost of the production process. This uncertainty of course increases perceived risks and generates prejudices associated with services integration in façades.

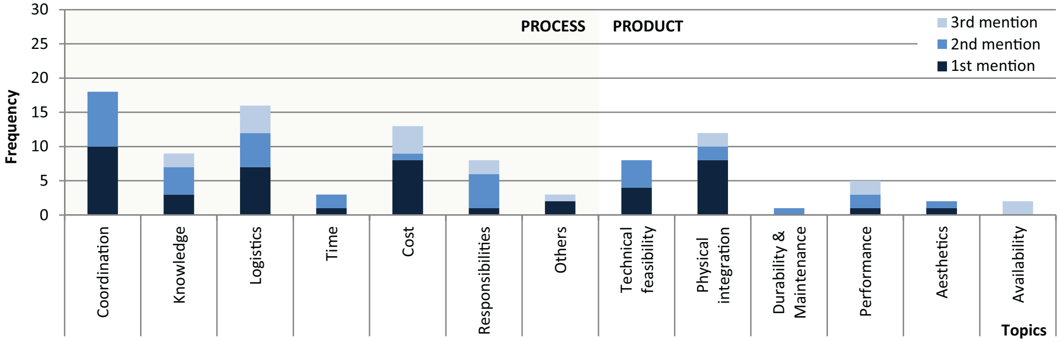


FIGURE 4.12 Main problems during production stage categorised on identified topics.

In terms of physical integration, the mentioned problems refer to the compatibility between the different systems to be integrated and the constructive components of the façade, and between the service systems themselves. From the responses, these compatibility problems mostly comprehend two aspects: the size and modulation of the components, which do not follow standardised dimensions that could facilitate their integration; and the definition of their interfaces, both in terms of the actual connections to be solved and the different materials that have to be accounted for. Furthermore, these issues add more complexity to the design of the systems, multiplying the necessary number and types of components to fulfil the required functions, which relates to the technical feasibility of the overall façade concept.

Problems related to the logistics of the process mainly refer to the lack of flexibility within the production and supply chain. The respondents declared that specially the façade assembly line is not typically equipped to integrate services during production, which hinders the use of prefabrication as a widespread method for production. Several respondents agreed to the fact that there is a need for new working models to assist the development of new integrated façade concepts.

Regarding problems about the required knowledge to fulfil the goals, the responses focused mostly on the lack of qualified technical staff overseeing the production process, combined with a lack of skilled workers on site, with experience handling these integrated façade components. Several respondents claimed the importance of having professionals with particular experience in integration, within façade building companies, in order to facilitate communication channels to service suppliers, and to properly advice designers in technical issues related with the production process. Nevertheless, as stated before, these issues were not perceived as relevant as others previously discussed.

§ 4.3.4 Main identified problems during the ASSEMBLY STAGE (n=109)

Figure 4.13 shows the word map for the identified problems during the assembly stage, which considers the activities destined to connect all façade components between themselves and the rest of the building. The fact that the main activities deal with the coordinated assembly of several components on site is clearly expressed by the choice of words by the respondents. Among the most used words are 'site', 'assembly', 'coordination', 'construction' and 'different', followed by words directly related with integration, such as 'technical', 'services', 'building', 'systems', 'façade' and 'time'.

FIGURE 4.13 Word map of main perceived problems during assembly stage.

In terms of the number of mentions by topic, Figure 4.14 shows an even distribution among the different categories, with the exception of four topics that remarkably stand out ('coordination', 'knowledge', 'logistics' and 'physical integration'). Regarding both total amount of mentions and 1st mentions, process related problems seem to be the most relevant ones, particularly considering 'coordination', 'knowledge' and 'logistics'. Constructive problems related to the physical integration of components and systems were identified as the most relevant product related aspects to overcome.

TOC

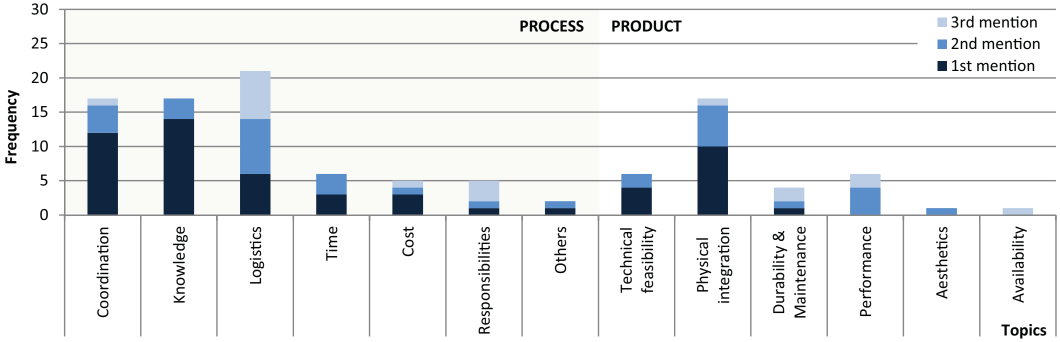


FIGURE 4.14 Main problems during assembly stage categorised on identified topics.

Besides communication problems among different specialists previously discussed on other stages, coordination problems during the assembly stage seem to be closely linked to the logistics to conduct the required activities on site. The assembly process appears to be seen by the respondents as a coordination exercise between different trades to build the final product. Furthermore, this fact is supported by the limited use of prefabricated unitised modules, leaving the physical integration and connection of the services to be conducted on site. Besides these aspects, other logistics issues mentioned were the transportation and handling of units and components on site, and unexpected issues related to particularities from the context.

As expected, problems regarding lack of knowledge, referred to the lack of training and competence of the workforce on site. This issue represents the large majority of responses related with this topic, with some respondents detailing the necessity to count with installers with multifunctional skills and experience to supervise the assembly process. Some respondents declared that façade contractors in charge of assembly tasks, do not usually know about technical aspects of building services, while others declared that the over specialisation of building services installers means that their knowledge is too focused, disregarding technical aspects of building envelope construction, which may cause risks for the overall quality of the building, as mentioned in the survey.

In terms of physical integration, most mentioned problems were related to the interfaces between the services to be integrated and other components. Several respondents advocated for the need to account for tolerances between the different components to allow for easy integration on site. Some cases were mentioned where products did not fit or where façade units became heavier than expected, due to a miscalculation during the design stage or due to a change on the specifications on later stages which was not considered until the assembly stage. Furthermore, it was stated that the connections should be designed considering the number of components, different materials and easiness of construction. An overly complex assembly method may be a source of countless problems, so, a low number of steps, based on a ‘plug & play’ assembly concept was recommended.

Overall, it was mentioned that the reality on site may differ greatly from the theoretical parameters considered during the design stage, which would imply extra work and time during the assembly stage to account for unforeseen variables. Some respondents addressed this issue by supporting more use of prefabricated integrated façade components, assembled off site under rigorous technical supervision.

§ 4.3.5 Summary of the main identified problems and recommendations

A summary of the main identified problems is shown below. Table 4.2 comprehends problems related with the process while Table 4.3 shows problems related with the product itself. The categories shown are the most mentioned categories overall. Furthermore, the relative relevance of each set of problems is addressed in the tables, using a scale of colours based on the total amount of mentions of each category per stage. Hence, darker categories are perceived as more pressing to overcome than lighter ones, within each stage.

By looking at Table 4.2, it is clear that problems related to coordination are perceived as the most relevant ones, which is a fact that holds true in all three defined stages. Hence, it seems highly important to promote clear communication channels between all professionals involved in the process. Secondly, there is a perceived lack of technical knowledge and expertise dealing with integrated building services, particularly during design and assembly stages. Trained designers would be able to incorporate technical input at early design stages, easing communication with façade engineers while minimising mismatches between design and production stages. Moreover, a skilled and trained workforce on site would decrease construction times and the occurrence of errors during assembly.

The fact that lack of knowledge does not appear to be as relevant during production stages, seems to be a sign that façade building companies have enough experience and maturity to undertake the required activities without relevant problems. However, it was pointed out that there are several logistical issues that need to be addressed to allow for façade integration. In general, a main concern stated was the lack of flexibility within the production chain, hindering innovation. In this aspect, the development of alternative production processes, with emphasis on off-site production, and the generation of new

TOC

business models for the development and management of high-performance facades, are regarded as promising ways to promote widespread façade integration of building services, promoting collaboration while reducing associated costs of current standalone enterprises (Azcarate-Aguerre, Klein, & den Heijer, 2016; Goulding et al., 2014).

TABLE 4.2 Main identified problems per development stage and category (process related problems).

	PROCESS RELATED PROBLEMS				
	COORDINATION	KNOWLEDGE	LOGISTICS	COST	RESPONSIBILITIES
DESIGN STAGE	· Communication difficulties between professionals from different areas. · Lack of coordination between designers/ façade consultants and building services specialists · No integral vision ruling the development process. Common targets not usually defined.	· Lack of knowledge of designers and façade consultants. · Lack of technical experience from supplier · Prejudice and misguided expectations based on unrealistic aims.	· Additional planning effort · Building services are addressed too late in the design and decision making process.	· Higher perceived cost of integrated facades · Difficulty for the designer to prove return of investments on the long term. · Budget structure of the development process, segmented on different trades.	· Responsibilities are not defined.
PRODUCTION STAGE	· Lack of communication between professionals from different areas. · Lack of communication channels and feedback between designers and manufacturers during production stages. · Difficult coordination of subcontractors and sub-suppliers.	· Lack of qualified technical staff overseeing the production process. · Lack of skilled workers on site with experience handling integrated façade components. · Need for professionals with experience in integration working at façade building companies.	· Lack of flexibility within the production and supply chain. · Façade assembly line is not typically equipped to integrate services during production. · Need for strong quality control and mid-production testing.	· Higher costs associated with the high quality of solutions required for the integration of building services. · Mismatch between predicted costs during design stages and the real costs of production.	· Responsibilities are not clearly defined. · Refrain of responsibility from façade contractors due to fear of risk.
ASSEMBLY STAGE	· Lack of communication between professionals from different areas. · Number of different trades and suppliers involved in assembly.	· Lack of training and competence of the workforce on site. · Need for installers with multifunctional skills and experience to supervise the assembly process.	· Transportation and handling of units and components on site. · Divergencies between designed assembly method and its application on site. · Context based issues. · Limited use of prefabrication: more activities to conduct / coordinate on site.	· Higher assembly costs · Projected costs do not usually match real assembly costs due to particularities from site.	· Unclear responsibilities and warranties.

Note: Darker colours represent higher amount of mentions per stage.

TABLE 4.3 Main identified problems per development stage and category (product related problems).

	PRODUCT RELATED PROBLEMS				
	TECHNICAL FEASIBILITY	PHYSICAL INTEGRATION	DURABILITY & MAINTENANCE	PERFORMANCE	AESTHETICS
DESIGN STAGE	· Overall feasibility of the intended design. · Size of components that Need to be integrated.	· Added complexity of integrating building physics, building services and façade construction principles. · Available space for service integration in facades. · Compatibility of systems and connections to be solved.	· Maintenance provision and durability of the components over time. · Consider access for maintenance in the design. · Distributed systems are more complicated to maintain (cost and effort).	· Lack of tools for the accurate predction of long term performance. · Technical limitations of current systems in terms of their performance. · Multifunctional performance of the façade component is not usually considered.	· Aesthetical quality of the façade concept shoud have more relevance during discussions on early design stages. · Lack of variety in terms of design solutions and available building systems
PRODUCTION STAGE	· Overall feasibility of the intended design. · Appropriate level of complexity.	· Compatibility between systems to be integrated and façade components. · Lack of standardised dimensions and modular components for an easy integration. · Multiple connections to solve and different materials to consider.	· Maintenance issues.	· Achieving expected performance in terms of the systems and façade functions.	· Meet aesthetical requirements from architects.
ASSEMBLY STAGE	· Feasibility of the assembly on site. · Unnacounted size/weight issues of the services to be integrated.	· Need to account for tolerances between components. · Connection of several number of components and different materials. · Lack of modularity and/or standardised dimensions and conections.	· Maintenance issues · Limited possibilities to conduct repairments.	· Testing of operation of systems and components. · Limited communication of operation modes and user control parameters to users.	· Low attention to aesthetical quality of joints and details.

Note: Darker colours represent higher amount of mentions per stage.

In general terms, the findings fall in line with the results from other research experiences previously discussed in the document, which state the relevance of process related barriers. Both Klein (2013) and Ledbetter (2001) advocated for the need for better coordination within the process, promoting feedback among the stakeholders from early design stages, while lack of knowledge was referred to by Zelenay et al. (2011), Ledbetter (2001) and Cappel et al. (2014). Cost is a relevant issue to overcome

TOC

according to Haase et al. (2009) and Zelenay et al. (2011); however, besides particular aspects to solve during production, it does not seem to be a pressing matter for the surveyed experts. This may be evidence of confidence on further technical development and advances that may decrease associated costs, while exploiting reported benefits related to comfort and efficient energy usage.

In terms of product related problems, physical integration seems to be the most relevant issue during both production and assembly stages (Table 4.3). Additionally, the lack of tools for the prediction of long term performance, and operational limitations of currently available systems were stated as problems during design stages.

Discussing integration issues, low compatibility between different systems was the main source of concerns, considering contrasting dimensions and multiple connections to solve among different materials and components, under no unified standard. Hence, recommendations for future product development revolve around the need for components especially designed for integration from early stages, solving connection and compatibility issues through standardisation and modularity. Furthermore, some respondents advocated for the use of modular and prefabricated components, under a ‘plug & play’ integration approach, to minimise problems during the assembly stage by simplifying complex connections on site; an statement shared by authors such as Mach et al. (2015).

In this sense, modularity has to be understood not only as the partitioning of a larger system, but as an holistic approach to the design of the components, defining their architecture and their interfaces to ensure the correct operation of each module and the whole systems. Moreover, the façade construction industry should aim to apply modularity not only in use and production, but also and particularly in design. Modular use allows for customisation through standard dimensions, while modularity is a key aspect for the mass production of components to be assembled later on. However, according to Baldwin & Clark (2004), a system is modular-in-design if the process itself can be split up and distributed across separate modules, coordinated by design rules instead of consultation amongst designers. This approach could potentially promote innovation, generating a new framework for a more cost-effective development of integrated facades.

At the same time, aesthetical aspects should be considered, providing an array of products in terms of shape, colours and sizes to allow for customisation (Munari Probst & Roecker, 2007). Furthermore, the performance of components and systems needs to be improved, considering not only their operation but also the durability of their individual parts, which has an impact on long term maintenance activities.

Several other technical aspects that need to be further enhanced were stated by the respondents, being regarded as relevant information for product development. Nevertheless it is important to reiterate that process related barriers in general, and coordination between stakeholders and lack of knowledge in particular, are perceived as the most crucial barriers to overcome. Hence, while it is important to further develop an array of products for façade integration, the most pressing efforts should be focused on devising new multidisciplinary façade design and production processes, and on including integration issues in designers' education, in order to promote the development and widespread application of building services integrated facades.

§ 4.4 Conclusions

This chapter aimed to discuss barriers for the integration of building services in façades, by identifying relevant problems and issues during design, production and assembly stages. The method chosen for the study was an exploratory survey addressed to professionals with practical experience in the development of façade systems for office buildings.

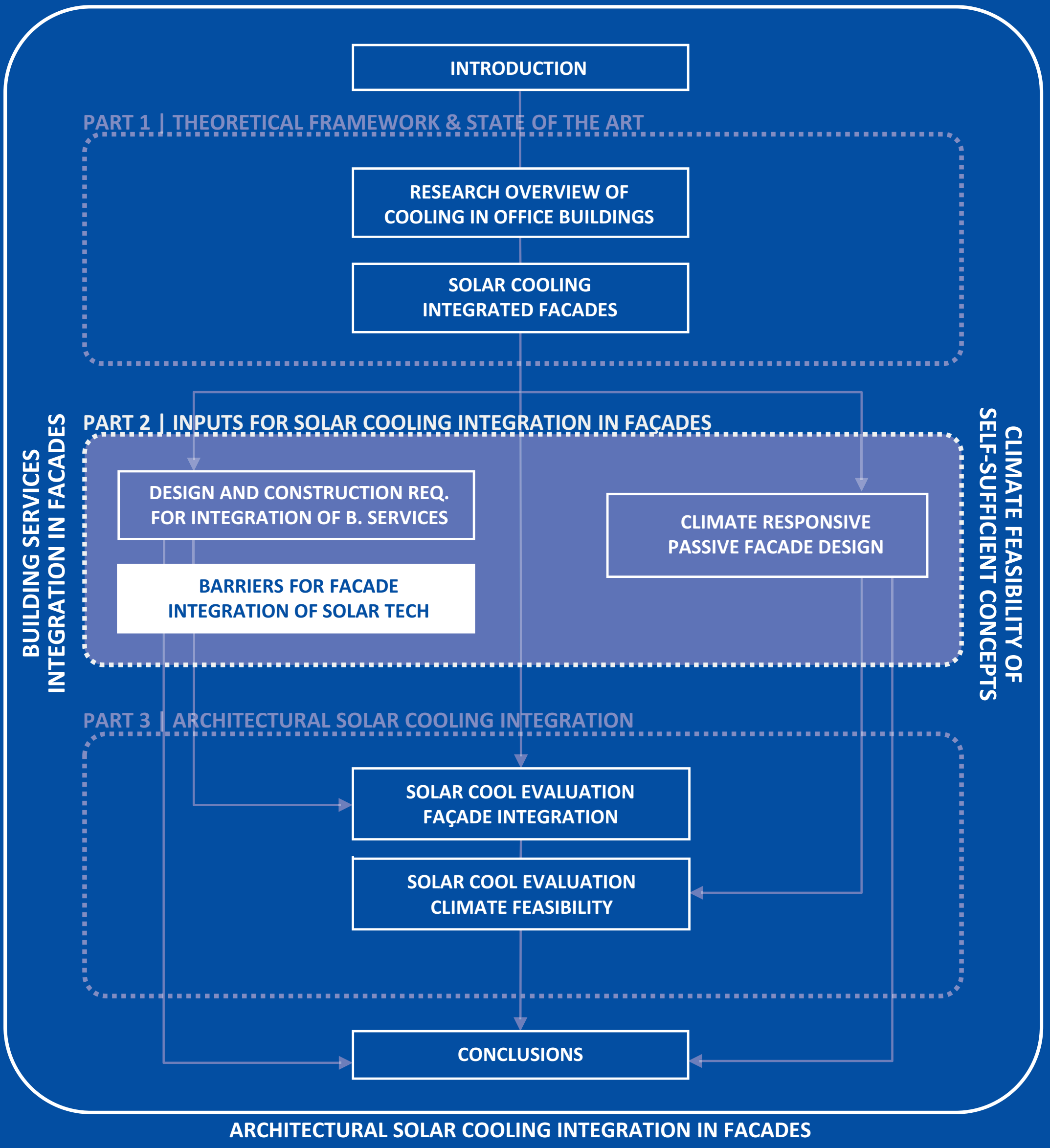
General results showed that barriers related to the process itself are perceived as more pressing to solve than issues about the end product, to promote façade integration of building services. Furthermore, specific issues were identified in all three defined development stages: main problems during design stages were particularly characterised by coordination and lack of knowledge. Main problems during the production stage were mostly perceived in relation to coordination, logistics, cost and physical integration, while lastly, main perceived problems during assembly stages dealt with coordination, lack of knowledge, logistics and physical integration of systems and components.

As particular recommendations, it seems highly important to promote clear communication channels between all professionals involved in the process, and encourage the development of alternative production processes, with emphasis on off-site production, and the generation of new business models for façade development, in order to incorporate more flexibility into the supply and production chain. In a similar note, product development efforts should aim to generate a wide array of components under a modular design approach, considering connection and compatibility issues related to their physical integration.

TOC

Finally, it is important to point out that given the scope and scale of the study, the analysis did not pretend to be exhaustive. Even though the findings represent relevant referential information for the development of integrated façades, more studies are needed to comprehensively assess barriers and possibilities for widespread façade integration of building services. The definition of local variables to assess potential for application on different contexts and the validation of the findings through case studies or in-depth interviews are regarded as possible research paths for the short-term future.

COOLFACADE



INTRODUCTION

PART 1 | THEORETICAL FRAMEWORK & STATE OF THE ART

RESEARCH OVERVIEW OF COOLING IN OFFICE BUILDINGS

SOLAR COOLING INTEGRATED FACADES

PART 2 | INPUTS FOR SOLAR COOLING INTEGRATION IN FAÇADES

BUILDING SERVICES INTEGRATION IN FACADES

DESIGN AND CONSTRUCTION REQ. FOR INTEGRATION OF B. SERVICES

BARRIERS FOR FACADE INTEGRATION OF SOLAR TECH

CLIMATE FEASIBILITY OF SELF-SUFFICIENT CONCEPTS

CLIMATE RESPONSIVE PASSIVE FACADE DESIGN

PART 3 | ARCHITECTURAL SOLAR COOLING INTEGRATION

SOLAR COOL EVALUATION FAÇADE INTEGRATION

SOLAR COOL EVALUATION CLIMATE FEASIBILITY

CONCLUSIONS

ARCHITECTURAL SOLAR COOLING INTEGRATION IN FACADES

TOC

5 Barriers for façade integration of solar technologies

Discussion of main perceived barriers from an exploratory expert survey[4]

Solar energy has been actively promoted as a clean energy source for a long time; however, solar technologies have not been widely used in the built environment, mostly limiting their operation to industrial and macroscale applications. Along with commercially available products such as building integrated PV panels (BIPV) or building integrated solar thermal collectors (BIST); novel solar cooling integrated facades are seen as interesting alternatives for the development of new active façade components for high-performing commercial buildings. Nevertheless, there are barriers to overcome to push for widespread application of architecturally integrated solar façades.

This chapter *identifies perceived barriers for widespread façade integration of solar technologies*, to explore the current scenario and generate guidelines for future developments. To achieve this, the chapter discusses the results of the second part of the survey presented in the previous chapter, which addresses the perceived potential and specific issues for the integration of solar technologies. General results point to economic aspects as the main barrier to overcome, followed by particular issues related to current limitations of components and architectural products. In this aspect, most mentions point to performance, aesthetics and technical complexity of current systems as issues to improve in order to promote the development of solar integrated architectural products.

---

[4] Published as: Prieto A, Knaack U, Auer T, Klein T. (2017). Solar façades – Main barriers for widespread façade integration of solar technologies. Journal of Facade Design and Engineering; 5: 51-62. doi: 10.7480/jfde.2017.1.1398.

TOC

§ 5.1 Introduction

Worldwide energy consumption is expected to greatly increase during the next three decades. Predictions elaborated by the US Energy Information Administration (EIA) show that by 2040, world energy consumption will present an increase of 48%, compared to consumption levels registered in 2012 (DOE/EIA, 2016). Similarly, in the last annual energy outlook released by BP, it was declared that an increase of 35% in total energy usage is expected between 2014 and 2035 (BP, 2016). This panorama clashes with IEA reports which state that energy production and use presently account for two thirds of worldwide greenhouse gas emissions, supporting the need to lower them, while sustaining the growth of the world economy (OECD/IEA, 2015). As a matter of fact, it has been stated that the expected consumption increase will be mostly supported by non-OECD nations, in order to drive long term economic growth, so even if energy saving campaigns and strategies are enforced worldwide, there will still be a demand for alternative sources of energy.

Solar energy has been actively promoted as a clean energy source since 1973's oil crisis, evidenced by the emergence of initiatives such as the Solar Heating & Cooling Programme of the International Energy Agency (IEA-SHC, 2016) or the US Department of Energy (DOE). Nonetheless, besides scattered examples, the introduction of solar technologies into the built environment has not been massively accepted, which seems relevant considering that the building sector accounts for 40%-45% of the total energy demand (EP, 2002). Important advances have been made in the development of solar driven building products for façade integration, such as semi-transparent PV glazing (Fung & Yang, 2008; D.H.W. Li et al., 2009), PV and solar thermal collector integrated shading devices (Frontini, 2011; Mandalaki et al., 2012), or coloured glazed thermal collectors by means of multi-layered films (Schüler et al., 2005) and selective paint coatings (Joly et al., 2013; Orel et al., 2007). However, these have been proven insufficient in order to promote widespread application in buildings.

This chapter seeks to contribute to the field, by presenting the results of an open ended survey addressed to professionals with practical experience in the development of façade systems for office buildings. The main goal of the survey was to identify main requirements and barriers for façade integration of building services, as a way to promote the development of new cost-effective multifunctional façade products for high-performance office buildings. The first part of the survey dealt with design and construction problems related to the integration of building services and was discussed on the previous chapter (Prieto, Klein, & Knaack, 2016). The second part was specifically aimed to identify the main barriers for façade integration of solar technologies. Hence, this chapter presents the perceived barriers and compares the findings along similar research experiences on the topic.

Among related experiences it is possible to count surveys carried out to identify barriers for the application of building integrated photovoltaics (BIPV) and building integrated solar thermal panels (BIST). Yang (2015) discussed technical barriers for façade integration of PV panels, considering design, construction, commissioning and operation stages. Her findings highlighted the need for advanced simulation tools and monitoring platforms to assist the role of designers and building managers. Cappel et al. (2014) stated that economic factors are seen as the most relevant barrier, with an important lack of knowledge from architects as the second most important problem for market penetration of facade integrated solar thermal systems. Also discussing thermal collectors, Munari Probst and Roecker (2007) stated the need for more design flexibility regarding aesthetical aspects such as shape and colour of integrated building components.

One of the most relevant works about barriers for architectural application of solar technologies was made as one of the outcomes of Task 41 of the Solar Heating & Cooling Programme of the International Energy Agency. A web-based multiple choice survey was distributed among architects in 14 participating countries, to assess their use of solar technologies, perceived barriers for implementation, and satisfaction levels of commercially available products. Results from 394 valid questionnaires showed that economic aspects are the main issues to overcome, followed by knowledge and information about solar technologies and product availability (Farkas & Horvat, 2012).

The information presented on this chapter is organized according to two main aspects. First, barriers are identified and assessed in terms of perceived relevance by the respondents, comparing the results to the findings of Farkas and Horvat (2012). Secondly, key aspects among the barriers are discussed, giving particular attention to perceived barriers related to the products themselves, in order to draft recommendations for future product development, based on requirements and experience from experts in the field.

TOC

§ 5.2 Methodology

§ 5.2.1 The survey

The survey was conducted from mid-September to mid-November, 2015 and was distributed both as an online form and in printed format among several professional and research networks related to façade design and construction. 133 questionnaires were recovered, consolidating a final number of 79 valid questionnaires after filtering empty (40) and half empty forms (14). The questionnaire was structured explored design and construction issues related to the integration of building services in general while also considered specific questions about the integration of solar technologies. This chapter focuses on the second part of the questionnaire.

Multiple choice questions were analysed through descriptive analysis, while open ended questions were processed following content analysis methods. The findings from Task 41 were used as reference for the evaluation of the responses, allowing for comparisons. The analysis does not pretend to be exhaustive nor completely representative, however, it is seen as valuable information to understand perceived barriers and detect key aspects to overcome in order to develop architecturally integrated solar façade components.

§ 5.2.2 The sample

The questionnaire was addressed to professionals with practical experience in the development of façade systems for office buildings, situated at any stage of the design and construction process, which meant different backgrounds and experience within the sample. In terms of the background of the respondents (n=79), the large majority corresponded to engineers (44%) and architects (39%) as shown in Figure 5.1. Regarding experience in the field, 67% of the respondents stated that they have between 5 and 20 years of experience, and 18% claimed to have more than 20 years. Only 15% of the professionals approached for the survey had less than 5 years of experience (Figure 5.2).

TOC

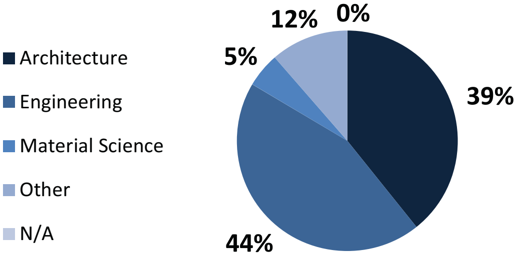


FIGURE 5.1 Declared background of the respondents.

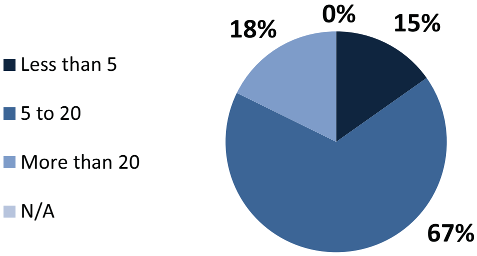


FIGURE 5.2 Declared years of professional experience.

Familiarity with solar technologies was evaluated, considering direct experience with PV panels, solar thermal collectors, and solar cooling technologies. The respondents were allowed to check more than one alternative, in case they had experience with more than one type of technology. Figure 5.3 shows that almost half of the sample (47%) declared to have had direct experience with photovoltaic cells, while 38% declared the same for the case of solar thermal collectors. As expected, a smaller group of respondents declared to have particular experience dealing with solar cooling technologies. Lastly, 33% declared not to have any experience working with solar technologies. This fact is worth mentioning because it means that around two thirds of the sample does have direct experience working with the cited technologies, which validates their appreciations on the topic.

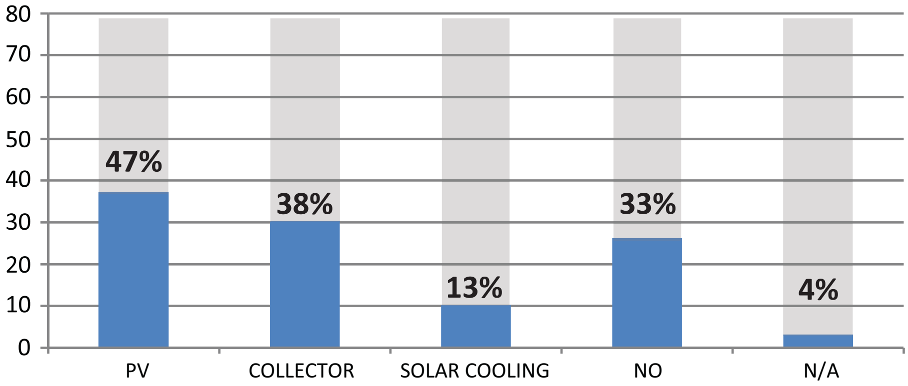


FIGURE 5.3 Declared experience with solar technologies.

§ 5.3 Results and discussion

First of all, Figures 5.4 and 5.5 show the overall perception of the respondents regarding possibilities for integration of solar technologies in façade systems. Figure 5.4 illustrates the perceived potential for further development of solar integrated façade products. The vast majority of the respondents (91%) believed that there is potential for integration, while only 6% were not sure and 3% did not provide an answer. It is worth mentioning that nobody declared to believe that there is no potential for further developing façade products integrating solar technologies. The main reason declared by those who were not sure about façade integration potential was the difficulty associated with the development of cost-effective solutions, due to low efficiency and high costs of current systems.

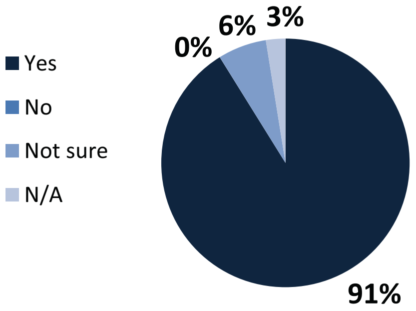


FIGURE 5.4 Perceived potential for solar façade integration

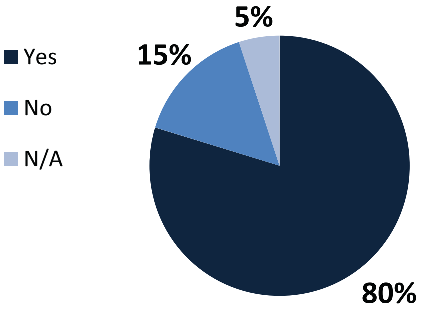


FIGURE 5.5 Current market for solar façade products

Furthermore, the respondents were asked if they believe that there are current market possibilities for commercial application of solar integrated architectural products. As shown in Figure 5.5, 80% of the sample believes that there is current commercial demand for these products, while 15% believes the contrary. The main reasons given to support the latter were the high costs of the systems compared with the low cost of energy, and budget management within the conventional facade design and production process, based on separate trends and contractors, obstructing the development of integrated products.

§ 5.3.1 Main perceived barriers to promote widespread façade integration of solar technologies.

The respondents were asked to state the most important barriers to overcome in order to promote widespread integration of solar technologies into the building envelope. This was an open ended question to assess their perceptions on the subject without external conditioning. Furthermore, the respondents were asked to mention up to three constraints in order of relevance, so the order of the mentions was considered on further analyses.

Figure 5.6 shows a word map of all issues declared by the respondents, as a first approach to data analysis. The size of the words represents their frequency within the sample. The word map was made using the exact words from the responses, considering all words mentioned at least twice, after filtering connectors and other auxiliary words without standalone meaning. No distinction was made based on the order of the mentions.

FIGURE 5.6 Word map of barriers declared by the experts

By looking at the word map, it is clearly noticeable that 'cost' stands out as the most used word to refer to integration barriers, which does not come as a surprise. Other topics which received a relevant amount of mentions were related to design aspects ('aesthetics', 'design'), performance of the systems ('performance', 'efficiency', 'energy'), the knowledge to design, implement or operate them ('knowledge'), or the need for extra maintenance activities ('maintenance').

As a second step for data analysis, the responses were processed and formatted into new limited categories to allow for further evaluation. This step was necessary in order to overcome false conclusions created by different phrasing or word choice by the respondents. However, detailed information from the original answers was preserved and used when discussing the results, to add depth to the analysis. It was decided to use the categories defined by the IEA SHC Task 41 research project (Farkas & Horvat, 2012), for the analysis of the sample (Table 5.1). Therefore, using categories already validated in the literature, while giving the opportunity to compare and discuss the results against previous experiences.

TABLE 5.1 Barriers and categories identified by IEA SHC Task41.

MAIN CATEGORIES	DESCRIPTION OF THE BARRIERS
INTEREST	Lack of interest in solar design by architects and clients/developers.
ECONOMY	Not economically justifiable and lack of governmental incentives.
KNOWLEDGE	Lack of sufficient technical knowledge by architect, by client/developer and by consultant.
INFORMATION	Lack of architecturally oriented literature about these technologies and useful data for architects in product datasheets.
PRODUCT	Lack of products suitable for quality building integration and complementary building components.
PROCESS	Lack of tools that support design and sizing of systems / Technology is considered too late in the design process (insufficient time and resources).

The categorised responses are shown in Figure 5.7. As expected, economy related issues have the most amount of first mentions, being perceived as the main barrier to overcome. Secondly, issues about the product itself arose as a relevant barrier, followed by knowledge and information related problems. Lastly, problems related with design and construction processes were also mentioned as the main barrier, along with other topics not considered in the previous categories. Lack of interest was not identified as a barrier in the first mention by any of the interviewed experts.

Considering the total amount of mentions under each category, 'economy', 'knowledge' and 'information' show a frequency increase without surpassing the number of first mentions. However, in the cases of 'product' and 'process' related barriers, second and third mentions surpass the first one. This shows that even if these are not strongly perceived as the main barrier to overcome, there are important 'product' and 'process' related issues to solve in order to promote widespread façade integration of solar technologies. This issue is particularly evident in the need for suitable products for integration. As shown in the graph, it becomes the most pressing issue to overcome

TOC

considering the total amount of mentions. Of course, different aspects related to the suitability of said products were considered, which will be further detailed in this document.

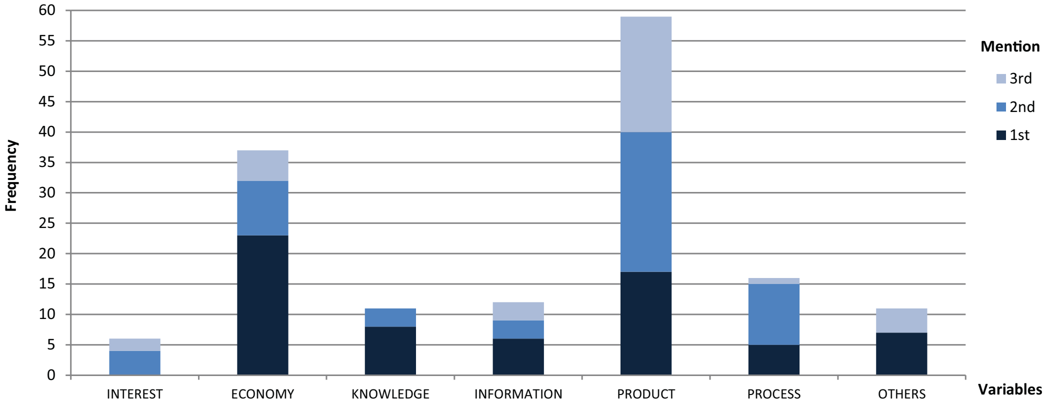


FIGURE 5.7 Main perceived barriers categorised on variables defined by IEA SHC Task 41

In general terms, the results obtained from the survey fall in line with the findings from IEA Task 41. Similarly, Farkas and Horvat (2012) declared that economic issues seem to be the main barriers for implementation of solar technologies, although this becomes clearer in the case of the application of PV panels, compared to the use of solar thermal technologies. Discussing possible strategies to overcome the barriers, besides economic measures, the authors declared that even if there have been considerable advancements in the design, look and efficiency of solar components, there is need for new developments and improvements of available products to appeal to architects. The recognition of these two issues by both experiences is seen as a sign of validation for this study, by comparison with a larger sample.

The most relevant differences between both experiences, refer to the perceived lack of knowledge and overall interest to architecturally integrate solar technologies into the building envelope. Task 41 results showed these issues as the second and third most relevant barriers for the use of both PV cells and solar thermal panels. While lack of knowledge was also declared as a relevant barrier during the present study, lack of interest was barely mentioned in comparison with other barriers, and not stated at all as the main barrier (under first mention). One the one hand, this fact could be seen as a sign of increasing interest on renewable energies since the application of the Task 41 survey. On the other hand, another reason to explain this could be the specialisation level of the interviewed experts (professionals from different disciplines with experience in façade design and/or construction) when compared to the surveyed sample from Task 41 (mostly architects). Furthermore, it is relevant to mention that more than 90% of the interviewed experts believed that there is potential for façade integration, whose probably take interest in this technologies for granted. This notion may be supported by looking at the disaggregated results from the Task 41 report, which differentiated between lack of interest by the client and lack of self-interest (by architects). In effect, clients' lack of interest was declared as an important barrier while architects' lack of interest was barely stated as an issue, in a similar way to the present study. Conjectures aside, the fact that 'lack of interest' did not appear in relevant numbers as answer to an open ended question, shows that it was clearly not perceived as a defining barrier for the surveyed sample.

Several statistical analyses were conducted to assess potential differences in the perceived barriers between independent groups among the sample, based on background, role, experience with façade integration or solar technologies. Even though some discrepancies were found among the groups, particularly between professionals with and without experience with solar technologies, the deviation was never found significant enough to unequivocally state that perceived barriers change according to different groups. Thus, the discussed results are valid for the different groups allowing for minor variations in judgement. More detailed studies with a larger sample are advised if there is further interest to explore these variations.

§ 5.3.2 Identified aspects to overcome within main barriers

Given that the survey was structured in open ended questions, the respondents had the possibility to freely declare the issues they perceived as the main barriers to overcome for widespread façade integration of solar technologies. This information is regarded as relevant in order to devise focused strategies to cope with the perceived barriers, discussing several mentioned aspects in each category for better understanding. It is worth mentioning that the depth of the discussion is constrained by the level of detail of the gathered responses, allowing for more insight in some topics than others. 'Product' related issues will be presented separately, due both to its relative perceived relevance within the sample and its potential to inform the development of future architectural products. Hence, the discussion will be conducted to the definition of key aspects to overcome for the development of appealing solar integrated façade components.

First of all, issues categorised under ‘economy’, largely refer to the cost of solar technologies in terms of the economic feasibility and payback time for the initial investment. An additional concern was the current energy price, which is not high enough to promote the emergence of competitive solar driven alternatives on a larger scale. Nevertheless, the energy cost is expected to rise in the future, while at the same time further developments and governmental incentives should encourage the offer of new solar based architectural products for façade integration.

Regarding knowledge, the main concern was the lack of experience and overall knowledge of architects about technical issues and solar technologies in general, obstructing its widespread application. Besides this, there were also mentions of the role of end users, referring to their lack of knowledge on how to operate these systems. Finally some concerns were also expressed about the experience of the workforce on site, required to successfully assemble the components minimising the occurrence of errors. The perceived lack of knowledge is closely linked with the need for useful information about solar technologies. The respondents declared that information should be focused on showing purposes and associated benefits to end users, while it also should be clear and complete enough to assist architects during design stages. In this regard, there were concerns about proper documentation of some properties, such as efficiency over time and reliable performance data; and also the need for updated standards for building integration, considering reputable references and state-of-the-art available technologies in the market.

The main issues categorised under ‘process’ revolved around the perceived need to rethink the overall façade design and construction process to incorporate solar technologies from earlier stages, allowing for closer collaboration between the different disciplines involved. It was stated that integration has to be further considered by both designers and manufacturers, pushing for optimised mass production processes while minimising planning efforts. It was also mentioned that more design oriented tools are needed in order to bring architects closer to technical issues during early design stages.

Declared barriers not considered in the main categories were related with building regulations, conflict of interest between different stakeholders, building management problems during occupation, and insurance and liability aspects. Safety of the installation and definition of clear responsibilities in case something does not work as expected were particularly stated among these barriers. Nonetheless, these issues were not perceived as relevant as other previously discussed in this document.

TOC

§ 5.3.2.1 Barriers to overcome in product design and development

As stated before, product related barriers received the most amount of total mentions. These barriers were further categorised for detailed analysis of the information, identifying key perceived aspects to guide future developments under the following topics: performance, technical complexity, aesthetics, durability and availability.

Figure 5.8 shows the subcategories of product related barriers, based on the gathered responses. Performance related barriers seem to be perceived as the most pressing to overcome, considering the amount of first and second mentions. Aesthetics is also seen as a relevant barrier, followed by the technical complexity of the systems involved. Lastly, the durability of the systems and product availability were also stated by the respondents as barriers to overcome, although they were not perceived as relevant as the other barriers.

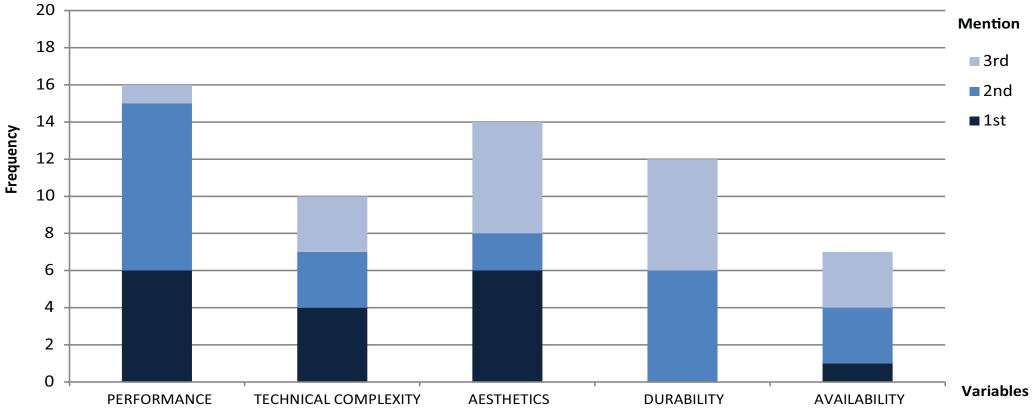


FIGURE 5.8 Main perceived barriers related to current products

In general terms, performance related barriers referred to the need to improve the efficiency of current systems and components. It was also specifically stated that the integration of storage strategies is a requirement to allow for continuous operation, improving the overall performance while supporting a better management of energy flows.

Regarding aesthetics, the answers were generally somehow vague, stating that the aesthetics of current components are something to improve, without further detailing parameters to be considered. Nevertheless, some specific aspects were mentioned by the respondents, focusing on the necessity to allow for customisation in the design, promoting variety in the development of architectural products for integration. Furthermore,

TOC

transparency was indeed mentioned as a factor to advocate for, minimising visual constraints in façade units. The findings from Task 41 support these results, especially in the case of solar thermal components. While it was found that both technologies need to be further developed to fully satisfy architectural integration requirements, Farkas and Horvat (2012) declared that photovoltaic applications present a higher degree of flexibility in formal characteristics, counting with more variety in terms of shape, colours, sizes, texture and possible translucency. Therefore, there is a particular need for incentives for manufacturers and a clear definition of aesthetical requirements, in order to develop architecturally appealing solar thermal components for façade integration; a fact supported by the work of Munari Probst and Roecker (2007) in the field.

Answers grouped under 'technical complexity' focused on problems associated with both overly complex assembly processes and operating modes of solar based façade components. In general terms, it was mentioned that further standardisation is advisable, without of course compromising design flexibility and customisation possibilities. It was specifically pointed out by some experts that the sum of modular components under a 'plug-and-play' connection logic should be the aspiration of future developments designed for façade integration, minimising assembly times and avoiding incompatibility issues between components.

The main issue regarding the durability of the systems was the need for maintenance activities which would have an impact on the operating cost of the building. The answers focused on two aspects as barriers for the integration of present technologies. First, durability of the components needs to be improved, while detailed information on the performance of aging components is needed to convince stakeholders and minimise economic risks. This issue is greatly connected with information barriers discussed above, being perceived as a knowledge gap within the performance of these technologies. Alternatively, it was also stated that even with enhanced durability, these components will need maintenance, so the possibility to easily maintain, repair or even replace several parts should be considered in the design along with end-of-life scenarios for the different components.

Finally, the responses categorised under 'availability' considered general complaints about the limited amount of suitable products for façade integration. In this aspect, it is greatly related to the other categories, which focus on particular barriers to overcome in order to provide new architectural products. It is the authors' opinion that this barrier is a secondary aspect, validated by the fact that it was not perceived as relevant as the rest by the respondents. The offer of suitable products is expected to increase if product development overcomes the issues discussed under 'performance', 'aesthetics', 'technical complexity' and 'durability'; provided of course that there is demand for them by tackling non-product related barriers previously discussed in this document.

TOC

A summary of the main identified topics under each category is shown in Table 5.2. The information in the table is presented in the form of recommendations to overcome the identified barriers and problems related to product development, based on the gathered responses. This is regarded not only as valuable practical information to inform future developments, but also as key aspects to consider for the evaluation of current solar technologies and components in terms of their suitability for façade integration purposes, based on how well they respond to issues related to performance, aesthetics, technical complexity and durability.

TABLE 5.2 Key aspects to overcome for solar integrated product development.

PERFORMANCE	AESTHETICS	TECHNICAL COMPLEXITY	DURABILITY	AVAILABILITY
Increase cost-effectiveness of components	Improve overall aesthetics	Avoid overly complex assembly and operation modes	Improve durability of components and systems	Develop array of products designed for integration
Improve/consider energy storage strategies	Allow for customisation of appearance	Promote modularity and plug and play components to ease integration	Devise long term maintenance strategies and end-of-life solutions	
Allow for energy management	Promote variety in design of components (form/materials)	Standardisation of components allowing for design flexibility	Allow for retrofitability	
	Minimise visual constraints			

§ 5.4 Conclusions

This chapter discussed perceived barriers for façade integration of solar technologies, by presenting the findings of an open ended survey addressed to professionals with practical experience in design and development of façade systems. The survey aimed to identify the main perceived barriers, and key aspects to overcome, comparing the findings with previous experiences. Furthermore, special attention was given to product related barriers, drafting recommendations to drive future product development based on the gathered responses from experts in the field.

TOC

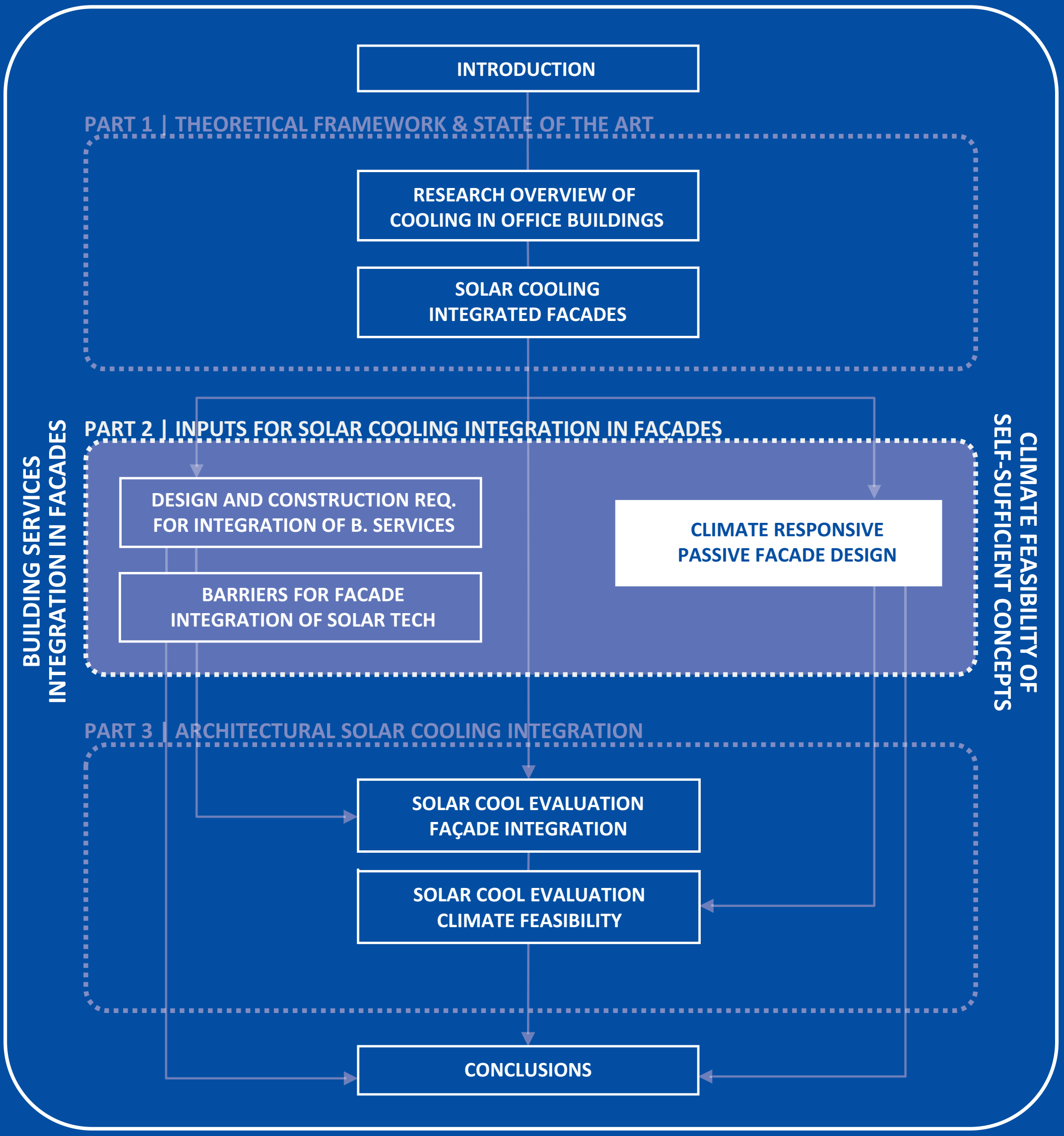
The vast majority of the respondents (91%) believed that there is potential for façade integration, while 80% of the sample believed that there is current commercial demand for architectural products. Regarding perceived barriers, economy was the most pressing barrier declared by the experts. Furthermore, the cost of current systems, energy prices, and the lack of economic incentives were mentioned as key aspects to overcome within this category. Product related issues were also identified as highly relevant, based on the total amount of mentions. Lack of knowledge and information and process related barriers, although mentioned, were not perceived as pressing as economic and product related aspects.

Key issues to overcome within product related barriers centred mostly around performance, aesthetics and technical complexity of current systems and components, with durability and product availability aspects also mentioned. Relevant recommendations based on the gathered responses are the need to increase the cost-effectiveness of individual components, without compromising aesthetics of the product; and the need to design for integration, avoiding overly complex assembly and operation modes. Appearance customisation through a variety of components for façade design was encouraged in order to appeal to architects and clients, while modularity and the use of standardised elements and connections were advised to minimise construction and operation problems.

The findings presented in this chapter fall in line with previous experiences on the topic in terms of the main perceived barriers. Additionally, the identification of key aspects based on the gathered responses allowed for a detailed discussion of product related barriers, in order to draft recommendations to inform future developments. Further research could be done to explore potential divergences in perceived barriers among different groups, expanding the sample to consider other contexts, backgrounds and roles not just in design and construction but also operation of these systems. Furthermore, the recommendations obtained from this study could be used to evaluate solar technologies in terms of their current suitability for façade integration. This would not only present the possibility to validate the findings against real experiences and commercially available products, but would also generate valuable feedback in the understanding of current limits for the development of solar integrated façade products.

TOC

COOLFACADE



INTRODUCTION

PART 1 | THEORETICAL FRAMEWORK & STATE OF THE ART

RESEARCH OVERVIEW OF COOLING IN OFFICE BUILDINGS

SOLAR COOLING INTEGRATED FACADES

PART 2 | INPUTS FOR SOLAR COOLING INTEGRATION IN FAÇADES

BUILDING SERVICES INTEGRATION IN FACADES

DESIGN AND CONSTRUCTION REQ. FOR INTEGRATION OF B. SERVICES

BARRIERS FOR FACADE INTEGRATION OF SOLAR TECH

CLIMATE RESPONSIVE PASSIVE FACADE DESIGN

CLIMATE FEASIBILITY OF SELF-SUFFICIENT CONCEPTS

PART 3 | ARCHITECTURAL SOLAR COOLING INTEGRATION

SOLAR COOL EVALUATION FAÇADE INTEGRATION

SOLAR COOL EVALUATION CLIMATE FEASIBILITY

CONCLUSIONS

ARCHITECTURAL SOLAR COOLING INTEGRATION IN FACADES

TOC

6 Climate responsive façade design

Exploring the performance limits of passive cooling strategies on various warm climates[5]

Cooling demands of commercial buildings present a relevant challenge for a sustainable future. They account for over half of the overall energy needs for the operation of an average office building in warm climates, and this situation is expected to become more pressing due to increasing temperatures in cities worldwide. To tackle this issue, it is widely agreed that the application of passive strategies should be the first step in the design of energy efficient buildings, only using active equipment if it is truly necessary. Nonetheless, there is still further need for information regarding the potential limits derived from their application.

This chapter explores the *impact of selected passive cooling strategies in commercial buildings from warm climates, discussing their effectiveness in multiple scenarios and climate contexts*. This task is carried out through the statistical analysis of results from documented research experiences, to define overall ranges and boundary conditions; and through software simulation of selected parameters to isolate their impact under a controlled experimental setup. General findings show that the mere inclusion of passive strategies is not enough to guarantee relevant savings. Their effectiveness is conditioned to both the harshness of a given climate and an adequate application of the strategies. Specific recommendations are discussed for the passive strategies considered in the evaluation, in order to optimise the overall performance of a given building in different climates.

---

[5] Published as: Prieto, A., Knaack, U., Auer, T., & Klein, T. (2018). Passive cooling & climate responsive façade design: exploring the limits of passive cooling strategies to improve the performance of commercial buildings in warm climates. Energy and Buildings; 175: 30-47. doi: 10.1016/j.enbuild.2018.06.016.

TOC

§ 6.1 Introduction

The energy required to provide cooling for commercial buildings is an issue of concern in the current global agenda for sustainability. It has been stated that refrigeration and air conditioning account for about 15% of the total electricity consumption in the world (CICA, 2002), while cooling may be responsible for over half of the overall energy needs for the operation of an average office building in warm climates (C. Qi, 2006). The relevance of cooling demands in commercial buildings responds to high internal gains (occupation density and equipment) in general, which is aggravated by the impact of solar radiation in commonly lightweight and highly glazed façades (Bustamante et al., 2014). On a global scale, the relevance of cooling demands will keep increasing, considering climate change and the impact of fast growing economies from warm climates, such as India and China, on energy consumption projections for the next decades (BP, 2016; DOE/EIA, 2016; Santamouris, 2016).

Several initiatives have been put in place to tackle this situation, focusing on the energy savings potential of the building sector. Good practices and benchmarks are being extensively promoted for referential purposes (ASHRAE, 2011; CIBSE, 2012), while regulation is being enforced to reduce the operational energy demands in buildings (EP, 2010). To accomplish this goal, it is widely agreed that the first step in the design of an energy efficient building should be the application of passive strategies under a climate responsive design approach (Lechner, 2014; Olgyay & Olgyay, 1963; Santamouris et al., 2007), before considering mechanical equipment driven by fossil fuels. Therefore, understanding the potential benefits from passive design strategies and the limits for their application has become a relevant research field, particularly concerning façade design, as the main filtering layer between outside and inside (Herzog et al., 2004).

The performance of passive cooling strategies in office buildings has been increasingly studied over the last couple of decades, mostly through the use of computer simulations (Prieto, Knaack, Klein, et al., 2017). Most experiences focus on specialised evaluations of one or more strategies, such as ventilation or solar control, under selected parameters. Regarding ventilation, relevant examples are the studies carried out by Kolokotroni et al. on night ventilation performance (Kolokotroni, Giannitsaris, & Watkins, 2006; 1998) and the extensive studies carried out by Gratia and De Herde on the potential for natural ventilation on double-skin facades (Gratia & De Herde, 2004a, 2007b). Solar control studies have mostly focused on design optimisation of sun shading components to improve their performance, through multi-variable analysis and parametric design (Kuhn, 2017; Maestre et al., 2015; Stevanović, 2013). Although these experiences are regarded as highly valuable referential information, their results

TOC

are constrained to the particularities defined for each evaluation setup, namely climate context or assumptions from the base model; hindering their direct translation under different conditions. On the other hand, it is possible to find more comprehensive approaches that explore the potential of different passive cooling strategies in various climates, throughout the review of climate factors (Panchabikesan, Vellaisamy, & Ramalingam, 2017; Tejero-González et al., 2016), or by developing and testing multi-objective assessment tools (Belarbi & Allard, 2001; Lapisa et al., 2018). Nonetheless, these studies mainly focus on the general suitability of passive strategies based on climatic considerations, but do not fully explore their potential limits and expected performance considering particularities of the building.

This chapter discusses the expected performance of selected passive cooling strategies in commercial buildings from warm climates, to explore the extents of passive design optimisation under varying conditions. Hence, the main goal of the article is to define ranges of performance for each addressed strategy, in terms of energy savings potential, identifying borderline situations and optimal scenarios based on previous research experiences. The decision to use results from the literature as main information source was driven by the desire to contrast multiple scenarios and parameters, to account for variability present on real conditions. A secondary reason was an aspiration to organise valuable scientific data in a systematic way in order to provide useful referential guidelines for passive design of commercial buildings, instead of generating redundant new data. The review and statistical analysis of the information was followed by a controlled series of simulations in order to explore certain aspects in more detail.

Therefore, the assessment was structured in two main consecutive stages: first, a review of research experiences was conducted, to establish performance ranges based on available information; followed by a sensitivity analysis to evaluate the different strategies in a controlled environment. The review served as referential information considering a wide array of variables, cases and contexts, while the sensibility analysis was used to understand the potential impact of selected variables and their interaction, on the cooling savings for a particular case in humid and dry warm climates. The variables for the detailed analysis were selected from the referential information gathered through the review of research experiences. The results from each stage are discussed individually, while the boundaries and defined parameters for the overall assessment are presented on a separate section dealing with material and methods.

§ 6.1.1 Passive cooling: definitions and selection of strategies to be evaluated

Passive cooling is commonly understood as a set of natural processes and techniques to reduce indoor temperatures, in opposition to the use of 'active' mechanical equipment. Nonetheless, this binary distinction present problems in practice, addressed by several authors when stating that the use of minor mechanical equipment such as fans and pumps is allowed under the term 'passive' if their application might result in a better performance (Givoni, 1994). Therefore, it is possible to find two distinct groups within passive cooling concepts, based on the use of auxiliary equipment. On the one hand, strategies such as solar control, building layout, orientation, and control of internal heat sources, are presented in the literature as 'bioclimatic design strategies' (Givoni, 1994), 'basic building design' (Lechner, 2014), or simply 'passive cooling' (Santamouris & Asimakopoulos, 1996). On the other hand, concepts which benefit by the use of pumps or fans, such as geothermal, evaporative and radiative cooling or night flush ventilation, are defined as 'natural cooling' (Santamouris & Asimakopoulos, 1996) or most commonly 'passive cooling systems' (Givoni, 1994; Lechner, 2014; Samuel, Nagendra, & Maiya, 2013). Nevertheless, the common attribute of all mentioned strategies is that they are driven by low valued energy, in the form of environmental heat sources and sinks (low-exergy instead of high-exergy sources such as electricity) (Ala-Juusela, 2003; Hepbasli, 2012). Thus, an extra layer in the discussion was added by Kalz and Pfafferott (2014) by categorising the discussed groups in 'passive low-ex' and 'active low-ex' cooling systems, in a declared effort to propose less ambiguous terminology.

From a physics standpoint, cooling strategies are also categorised in the literature according to the way they handle heat, basically distinguishing heat avoidance/protection, heat modulation, and heat dissipation principles and according strategies (Geetha & Velraj, 2012; Santamouris & Asimakopoulos, 1996). The fact that heat modulation techniques do not reduce cooling loads by themselves has been discussed by some authors, choosing to present them as a complement of heat dissipation/heat rejection cooling strategies (Givoni, 1994; Lechner, 2014), storing heat indoors to be released outside at a more convenient time. Hence, basic passive cooling principles seek to primarily avoid unwanted heat, while dissipating the surplus throughout environmental heat sinks. These two sets of principles define different technical possibilities, which match the distinction between building design strategies and passive systems, allowing a comprehensive categorisation of passive cooling principles (Figure 6.1).

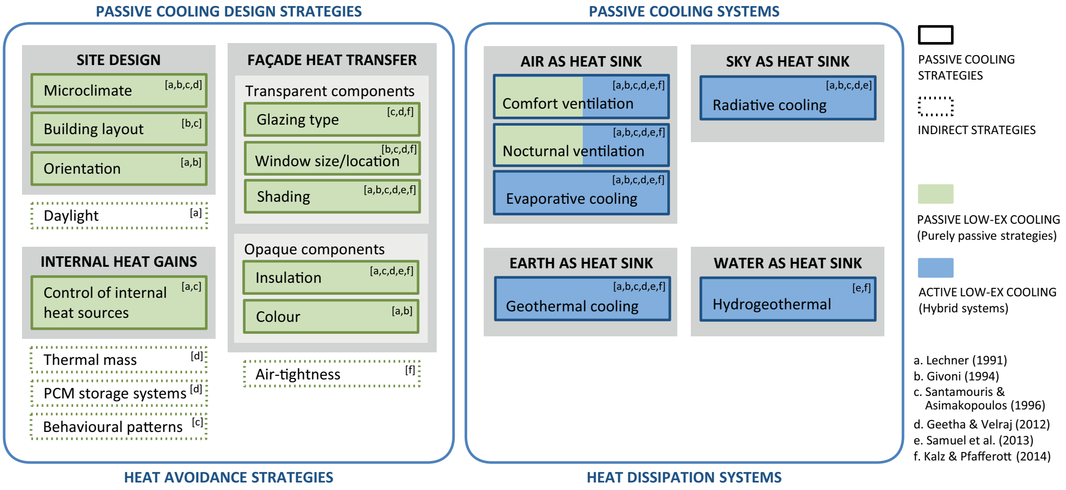


FIGURE 6.1 Categorisation of passive cooling principles based on the literature review

Figure 6.1 shows an overview of passive cooling strategies and systems mentioned in the literature, categorised according to the discussed variables. Consequentially, two main groups were identified: passive design strategies and passive cooling systems, dealing with heat avoidance and heat dissipation respectively. The different possibilities are shown within the groups, with reference to the authors who mentioned them. Moreover, the overview also considers indirect strategies, which do not particularly provide a cooling effect, but their correct application could result on reduced cooling demands (use of daylight, air-tightness), or serve as a complement for heat dissipation strategies (thermal mass, PCM storage). Cooling strategies are further categorised within the main groups, in terms of their working principles. Hence, passive systems are classified according to the heat sinks they employ, being air, earth, water or sky; and passive design strategies are distinguished by their effect at whole building or site design level, management of internal heat gains, or design decisions concerning heat transfer through the façade, either through opaque or transparent components.

For purposes of the analysis, it was decided to focus on passive low-ex cooling strategies, as they represent the first step of building design optimisation, before adding additional equipment. Furthermore, the evaluation sought to consider relevant heat prevention and heat dissipation strategies for commercial buildings, so a second decision was to focus on solar control and ventilation cooling strategies. On the one hand, diurnal and nocturnal ventilation have been proven to be effective and simple heat dissipation strategies, with zero (natural ventilation) or nearly zero (mechanical ventilation with the use of fans) energy consumption. On the other hand, the impact

TOC

of solar radiation on the cooling demands of commercial buildings is a particularly important aspect to consider in warm climates. Moreover, façade design is specially determinant in urban contexts, where site restrictions and orientations are set beforehand, so the potential for passive optimisation falls on an adequate design of the building envelope, according to the particular climate context, with emphasis on the treatment of its transparent components.

§ 6.2 Strategy and methods

As explained before, the evaluation was conducted in two sequential steps. First, a review of performance results from previous research experiences was carried out, to define performance ranges for each passive cooling strategy considering multiple scenarios. This was followed by a sensitivity analysis through the use of an energy simulation software, to discuss and compare the general results under a controlled experimental setup, in order to assess the impact of certain variables on the expected cooling performance. The methods, boundary conditions and parameters set for each evaluation stage are presented separately.

§ 6.2.1 Review of passive cooling research experiences

Published results in peer reviewed scientific articles were considered as source material for the evaluation. The articles were selected from several journal online databases, following initial search queries to explore the field, presented and discussed in Chapter 2 (Prieto, Knaack, Klein, et al., 2017). The review considered research experiences conducted on cooling dominated climates in tropical, dry and temperate zones (class A, B and C in Koppen's classification), focusing exclusively on passive cooling. As mentioned before, the strategies considered in the evaluation were ventilation and solar control strategies, namely shading, glazing type, and window-to-wall ratio.

Given that the goal of the review was to define performance ranges for several cooling strategies, it was necessary to consider the same type of output from the findings to allow for comparisons. Because of its referential value for design purposes, cooling demands savings was chosen as the unit for comparison, understood as the reduction (in percentage) from the cooling demands of a base case scenario, after the application

TOC

of a particular cooling strategy. This decision directly influenced the article selection process, considering research experiences which analysed the performance of diverse cooling strategies in terms of cooling demands, instead of temperature differential, or perceived thermal comfort. In some cases, cooling savings were directly given, while in some others were calculated based on the reported total cooling demands of several scenarios before and after intervention. Moreover, the goal was to assess the reduction potential of different cooling strategies, so it was a prerequisite to be able to isolate their specific influence from the available information published in the papers. Hence, the research methods and published data had to be comprehensive enough to allow for correct interpretation. As an additional fact, all selected articles used energy simulation software for evaluation purposes, clearly detailing the experimental setup. So, in all selected research experiences, it was possible to define a primary strategy being tested, in which case only parameters related with that particular strategy were modified from base case to the intervened scenario. In some cases, a secondary strategy was identified, but they were regarded as auxiliary to the main strategy evaluated, such as the increase of thermal mass to further improve night ventilation strategies. The possible impact of these secondary strategies on cooling demand reduction was considered when discussing the results.

Table 6.1 shows the selected articles for the review, based on the criteria discussed above. Besides references, the table shows the climate zones referred in each document and the passive cooling strategies evaluated by the authors. These articles were reviewed to generate a database which considered not only the reported results in terms of cooling demand savings, but also relevant information about the experimental setups and parameters set by the researchers. The database consists of 526 rows of data, from 41 scientific articles. Each data row in the database corresponds to one reported experiment, based on the evaluation of the effect of a particular parameter in the performance of a passive strategy in a given climatic context. This meant that if the evaluation was carried out in more than one climate, or multiple strategies were analysed, this resulted in separated data rows for each one of the cases. Likewise, if several parameters were evaluated for a particular strategy, such as the performance of different shading types, it also resulted on separate rows for each one of the defined types, associated with each different reported cooling demand savings. Results from evaluations conducted on cold climates were not considered in the databased, even if they were reported in the reviewed articles.

TOC

TABLE 6.1 Articles considered in the review, with climate zones and passive cooling strategies evaluated by the authors.

BASIC INFORMATION		PASSIVE COOLING STRATEGIES			
REFERENCE	CLIMATE ZONES (KOPPEN)	SHADING	GLAZING TYPE	GLAZING SIZE	VENT.
(Ahmed & Wongpanyathaworn, 2012)	Cfa				●
(Appelfeld, McNeil, & Svendsen, 2012)	Cfb/Csa/Dfb	●			
(Assem & Al-Mumin, 2010)	BWh	●	●		
(Aste, Compostella, & Mazzon, 2012)	Cfa	●	●		
(Bahaj, James, & Jentsch, 2008)	BWh	●	●		
(Baldinelli, 2009)	Csa	●		●	
(Bellia, De Falco, & Minichiello, 2013)	Csa/Cfa	●		●	
(Ben-David & Waring, 2016)	Aw/BWh/BWk/BSk/Csa/Cfa				●
(Chiesa & Grosso, 2015)	Cfa/BSh/Csa/BWh/BSk				●
(Eskin & Türkmen, 2008)	Dsa/Csa	●	●		
(Ezzeldin & Rees, 2013)	BWh				●
(Fathoni, Chaiwiwatworakul, & Mettanant, 2016)	Aw	●			
(Favoino, Overend, & Jin, 2015)	Csa		●		
(Ferrari & Zanotto, 2012)	Cfa/Csa	●			●
(Geros, 1999)	Csa				●
(Goia, 2016)	Cfb/Csa			●	
(Hammad & Abu-Hijleh, 2010)	BWh	●			
(Hamza, 2008)	BWh		●		
(Hee et al., 2015)	Af/Cfa		●		
(Huang & Niu, 2015)	Cwa		●		
(Hwang & Shu, 2011)	Am	●	●	●	
(Ji, Lomas, & Cook, 2009)	Cfa				●
(Kolokotroni & Aronis, 1999)	Cfa				●
(Lau, Salleh, Lim, & Sulaiman, 2016)	Af	●	●		
(Lee, Jung, Park, Lee, & Yoon, 2013)	Af/Cfa			●	
(Manzan, 2014)	Cfa/Csa	●	●		
(Chaiwiwatworakul, Matuampunwong, & Chirarattananon, 2012)	Aw		●	●	
(Moretti & Belloni, 2015)	Cfa		●		
(Pino, Bustamante, Escobar, & Encinas, 2012)	Csb	●	●	●	
(Roach, Bruno, & Belusko, 2013)	Csa				●
(Samaan, Farag, & Khalil, 2016)	BWh	●	●	●	●
(Schulze & Eicker, 2013)	Csa/Cfa/Cfb	●		●	●
(Sherif, El-Zafarany, & Arafa, 2012)	BWh	●			

>>>

TOC

TABLE 6.1 Articles considered in the review, with climate zones and passive cooling strategies evaluated by the authors.

BASIC INFORMATION		PASSIVE COOLING STRATEGIES			
REFERENCE	CLIMATE ZONES (KOPPEN)	SHADING	GLAZING TYPE	GLAZING SIZE	VENT.
(Solgi, Fayaz, & Kari, 2016)	BWh				●
(Stazi, Marinelli, Di Perna, & Munafò, 2014)	Cfa	●			
(Tsikaloudaki, Laskos, Theodosiou, & Bikas, 2012)	Csa	●			
(Wan Nazi, Wang, & Roskilly, 2015)	Af		●		
(Wan Nazi, Royapoor, Wang, & Roskilly, 2017)	Af		●		
(Wang & Greenberg, 2015)	Cfa				●
(Yang & Li, 2008)	Cwa				●
(Yoon, Kim, & Lee, 2014)	Cwa	●	●		

The database was categorised and explored through descriptive analysis techniques with the use of IBM SPSS Statistics software. An initial overview of the sample was conducted, to characterise the gathered information and present the array of research experiences considered in the database, accounting for climate variations and the share of each passive cooling strategy in the total amount of data rows (n=526). Figure 6.2 shows the amount of results per climate context, classified in four groups: tropical (Af, Am, Aw), dry (BWh, BWk, BSh, BSk), humid temperate (Cfb, Cwb, Cfa, CWa), and dry temperate climates (Csa, Csb), representing 16%, 21%, 21% and 42% of the total sample respectively. Considering humidity as a defining parameter, warm dry climates comprehend 63% of the sample (n=331), while warm humid climates account for the remaining 37% (n=195).

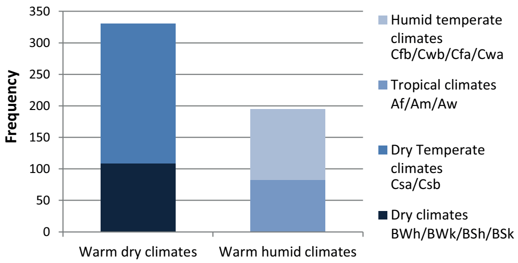


FIGURE 6.2 Number of reviewed results per climate context.

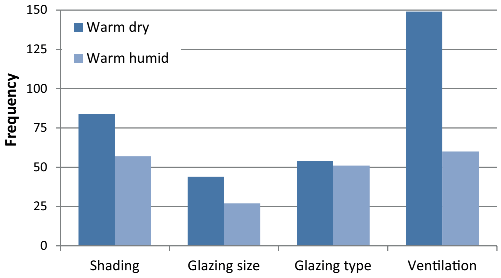


FIGURE 6.3 Number of results per strategy and main climate groups.

The composition of the sample in terms of selected passive strategies is shown in Figure 6.3, considering an initial distinction between warm dry and warm humid climates. It is possible to see that even though the sample considers more research conducted on dry climates, all strategies are covered in both main climate groups. Performance ranges for each passive cooling strategy are defined and discussed separately, in Section §6.3, considering climate variation. Furthermore, relevant experiences are discussed in detail, identifying average performance values and borderline scenarios, to assess expected savings from each strategy and reported limits of their impact in different warm climates.

§ 6.2.2 Sensitivity analysis of passive cooling strategies

The sensitivity analysis sought to complement the results from the review with results obtained under a controlled setup, isolating the impact of the evaluated strategies on two different reference buildings, located on representative cities from selected warm climates. While the review aimed to provide overall performance ranges considering a high variation of scenarios, the sensitivity analysis allowed to directly compare cooling savings potential of the evaluated strategies and possible relations between them on two reference cases. Furthermore, it allowed to compare not only cooling reduction in terms of percentage, but also discuss brute cooling demands per square meter before and after the application of each strategy.

DesignBuilder v4.7 was used for the analysis, as the graphical interface of EnergyPlus v8.3. The base model consisted of a complete office floor of 2.7 m high and a plenum of 0.7 m, with perimeter offices of 4 x 4 m each as shown in Figure 6.4. Only highlighted offices were considered in the analysis, using their cooling demand values to define a floor average as unit for comparison during the evaluation. Basic building parameters and internal heat gains were set based on referential values commonly used in the reviewed research experiences. Hence, occupancy was set at 0.1 people/m^2, equipment loads at 11.77 W/m^2 and infiltration rate was set at 0.2 air changes per hour (ach). Ventilation was kept at a minimum rate for hygienic purposes (10 l/s per person), while lighting was controlled, with a target illuminance of 400 lux and a lighting power density of 3 W/m^2 for 100 lux. Thermal comfort ranges considered a maximum temperature of 26 °C and relative humidity between 25 and 55%.

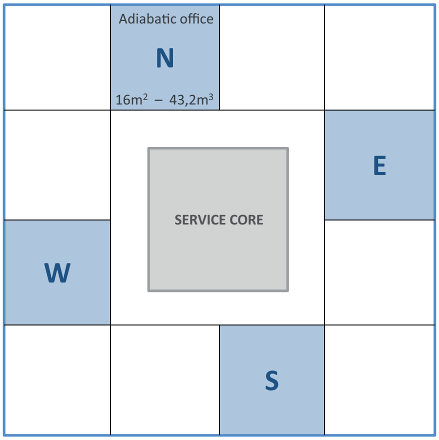


FIGURE 6.4 Office floor plan used as base case.

To define the scenarios to be simulated, two conditions were set for each passive cooling strategy: an initial condition (0), where the strategy is not applied in the building, and a second condition (1), considering its application by changing a specific parameter, as shown in Table 6.2. Simulated parameters were based on the reviewed experiences, considering high energy savings potential as reported by the researchers. Consequentially, different combinations of these parameters were considered in a matrix, for the definition of the simulation scenarios, as shown in Table 6.3. Ten different scenarios were defined: an initial case without the application of any passive cooling strategy (0000), a case which considered all strategies (1111) and all combinations resulting from the single application of each evaluated strategy (1000-0001), and the application of all others with the exemption of the one to be evaluated (0111-1110). This set of scenarios allowed for the assessment of the isolated impact of each strategy on a case without any other passive measure, and a case where other measures were already in place. It is relevant to point out that the application of all strategies is not necessarily presented as an optimal scenario, acting only as an example of the application of several passive cooling strategies into a reference building, without a process of conscious optimisation or integral design.

The scenarios were simulated in representative cities from each climate group. It was decided to consider two examples instead of one in the case of temperate climates, to account for variations in climate severity within the group. Hence, six representative cities were selected for the evaluation, as shown in Table 6.4 along with their cooling degree days (CDD) considering 26 °C as base temperature. In summary, the total number of simulations was set at 60, comprising 10 scenarios in 6 representative cities, for a comprehensive evaluation and comparison of the results.

TOC

TABLE 6.2 Simulated parameters for each passive cooling strategy.

COOLING STRATEGY	SIMULATED PARAMETERS	
	0	1
Shading	NO	Dynamic exterior shading (high reflectivity slats) on operation over 100 W/m² of solar irradiance on facades.
Glazing size (WWR)	100%	25%
Glazing type	Double clear glass	Double reflective glass (6/13/6 mm with air in cavity)
Ventilation	NO	5 ACH max when it's thermodynamically feasible (external temperature below internal temperature)

TABLE 6.3 Simulated scenarios based on the application of the evaluated strategies.

SIMULATED SCENARIOS PER CLIMATE	PASSIVE COOLING STRATEGIES			
	Shading	Glazing size (WWR)	Glazing type	Ventilation
No strategies applied	0	0	0	0
Only shading applied	1	0	0	0
Only WWR applied	0	1	0	0
Only glass type applied	0	0	1	0
Only ventilation applied	0	0	0	1
All strategies applied	1	1	1	1
No shading applied	0	1	1	1
No WWR applied	1	0	1	1
No glass type applied	1	1	0	1
No ventilation applied	1	1	1	0

TABLE 6.4 Representative cities per climate group.

CLIMATE GROUP	CITY	CDD (26 °C)
Desert	Riyadh	1583
Tropical	Singapore	992
Temperate humid	Hong-Kong	602
Temperate dry	Athens	212
Temperate humid	Trieste	88
Temperate dry	Lisbon	69

§ 6.3 Results and discussion

§ 6.3.1 Definition of performance ranges for passive cooling strategies: exploration of a database of research experiences.

As explained before, the first part of the evaluation was based on the statistical exploration of a database comprising performance results obtained from several scientific articles. Table 6.5 shows basic statistical data to assess the energy savings potential of the selected strategies, for two main climate groups: warm-dry and warm-humid climates. A first issue worth mentioning is the fact that reported energy savings reach higher values in the case of warm-dry climates, evidenced by the large difference between maximum reported values (from 22 to 37 percentage points depending on the strategy), and the higher average and median values for all strategies, with the exemption of the use of shading devices, which average similarly on both groups. This means that the application of passive cooling strategies has more potential for lowering cooling demands on warm-dry climates, instead of warm-humid ones; which corresponds with the well-known complexity and particular challenges associated with high humidity contexts and tropical regions.

TABLE 6.5 Statistical values to assess cooling demand savings per evaluated strategy.

STRATEGIES	WARM DRY					WARM HUMID				
	N	Mean	Median	Minimum	Maximum	N	Mean	Median	Minimum	Maximum
Shading	84	26%	25%	4%	93%	57	28%	24%	5%	56%
Glazing size (WWR)	44	34%	34%	2%	76%	27	18%	14%	-2%	44%
Glazing type	54	22%	15%	1%	70%	51	12%	10%	1%	40%
Ventilation	149	50%	52%	6%	91%	60	33%	30%	2%	69%

Furthermore, the reported energy savings in both climate groups vary differently among the evaluated strategies. In the case of warm-dry climates, the best average results are experienced through the use of ventilation strategies (50%) and the reduction of the window-to-wall ratio (34%); while in the case of warm-humid climates, it is through ventilation and shading strategies, with lower values of 33% and 28% respectively. The use of natural ventilation has been largely considered as a feasible cooling strategy for dry climates, but its application in humid climates presents more challenges due to specific humidity control requirements, which clearly affects its expected performance. On the contrary, the results from the use of shading devices present the lowest variation between both climate groups, which seem to position them as suitable alternatives with comparable effectiveness regardless the context. These statements are based on the initial assessment of general statistical data, so they will be expanded and compared when discussing particular cases in detail in subsequent sections.

Figure 6.5 shows all reported energy savings data in a box-plot graph to visualise the range of action of all evaluated passive cooling strategies, in the two main defined climate groups: warm-dry and warm-humid climates. On the one hand, it is possible to identify short ranges, which mean that there is consistency between the gathered results for a particular strategy. This is the case of window-to-wall ratio and glazing type reported energy savings for warm-humid climates. On the other hand, long ranges mean more dispersion among the results, such as the case of ventilation strategies in both climate groups, and window-to-wall ratio in warm-dry climates. Furthermore, a long performance range means that the expected energy savings of a given strategy varies considerably within the sample, thus, it depends on other factors and variables to ensure a satisfying performance. Therefore, it is important to detect and discuss boundary cases in order to isolate the characteristics that make higher energy savings possible. The same goes for the existence of outliers with markedly higher savings, identifying and assessing their uniqueness within the larger sample, and possibilities for replicability. In that sense, the fact that all strategies considered minimum cooling savings from -2 to 6%, means that the mere application of a passive strategy is not always enough to ensure a satisfying performance, but it depends on several parameters that need to be carefully controlled to achieve the expected results.

Each evaluated passive strategy is discussed separately, exploring the gathered information to provide context to the results and identify relevant parameters for performance optimisation. The discussion focuses on the best reported result, comprising variables such as the climate severity of each evaluated context (variations based on different climates within the climate groups), characteristics of the intervention (internal parameters related to the evaluated strategy), and characteristics of the base case (external parameters related to the experimental setup and defined base scenario).

TOC

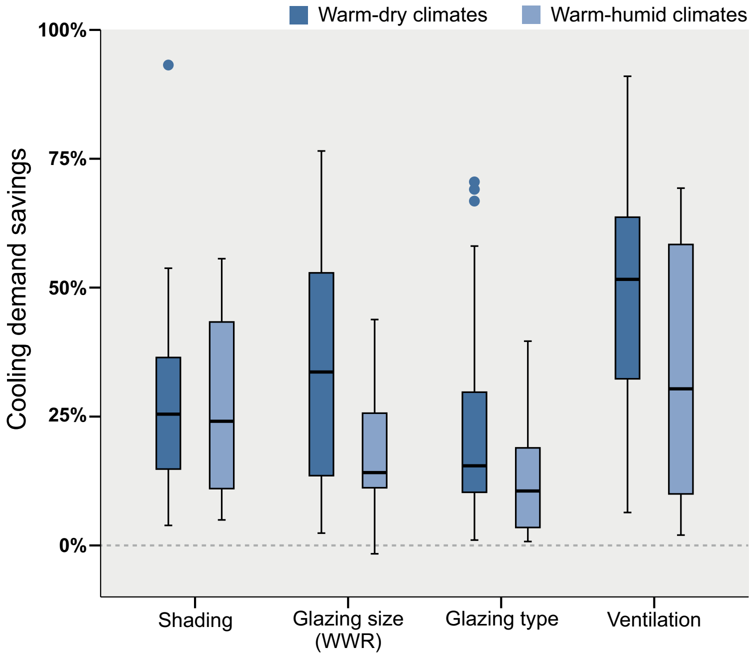


FIGURE 6.5 Performance ranges considering all reviewed results per passive cooling strategy and main climate groups.

§ 6.3.1.1 Shading

The results obtained by the application of shading systems show higher mean and median values, compared to cooling demands savings from glazing type improvements. In general, shading reported values are consistent in both major climate groups, averaging around 25% in potential cooling demand savings for warm-dry and warm-humid contexts. Similarly, best reported results are comparable, reaching maximum values of 55.6% and 54.6% in the warm-humid climates of Bangkok(Aw) (Fathoni, Chaiwiwatworakul, & Mettanant, 2016) and Trieste (Cfa) (Manzan, 2014); and 53.8% and 45.2% in the hot-summer mediterranean climate of Santiago, Chile (Csb) (Pino et al., 2012) and the hot desert climate of Dubai (BWh) (Bahaj et al., 2008), respectively. The 93.2% cooling savings reported by Baldinelli (2009) for a case in central Italy (Csa) was identified as an outlier considering its large difference and uniqueness compared to the rest of the sample. Hence, it should be excluded from expected performance ranges from the application of shading strategies.

TABLE 6.6 Research experiences about shading, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Appelfeld et al., 2012)	Hot summer mediterranean (Csa)	ITALY	ESP-r	Test office room with low-e double glazing, WWR of 32% and temperature comfort range between 20-26 °C	Evaluation of microperforated steel screen, roller shade, and venetian blinds, as shading devices between glass panes.	18% - 24%
(Assem & Al-Mumin, 2010)	Hot desert (BWh)	KUWAIT	Energy Plus	North-west facing office with clear double glass 100% WWR	Overhang of 1 m width	8% - 9%
(Aste et al., 2012)	Humid subtropical (Cfa)	ITALY	Energy Plus	South facing office room with Low-e double glazing (Argon in the cavity) and 17% WWR. Temperature comfort range between 20-26 °C.	External automated aluminium venetian blind.	18%
(Bahaj et al., 2008)	Hot desert (BWh)	UAE	TRNSYS	North facing office with clear low-E double glass as glazing unit with undisclosed window-to-wall ratio, and temperature set-point defined at 23 °C.	External blinds with 0% transmission	45%
(Baldinelli, 2009)	Hot summer mediterranean (Csa)	ITALY	CFD simulation	South facing office room with clear double glazing and 100% WWR.	Movable aluminium horizontal slats within the cavity of a double skin façade prototype.	93%
(Bellia et al., 2013)	Hum Subtrop (Cfa) Hot-summer mediterra (Csa)	ITALY	Energy Plus	Complete typical office building with double glazing and 30% WWR. Temperature comfort range between 20-26C.	Overhangs on south façade (1 m) and fixed louvers on east-west facades	26% - 30%
(Eskin & Türkmen, 2008)	Hot summer mediterranean (Csa)	TURKEY	Energy Plus	Complete office building with aspect ratio of 1.36, clear single glazing and 40% WWR. Temperature comfort ranges between 22-24 °C and 18-26 °C for day and night time respectively. Infiltration of 0.2 ACH.	Internal light colour curtain (close weaved).	4% - 7%
(Fathoni et al., 2016)	Tropical savanna (Aw)	THAILAND	Visual Basic 6	South facing office room with variable depth. Heat reflective single laminated glazing with 53% WWR and temperature setpoint of 25 °C.	Horizontal slats in the cavity of a double glazing unit.	37% - 55%
(Ferrari & Zanotto, 2012)	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	ITALY	TRNSYS	South facing room in five different office building types, based on decade of construction and WWR. Glazing type considers clear and tinted double glazing, with 23%, 63% and 100% WWR according to each building type. Temperature setpoint of 26 °C, infiltration rate of 0.2 ACH	Light coloured external venetian blinds, with shading factor of 0.3. Shadings are manually activated when direct solar radiation exceeds 100 W/m^2.	10% - 27%

>>>

TOC

TABLE 6.6 Research experiences about shading, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Hammad & Abu-Hijleh, 2010)	Hot desert (BWh)	UAE	IES-VE	Isolated office room with clear double glazing, WWR of 60% and a temperature set-point of 24 °C. South, west and east orientations were considered in the analysis	Evaluation of fixed vertical (west-east) or horizontal (south) lovers at 0°, and dynamic louvers for all orientations	25% - 38%
(Hwang & Shu, 2011)	Monsoon (Am)	CHINA	Energy Plus	South facing room of a real building, with tinted-blue single glazing and 72% WWR.	Evaluation of overhangs with different width (1.2; 2.4; 3.6; 4.8)	7% - 11%
(Lau et al., 2016)	Tropical rainforest (Af)	MALAYSIA	IES-VE	Complete high-rise office buildings with clear single and low-e clear double glazing, and 100% WWR. Operative temperature set at 23 °C.	Evaluation of horizontal and vertical louvres and egg-crate shading devices.	5% - 10%
(Manzan, 2014)	Humid subtrop (Cfa) Hot-summer mediterranean (Csa)	ITALY	ESP-r	South facing office room of 20 m^2, with low-e clear double glazing and 45% WWR. Window with and without reveal were used as base scenarios.	Flat panel positioned parallel to the window, inclined by its horizontal axis and widths of 1 and 2 m.	30% - 56%
(Pino et al., 2012)	Hot-summer mediterranean (Csb)	CHILE	EDSL TAS	Evaluation of an entire floor for different reference cases, based on the use of different glazing types (clear single and double, and tinted single and double glazing) and WWR (20%, 50%, 100%)	The evaluation considered blinds at west and east orientations, and the use of either overhangs or blinds facing north.	22% - 54%
(Samaan et al., 2016)	Hot desert (BWh)	EGYPT	Energy Plus	Evaluation of real rooms in an University Campus, facing north, south and west. Clear single glazing and 50% WWR is considered. Operative temperature is set to 23 °C.	Shading devices evaluated consider horizontal louvres (0.5 m) and the use of overhang of diverse width (0.5 m; 1 m; 1.5 m)	4% - 20%
(Schulze & Eicker, 2013)	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	ITALY TURKEY	Energy Plus	Evaluation of 18 office rooms in a referential building, facing east and west orientations, with low-e double glazing and 50% WWR. Temperature cooling setpoint is 25 °C during work hours and 30 °C during night time.	External venetian blinds with slat angle of 45°, 50% reflectivity, slat separation and width of 4 and 5 cm respectively. Automated shading system depending on solar intensity on façade (250 W/m^2).	36% - 39%
(Sherif et al., 2012)	Hot desert (BWh)	EGYPT	Energy Plus	Isolated office room with low-e clear double glass and 20% WWR. Evaluation was conducted for all four orientations separately. Operative temperature set at 23 °C	Wooden solar screen (oak-wood) of 2.7x1.8 m at 50 mm from the wall. Perforation area: 90% Depth ratio:1.0	7% - 30%

>>>

TOC

TABLE 6.6 Research experiences about shading, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Stazi et al., 2014)	Humid subtropical (Cfa)	ITALY	Energy Plus	Single west facing room of 28 m^2, with low-e double glass and 57% WWR. T° comfort range between 20-26 °C.	External aluminium slats with different angles, width and separation.	18% - 29%
(Tsikaloudaki et al., 2012)	Hot summer mediterranean (Csa)	GREECE	Energy Plus	South and east facing office rooms within a reference building defined in ISO15265 and ISO13790. Operative temperature setpoint is 24.5 °C and infiltration rate is 0.5 ACH. WWR and Glazing types vary (WWR: 10-100% and 9 glazing units are tested).	Movable shading device, activated when incident solar radiation on vertical plane exceeds 300 W/m^2. Evaluation of shading factors of 25%, 50% and 75%	9% - 45%
(Yoon et al., 2014)	Humid subtropical (Cwa)	SOUTH KOREA	Energy Plus	South facing office room of 100% WWR and various glazing types (clear single, double and triple, and low-e double and triple glazing). T° comfort range between 22-26 °C.	External slats (25 mm slat separation, width and distance to glass). Reflectance of 0.1	9% - 14%

Table 6.6 shows all shading related research experiences considered in the database, detailing their climate context, reported range of cooling savings, information from the base case and details of the intervention and evaluated parameters. Exploring the differences from the evaluated cases, it could be seen that in general, equator facing offices have larger cooling savings potential, basically due to the high solar incidence in the north and south façade in southern and northern hemispheres respectively. Maximum reported values for equator facing offices are 55.6% (Fathoni et al., 2016) while maximum savings reach 39% in the case of east-west oriented rooms in the humid subtropical climate of Turin (Schulze & Eicker, 2013).

Regarding evaluated shading types, it is possible to state that the use of different shading systems does not categorically result on markedly different cooling demand savings. Nonetheless, reported results seem to hint at louvers and screens having more savings potential than the use of overhangs, which make sense considering the amount of exposed window area. Maximum reported cooling savings are 55.6%, 53.8% and 41.1% for the use of screens (Fathoni et al., 2016), external louvres (Pino et al., 2012), and overhangs (Pino et al., 2012), respectively. In any case, further information would be needed for a detailed evaluation of several shading types in different climate zones, besides considering particularities from each case and shading design. It is the author’s opinion, that especially in the case of shading strategies, referential information is useful and relevant for early design stages but it should always be contrasted with a detailed analysis of the actual devices being used, due to design particularities and dynamic shading patterns of a specific location and orientation.

§ 6.3.1.2 Glazing size (WWR)

The results of glazing size evaluations show a considerable difference between warm-dry and warm-humid climate groups. In the first group, average cooling demand savings are 34%, while in the second they only reach 18%. The fact that median values are lower than the average in the latter (14%), mean that expected average cooling savings for warm-humid climates could be assumed to be lower (around 14%-18%), based on the analysed sample. In terms of maximum reported values, the difference grows apart, evidenced by the 76.4% savings obtained for the warm-dry climate of Santiago, Chile (Csb) (Pino et al., 2012) and the 43.7% and 41.1% registered by Lee et al. (2013) for warm-humid cases in Shanghai (Cfa) and Manila (Af), respectively. It is relevant to point out that the research experiences that reported higher cooling savings, also considered a reference case of 100% window-to-wall ratio (WWR), by looking at the detailed information in Table 6.7 and the graph in Figure 6.6. Of course this is not a coincidence, because any intervention conducted on a 'worst case' base scenario, should have higher potential savings in terms of percentage, so this needs to be considered when looking at the results. Nonetheless, as Figure 6.6 shows, there are low savings values regardless of the initial reference case, explained by different WWR values evaluated in the second scenario.

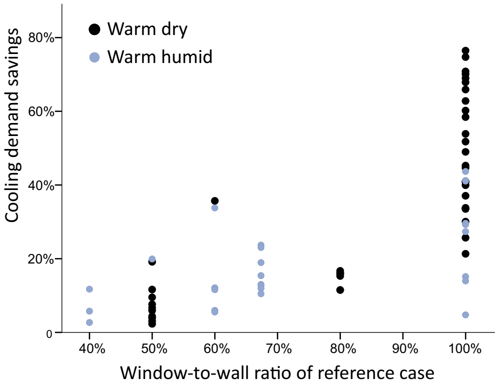


FIGURE 6.6 Cooling demand savings compared to reference case WWR

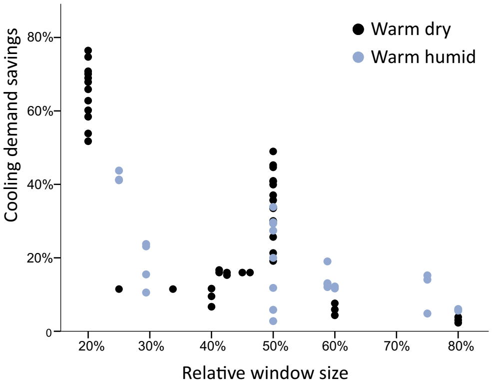


FIGURE 6.7 Cooling demand savings compared to relative window size

TABLE 6.7 Research experiences about glazing size (WWR), considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Baldinelli, 2009)	Hot summer mediterranean (Csa)	ITALY	CFD simulation	South facing office room with clear double glazing and 100% WWR.	50% WWR	49%
(Bellia et al., 2013)	Hot-summer mediterra. (Csa) Humid subtropical (Cfa)	ITALY	Energy Plus	Entire typical office building with double glazing and 60% WWR. Temperature comfort range between 20-26 °C.	30% WWR	34% - 36%
(Goia, 2016)	Hot-summer mediterranean (Csa)	ITALY GREECE	Energy Plus	Entire office building with low-e clear triple glazing, 80% WWR and external automated venetian shading. Evaluations per orientation with T° comfort range of 20-24 °C	Several WWR values were evaluated from 20% to 37% (optimised values per orientation)	11% - 17%
(Hwang & Shu, 2011)	Monsoon (Am)	CHINA	Energy Plus	South facing room of a real building, with tinted-blue single glazing and 60% WWR.	36% and 48% WWR. Additionally, a 2.4 m overhang was evaluated for both cases.	6% - 12%
(Lee et al., 2013)	Trop rainforest (Af) Humid subtropical (Cfa)	THE PHILIPPINES CHINA	Energy Plus COMFEN	Complete building consisting of 4 perimeter zones with 5 office rooms each. Clear double glazing on windows with 100% WWR.	Several WWR values (25%, 50%, 75%)	5% - 44%
(Chaiwiwatworakul et al., 2012)	Tropical savanna (Aw)	THAILAND	Numerical calculations	South facing room with several glazing types (heat reflective, tinted and low-e laminated glazing) and either 40% or 68% WWR. Six external slats per window as shading device.	WWR values of 40% and 20% were evaluated	-2% - 24%
(Pino et al., 2012)	Hot-summer mediterranean (Csb)	CHILE	EDSL TAS	Entire office floor considering different reference cases, based on the use of different glazing types (clear single and double, and tinted single and double glazing) and 100% WWR. Variations considered no shading and the use of overhang or louvres in north, east and west orientations.	WWR values of 50% and 20% were evaluated	21% - 76%
(Samaan et al., 2016)	Hot desert (BWh)	EGYPT	Energy Plus	Evaluation of real office rooms in an University Campus, facing north, south and west orientations. Clear single glazing and 50% WWR is considered. Operative temperature is set to 23 °C.	Several WWR values (40%, 30%, 20%)	2% - 12%

>>>

TABLE 6.7 Research experiences about glazing size (WWR), considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Schulze & Eicker, 2013)	Hot-summer mediterranean (Csa) Humid subtropical (Cfa)	ITALY TURKEY	Energy Plus	Evaluation of 18 rooms in a referential building, facing east and west, with low-e double glazing and 50% WWR. External venetian blinds are used as shading device. T° cooling setpoint is 25 °C (work hours) and 30 °C (night time).	25% WWR	19% - 20%

The fact that the reviewed experiences considered different WWR values in both the reference case and the intervened scenario, makes a direct comparison of energy savings troublesome. Hence, a dimensionless unit named 'relative window size' was introduced, as a way to visualise the savings impact of varying WWR under a normalised unit which simply shows the proportion of the new window compared to the reference case (eq. 6.1).

$$\frac{WWR_{intervention}}{WWR_{reference}} = relative\ window\ size \qquad \text{(eq. 6.1)}$$

Figure 6.7 shows the reported results compared to the 'relative window size', differentiating both major climate groups. As expected, highest cooling demand savings tend to be related to the smallest relative window sizes; however, again it is relevant to consider the WWR of the reference case to explain reported differences on cooling savings. For instance, comparing results from cases which considered a relative window size of 50% (highest frequency within the sample), it is possible to see that reported savings are between 21% and 49% for $\text{WWR}_{\text{reference}}$ of 100% (Baldinelli, 2009; J. Lee et al., 2013; Pino et al., 2012), while they reach maximum values of 36%, 20%, and 12% in cases with $\text{WWR}_{\text{reference}}$ of 60% (Bellia et al., 2013), 50% (Schulze & Eicker, 2013) and 40% (Chaiwiwatworakul et al., 2012) respectively. The differences within each range depend on the application of other strategies, such as considering tinted glass or shading in both the base case and the intervention (the only changed parameter being WWR). However, there is no clear correlation between the application of extra strategies in the base case and expected cooling savings, for cases with the same relative window size and $\text{WWR}_{\text{reference}}$. The relation between different cooling strategies and the impact of their combined application will be further discussed in Section §6.3.2, considering a normalised base case for comparison. This issue is highly relevant for design purposes, optimising an integral solution or building element, avoiding redundant passive strategies or even counterproductive effects. The latter are evidenced by the reported results from Chaiwiwatworakul et al. (2012), showing an increase of 2% in cooling demands by reducing the WWR from 40% to 20% in a reference case with tinted low-e double glass and external slats as shading device.

§ 6.3.1.3 Glazing type

Results seem to show that the use of different glazing types has the lowest energy savings potential among the reviewed strategies. This is the case for both main climate groups, although the reported performance is higher in the case of warm-dry contexts, following the general trend discussed before. Results for warm-dry climates show average and median values of 22% and 15% respectively, with maximum reported savings of 58%, considering in-range experiences, and three identified outliers with values up to 70%. All best cases (in-range and outliers), correspond to the same evaluation for the hot-summer Mediterranean (Csa) climate of Rome (Favoino, Overend, & Jin, 2015). Mean and median values for warm-humid climates are 12% and 10% respectively, while maximum values reached 39% for the humid subtropical (Cfa) climate of Milan (Aste et al., 2012).

Differences in reported performance may be further explained by looking at distinct parameters considered to define the glazing types. By looking at detailed information of each research experience in Table 6.8, it is possible to identify five different types of interventions, based on the change of specific glazing parameters between the initial case and the evaluated scenario: number of layers, glass colour, use of coatings, a combination of these variables, and the replacement of conventional static glazing for switchable or dynamic glazing technologies. As expected, the sole increase of the number of glass layers do not carry relevant cooling demand savings, evidenced by the 1%-2% reported savings by replacing clear single with clear double glazing in both warm-humid (Hee et al., 2015) and warm-dry (Samaan, Farag, & Khalil, 2016) climate contexts.

TOC

TABLE 6.8 Research experiences about glazing type, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Assem & Al-Mumin, 2010)	Hot desert (BWh)	KUWAIT	Energy Plus	North-west facing office with clear double glazing and 100% WWR.	Evaluation of different glazing types (clear, tinted and reflective low-e glazing).	7% - 27%
(Aste et al., 2012)	Humid subtropical (Cfa)	ITALY	Energy Plus	South facing room with Low-e double glazing (Argon in the cavity) and 17% WWR. T° comfort range of 20-26 °C.	Electrochromic glass pane in double glazing unit.	39%
(Bahaj et al., 2008)	Hot desert (BWh)	UAE	TRNSYS	North facing room with clear low-E double glass as glazing unit with undisclosed WWR, and T° set-point of 23 °C.	Several glazing types (reflective, aerogel, electrochromic, tinted glazing).	10% - 49%
(Eskin & Türkmen, 2008)	Hot summer mediterranean (Csa)	TURKEY	Energy Plus	Entire building with aspect ratio of 1.36, clear single glazing and 40% WWR. T° comfort ranges of 22-24 °C (day) and 18-26 °C (night). Infiltration of 0.2 ACH.	Low-e clear double glazing	13% - 16%
(Favoino et al., 2015)	Hot summer mediterranean (Csa)	ITALY	EnergyPlus GenOpt MatLab	Isolated office room with clear double glazing, 40% WWR and no shading. Orientations were evaluated separately. T° comfort range set at 20-26 °C.	Evaluation of an optimised glazing unit and the use of switchable glazing.	30% - 70%
(Hamza, 2008)	Hot desert (BWh)	EGYPT	IES-VE	Office room with clear single glazing and 40% WWR. All orientations were evaluated separately. T° comfort range set between 22-24 °C.	Reflective glazing	6% - 12%
(Hee et al., 2015)	Tropical rainforest (Af) Humid subtropical(Cfa)	MALAYSIA CHINA	Energy Plus	Isolated office room with clear single glass and undisclosed WWR. All orientations were considered separately.	Several glazing types (clear double, low-e double, reflective double, and thermotropic glazing).	1% - 19%
(Huang & Niu, 2015)	Humid subtropical (Cwa)	CHINA	Energy Plus	Entire referential building according to Hong Kong guidelines. Clear double glazing on windows, 36% WWR and no shading. T° set at 25 °C.	Clear double glass low-e and silica aerogel glazing are evaluated.	2% - 6%
(Hwang & Shu, 2011)	Monsoon (Am)	CHINA	EnergyPlus	South facing room of a real building, with clear float glazing, 72% WWR and 2.4 m overhang as shading device.	Several glazing types (tinted-blue single, tinted-bronze single, film on clear pane, low-e single and reflective).	3% - 17%
(Lau et al., 2016)	Tropical rainforest (Af)	MALAYSIA	IES-VE	Entire building with clear single glass and 100% WWR. No shading and the use of egg-crate, horizontal and vertical louvres were considered. Operative T° set at 23 °C.	Clear double glass low-e.	10% - 11%

>>>

TABLE 6.8 Research experiences about glazing type, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Manzan, 2014)	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	ITALY	ESP-r	South facing room of 20 m^2, with clear double glazing and 45% WWR. A flat panel parallel to the window, inclined by its horizontal axis was used as shading for base case. Window with and without reveal were used as base scenarios.	Clear double glass low-e.	2% - 32%
(Chaiwiwatworakul et al., 2012)	Tropical savanna (Aw)	THAILAND	Numerical calculations	South facing office room with heat reflective laminated tinted glass and either 40% or 68% WWR. Six external slats per glass pane are used as shading device.	Several glazing types were evaluated (laminated tinted green + clear, laminated tinted green + clear low-e, tinted double glass low-e).	17% - 29%
(Moretti & Belloni, 2015)	Humid subtropical (Cfa)	ITALY	Energy Plus	South-west facing office room in the University of Perugia, with clear double glazing and 50% WWR, and no shading devices.	Solar control film on glazing.	29%
(Pino et al., 2012)	Hot-summer mediterranean (Csb)	CHILE	EDSL TAS	Evaluation of an entire office floor considering different base cases: variation of window-to-wall ratios (20%, 50%, 100%); the use of overhang or louvres in north, east and west orientations, or no shading at all; and clear single and clear double glazing as base case.	Tinted single and tinted double glass were compared to clear single and clear double glazing respectively.	9% - 32%
(Samaan et al., 2016)	Hot desert (BWh)	EGYPT	Energy Plus	Evaluation of real office rooms in an University Campus, facing north, south and west orientations. Clear single glazing and 50% WWR is considered. Operative temperature is set to 23 °C.	Several glazing types were evaluated (clear double, clear double low-e, and tinted single glazing).	1% - 15%
(Wan Nazi et al., 2015)	Tropical rainforest (Af)	MALAYSIA	Energy Plus	Complete medium sized office building with clear double glazing, undisclosed WWR and no shading. Operative temperature setpoint set at 24 °C.	Several glazing types were evaluated (reflective, tinted double, and tinted double low-e glazing).	12% - 19%
(Wan Nazi et al., 2017)	Tropical rainforest (Af)	MALAYSIA	Energy Plus	Complete medium sized office building with green tinted single glazing, 85% WWR and local shading. Operative temp. setpoint at 22 °C.	Low-E double glazing.	3%

>>>

TABLE 6.8 Research experiences about glazing type, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Yoon et al., 2014)	Humid subtropical (Cwa)	SOUTH KOREA	Energy Plus	South facing office room of 100% WWR and either double or triple clear glazing. Internal blinds are used for shading. Temperature comfort range between 22-26 °C.	Low-E double and triple glass were compared to clear double and triple glazing respectively.	4% - 6%

The change in colour properties and the use of coatings seem to achieve similar cooling savings, obtaining peak values around 30%. Pino et al. (2012) reported a maximum value of 32% evaluating the use of a tinted double instead of a clear double glazing unit in Santiago, Chile; while Manzan (2014) obtained the same value applying a low-e coating on a clear double glass, in the humid subtropical (Cfa) context of Trieste, Italy. Moreover, Moretti and Belloni (2015) found cooling savings up to 29% through the use of solar control films on glass, in the same climate of Perugia. Interestingly, higher savings values were reported by using glazing types which combined both parameters. The results from Favoino, et al. (2015) showed savings up to 53% by comparing the use of clear double glass to the application of a tinted double low-e glazing unit in Rome, Italy. Nevertheless, in this case it is important to highlight that the glazing unit evaluated was the result of a design optimisation process, so it could be regarded as a best case scenario. In this sense, a comparison could be made to the 19% obtained by Wan Nazi et al. (2015) through the evaluation of similar glazing units (clear double and tinted double low-e) for a building located in the tropical rainforest climate (Af) of Putrajaya, Malaysia.

Finally, the best results coincided with the application of dynamic glazing technologies. Both Aste et al. (2012) and Bahaj et al. (2008) evaluated the performance of electrochromic glazing, compared to the use of low-e double glazing, obtaining similar cooling demand savings. The former obtained 40% for a test office in Milan (Cfa), while the latter reported savings from 45% to 49% for a case study in Dubai, UAE (BWh). Moreover, Favoino et al. (2015) reported savings ranging from 58% to 70% related to the use of switchable glazing instead of clear double glass. These results correspond to the outliers discussed earlier, so they are regarded as evidence of the higher potential performance ranges of these technologies, compared to 'static' solar control glazing. Nonetheless, their widespread application in façades is still limited, mostly due to cost restrictions.

TOC

§ 6.3.1.4 Ventilation

The application of ventilation strategies achieved the highest cooling demand savings among all evaluated strategies. In general numbers, this seemed to be the case in both main climate groups, obtaining mean and median values of 50% and 52% for warm-dry climates, and 33% and 30% for warm-humid climate zones. Maximum values in each main group corresponded to research experiences in temperate climates. Chiesa & Grosso (2015) reported cooling savings up to 91%, based on the combined use of stack and wind driven ventilation in a simulated office building in the hot-summer Mediterranean (Csa) climate of Ankara, Turkey. The same authors obtained savings up to 69.3% and 68.8% as the result from evaluating the building model in the humid subtropical climate of Plovdiv, Bulgary; and Rimini, Italy, respectively. The performance of ventilation strategies decreased in more harsh climates, particularly in the case of tropical environments. Maximum values in dry climates were 78% and 70%, reported by Ezzeldin & Rees (2013), from evaluating the effect of night ventilation strategies and diurnal natural ventilation when applicable, in El Arish (Egypt) and Alice Springs (Australia); respectively. In the case of tropical climates, maximum savings of 25.7% were found by Ben-David & Waring (2016) for a typical office in Miami (USA), after ventilating through the façade when it was thermodynamically favourable (mostly during night time). It is important to point out that this maximum value was obtained by also accepting a wider range in comfort temperatures, following the adaptive model proposed by Nicol et al. (2012). The authors also carried an evaluation under the same temperature ranges for both reference case and intervened scenario, obtaining cooling savings of only 8.5%, which seems to be more realistic for tropical climates based on the rest of the sample. The application of natural ventilation strategies is particularly challenging in tropical climates, due to high humidity levels which need to be controlled to prevent not only discomfort but also health issues and deterioration of building components through internal condensation.

Particular parameters considered in each research experience are shown in Table 6.9. Examining the results, it is noteworthy to point out that experiences that explicitly declared the use of high thermal mass obtained the highest cooling demand savings. The maximum value of 91% already discussed is an example of this, along with values up to 82.7% and 79.1% declared by Roach et al. (2013) and Geros et al. (1999) respectively. The former was obtained following the evaluation of a complete floor in the hot summer Mediterranean climate (Csa) of Adelaide, Australia; while the latter was the result of a TRNSYS model of a real building calibrated through on-site measurements in the similar climate of Athens, Greece.

TABLE 6.9 Research experiences about ventilation, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Ahmed & Wongpanyathaworn, 2012)	Humid subtropical (Cfa)	AUSTRALIA	IES-VE	WWR over 50%, no shading and west orientation. Upper boundary for T° comfort range set to 28 °C. No equipment and 0.1 person/m^2.	Louvres are set to open automatically if temperature difference outside/inside is satisfactory. Operation mostly during night time.	61%
(Ben-David & Waring, 2016)	Tropical savanna (Aw) Hot desert (BWh) Semi-arid (BSk) Hot-summer mediterranean (Csa) Humid subtropical (Cfa)	USA	Energy Plus	Entire floor of a typical office building in 14 representative locations with 14% WWR, undisclosed glazing type and no shading. T° comfort range of 21-24 °C.Internal gains of 9 W/m^2 (lighting), 15 W/m^2 (equip.) and 5 persons per 100 sqm. Minimal ventilation solely for hygienic purposes during work hours. Natural and mechanical ventilation were evaluated separately.	Evaluation considers natural ventilation through the façade, and mechanical ventilation though both façade and air-handling units (AHUs), when it is thermodynamically favourable (mostly during night time). Dynamic operation with cutbacks in the case of temperature and/or wind excess were considered.	4%-59%
(Chiesa & Grosso, 2015)	Humid subtropical (Cfa) Semi-arid (BSk) Hot-summer mediterranean (Csa) Hot desert (BWh)	Several cities in southern Europe and Northern Africa	Energy Plus	Entire building with high thermal mass and south-north orientation, 28% WWR and overhang as shading. Mech. ventilation during work hours is kept at the minimum, for air quality. Upper limit of T° comfort range at 26 °C. Internal heat gains of 11.77 W/m^2 (equip.) and 0.1 people/m^2.	Evaluation considered natural wind driven ventilation and stack + wind driven ventilation through vents automatically operated during all day, but mostly allowing fresh air over night time.	17%-91%
(Ezzeldin & Rees, 2013)	Hot desert (BWh)	AUSTRALIA BAHRAIN EGYPT SAUDI ARABIA	Energy Plus	Entire floor of a typical building. Glazing type complies with ASHRAE 90.1, with 30% WWR and 90% WWR on south and north façades. Adaptive T ° comfort ranges are assumed. Evaluation considers low (25 W/m^2) and high (50 W/m^2) internal heat gains separately.	Natural ventilation during office hours when feasible, and night ventilation.	56%-78%
(Ferrari & Zanotto, 2012)	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	ITALY	TRNSYS	South facing room in five building types, based on decade of construction and WWR. Clear and tinted double glass, with 23%, 63% and 100% WWR, and no shading. T° setpoint of 26 °C, infiltration rate of 0.2 ACH and natural ventilation rate of 1.7 ACH during working hours.	Increase of air change rate to 5 ACH between 23:00 and 07:00 for night ventilation purposes.	22%-62%

>>>

TABLE 6.9 Research experiences about ventilation, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Geros, 1999)	Hot summer mediterranean (Csa)	GREECE	TRNSYS	Three buildings with high and low-to-medium thermal mass, validated through monitoring campaigns. Glazing type and WWR were undisclosed, with no shading.Upper T° limits of 25 and 27 °C.	Night ventilation from 23:00 to 07:00, considering several ACH values (5, 10, 20 and 30 air changes per hour).	14%-79%
(Ji et al., 2009)	Humid subtropical (Cfa)	CHINA	IES-VE	Several rooms with different orientations, clear double low-E glazing, undisclosed WWR and shading. T° comfort range set at 20-27 °C. Heat gains of 35 to 45 W/m^2, considering lighting (12 W/m^2), occupants (90 W each) and PCs (116 W each). Infiltration rate of 0.2 ach. Minimum ventilation rate for air quality.	Night ventilation automatically operated considering temperature cutbacks, only for work days.	30%-38%
(Kolokotroni & Aronis, 1999)	Humid subtropical (Cfa)	UK	3TC (BRE)	South facing room with clear double glass, WWRs of 20%, 40%, 60%, 80%. Shading coefficient of 0.2. T° setpoint at 24 °C and internal heat gain values of 20, 30, 60 W/m^2.	Single sided night ventilation through the building façade. Air changes per hour (ACH) values of 1;3;5;7 and 9 were evaluated.	2%-15%
(Roach et al., 2013)	Hot summer mediterranean (Csa)	AUSTRALIA	Energy Plus	Entire building floor with clear double glass, 60% WWR and no shading. Occupancy gains of 8 W/m^2. No internal heat gains and 40 W/m^2 heat gains analysed separately. Minimum air supply for air quality.	Night ventilation considering several ventilation rates (3;6;9;12 ACH) and direct contact with thermal mass indoors.	29%-83%
(Samaan et al., 2016)	Hot desert (BWh)	EGYPT	Energy Plus	Rooms at an University Campus, facing north, south and west, with clear single glazing and 50% WWR. Operative T° is set to 23 °C. High occupancy (2.5 m^2/person) and base ventilation of 10 l/s.	Application of night ventilation and minimisation of diurnal ventilation during summer.	15%-19%
(Schulze & Eicker, 2013)	Humid subtropical (Cfa) Hot-summer mediterranean (Csa)	ITALY TURKEY	Energy Plus	18 office rooms facing east and west, with low-e double glazing, 50% WWR and external venetian blinds. T° cooling setpoints are 25 °C and 30 °C (day/night). Internal gains of 2 pp./room and 7 W/m^2 (equip.), high thermal mass and infiltration rate of 1.5 ach.	Single sided night ventilation through sliding windows.	6%-10%

>>>

TABLE 6.9 Research experiences about ventilation, considering experimental setup, climate zones and reported cooling savings ranges.

REFERENCES	CLIMATE ZONES (KOPPEN)	COUNTRY	SOFTWARE	REFERENCE CASE DETAILS	EVALUATED PARAMETERS	COOLING SAVINGS
(Solgi et al., 2016)	Hot desert (BWh)	IRAN	Energy Plus	Isolated south facing room with clear single glass, undisclosed WWR and no shading. PCM (1 cm) on walls, roof and floor. Temperature comfort range of 21-28 °C.	Mechanical night ventilation (00:00 - 07:00), automatically operated if outside T° is lower than setpoint. Several ventilation rates were evaluated (5;10;15;20;25;30 ACH).	14%-19%
(Wang & Greenberg, 2015)	Humid subtropical (Cfa)	USA	Energy Plus	Entire building floor with clear double glass, 48% WWR and no shading. Internal heat gains of 16 W/m^2 and operative T° setpoint at 24 °C.	Mixed-mode vent. strategies (concurrent, change-over, and zone dependent operation). Automatic use of natural vent. when external factors allow it).	17%-32%
(Yang & Li, 2008)	Humid subtropical (Cwa)	CHINA	Numerical model	Isolated room with undisclosed glazing type and WWR, and no shading. No thermal mass was assumed.	Natural night ventilation	10%

Ventilation rates were also particularly addressed by some researchers, evaluating their impact on the overall effectiveness of the strategy. The graph in Figure 6.8 shows the correlation between cooling demand savings and different ventilation rates, expressed in air changes per hour (ach). It is important to point out that information about ventilation rates was reported in just 60 out of the 209 total cases, so this particular analysis only considered a fraction of the sample (29% of all ventilation results). Ventilation rates considered in the evaluations range from 1 to 30 ach. Looking at the results, there is no direct correlation between reported savings and any given ventilation rate, so it does not seem to have a definitive impact on the overall performance. Results from applying 30 ach vary greatly, considering values between 36.2% and 79.1%, reported by Geros et al. (1999) in Athens (Csa); and a minimum of 15.4% reported by Solgi et al. (2016) in the hot desert climate of Yazd, Iran (BWh). On the other hand, savings up to 82.1% and 79% were reported by Roach et al. (2013) under 6 and 3 ach respectively. Furthermore, most cases considered 5 ach in the evaluation, with a wide range of resulting savings (4-63%), so akin ventilation rates are judged as enough to achieve a good performance under adequate design considerations.

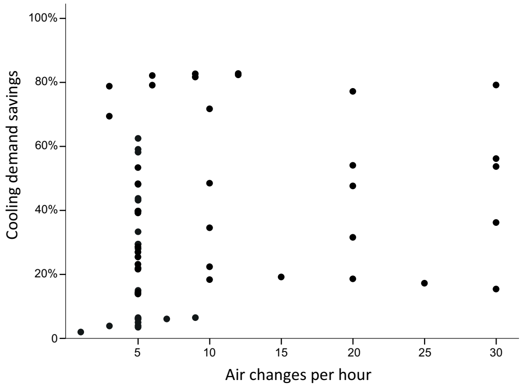


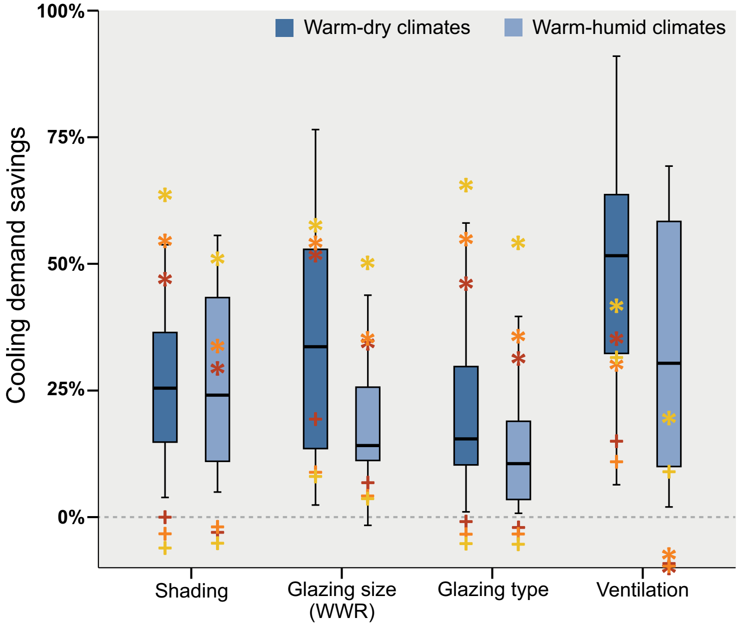
FIGURE 6.8 Relation between cooling demand savings and reported ventilation rates used in the evaluations.

§ 6.3.2 Impact of the evaluated strategies under a controlled setup: sensitivity analysis of selected parameters

As explained before, a sensitivity analysis was conducted to check the impact of selected parameters on the cooling demands of two reference cases, under a controlled experimental setup. Boundary cases were defined to assess the specific impact of the selected cooling strategies in extreme conditions: a scenario without any strategy applied on and another where all other strategies were applied.

Figure 6.9 shows the results obtained from the simulations in terms of cooling demand savings, contrasted to the performance ranges obtained through the review of research experiences. The results are represented using different colours for the selected cities, and different symbols for the impact on the defined reference cases, according to the attached legend. As a starting point, it was assumed that the impact from the application of the evaluated strategies would be higher in reference cases that did not consider any particular passive measures or bioclimatic design attributes, and vice versa. So, the comparison was useful to correlate the results from the simulation to the larger context of experiences, while also exploring the differences on the resulting performance of the strategies considering boundary reference cases.

From the graph it is possible to see that with the exemption of ventilation strategies, results from the simulations align with the identified performance ranges. Mean values obtained from the review, for strategies without ventilation, were between 22%-34% and 12%-28% for warm-dry and warm-humid climates; while the average values from the simulated scenarios were between 26%-33% and 17%-22% respectively. On the one hand, the results are mostly contained within the outer limits of each performance range, given that the reference cases represent somehow boundary cases. In the particular case of glazing types, the results from the simulation seem to be overestimated compared to the data from the review. This may be explained by the high reflectivity glass pane used in the simulations, with an assumed better behaviour than most of the examples from previous experiences, in order to test performance limits. On the other hand, most results are aligned in terms of the climate context they refer, which is particularly true in the worst case scenario comparisons (*). Hence, the impact of passive strategies on the mild temperate context of Lisbon and Trieste is higher (in percentage points) than the response of their application on extreme environments such as Riyadh or Singapore.



CLIMATE GROUP	CITY
Desert	Riyadh
Tropical	Singapore
Temperate humid	Hong-Kong
Temperate dry	Athens
Temperate humid	Trieste
Temperate dry	Lisbon

✱ Cases without any strategy
+ Cases with all other strategies

FIGURE 6.9 Cooling demand savings from the simulations (in percentage points) contrasted to the performance ranges defined by the review.

The most evident difference between reviewed experiences and simulations occurs for ventilation strategies, with mean values dropping from 50% to 27% for warm-dry climates, and from 33% to -2% in the case of warm-humid climates. Two reasons may explain this mismatch. Firstly, the reviewed database considers more experiences located in temperate rather than extreme environments, which is especially true in the case of ventilation strategies on warm-humid climates. As the simulations show, the impact of ventilation strategies is markedly different from temperate to extreme warm-humid climates; while they may be beneficial in the former, they are largely counterproductive in the latter cases. Secondly, another explanation could be the possible disregard of dehumidification loads in some of the reviewed calculations. For the simulations, an upper relative humidity limit of 55% was set, keeping absolute humidity below 12 gr/Kg of dry air at 26 °C (ASHRAE, 2010). This could also explain the larger difference between warm-dry and warm-humid climates, evidencing limits for the application of ventilation in highly humid environments, due to their high latent loads.

Interestingly, results from the application of ventilation strategies in four out of the six locations result on cooling savings in all events, either as a single strategy or applied in a case that already considers other passive strategies. The extra savings in the latter cases may be explained due to the fact that ventilation strategies are based on heat dissipation, serving as an important complement for heat prevention strategies. Nonetheless, simulation results show that the difference between reference cases is not as important as the difference between climate contexts for ventilation strategies. Thus, while it is true that passive ventilation strategies may improve the cooling performance of an optimised building in terms of heat prevention strategies, their efficacy is strongly limited by the climate context. So their application must follow an adequate assessment. The results advocate for the application of passive ventilation in warm-dry climates in any event, while also showing benefits in temperate humid climates to a lesser degree. However, counterproductive results were found not only for Singapore, but also for Hong Kong, evidencing high dehumidification requirements for air intake.

On the other hand, the behaviour of the heat prevention strategies (shading, window-to-wall ratio, glazing type) is similar among them, as pointed out in the scenarios with no strategies (worst case), with particular differences according to their specific impact on the evaluated climates. However, in the case that considers other strategies, the results show larger differences, particularly comparing the impact of glazing size (WWR) with the other two strategies. Most notably, results from glazing size show cooling demand savings in all events, while the use of shading and glazing type may have an adverse effect if all other strategies are applied. This means that regardless other parameters, to consider smaller glazed areas is always recommended in warm climates, and its application should be particularly prioritised in extreme climate zones due to its relative effectiveness. Contrarily, the application of shading and glazing type strategies at the same time either shows no difference or shows an adverse effect on cooling demands, due to an overplay of their performance, blocking too much solar radiation which in turn increases indoor lighting needs that have to be fulfilled by active equipment. Both strategies work under the same principle, so the decision to apply either one or the other may be subjected to other façade design requirements. Similarly, their combined use needs to be carefully assessed to achieve optimal results.

TOC

TABLE 6.10 Average cooling demands for the entire floor, for each simulated scenario.

SCENARIOS		CODE	AVG COOLING DEMANDS ENTIRE FLOOR (KWH/M^2 YEAR)					
			RIYADH	SINGAPORE	HONG KONG	ATHENS	TRIESTE	LISBON
*	No strategies	0000	288.36	366.73	234.12	181.75	108.27	168.20
	Only Shading	1000	157.06	261.00	157.37	83.01	53.22	61.90
	Only WWR	0100	**138.76**	**242.06**	152.31	84.08	53.63	72.78
	Only Glass type	0010	157.12	252.77	**150.77**	**81.09**	**49.91**	**58.15**
	Only Ventilation	0001	186.21	407.93	252.01	126.90	87.26	98.59
+	All strategies	1111	91.43	246.83	158.75	56.05	41.01	33.57
	No Shading	0111	91.44	240.78	154.90	54.51	**38.92**	**31.73**
	No WWR	1011	112.85	264.71	165.03	61.45	42.92	36.31
	No Glass type	1101	**90.93**	241.82	154.08	**54.48**	38.97	31.84
	No Ventilation	1110	107.98	**223.11**	**141.15**	63.05	44.88	48.62

The examination of the cooling demands in terms of absolute values reinforces the idea of clashing strategies. Table 6.10 shows the average cooling demands for the entire floor in all analysed cases. Best results obtained in both sets of scenarios are highlighted (application of a single strategy or their combined use). Best results for Singapore and Hong Kong were obtained avoiding ventilation altogether as previously discussed. In all other cases, the lowest overall cooling demands were obtained either using shading or a better glass unit (not both), along with an optimised window-to-wall ratio and ventilation strategies. It is important to point out that this comparison is based on cooling demands, so dynamic shading systems may present advantages regarding heating demands on temperate climates, supporting their application over reflective glazing units in particular contexts.

The relative impact from the application of a single strategy and their combined use is further presented in Figure 6.10. The graph shows the average cooling demands for an entire floor for all evaluated cities, under three different scenarios. The first scenario considers the worst case used as reference, without considering any passive cooling strategy. Next to it, the highest impact from a single strategy is shown, presenting also the referred strategy. Finally, the best case is presented as third scenario, considering the combined action of several measures, thus showing the maximum cooling demand savings obtained within the boundaries of the experimental setup. The bars show the brute demands, while the cooling savings are expressed in percentage value compared to the first (worst) scenario.

TOC

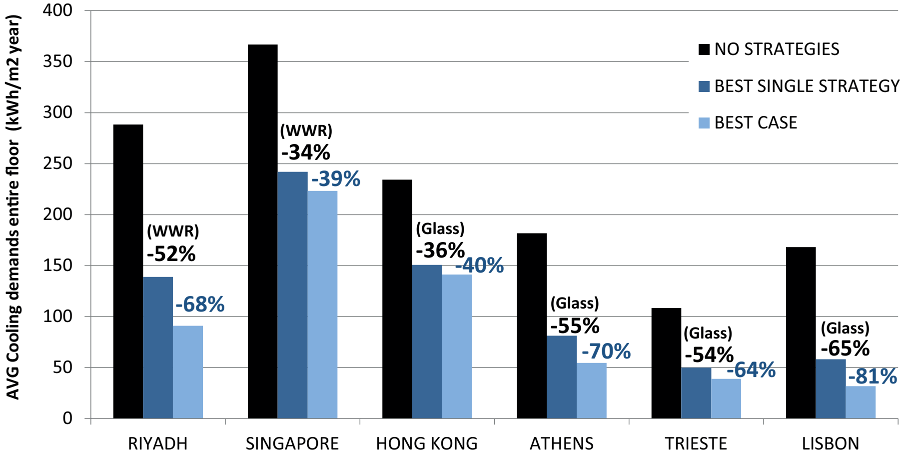


FIGURE 6.10 Average cooling demands for each evaluated city, considering the worst case and best results obtained by the use of a single strategy and their combined application.

It is possible to notice an important reduction in all cases by using only one strategy. In the extreme climates of Riyadh and Singapore, the best results were obtained by reducing the window-to-wall ratio, with a 52% and 34% of respective cooling demand savings. In all other contexts, the strategy with more isolated impact was the change from clear double glazing to reflective glazing. On a side note, the worst results considering isolated strategies were obtained through the application of ventilation strategies. This suggests an order for the application of passive cooling strategies, starting from heat prevention through a careful design of the building envelope, and then considering heat dissipation strategies such as diurnal or nocturnal ventilation if they apply. Ventilation strategies will not report important benefits without an adequate designed façade system already in place.

The relations between the different strategies are further evidenced by the results from the best case, which considers more strategies on top of the best single one already discussed. The difference between the second and third scenario is smaller in hot-humid climates when compared to dry climates, constraining further optimisation. The resulting improvement is due to the combined effectiveness of extra strategies. In all cases except Singapore and Hong Kong, the main strategy responsible for this was found to be ventilation. This fact reinforces the idea that even if ventilation is not the first strategy that needs to be applied, its complementary use along with heat prevention façade strategies, is highly advised, with a different range of benefits in all climates except highly humid environments.

The results from the application of combined strategies are evidence of the whole potential of passive measures on lowering cooling demands of commercial buildings. When compared to a worst case scenario, obtained cooling savings range from 40% up to 80%, with annual total cooling demands per square meter of 30 kWh/m^2 in the temperate climate of Lisbon. Therefore, the integration of passive cooling strategies under a climate responsive architectural concept is regarded as a minimum condition for the design of office buildings in warm climates. Even if these strategies are not capable of coping with comfort requirements entirely by themselves, it is proven that their adequate application will report relevant energy savings, along with the associated reduction of the environmental impact derived by the use of smaller mechanical equipment and less overall consumption of fossil fuels.

§ 6.4 Conclusions

This chapter sought to explore the effectiveness of selected passive cooling strategies in commercial buildings from warm climates, defining performance ranges based on the assessment of multiple scenarios and climate contexts. This task was conducted through the statistical analysis of results from documented research experiences, to define overall ranges and boundary conditions; and through software simulation of selected parameters to isolate their impact under a controlled experimental setup.

First of all, it was corroborated by both the review and the simulations that passive cooling strategies are more effective in warm dry climates, reaching higher cooling demand savings in these contexts than in humid environments. Mean cooling demand savings considering all analysed strategies ranged between 22%-50% and 26%-33% based on the review and the simulations respectively in the case of warm dry climates, while the overall ranges obtained for warm humid climates were 12%-33% and -2%-22%. The potential effectiveness of all strategies was also found to be higher in temperate climates, in terms of percentage points, which holds true for both dry and humid climate groups. Nevertheless, the dispersion among the results showed that the mere application of passive strategies is not enough to guarantee relevant savings. Their effectiveness is conditioned to both the harshness of a given climate and different parameters that need to be carefully considered during the design of a specific building. Particular findings for each evaluated strategy are drafted below.

Regarding shading strategies, the review showed consistent average savings among warm-dry and warm-humid climate groups. Furthermore, the sample revealed that different types of shading devices do not categorically result on markedly different cooling demand savings, so it becomes important to promote further detailed studies on this topic, and advocate for a careful evaluation of different shading possibilities during the design of any given building on a particular context. Similarly, the application of shading devices must be analysed considering the glazing type used in the window, following an integrated approach for the design of the whole fenestration. Simulation results showed redundancy and negative effects by using both strategies at once without a conscious optimisation process. Looking exclusively at cooling demands, the compared effectiveness of using shading systems or reflective glazing was negligible in most cases. However, the use of dynamic shading devices may present advantages on temperate climates, considering lighting and heating demands.

Discussing window-to-wall ratio, highest cooling savings were unsurprisingly related to the smallest window sizes. However, it is necessary to consider lighting needs and the action of complementary heat prevention strategies when sizing a window, to prevent counterproductive effects. The review revealed a considerable difference in its expected performance between warm-dry and warm-humid climates, with average values of 34% and 18% respectively. Nonetheless, results from the simulation showed cooling savings on all evaluated scenarios, which added to previous results lead to recommend its application as an effective design strategy in all events, especially in extreme climate zones due to its specific relative performance.

According to the review, glazing type strategies had the lowest potential for cooling demand savings, although this is highly dependent on the type of glazing units being used. Changes on the number of layers do not report relevant improvements, while the combined use of coloured panes and reflective coatings was found to be promising. Dynamic glazing technologies evaluated in previous experiences reported the best results but their widespread application is still limited. The impact on cooling demands from the use of reflective glazing was found to be comparable to the use of external shading devices in the conducted simulations, being a matter of choice between them in all analysed cities.

In turn, ventilation strategies had the highest potential for cooling savings, based on the reviewed experiences, in desert, dry temperate and humid temperate climates. Best results were strongly related to the explicit use of thermal mass, to modulate heat during the day allowing for night-time ventilation. The examination of previous experiences also revealed no relevant correlation between cooling savings and ventilation rates, considering 5 air changes per hour to be enough to achieve good results, under the right conditions. The controlled simulated scenarios revealed that ventilation may indeed promote high cooling savings, especially improving the performance of cases that already considered heat prevention strategies, thus serving as a good complement to climate

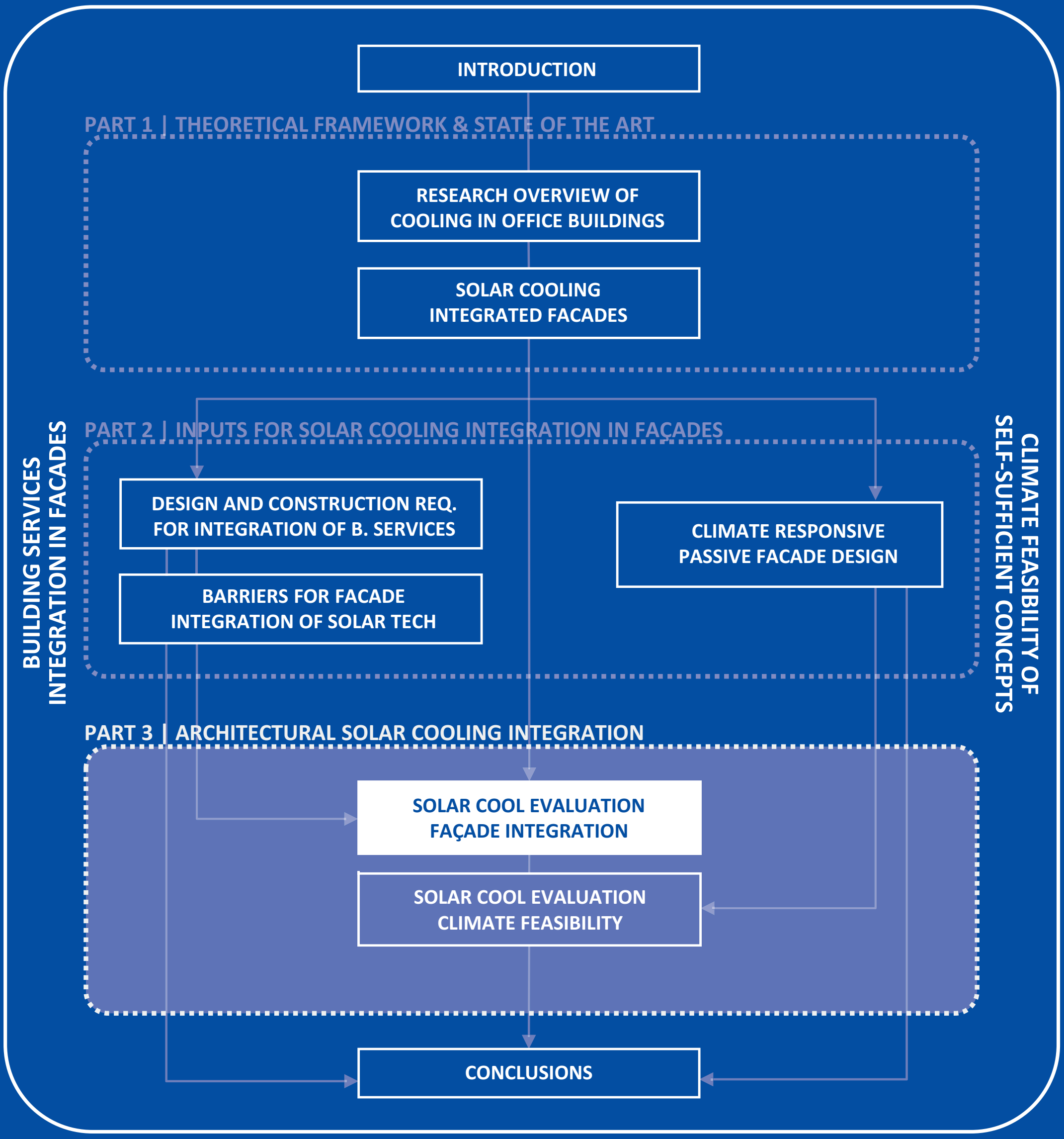
TOC

responsive façade design. Nevertheless, the overall effectiveness of ventilation strategies was found to be strongly dependent to the climate conditions instead of the building itself, reaching better performances in temperate climates, but actually making matters worse in highly humid environments.

The potential from the application of passive cooling strategies in commercial buildings is evidenced by both the review of experiences and the results from the simulations. Further studies should tackle the evaluated strategies in detail, assessing the impact of varying parameters under a combined integrated application. However, it feels important to reiterate that these or future general guidelines should not replace detailed analyses of a specific building in a particular context, but are being regarded as valuable referential information in early design stages. Another field worthy of exploration is the architectural integration of hybrid systems (active low-ex cooling) and renewable sources of energy, out of the scope of this document, to cope with the remaining cooling demands after a conscious process of passive design optimisation of new and refurbished buildings in warm climates.

TOC

COOLFACADE



INTRODUCTION

PART 1 | THEORETICAL FRAMEWORK & STATE OF THE ART

RESEARCH OVERVIEW OF COOLING IN OFFICE BUILDINGS

SOLAR COOLING INTEGRATED FACADES

PART 2 | INPUTS FOR SOLAR COOLING INTEGRATION IN FAÇADES

DESIGN AND CONSTRUCTION REQ. FOR INTEGRATION OF B. SERVICES

BARRIERS FOR FACADE INTEGRATION OF SOLAR TECH

CLIMATE RESPONSIVE PASSIVE FACADE DESIGN

PART 3 | ARCHITECTURAL SOLAR COOLING INTEGRATION

SOLAR COOL EVALUATION FAÇADE INTEGRATION

SOLAR COOL EVALUATION CLIMATE FEASIBILITY

CONCLUSIONS

BUILDING SERVICES INTEGRATION IN FACADES

CLIMATE FEASIBILITY OF SELF-SUFFICIENT CONCEPTS

ARCHITECTURAL SOLAR COOLING INTEGRATION IN FACADES

TOC

7 Solar cooling evaluation – Façade integration

State-of-the-art solar cooling technologies and assessment for façade integration potential[6]

Increasing cooling demands in buildings call for innovative environmentally friendly systems to cope with remaining loads after the application of passive design strategies. Solar cooling technologies present interesting assets, but their application in the built environment remains greatly limited. Hence, this chapter seeks to *assess their potential for widespread application, identifying possibilities and current bottlenecks for the architectural integration of solar cooling technologies in façades*.

The assessment is based on a state-of-the-art review and discussion of key attributes for façade integration of selected technologies; and a qualitative evaluation of their suitability to respond to main product related barriers for the integration of building services identified in Chapter 4. An overview of the cooling principles behind the operation of the assessed technologies was presented in Chapter 3, so this chapter focuses exclusively on key aspects to overcome barriers related to the technical feasibility, physical integration, durability, performance, and aesthetics of future integrated concepts.

Results show that the suitability of the assessed technologies varies according to each particular barrier. Hence, no technology currently fits all required aspects. Nonetheless, the use of thermoelectric modules and compact units based on absorption technologies are regarded as the most promising for the development of either integral building components, or modular plug & play systems for façade integration. In any case, this is heavily conditioned to further efforts and explorations in the field to overcome identified challenges and knowledge gaps.

---

[6] Published as: Prieto, A.; Knaack, U.; Auer, T.; Klein, T. (2019). Coolfacade: State-of-the-art review and evaluation of solar cooling technologies on their potential for façade integration. Renewable and Sustainable Energy Reviews; 101: 395-414. doi: 10.1016/j.rser.2018.11.015.

§ 7.1 Introduction

Cooling demands in the built environment present a highly relevant challenge for the design of sustainable buildings and cities. On the one hand, several studies have attributed around 15-17% of global electricity consumption to air-conditioning and the refrigeration sector (CICA, 2002; Mujahid et al., 2017; Reda et al., 2016). This demand is expected to increase continuously during the coming years, following current trends (Jochem & Schade, 2009; Weiss & Biermayr, 2009), due to several factors such as increasing standards of life, climate change, and affordability of air conditioning (Santamouris & Kolokotsa, 2013). Yearly sold room size AC units surpassed 100 million worldwide on 2014, and they are expected to reach over 1.6 billion by 2050, with yearly sales growing at 10-15% in fast growing developing countries from warm climates (Montagnino, 2017). Moreover, it has been stated that just Non-OECD Asia will account for more than half of the world's total increase in energy consumption between 2012 and 2040 (DOE/EIA, 2016), which puts pressure on design guidelines, regulations and further exploitation of renewable sources of energy.

On the other hand, refrigerants used as working fluids have serious environmental impact. Chlorofluorocarbons (CFCs) were banned and hydrochlorofluorocarbons (HCFCs) are being phased out according to the schedules set by the Montreal Protocol in 1987, due to their impact on the ozone layer (UNEP, 2017). The most common refrigerants currently used are hydrofluorocarbons (HFCs), such as R134a, a non-ozone-depleting substance, but with a global warming potential (GWP) 1,430 times that of CO_2 (EIA, 2015; IPCC/TEAP, 2005). As a result of the Kigali amendment to the Montreal Protocol, signed in 2016, the use of these substances will be also phased down, over the period of 2019-2036 and 2024-2047 in developed and developing countries respectively (UN, 2016). This milestone means breaking the vicious circle established by the operation of refrigerants that contribute to temperature rise in urban areas, in turn increasing cooling demands and further need for refrigerants.

The current challenge for sustainable cooling in the built environment is then threefold: there is (a) a need for climate-responsive building design to decrease cooling demands as much as possible through the application of passive strategies; while the remaining load is covered by (b) efficient building systems that not only use renewable energies as input, but also (c) consider environmentally friendly working materials and processes. In that regard, solar cooling technologies have experienced increasing interest over the last couple of decades, being widely recognised as promising alternatives to traditional vapour compression based refrigeration (Brown & Domanski, 2014; Goetzler et al., 2014; Prieto, Knaack, Klein, et al., 2017). The main benefits of these

TOC

systems are the direct use of solar radiation as a renewable energy source, and the use of environmentally friendly working materials in the cooling process. Nonetheless, building application remains mostly limited to demonstration projects and pilot experiences (Balaras et al., 2007; Henning & Döll, 2012).

One alternative to promote further application in the built environment, is the development of multifunctional building components for architectural design. Working experiences of decentralised services integration in façade modules, plus the exposed area available for solar collection, point towards façade integration of solar cooling technologies as a clear road to develop small-scale, flexible products for widespread application. The potential for solar collection in facades has been explored through the development of building integrated photovoltaics (BIPV) and building integrated solar thermal collectors (BIST), resulting in guidelines, prototypes and commercialised products (Escarré et al., 2015; Munari-Probst & Roecker, 2012; Schüler et al., 2005). On the other hand, solar driven refrigeration has been described and categorised in terms of working principles (Henning, 2007; Kohlenbach & Jakob, 2014), and evaluated and compared considering performance (Eicker et al., 2015; Ma et al., 2017) and to a lesser degree, economic aspects (Eicker, Colmenar-Santos, et al., 2014; Otanicar et al., 2012). However, besides stand-alone prototypes and integrated concepts, there is a knowledge gap regarding guidelines for building application and especially integration possibilities within façade components.

The goal of this chapter is to assess the potential for façade integration of several solar cooling technologies, based on a state-of-the-art review and discussion of specific attributes, and their capability to respond to main identified barriers for façade integration of building services. The assessment focuses 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 et al., 2017a). Even though the energy input is a fundamental part of the system, the assessment will concentrate on the cooling process and the required components to generate, distribute and deliver the cooling effect indoors. Hence, façade integration possibilities of PV panels and/or solar collectors will not be directly addressed. In turn, the outcome of this assessment is expected to serve as complement to previous and established research on BIPV and BIST (Cappel et al., 2014; Munari Probst & Roecker, 2007; Prieto et al., 2017b), providing feedback to system developers and façade designers for the development of fully self-sustaining solar cooling façade modules for buildings in warm climates.

TOC

§ 7.2 Strategy and methods

The assessment of the defined solar cooling technologies was carried out in two separate stages, sequentially presented in this chapter: a state-of-the-art review of the solar cooling technologies focused on relevant aspects for façade integration; and the evaluation of these technologies, based on the addressed aspects, on their potential to overcome previously identified barriers for façade integration of building services.

The review focuses on façade integration potential, by characterising the selected technologies in four main aspects: performance, component complexity, operation, and development level, providing an specialised overview of the state-of-the-art of the particular technologies, for each aspect addressed. A brief description of the considered aspects and sub-aspects is shown in Table 7.1. Many sources were considered for the review, such as peer-reviewed scientific publications, research reports, patented concepts, and technical info from manufacturers and distributors in the case of market-ready products. Façade integration potential means the integration of small decentralised units, so the review focused on small-scale developments, ranging up to 20 kW. Larger capacities were discussed as reference if applied, but they were not explored in detail.

TABLE 7.1 Key aspects considered in the review

KEY ASPECTS	SUB-ASPECTS
PERFORMANCE	General reported performance
	Reported performance of small scale applications
COMPONENT COMPLEXITY	Dimensions – size, volume and weight of systems and components
	Components – number and types of required components
	Connections – types of required connections and materials involved
OPERATIONAL ISSUES	Health, safety and comfort issues
	Maintenance requirements
DEVELOPMENT LEVEL	Technical maturity
	Market/commercial maturity

The review does not consider a detailed description of the cooling principles and processes behind each technology, having been extensively described on the literature and showcased in Chapter 3 (Kohlenbach & Jakob, 2014; Prieto et al., 2017a). Similarly, economic aspects were not explicitly considered in the review. Even though cost is a relevant issue for the development of integrated concepts, there is limited amount of

TOC

information on small-scale concepts, due to their early research and development stage. Hence, cost estimations of integrated concepts may be troublesome. In any case, broad economic considerations are implicitly considered in the discussed aspects, in terms of the materials used, complexity of the system, and overall performance during operation, providing less payback time with a more efficient solution, compared to a base initial cost.

The potential for façade integration of these technologies was evaluated based on their prospects to overcome main barriers for the integration of building services in façade components. These barriers were previously identified and discussed in Chapter 4, based on a survey addressed to specialised professionals with practical experience in the development of façade systems for office buildings. The main outcome of the survey was the identification of the main perceived barriers for integration, through open questions, during three main product development stages: design, production, and assembly. Open ended responses by the experts were then categorised into main process and product related issues, as shown in Figure 7.1.

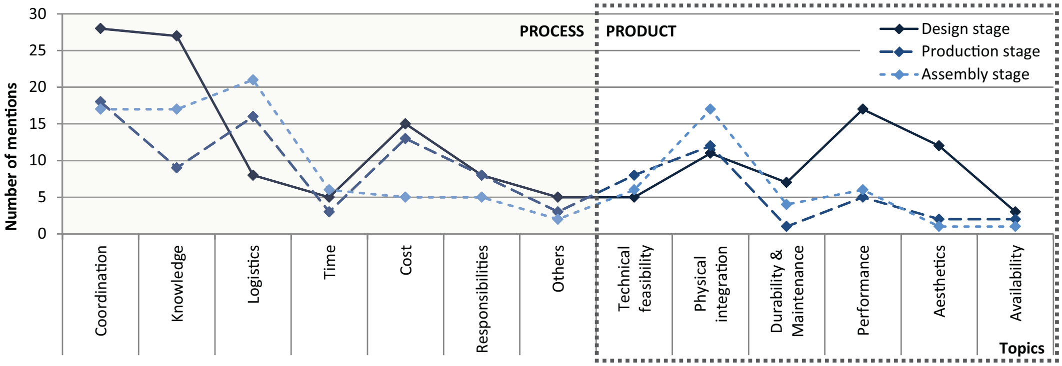


FIGURE 7.1 Main perceived barriers for façade integration of building services: number of mentions per development stage by respondents.

Only product related barriers and subsequent issues are considered in the evaluation of solar cooling technologies, focusing the discussion on key characteristics for potential future integrated products, rather than the logistics, knowledge and coordination required to successfully produce them. Moreover, process related aspects need to be tackled in general, to allow further application of all of the assessed technologies, so these barriers do not provide direct and discernible criteria for comparison between current solar cooling technologies. Therefore, the evaluation centres around the identified product related barriers, discussing and assessing the potential of the different technologies in overcoming them.

TOC

TABLE 7.2 Main identified barriers for façade integration and score system for the evaluation.

BARRIERS	DESCRIPTION	SCORE VALUES			
		o	+	++	+++
TECHNICAL FEASIBILITY	Overall feasibility to integrate systems into façade modules based on each cooling principle. This considers functional and physical constraints for integration	Required components cannot be integrated in a façade module.	Standalone examples of compact systems (R&D needed).	Development of small compact units and stand-alone facades	Several façade integrated concepts and tested prototypes
PHYSICAL INTEGRATION	Externalities derived from the physical integration of components and parts, considering compatibility of sub-systems, modularity, working materials and connections.	Components & working mat. incompatible with façade functions.	Complex connections between operating sub-systems.	Connections of mild complexity / compatible components	Modular components with simple plug & play connections.
DURABILITY & MAINTENANCE	Durability of components over time, maintenance requirements and ease to perform repairs or replace components and parts.	Fragile components with costly and frequent maintenance.	Robust components w/ complicated maintenance.	Robust components with periodic but simple maintenance.	Robust systems and components virtually maintenance free.
PERFORMANCE	Technical limitations based on past experiences. It also considers externalities for indoor comfort, derived from the operation of the systems.	Performance is out of required range / Hazardous operation.	Isolated in-range experiences / Minor externalities	Several cases of high, reliable performance / Minor externalities.	High & proven relative performance, with no externalities.
AESTHETICS & AVAILABILITY	Potential to allow for design flexibility and variability, which may grant freedom for architectural expression and façade composition.	Operating principles & potential sizes greatly restrict design choices.	Some restrictions and isolated options for façade design	Minor restrictions / various options for components.	High design flexibility and variety of options and components.

It is worth pointing out that the results from the survey showed that some barriers seem to be more relevant that others, based on the total amount of mentions. This suggests perceived priorities for current exploration; however, the assessment considers them separately, exploring the current state of each technology without attempting an overall comparison. Hence, each barrier is discussed separately, while the barrier-specific integration potential of each technology is illustrated and compared by a qualitative score system depicted in Table 7.2, along with a brief description of the barriers. The barrier-based assessment of the façade integration potential of the selected technologies aims to identify specific bottlenecks and propose recommendations to bring them closer to façade integration, sketching a roadmap for the future development of solar cooling integrated architectural products.

TOC

§ 7.3 State-of-the-art review of solar cooling technologies on key aspects for façade integration

Solar cooling technologies are usually categorised according to their energy input, under either solar electric or solar thermal processes, hence using electricity from PV panels or heat stored in solar thermal collectors as the main input for the cooling process (Henning, 2007; Prieto et al., 2017a). Table 7.3 shows the main solar cooling principles and associated common technologies in existence. Even though the use of a vapour compression heat pump could be considered under solar electric processes, provided that is driven by PV panels, it is not considered in the review due to the environmental hazards of commonly used refrigerants. Similarly, thermomechanical cooling technologies are not discussed due to the lack of development and consequent available information compared to the rest. Therefore, the review and evaluation focus on five solar cooling technologies regarded as the most promising options for further development of integrated building components: thermoelectric, absorption, adsorption, and (solid and liquid) desiccant cooling.

TABLE 7.3 Available cooling technologies based on solar electric and solar thermal processes.

ENERGY INPUT	COOLING PRINCIPLE	COOLING TECHNOLOGIES
SOLAR ELECTRIC PROCESSES - ELECTRICITY	Vapour compression cooling	Compression heat pump
	Thermoelectric cooling	Peltier modules
SOLAR THERMAL PROCESSES - HEAT	Sorption cooling	Absorption heat pump
		Adsorption heat pump
	Desiccant cooling	Solid desicc. (+ Evaporative cooling)
		Liquid desicc.(+ Evaporative cooling)
	Thermomechanical cooling	Steam ejector system
		Stirling engine
		Rankine cycle heat pump

All technologies addressed in the review share general advantages and disadvantages compared to commonly used vapour compression systems. The most relevant advantages are the use of renewable energy as main direct input, either directly supplied as electricity or low-grade thermal energy; and the use of environmentally friendly working materials as refrigerants, with no global warming nor ozone depletion potential. The most important disadvantage is the performance of these systems in terms of their electrical or thermal efficiency, besides the technical and commercial maturity of systems and components.

TOC

Aside from these, specific advantages and disadvantages inherent to each technology are presented in Table 7.4, as an initial overview of possibilities and constraints for widespread application. The specific review of each technology regarding key aspects for façade integration is carried out separately, in the following sections.

TABLE 7.4 Specific advantages and disadvantages of selected solar cooling technologies.

SOLAR COOLING	ADVANTAGES	DISADVANTAGES
THERMOELECTRIC	• Solid-state technology, refrigerant free. • No moving parts in the core system. • Small size of components comprehend packaging advantages for product development. • Quick operation (to reach steady-state conditions).	• Low power/efficiency of current materials. There is a trade-off between reported efficiency (COP) and cooling power of researched concepts. • Technology in early R&D stages for HVAC application.
ABSORPTION	• Mature technology with high reliability. Current efforts target cost and complexity. • Larger COP than other thermally operated technologies.	• Potential solution crystallisation, which could cause irreparable damage, added to corrosion risk and need to maintain vacuum. • High upfront costs. Economics become more favourable for larger buildings.
ADSORPTION	• Few moving parts and factory sealed units (maintenance free system) • Non-toxic, non-flammable working fluid (silica gel/water) • No crystallisation nor corrosion in inner components	• Large sizes and weight (bulkiness) due to inefficiency of the cycle (expected cooling capacity). • Alternating operation and long cycles (intermittent) under simplest mode (1 adsorption bed)
SOLID DESICCANT	• Non-flammable and non-corrosive materials • Easy to clean and low maintenance costs, due to its operation at almost atmospheric conditions • Temperature and humidity control separately (sensible and latent loads)	• Limited performance of materials (adsorption capacity of silica gel is low while zeolites have low water capacities and higher cost of regeneration) • Slightly complicated system instalment • Generally larger in size/shape than conventional systems
LIQUID DESICCANT	• High potential indoor air quality, capacity of absorbing pollutants and bacteria • Low-pressure drop, for use with low regeneration temp. • Potential small and compact units by pumping solution. • Desiccant storage when heat source is not available	• All aqueous solutions are highly corrosive (plastic materials must be used) • Health hazards due to carry-over with supply air stream • Aqueous salts are subject to crystallisation, and freezing risk.

TOC

§ 7.3.1 Thermoelectric cooling

§ 7.3.1.1 Performance of cooling systems and integrated concepts

General reported performance

The efficiency of a thermoelectric (TE) module mostly depends on the ability of the base material to produce thermoelectric power from a temperature differential (or vice versa). This material property is measured with a dimensionless figure of merit denominated ZT. Commercially available common materials such as Bismuth telluride (Bi_2Te_3) have ZTs around 1.0-1.2 (Evident, n.d.), while it has been reported that it is possible to achieve COP values between 1.0 and 1.5 for TE HVAC systems using currently available TE materials of ZT=1 (Brown et al., 2010; Goetzler et al., 2014). Furthermore, it has been stated that TE cooling reaches Carnot efficiencies between 0.1 and 0.15 (Bell, 2008), with a theoretical potential up to 0.37-0.4 assuming reported developments in material science (Allouhi, Kousksou, Jamil, Bruel, et al., 2015; Brown et al., 2010; Brown & Domanski, 2014). These efficiencies would mean comparable values to vapour compression technologies (~0.45), so research on new materials has been a priority in the field. It has been stated by several authors that achieving a ZT value of 2 (Bell, 2008; Liu, Zhang, Gong, Li, et al., 2015; Zhao & Tan, 2014), or 3 (Goetzler et al., 2014; Riffat & Ma, 2004; Sales, 2002; Yilmazoglu, 2016) would make domestic & commercial HVAC TE systems competitive and practical for widespread application. More conservative estimates declare that a ZT=4.4 would be needed accounting for losses in the system (Brown & Domanski, 2014). In the last decades, new nanotechnology driven materials with ZTs of 1.5-2.0 and even 2.4 have been reported (Venkatasubramanian et al., 2001); however, these remain experimental and outside of the market.

Reported performance of small scale applications

There are several experimental TE driven HVAC concepts in the literature, with reported COP ranging from 0.38 to ~2.00 under diverse operating conditions. It is relevant to mention that in thermoelectric technology, there is a trade-off between COP and cooling power, so a balance between them is usually identified as the optimal operating condition. Tan & Zhao (2015) reported a maximum COP of 1.71 for a TE AC system, however, the optimum balance was found to achieve a COP of 0.82, under 5 A and cooling power of 37 W. Cosnier et al. (2008) reported COP values around 1.5-2.0 for an air cooling/heating system, with 50 W per module under 4 A, maintaining 5 °C difference between hot and cold sides (10 °C maximum). Shen et al. (2013) achieved a COP of 1.77, with 1.2 A and 8.82 W, while Zhao & Tan (2014) obtained an average and maximum COP of 0.8 and 1.22 respectively, for a PCM integrated TE AC, with a maximum cooling capacity of 210 W corresponding to the maximum COP value. Regarding TE cooling integrated façade concepts, COP values range between 0.5 and 1.8 for the reported experiences shown in Table 7.5. Considering these, it could be feasible to estimate a COP of 1.0-1.2 for performance assessment of building integrated TE cooling systems, although this value needs to be corroborated, taking into account the required cooling capacity of a designed system for a particular context.

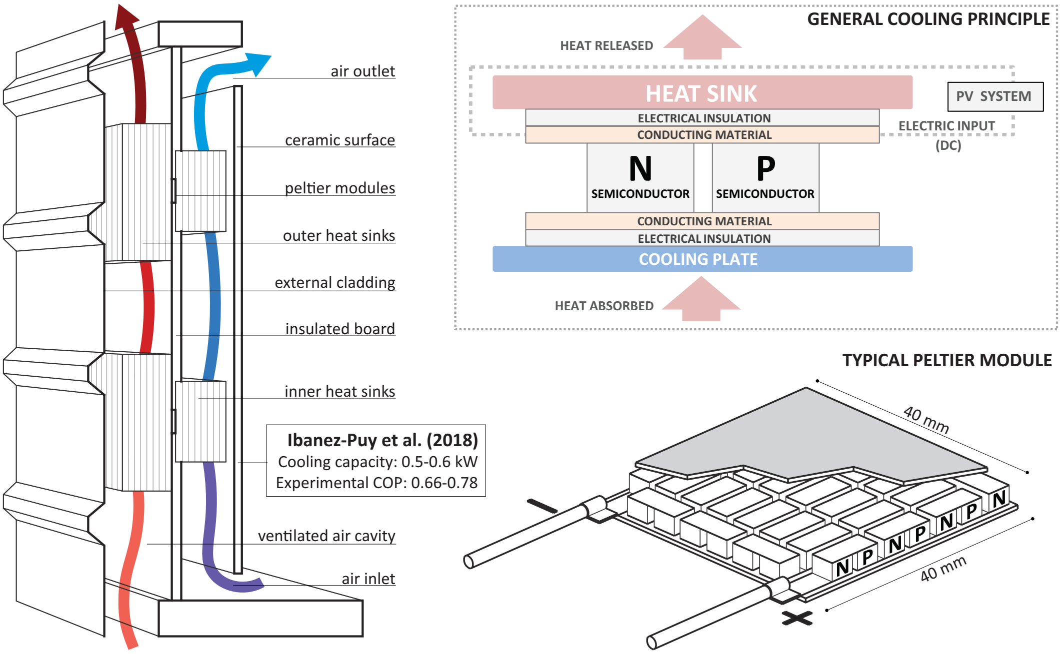
TABLE 7.5 Thermoelectric cooling integrated concepts reported in the review.

REFERENCES	DESCRIPTION
Liu et al. (2014, 2015)	PV coupled TE wall systems with COP values of 0.95 and 1.28 for tilted PV at 60° and 90° Calculated final COP of 0.74 for both after accounting for thermal losses in the system.
Luo et al. (2016, 2017, 2018)	Instantaneous COP values of 0.7-1.8 for an active building integrated PV panel coupled with a TE wall system in the back of the room.
Ibañez-Puy et al. (2013, 2014, 2015, 2018)	Experimental evaluation of a TE façade on a 1:1 test cell. Façade composed of 16 peltier cells of 51.4 W each, under variable voltage of 7.2 V and 12 V. Measured COP of 0.66-0.78
Vasquez et al. (2001); Arenas et al. (2008)	COP values of 0.56-2.06 through simulations of TE window unit with electrical currents of 6-1.5 A. COP values of 1.01-1.04 under 4 A for best balance COP/cooling power.
Xu et al. (2007, 2008a, 2008b)	Experimental COP of 0.51-1.42 for a single TE unit. Best COP values of 1.31-1.33, considering balance with cooling power, for 8 TE units connected in series and parallel under 5 V.
Le Pierrès et al. (2008)	Simulation and experimental evaluation of PV+TE modules for air pre-heating and pre-cooling in dwellings. Cooling COP was over 1 only for input currents lower than 3 A.
Khire et al. (2005)	Numerical calculations for different TE configurations. Best combination at COP of 1.529 for a TE active wall concept, with a cooling power of 30 W, under 1.393 A and 0.741 V.
Irshad et al. (2017)	TE air duct system coupled with a PV wall for the tropical climate, reporting a COP of 1.15, with a cooling capacity of 517.24 W under 6 A, and an optimal T° difference of 6.8 °C.

§ 7.3.1.2 Complexity of systems and components

Dimensions – size, volume and weight of systems and components

Thermoelectric technologies are conceived for small scale application, such as cooling of electronic equipment or spot AC. Common dimensions of TE modules are in the range of 40 x 40 mm, so they are highly suitable for assembly in a compact and modular package (Brown et al., 2010; Cheng et al., 2011; Zhao & Tan, 2014). Because of these characteristics, several authors have explored building application through prototype TE cooling façade concepts (Figure 7.2).



Ibanez-Puy et al. (2018)
Cooling capacity: 0.5-0.6 kW
Experimental COP: 0.66-0.78

FIGURE 7.2 Thermoelectric cooling façade prototype developed by Ibanez-Puy et al. and general thermoelectric cooling principle.

Components – number and types of required components

The core of a TE HVAC system basically consists of a PV panel, a Peltier module (Figure 7.2), a heatsink for heat rejection, and the connecting wires for electricity transfer. TE modules are powered by direct current, thus it is not necessary to consider an inverter as part of the system, providing a good match with PV panels (Allouhi, Kousksou, Jamil, Bruel, et al., 2015; Goetzler et al., 2014; Y. Luo et al., 2016; Shen et al., 2016). Additionally, heat rejection may be improved by the use of fans, and the system may be benefited by steady current input by means of integrating a battery for electricity storage, between the PV panel and the TE module (Cosnier et al., 2008; Xu et al., 2007).

Connections – types of required connections and materials involved

This technology does not consider moving parts nor working fluids in the core refrigerating machine (He et al., 2013; Y. Luo et al., 2016; Shen et al., 2013). Hence, the connections between the core components are solved with electrical wires. Furthermore, being a solid-state technology, cooling transmission is produced by direct contact between the cold side of the TE module and the transfer medium (air-water), or directly the indoor environment via a radiant panel/ceiling (Prieto et al., 2017a).

§ 7.3.1.3 Cooling system operation

Health, safety and comfort issues

Thermoelectric technology is ecologically clean, given that is refrigerant free. Because of that, its operation does not present particular hazards nor safety concerns (Cheng et al., 2011; Liu, Zhang, Gong, Li, et al., 2015; Shen et al., 2016).

Maintenance requirements

A basic TE system only requires basic electrical maintenance. Moving parts such as fans will require specific maintenance activities. However, the fact that currently there are not commercially available TE HVAC systems, means that these systems are not fully tested on the long-term. Furthermore, PV panels are commonly guaranteed for around 25 years, so life expectancy has to be considered in cost/performance analysis (VDMA, 2017).

§ 7.3.1.4 Level of development / maturity

Technical maturity

The thermoelectric principle was discovered in the early 1800s (Seeback and Peltier effect), and cooling technology driven by it has been explored since, for several applications such as medical and space equipment, electronics, and household devices such as portable refrigerators and camping gear. The principles are quite well understood and their use for small scale applications is well documented. Nonetheless, TE HVAC applications are still in early R&D development, with effort focused on improving the efficiency of several concepts by researching at material level through nanotechnology, or by enhancing the performance of auxiliary components of the system, such as heat rejection units, PV panels, or cooling delivery methods (Jeong, 2014; Riffat & Ma, 2004).

Market/commercial maturity

Currently there are not commercially available thermoelectrically driven HVAC systems for building application. Nevertheless, small scale cooling equipment, such as recirculating chillers, refrigerators, or spot air-conditioners are marketed by several companies, with cooling power up to 700 W (CustomChill, n.d.; Sheetak, n.d.; SScooling, n.d.). Besides commercialising these products, companies such as Phononic

TOC

(Phononic, n.d.) and Evident Thermoelectrics (Evident, n.d.) offer custom made scalable devices, and even distribute 'test kits' to encourage research and development of new applications for future market possibilities. This is seen as a promising fact, related to further development and commercial interest for TE technologies.

§ 7.3.2 Absorption cooling

§ 7.3.2.1 Performance of cooling systems and integrated concepts

General reported performance

The performance of absorption chillers has been extensively reported during the last couple of decades, with early developments ranging back to the late 70s and 80s (Bong, Ng, & Tay, 1987; Nakahara, Miyakawa, & Yamamoto, 1977). The decisive difference regarding the performance of available systems is the number of successive stages where regeneration of the working pair takes place, defining single-effect, double-effect and triple-effect absorption chillers. Common reference COP values are 0.6-0.7 (single); 1.1-1.3 (double); and 1.6-1.7 (triple) (Goetzler et al., 2014; Sarbu & Sebarchievici, 2013). Although double and triple effect chillers have markedly higher COP, their application considers higher complexity on systems and connections involved, and higher heat input as driver for the system (input temperatures over 130 °C, compared to 75-100 °C required for single-effect chillers) (Kohlenbach & Jakob, 2014). For these reasons, double and especially triple-effect chillers are constrained to large scale applications, leaving single-effect chillers for medium sized buildings and potentially decentral applications. Commercially available single-effect absorption chillers cover a wide range of cooling capacities, typically ranging from 4.5 to 20,500 kW, with reported COP from 0.5 to 0.8, depending on their working pair and sizes (Balaras et al., 2007; Jaehnig, 2009; KeepCool, 2005; SOLAIR, 2009). This review focuses on small scale applications, exploring possibilities for architectural integration. Hence, the mention of absorption chillers will only consider single-effect technologies from this point onwards.

Reported performance of small scale applications

Most commercially available chillers cover large scale requirements. Nonetheless, it is possible to find market-ready units with cooling capacities around 10-12 kW, with COP values between 0.62-0.77 (Solarcombi+, 2009; SolarNext, n.d.); and even a smaller

TOC

unit of 4.5 kW, commercialised until 2010 by Rotartica, with nominal COP of 0.67 and reported experimental COP values between 0.58 and 0.66 (Agyenim, Knight, & Rhodes, 2010; Ullah et al., 2013). Small size heat pumps have been consistently designed and prototyped in the last years. Said et al. (2012) tested an ammonia-water heat pump of 5 kW, reporting a COP of 0.6. Similarly, Franchini et al. (2015) designed a micro-scale chiller of 5 kW nominal cooling capacity. Experimental results showed 3.25 kW on average with a COP of 0.36. Besides considering smaller sizes, several researchers have explored concepts that integrate heat rejection into the cooling unit, hence devising air cooled absorption heat pumps, depicted in Table 7.6. Evidence seems to show that a COP of 0.6 would be a conservative estimate for the efficiency of a small scale unit, while a solar COP around 0.2-0.25 could be expected for collector integrated concepts. These values should potentially increase following further development of current prototypes.

TABLE 7.6 Absorption based integrated concepts reported in the review.

REFERENCES	DESCRIPTION
Castro et al. (2008)	COP values between 0.37 and 0.68 for a 2 kW LiBr-H_2O serpentine based heat pump design, to allow for air currents.
Lizarte et al. (2012)	Air-cooled heat pump of 4.5 kW, coupled with a flat-plate collector array (42.2 m^2) and a storage tank (1.5 m^3) in a 40 m^2 room in Madrid. Reported COP was of 0.55-0.62.
Izquierdo et al. (2012)	Mean daily COP of 1.05, by testing an air-cooled prototype of 7 kW (nominal) coupled with a flat-sheet absorber for solar input, in Madrid.
Hallstrom et al. (2014, 2015, 2016); Blackman et al. (2014)	Integrated LiCl-H_2O absorption system within vacuum tubes collector. Experimental solar COP values of 0.19-0.25 through outdoor tests in **rooftop application** in Sweden. Module operates in absorption-regeneration cycles based on solar availability.
Avesani et al. (2014, 2016); Bonato et al. (2016)	Integrated LiCl-H_2O absorption system within vacuum tubes collector for **façade application**. Simulated solar COP values of 0.27-0.36 and 0.17-0.23 in Stockholm and Rome, with cooling capacities of 1.44 kWh/day per module. Best results in east orientations, regenerating the solution during the morning and providing cold air during the afternoon (alternate operation in sorption/desorption).

§ 7.3.2.2 Complexity of systems and components

Dimensions – size, volume and weight of systems and components

Sizes of common small-scale commercially available chillers (4.5 kW-17.5 kW) range from 0.85 to 2.3 m^3, (Yazaki WFC-SC5, 17.5 kW and EAW Wegracal SE15, 15 kW), with length and depth as low as 80 x 60 cm and heights from 175 to 220 cm for that given area (Yazaki WFC-SC5 and SolarNext ACS08). Nominal weight of these units ranges from 290 Kg to 660 Kg (Rotartica, 2.5 kW; EAW Wegracal SE15). Smaller concepts have been explored as 'micro-scale heat pumps' (Franchini et al., 2015), with a 2.5 kW LiBr-H_2O heat pump developed and commercialised by Purix as the leading example (Purix, n.d.). This chiller unit measures (LxWxH) 64 x 45 x 135 cm (0.4 m^3) and weighs only 75 Kg, driven by a thermal collector array of 5 m^2, while using decoupled water-based cooling delivery systems in each room. This unit is regarded as a notable example of the sizing limits inherent to the principles in play.

In general, bulky sizes and weight are stated as important drawbacks of the technology, casting doubts about the feasibility and the rationale behind potential decentral applications. Nonetheless, the flexibility given by the use of liquid working materials has been also cited as an advantage for the development of compact units, compared to solid based adsorption technologies (Infante Ferreira & Kim, 2014; Montagnino, 2017). This characteristic has been greatly explored by a group of researchers for the design of an integrated sorption collector (Figure 7.3). This unit has been developed with compactness and simplicity in mind, being tested for rooftop application and even façade integration within an unitised curtain-wall ensemble (Avesani et al., 2014; Bonato et al., 2016). The dimensions of the optimised façade unit were 150 x 40 x 90 cm (0.54 m^3), as a fully air-based decentralised unit with all required mechanical components (Avesani, 2016), being a promising alternative for building integration and particularly retrofit applications.

Components – number and types of required components

Absorption chillers consist of a condenser and evaporator, like vapour compression systems, but with a heat driven generator and absorber instead of the electric compressor commonly used (Figure 7.3). This equipment is enclosed in a sealed unit with few moving parts, namely an integrated pump for the circulation of the solution in a closed loop (Goetzler et al., 2014). Besides the inner mechanisms and components, a heat rejection system is needed, as well as input heat from a solar array or a gas fired boiler. Heat/cold storage is optional, although it increases the capabilities and flexibility of the overall system. The common use of cooling towers as heat rejection system for absorption chillers has been cited as one of the disadvantages for their application on small scales (Aliane et al., 2016; Kohlenbach & Jakob, 2014; Montagnino, 2017). Consequently, air-cooled systems, with integrated heat rejection have been prototyped and tested by several researchers (Castro et al., 2008; Izquierdo et al., 2012; Weber, Berger et al., 2014), striving for simplicity and compactness. This line of research was pushed even more in the aforementioned sorption collector unit (Avesani et al., 2014; Bonato et al., 2016), where heat rejection, cooling generation and solar collector were integrated in a stand-alone ventilation unit for façade application. Even though heat storage is needed for continuous operation, this is regarded as the best available example of integrated modular design based on absorption technology.

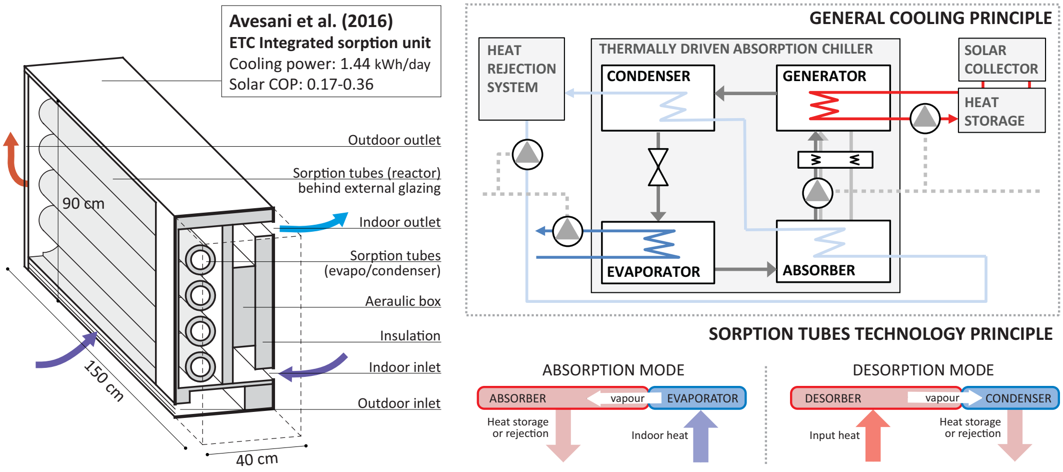


FIGURE 7.3 Integrated sorption collector & sorption tube technology developed by Avesani, Hallstrom et al., and general absorption cooling principle.

Connections – types of required connections and materials involved

Absorption chillers are factory sealed units, comprising necessary inner equipment and connections to input and output circuits. Common commercially available water-based chillers require connection to the heat source, heat rejection system and the cooling delivery system through pump driven water pipes. Nonetheless, air-based integrated designs have been prototyped and tested for stand-alone operation, only requiring electric input to power low consumption fans and dampers.

§ 7.3.2.3 Cooling system operation

Health, safety and comfort issues

Health hazards largely depend on the working fluids used to drive the absorption cycle. The most common absorbent/refrigerant pairs utilised are lithium bromide/water (LiBr/H_2O) and water/ammonia (H_2O/NH_3), respectively. Additionally, the use of lithium chloride (LiCl) has been explored as absorbent, with water as refrigerant; but its use is still limited in current experiences (SaltX, n.d.). All fluids are environmentally friendly, but have certain drawbacks. Ammonia is toxic in high concentrations, causing immediate irritation in eyes and the respiratory track (Bolocan et al., 2015; Sarbu & Sebarchievici, 2013). Lithium bromide and lithium chloride have low toxicity, but they are corrosive materials, so proper maintenance must be conducted to ensure correct operation of the system.

TOC

Regarding general comfort, silent operation has been regarded as an advantage compared to conventional systems, solely depending on pumps to recirculate the solution (Allouhi, Kousksou, Jamil, Bruel, et al., 2015; Montagnino, 2017).

Maintenance requirements

Absorption chillers have minimal moving parts, so maintenance activities are focused on handling their working fluids to allow for correct operation. This may imply complicated maintenance activities to meet optimal operation requirements. One of the main concerns associated with absorption chillers is the risk of crystallisation of lithium bromide by temperature differentials, which may cause irreparable damage (Baniyounes, Ghadi, et al., 2013; Soussi et al., 2017; Ullah et al., 2013). Hence, measures must be taken to mitigate the risk and prevent this from happening. Additionally, leakages must be checked periodically to prevent health hazards, and avoid corrosion, as mentioned before. In this sense, an added difficulty is that absorption chillers' operation relies on having internal vacuum conditions, which need to be maintained over time, to avoid continuous air leakage into the system that induces corrosion by reacting with the working fluids (Baniyounes, Ghadi, et al., 2013; Bolocan et al., 2015).

§ 7.3.2.4 Level of development / maturity

Technical maturity

Absorption cooling is regarded as a mature technology with high reliability; being one of the oldest refrigeration technologies registered (Baniyounes, Ghadi, et al., 2013; Eicker, Pietruschka, et al., 2014; Franchini et al., 2015). First experiences in the field go as far back as the 1700s, with water/ammonia chillers first designed by Ferdinand Carré in 1859 (Aliane et al., 2016; Sarbu & Sebarchievici, 2013). Lithium bromide/water chillers have been around since mid-1900s, with a first commercial absorption chiller developed by Carrier in 1945 (Kalogirou, 2013). The expected performance of the refrigeration cycle has reached stable and optimised values under single, double and triple effect operation, so its use is justified in large applications when waste heat is available. Hence, current challenges for absorption cooling are directed to allow for widespread application, simplifying the operation of centralised units, while exploring alternatives for small scale decentral application. On the one hand, new working pairs are being tested, such as lithium chloride / water units, to reach good performances without the risk of crystallisation (Preisler et al., 2012). On the other hand, new simpler designs are being explored based on proven working principles, reducing sizes and weight of units to lower initial costs. Current examples also consider an integrated and multifunctional approach, striving for direct heat rejection and less connections and overall complexity (Baniyounes, Ghadi, et al., 2013; Preisler et al., 2012).

Market/commercial maturity

As mentioned, absorption chillers have been commercialised since the 1940s. Several researchers have estimated that there are currently between 1,000 and 1,200 solar assisted cooling units installed worldwide (Henning & Döll, 2012; Montagnino, 2017), with absorption chillers accounting for about 80% of the total (Allouhi, Kousksou, Jamil, Bruel, et al., 2015). It has also been reported that Asian markets have around 85% of the stock of absorption chillers with capacities over 350 kW, being by far the largest regional market followed by Europe (Brown & Domanski, 2014). Consequently, the market for large scale systems, ranging from 100s to 1,000s kW is dominated by Asian companies (Broad, n.d.; Hitachi, n.d.; Yazaki, n.d.); followed by large American corporations with vast experience in refrigeration (Carrier, n.d.; Trane, n.d.; York, n.d.). In recent years, several European companies have been exploring the development of small scale units for light commercial and residential application, either providing small size chillers (MultiChill, n.d.), comprehensive solar kits (Purix, n.d.; SolarNext, n.d.), or integrated designs striving for efficiency (SaltX, n.d.). Evidence seems to point out that small size absorption is a developing niche, so further products should follow in the coming years.

§ 7.3.3 Adsorption cooling

§ 7.3.3.1 Performance of cooling systems and integrated concepts

General reported performance

The performance of commercially available adsorption systems has been well documented by several researchers during the last 15 years, with small changing COP values from 0.5 to 0.7, and cooling capacities commonly ranging from 5.5 to 1,000 kW (Balaras et al., 2007; ClimaSol, 2002; KeepCool, 2005; Kohlenbach & Jakob, 2014). The performance mainly depends on the heat and mass transfer potential of the utilised adsorbent. Possible working pairs of adsorbent/adsorbate are activated carbon / methanol, ethanol or ammonia; zeolites / ethanol or water; or silica gel / water. The latter has been found to be the most efficient combination for AC applications (Allouhi, Kousksou, Jamil, El Rhafiki, et al., 2015), although its performance is still limited to be

TOC

a competitive alternative against vapour compression technologies (El Fadar, 2016). In terms of the adsorption process, the fact that basic operation is intermittent, constrained to adsorption/desorption cycles, is often cited as a disadvantage (Bataineh & Taamneh, 2016; El Fadar, 2016; Khattab, Sharawy, & Helmy, 2012). This is overcome by using two adsorption beds, alternating them for continuous operation, but of course this increases the size of the system. Other factors that have an impact on the performance of adsorption systems are the length of the absorption/desorption cycle, temperature of hot water from the solar source, and the use of heat/cold storage units. It has been found that longer cycles, allow for larger COP values, with optimum lengths of 10-15 min (Bakker & de Boer, 2010; Habib, Saha, & Koyama, 2014). Similarly, COP has been reported to increase with higher inlet temperatures (Alahmer et al., 2016) and when hot storage is considered (El-Sharkawy, AbdelMeguid, & Saha, 2014; El Fadar, 2016).

Reported performance of small scale applications

Common commercial applications consider large chiller units, up to 1,000 kW. Nonetheless, in the last years, researchers have been increasingly interested in the development of small scale adsorption units, mostly thinking about the residential market (Jaehnig, 2009). Examples of small capacity commercially available systems are InvenSor LTC10e, and SorTech ACS08, with nominal power of 10 kW and 8 kW and nominal COP values of 0.7 and 0.6 respectively (InvenSor, n.d.; Jakob & Mittelbach, 2008). The latter has been tested and monitored in different European countries as part of an standardised assembly, within the SolCoolSys project, measuring COP values between 0.4 and 0.5 (Weber, Mehling, et al., 2014). Smaller units have been explored using different methods by several researchers, as shown in Table 7.7. Based on the presented examples, it would be possible to expect a COP of 0.4-0.5 for adsorption units below 5 kW.

§ 7.3.3.2 Complexity of systems and components

Dimensions – size, volume and weight of systems and components

One of the main disadvantages of adsorption units usually mentioned in the literature, is their large sizes and weight compared to their cooling capacity (Baniyounes, Ghadi, et al., 2013; Bataineh & Taamneh, 2016; El Fadar, 2016). The smallest commercially available chillers (SorTech ACS08, 8 kW nominal cooling power) are 79 x 106 x 94 cm (LxWxH) with a weight without water of 265 Kg (Jakob & Mittelbach, 2008). Smaller prototypes have been developed, reaching dimensions of 60 x 60 x 100 cm (LxWxH) for a 2.5 kW chiller under the EU project PolySmart (Bakker & de Boer, 2010) (Figure 7.4). Moreover, small sizes able to fit in the back of a car, have been developed for demonstration purposes of automobile AC applications, reaching a weight without water of 86 Kg (De Boer, Smeding, & Mola, 2009). Another explored alternative to decrease sizes has been the integration of adsorption systems and solar thermal collectors, to develop so-called adsorption tubes (Chekirou, Boukheit, & Karaali, 2016; Islam & Morimoto, 2016; Khattab et al., 2012). Nonetheless, these experiences are in early R&D stages.

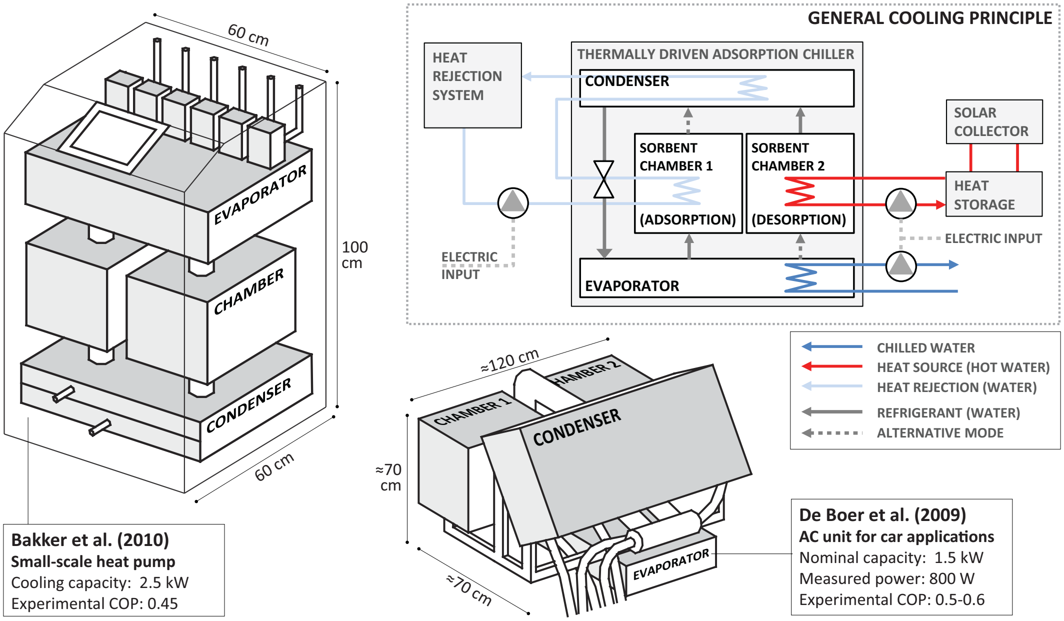
TABLE 7.7 Small-scale adsorption based concepts reported in the review.

REFERENCES	DESCRIPTION
Clausse et al. (2008)	Model to simulate the performance of a 4.6 kW activated carbon/methanol chiller for residential application in Orly, France, obtaining COP values between 0.12 and 0.6 and an average COP of 0.49.
de Lieto et al. (2014)	Simulation of a 2 kW silica gel/water chiller in Rio de Janeiro. COP values of 0.43-0.58 using 20 m^2 of solar thermal collectors, which were found to be enough to provide the necessary input.
Luo et al. (2010)	Design and construction of a silica gel/water chiller powered by 49.4 m^2 of evacuated tubes collectors. Experimental results of max. cooling power of 4.96 kW and a peak average COP of 0.324.
Lu et al. (2013)	Experimental assessment of a silica gel/water prototype, reporting a cooling power of 4.9 and 5.7 kW, with COP values of 0.42 and 0.41, respectively.
Bakker et al. (2010) Sjipheer et al. (2010)	Small scale 2.5 kW adsorption heat pump for residential application. Experimental reports of cooling power of nearly 2.5 kW and COP = 0.45 for a 10 min operating cycle. Performance also monitored in a real house, reporting a decrease of 25-30% of cooling power compared to lab results (EU Project PolySmart).
De Boer et al. (2009) Verde (2015)	1.5 kW silica gel/water adsorption AC unit for car applications, driven by waste heat from the engine. Monitoring results on a Fiat Grande Punto showed a cooling power of 800 W and COP of 0.5-0.6; in contrast to lab results of 2 kW and 0.4 respectively.

Components – number and types of required components

A basic solar driven adsorption cooling system needs the adsorption unit, a solar collector, a heat rejection system, and an hydronic system for water circulation, with small pumps to control the flow. Additionally, the use of hot and/or cold storage units could be beneficial to increase the efficiency of the system and achieve higher cooling capacities at the beginning and end of the adsorption/desorption cycle (El-Sharkawy et al., 2014). Furthermore, it is necessary to consider a cooling delivery system, such as fan-coils or water based radiative cooling devices such as chilled ceilings or beams (Prieto et al., 2017a).

TOC



Bakker et al. (2010)
Small-scale heat pump
Cooling capacity: 2.5 kW
Experimental COP: 0.45

De Boer et al. (2009)
AC unit for car applications
Nominal capacity: 1.5 kW
Measured power: 800 W
Experimental COP: 0.5-0.6

FIGURE 7.4 Small-scale heat pump and AC unit for car application developed by Bakker et al. and De Boer et al.; and adsorption cooling principle.

Connections – types of required connections and materials involved

Commercially available adsorption units are factory sealed, so they only require connection to the heat rejection system, the heat source (solar thermal collector), and the cooling delivery system. Connections are made through pipes, in closed water circuits driven by pumps (heat rejection, driving heat, and chiller water circuits). The main issue then, is preventing leakages throughout the whole system.

§ 7.3.3.3 Cooling system operation

Health, safety and comfort issues

Health and safety hazards related to adsorption technology highly depend on the materials used as working pairs. Although all adsorption units are sealed, there could be a risk of contamination through leakages. Direct exposure to ammonia mixed with indoor air could cause problems in the respiratory track, while methanol is regarded as a toxic and highly flammable material (Allouhi, Kousksou, Jamil, El Rhafiki, et al., 2015; NIOSH, n.d.). Nevertheless, the most common working pair used in adsorption chillers is the combination of silica gel and water, which does not consider any hazard risk to building occupants, being both non-toxic and non-flammable (Goetzler et al., 2014). Moreover, the fact that silica gel/water adsorption chillers are based on an environmentally friendly process, is usually cited as one of the main advantages of adsorption systems (Choudhury et al., 2013; Mahesh, 2017; Rouf, Alam, & Khan, 2015; Rouf et al., 2014). Regarding other comfort issues, the fact that no moving parts are involved mean that noise levels are lower than conventional cooling systems (Bataineh & Taamneh, 2016; El Fadar, 2016; Habib et al., 2014).

Maintenance requirements

Adsorption units are factory sealed and consider no moving parts (Habib et al., 2014; Yeo et al., 2012). Additionally, there is no risk of crystallisation nor internal corrosion in inner components (Alahmer et al., 2016; Bataineh & Taamneh, 2016; Choudhury et al., 2013), so the basic refrigeration machine is regarded as virtually maintenance free. Nonetheless, water pipe connections from and to the adsorption unit must be checked to prevent leakages, while small pumps needed for water circulation would need basic maintenance to allow for continuous operation.

§ 7.3.3.4 Level of development / maturity

Technical maturity

Overall, adsorption chillers are a mature technology, with several decades of research development. First adsorption based refrigerating systems appeared in USA around 1920, while solar driven experiences have been reported since the late 70s (Choudhury et al., 2013). Since then, research has been focused on improving the performance of the units, experimenting with different working pairs of adsorbent/adsorbate; and lately, on decreasing the size of systems to allow for easier application in residential buildings. Given that the performance heavily relies on the working pairs within the process itself, it is difficult to think that there will be an increase of COP values, having been optimised up to this point. Hence, future challenges will keep focusing on decreasing sizes and weight, and achieving shorter cycle times to allow for a greater array of applications.

Market/commercial maturity

Adsorption chillers represent the second largest market for solar cooling, after absorption chillers. Until 2014, 1,200 solar cooling installations had been reported worldwide, mostly located in Europe (Montagnino, 2017). Out of this total, 10-11% are reported to

TOC

be adsorption based technologies with cooling capacities ranging from 8 to 1,000 kW (Alahmer et al., 2016; Reda et al., 2016). Among well-known companies commercialising adsorption chillers, are InvenSor and Fahrenheit (formerly known as SorTech). The former distributes zeolites/water adsorption chillers in the 10-105 kW range (InvenSor, n.d.), while the latter commercialises silica gel/water and zeolites/water chillers from 8 to 50 kW, as a spinoff of Fraunhofer Institute for Solar Energy (ISE) (Fahrenheit, n.d.). It is stated in both websites that zeolites/water chillers are the next generation (eZea was the first one to be commercialised in 2015, by Fahrenheit), being relatively smaller and lighter than conventional silica gel/water units.

§ 7.3.4 Solid desiccant cooling

§ 7.3.4.1 Performance of cooling systems and integrated concepts

General reported performance

Widespread general assessments of solid DEC technology give it COP values between 0.5 and 1.0, with cooling capacities ranging from 6 to 350 kW (ClimaSol, 2002; Jani, Mishra, & Sahoo, 2016; KeepCool, 2005; Kohlenbach & Jakob, 2014; La et al., 2010; SOLAIR, 2009). These values come mostly from several monitoring campaigns carried out over the last 20 years on demonstration projects throughout Europe. Thus, solar driven DEC pilot experiences have been designed and evaluated in Germany (ClimaSol, 2002; Henning et al., 2001; SOLAIR, 2009), Austria (ClimaSol, 2002; Selke et al., 2016; SOLAIR, 2009), Spain (Eicker et al., 2010; SOLAIR, 2009), Portugal (ClimaSol, 2002) and Greece (SOLAIR, 2009); with cooling capacities from 18 kW to 75 kW and thermal COP values ranging from 0.43 to 0.86. Additionally, the potential to reach higher COP values under optimised system configurations has been simulated and experimentally tested. Ge et al. (2010) obtained a COP of 1.28 for a 101 kW 2-stage silica gel rotary DEC for a complete floor in Shanghai, with 680 m^2 of vacuum tube collectors. Similarly, Fong et al. (2010b) reported a COP of 1.38 for a solid DEC system driven by 100 m^2 flat-plate air collectors. Besides the configuration of the system, performance of the cooling cycle relies on the materials. Commonly used silica gel and zeolites have lower sorption capacity than liquid desiccants, so research efforts are focused on advanced materials by combination of silica gel with other salts. Jia et al. (2007) experimentally obtained a COP of 1.28 by employing compound desiccants, improving the performance of a silica gel based DEC system by 20-30%; providing evidence of further potential on this field.

TOC

Reported performance of small scale applications

Smaller cooling capacities have been explored in an effort to promote the development of compact units targeting new application niches, depicted in Table 7.8. Besides these, some of the most relevant experiences in the development of small-scale DEC systems for building integration have been the results and prototypes developed by SolarInvent under their FREESCOO patent (SolarInvent, n.d.). Working prototypes for a rooftop unit have been installed and monitored in Palermo (2.7 kW) and Rome (5.5 kW), obtaining daily thermal COP values of 1.1 and 1.36 (Finocchiaro, Beccali, Brano, & Gentile, 2016; Finocchiaro et al., 2015; Finocchiaro, Beccali, & Gentile, 2016). As a logical next step, the developers are currently working on the design of façade units, with decoupled solar regeneration modules on the roof (circulating hot water to regenerate the packed-bed desiccant material). These have not been tested on the field yet, but preliminary evaluation shows nominal thermal COP values around 1.25, for maximum cooling power of 2.5 kW (SolarInvent, n.d.).

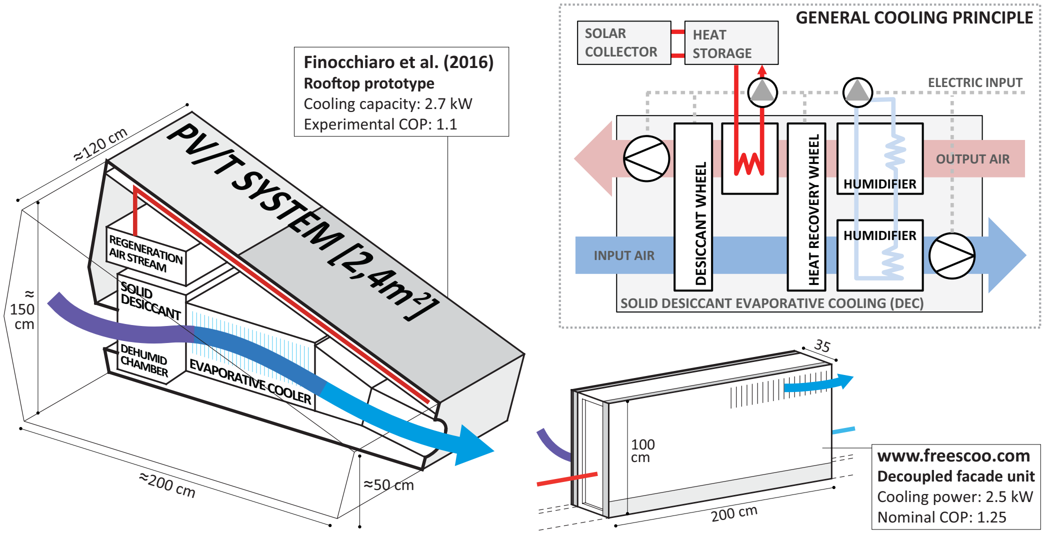
§ 7.3.4.2 Complexity of systems and components

Dimensions – size, volume and weight of systems and components

One of the main drawbacks of solid desiccant evaporative cooling systems (solid DEC) is their dimensions, being larger in size than other solar cooling technologies, especially considering relative dimensions per cooling capacity (Goetzler et al., 2014). Commercially available DEC systems may occupy an entire room, with dimensions (LxWxH) starting from 500 x 160 x 180 cm and weight of 1,600 Kg (DesiCool® 2.2 unit, (Munters, n.d.-a)). This is due to the different stages needed for air treatment and the accompanying equipment, and particularly due to the use of desiccant wheels as common carrier method. A noteworthy effort in size reduction was conducted by Finocchiaro et al. (2015) in the design of their FREESCOO system. The compact rooftop prototype developed in Palermo considered 2.4 m^2 of PVT surface, and occupied a volume of about 2.5 m^3, considering a floor area of 200 x 120 cm (LxW) and a maximum and minimum height of about 150 and 50 cm respectively (Figure 7.5). While these dimensions are still considerable, they imply a reduction of over 80% of the total volume compared to a currently commercially available DEC unit, even considering integrated equipment for desiccant regeneration. Additionally, the developers are currently exploring potentially smaller sizes for façade integration. The dimensions of concepts for façade units (without equipment for solar input) are 200 x 35 x 100 cm (LxWxH), being regarded as a promising alternative for building integration in the coming years (SolarInvent, n.d.).

TABLE 7.8 Small-scale solid desiccant based concepts reported in the review.

REFERENCES	DESCRIPTION
Goldsworthy & White (2011)	Mathematical model for a DEC system, obtaining COP values of 0.2-0.7, where 0.4 was found to be the optimal value to achieve a balance with the system's cooling capacity of about 1.5 kW.
Wang et al. (2016)	COP values of 0.46-0.49 obtained from the experimental evaluation of a novel self-cooled solid desiccant coated heat exchanger in Shanghai, with cooling capacities below 714 W.
Kabeel (2007)	CaCl based DEC system coupled to a porous type solar air heater of 1.2 m^2 in Egypt, achieving cooling capacities of 0.8-1.0 kW and COP values from 0.65 to 0.9.
Ge at al. (2008, 2009)	Design and evaluation of a 5 kW 2-stage DEC using silica gel-LiCl composite desiccant and a flat-plate air collector array of 15 m^2, reporting COP values over 1.0.
Alahmer (2016)	Numerically assessment of a DEC system for car application: rotary desiccant dehumidifier, compact heat exchanger and evaporative cooler, with regeneration heat from the engine. Cooling capacity of 4.2 kW with thermal COP of 0.7-0.9.
Finocchiaro et al. (2015, 2016)	Prototype for integrated DEC + thermal collector unit. 2.7 kW unit monitored in Palermo with a daily thermal COP of 1.1. An 5.5 kW unit monitored in Rome, with daily thermal COP of 1.36.



Finocchiaro et al. (2016)
Rooftop prototype
Cooling capacity: 2.7 kW
Experimental COP: 1.1

www.freescoo.com
Decoupled facade unit
Cooling power: 2.5 kW
Nominal COP: 1.25

FIGURE 7.5 Compact solid-desiccant prototypes developed by SolarInvent, for rooftop and façade applications; and general cooling principle.

TOC

Components – number and types of required components

Solar driven solid desiccant cooling systems basically consist of desiccant assisted evaporative coolers as air handling units, comprising a small number of simple and robust components (Elmer et al., 2016; Enteria & Mizutani, 2011; Goldsworthy & White, 2011). Incoming air gets in contact with the desiccant, commonly placed in a slowly rotating wheel (although it could also be stored in adsorbent beds). After dehumidification, the air is cooled down by means of an evaporative cooler (direct or indirect), to then be delivered to the room. Exhaust air gets in contact with heat from the regenerator (solar thermal collectors with optional heat storage), and then passes through the desiccant wheel again on its way out, evaporating the previously absorbed water. Fans are required to drive in and out air streams through separate ducts, while pumps are required to circulate water in the regeneration and evaporative cooling loops. Additional components commonly used are heat exchangers for heat recovery between incoming and outgoing streams and cooling towers for heat rejection.

Connections – types of required connections and materials involved

The main connections needed for the operation of the system are between the heat source and the desiccant machine. If heat is supplied by water based solar collectors, this would mean pipes in closed water circuits driven by pumps. Alternatively, an air-based flat plate may be used, directly mixing warm air from the collector with the outgoing air stream for the regeneration of the desiccant, throughout air ducts. Accordingly, the system instalment has been judged as slightly complicated (Goetzler et al., 2014; Mujahid et al., 2015). Additionally, a water source and pipes are needed for the evaporative cooler, besides electric input for auxiliary equipment such as fans, pumps and the desiccant wheel rotor (Goldsworthy & White, 2011).

§ 7.3.4.3 Cooling system operation

Health, safety and comfort issues

The use of desiccants to cope with latent loads potentially leads to better indoor air quality when compared to common AC technologies, especially in hot-humid climates. Vapour compression systems cool down the incoming air below dew point, to drop humidity levels, to then reheat it to desired temperatures. This process considers condensation, which creates a suitable environment for microorganisms and mold within the system, which are avoided under desiccant operation (Angrisani, Minichiello, & Sasso, 2016). Additionally, common materials such as silica gel and zeolites are non-

TOC

toxic and non-flammable, working under an entirely environmentally friendly process (Goldsworthy & White, 2011; Sahlot & Riffat, 2016).

Maintenance requirements

Solid desiccant systems consist of simple and robust components, and non-corrosive working materials (Daou, Wang, & Xia, 2006; Elmer et al., 2016). Because of this, they are easy to clean and maintain in their simplest forms. Furthermore, the fact that solid desiccant units operate at almost atmospheric conditions (there is no need to maintain vacuum), helps keeping maintenance costs low (Mujahid et al., 2015). Nevertheless, their operation in combination with evaporative coolers, to handle sensible loads, increases the complexity of the entire system, adding water connections that need to be checked for leakages from time to time (Goetzler et al., 2014).

§ 7.3.4.4 Level of development / maturity

Technical maturity

Desiccant AC using a rotary wheel has been explored for over 50 years, with the first patent being introduced by Pennington in 1955 (La et al., 2010). Currently, solid desiccant dehumidification is a mature technology, used for moisture control in large industrial sites; while evaporative cooling is regarded as the oldest cooling technique (Daou et al., 2006). However, their combined use was not fully explored until the turn of the century, promoted by the potential to use low-grade heat (and particularly solar energy) as the driver of a refrigerant-free cooling process. Today, solid desiccant cooling installations mount up to around 7% of all solar driven cooling systems installed worldwide, being third in numbers behind absorption and adsorption chillers (Allouhi, Kousksou, Jamil, Bruel, et al., 2015). These experiences mostly consist of pilot and demonstration projects carried out by researchers with private or governmental funding to promote these systems and overcome present boundaries for mass-application (SOLAIR, 2009). Current development efforts are focused on performance issues, researching new advanced desiccant materials and optimising the configuration of the overall system; while striving for smaller and compact units for new markets (La et al., 2010).

Market/commercial maturity

Solid desiccant components such as rotary wheels have been commercialised since the 1980s, experiencing an important increase in the last decades (Goetzler et al., 2014;

TOC

La et al., 2010). Certain companies have specialised on desiccant rotors (ProFlute, n.d.; RotorSource, n.d.), while companies such as DehuTech and big corporations like Munters (DehuTech, n.d.; Munters, n.d.-b) have achieved large experience on both solid desiccant air dehumidification units, and evaporative coolers. This combined expertise has resulted on the development and commercialisation of solid desiccant AC units, such as DehuTech's DS units and Munters' DesiCool® units, but solar thermal has not been fully explored yet for market introduction under integrated systems. Nonetheless, the FREESCOO system is being further developed for market release by SolarInvent, a start-up company created in 2014 explicitly with that goal in mind, offering customised units for specific applications for the time being (SolarInvent, n.d.).

§ 7.3.5 Liquid desiccant cooling

§ 7.3.5.1 Performance of cooling systems and integrated concepts

General reported performance

Although LDAC systems are relatively new compared to other solar cooling principles and technologies, the general assessment is that they may reach higher potential efficiencies in comparison, backed by several research projects and standalone experiences. Different overviews on the state of the technology over the last 15 years have shown COP values circling 1.0, with the potential to go higher (ClimaSol, 2002; Kohlenbach & Jakob, 2014; SOLAIR, 2009). Standalone experiences have been designed and tested, with cooling capacities ranging from 0.3 kW (Chen, Zhu, & Bai, 2017; Chen, Zhu, Bai, Yan, & Zhang, 2017) to around 25 kW (Abdel-Salam, Ge, & Simonson, 2014; Hellmann & Grossman, 1995), besides demonstration projects of 11-30 kW monitored on existing buildings (Crofoot & Harrison, 2012; Gommed & Grossman, 2007; SOLAIR, 2009), with registered COP values between 0.47 and 0.8 under real operating conditions. The efficiency of a LDAC system mainly relies on the dehumidification capacity of the desiccant material and its application, and the cooling performance of the evaporative cooler. Hence, current efforts deal with the optimisation of each sub-system separately, testing new materials and performance-based designs; while at the same time exploring integration potential between them striving for compact units for mass-market production.

TOC

Reported performance of small scale applications

Most experiences on LDAC systems have focused on small capacity ranges (below 30 kW), benefiting on potentially compact units for residential application. Relevant examples are shown in Table 7.9. Thermal COP values around 0.7 seem to be consistent among small systems, especially on those below 6 kW, with potential for building integration. At the same time, maximum COP values around 1.2 were found, which evidences that there is room for future improvements in the performance of small scale units.

TABLE 7.9 Small-scale liquid desiccant based concepts reported in the review.

REFERENCES	DESCRIPTION
Kozubal et al. (2011)	Simulation of a desiccant enhanced evaporative cooler in several cities in USA, with cooling capacities of 3.5-14 kW. Estimated cooling energy savings up to 61% compared to common VC technologies.
Zhang et al. (2017)	Experimental assessment of a LD unit + 2-stage evaporation cooling system, with cooling capacities from 6 to 12 kW. Measured COP values were 0.4-0.6, with an average of 0.56.
Jain et al. (2011)	Experimental evaluation of an indirect contact LDAC system in tropical climates, obtaining COP values of 0.4-0.8 for cooling capacities between 2.5 and 5.5 kW.
Das & Jain (2017)	1.7-5.5 kW LDAC dedicated outdoor air system including a 12.5m^2 ETC array as input for the regeneration. COP values of 0.25-0.83 were experimentally obtained.
Buker et al. (2015)	Experimental thermal COP of 0.73 for a 5.2 kW membrane based LDAC with an indirect evaporative cooler and a BIPVT for regeneration and electricity generation.
Chen et al. (2017)	Experimental thermal COP of 0.7 for a membrane based LDAC based on modular units for dehumidification and regeneration. Solution concentration of 36% $CaCl_2$ was found to be optimal in the 0.34-0.43 kW system
Elmer et al. (2016)	Novel integrated membrane based LDAC system. Average COP values of 0.72 were experimentally obtained for the 0.57-1.36 kW system, using $CHKO_2$ as desiccant material. Maximum reported COP around 1.2.

§ 7.3.5.2 Complexity of systems and components

Dimensions – size, volume and weight of systems and components

One of the most reported advantages of LDAC systems is the potentially small and compact sizes that they may reach, being based on a liquid and easy to handle solution (Daou et al., 2006; Shukla & Modi, 2017). Current efforts have focused on designing compact systems to explore new markets such as residential air-conditioning. Buker et al. (2015) and Das & Jain (2017) evaluated the performance of small scale LDAC systems (around 5 kW of cooling capacity), considering dehumidifier units of 90 x 50 x 130 cm and 30 x 60 x 80 cm respectively. Even smaller units were designed and tested by Chen et al. (2017) and Elmer et al. (2016), with integration potential in mind. The former designed a membrane based LDAC, comprised of highly compact modules for regeneration and dehumidification of 41 x 23 x 21 cm each. Elmer et al. designed an integrated system, combining a regenerator, dehumidifier and evaporative intercooler into a single membrane based heat and mass exchanger (Figure 7.6). The entire unit dimensions were 100 x 42 x 24 cm plus split desiccant and water tanks and small pumps (Elmer et al., 2016). Similarly, Kozubal et al. (2011) developed and evaluated a membrane based desiccant indirect evaporative system, within a sealed packaged unit of 60 x 50 x 48 cm to cover a cooling demand of around 3.5 kW.

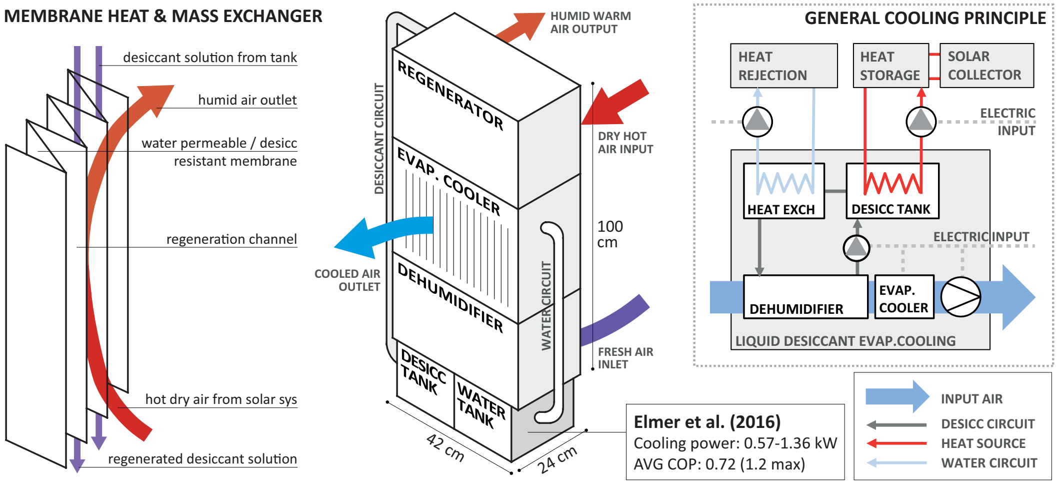


FIGURE 7.6 Integrated small-scale membrane based LDAC unit developed by Elmer et al. and liquid desiccant general cooling principle

Components – number and types of required components

Basically, a solar driven liquid desiccant cooling system consists of three main parts: the dehumidifier, the regenerator, and the sensible cooling machine, commonly an evaporative cooler. The dehumidifier is where intake air gets in contact with the desiccant, either directly (applied in packed beds, spray tower, or falling film), or indirectly (membrane based exchangers). It considers a storage tank for the desiccant solution, and the contact medium within a dehumidification chamber. The regenerator consists of a solar thermal collector array to collect heat to be used to regenerate the desiccant. The regeneration may take place in a regeneration chamber where stored

TOC

heat is applied to the solution, or the desiccant itself may pass through the collector via permeable pipes. Thermal storage units are advised under the former operation mode. Lastly, evaporative cooling may be direct or indirect, adding moisture to the incoming air or not, respectively. This considers the need for a water tank and a pump, increasing the complexity of LDAC systems (Abdel-Salam & Simonson, 2016), thus the design of simple and compact evaporative coolers is an essential aspect in the promotion of LDAC systems.

Connections – types of required connections and materials involved

A common arrangement for LDAC systems requires two independent circuits of circulating liquid: the first carries the desiccant solution and goes from the dehumidifier to the regenerator and back; while the second carries water for the evaporation cooler. An hydronic system and pumps are needed, besides storage tanks for the desiccant and water (Prieto et al., 2017a). These circuits come in contact sequentially with the incoming air flow, which needs to be carried inside through vents and ducts, driven by fans. Electricity is needed to power these components, causing parasitic loads of varying importance depending on the specific design. Among relevant new developments aimed to simplify these systems, natural convection driven units and photovoltaic electrodyalisis stand out. The former benefit by the concentration gradient of the solution to generate free motion of the desiccant without pumps (Fazilati, Alemrajabi, & Sedaghat, 2017); while photovoltaic electrodyalisis (PV-ED), uses PV panels instead of thermal collectors for desiccant regeneration by transporting ions through selective membranes under the influence of an electrical field (Buker & Riffat, 2015; Q. Cheng & Zhang, 2013). Nonetheless, these technologies are still in early development stages.

§ 7.3.5.3 Cooling system operation

Health, safety and comfort issues

The use of desiccants directly improves indoor air quality in humid environments, by avoiding overcooling to cope with latent loads. Condensation derived by lowering ambient temperature below dew-point creates an environment suitable for mold and bacteria, present when using common compressor based HVAC technologies (Angrisani et al., 2016). Additionally, liquid desiccant materials exhibit the capacity of absorbing pollutants and bacteria present in the incoming air (Goetzler et al., 2014; Sahlot & Riffat, 2016). On the other hand, one of the main concerns regarding the use of desiccants is the risk of material carry-over with the supply air stream, being an open cycle air treatment system (Daou et al., 2006; McNevin & Harrison, 2017; Mujahid et al., 2017). Liquid desiccants have reported low-toxicity, but may still be a source for discomfort and a hazard in high concentrations. Nonetheless, this issue has been solved in latter experiences, by using semi-permeable membranes as contact barrier between desiccants and inlet air, allowing heat and moisture transfer but preventing transfer of the desiccant material, in liquid-to-air membrane heat exchangers (Abdel-Salam et al., 2014; Chen, Zhu, Bai, et al., 2017).

Maintenance requirements

The most common liquid desiccant materials currently available are aqueous halide salts, which have strong dehumidification capabilities but are highly corrosive (Baniyounes, Liu, et al., 2013; Sahlot & Riffat, 2016). Hence, periodical maintenance is mandatory to assess possibly damage in the system due to filtration or material carry-over through the air flow. Among these salts, lithium chloride (LiCl) has low vapour pressure and more stability, while the regeneration performance of lithium bromide (LiBr) is better, and calcium chloride ($CaCl_2$) has less absorption ability but is cheaper and easily available. Additionally, these salts are subject to crystallisation at higher concentrations, which needs to be checked (Abdel-Salam & Simonson, 2016; Goetzler et al., 2014). Alternatively, there are current explorations of salts of weak organic acids such as potassium formate (HCOOK/$CHKO_2$) and sodium formate (HCOONa), which have low toxicity and are not corrosive, but have less absorption capacity, so higher concentrations are needed (50% of $CHKO_2$ solution concentration roughly equals the performance of 27% of LiCl) (Elmer et al., 2016). In any case, these latter materials are not fully explored so there is room for new developments in the coming years.

§ 7.3.5.4 Level of development / maturity

Technical maturity

Solar driven liquid desiccant systems for space cooling are still in early R&D stages, with different levels of development depending on particular applications. First experimental studies on LD systems go back to the 1950s (Lof, 1955), but interest on these materials and technologies really sparked in the mid-90s conducing to an increasing number of experiences over the last 20 years (Hellmann & Grossman, 1995; Lowenstein, Slayzak, & Kozubal, 2006; Mujahid et al., 2017). The use of liquid desiccants as complement to vapour compression chillers has been widely explored in the last years, seeking an energy efficient way to handle latent heat in hot-humid climates, instead of recurring to overcooling and subsequent heating to control humidity. This has given room for experiences coupling LD with evaporative cooling systems, as the best alternative to

TOC

vapour compression chillers. Hence, the development of LDAC goes hand in hand with the development of evaporative cooling systems. The dehumidification capacity of common LD materials has been largely explored, designing and testing several application modes; while evaporative coolers are regarded as a mature technology but have only achieved limited market penetration (Goetzler et al., 2014). Hence, current development efforts focus on integration and simplicity on the design of the system to allow for small capacity LDAC+EC units, while at the same time exploring efficient ways to use solar heat for regeneration purposes.

Market/commercial maturity

Currently, there are no solar driven LDAC systems commercially available. The most developed experiences consist of several prototypes and patents, besides a few demonstration projects for long term monitoring purposes and raising awareness and interest in the technology. Advantix Systems, an US based company founded on 2006 received great attention between 2010 and 2013, by manufacturing and commercialising hybrid LDAC systems (LiCl system coupled with a vapour compressor) for commercial and industrial buildings, being regarded as pioneers in the field ("Advantix announces exclusive Rep. agreement with Trane in Southeast," 2014; "Advantix Systems' Dehumidification & Cooling System reduces energy consumption in schools by more than 40 percent," 2010; Brinkmann, 2012; "Cool innovation: an upstart hopes to make rival cooling companies sweat," 2012). Nonetheless, there are no signs of the company after 2014, suggesting that it went out of business. Additionally, Alfa Laval Kathabar (Kathabar, n.d.), a company specialised on dehumidification and HVAC, has recently developed large scale LD based dedicated outdoor air systems using LiCl, also considering a compressor as part of the unit. In any case, ostensibly R&D efforts are still needed to allow for the integration of small size units into the market.

§ 7.4 Evaluation & discussion: Potential for façade integration

An assessment of the technologies is presented, discussing their potential to overcome identified barriers for façade integration of building services. The evaluation was conducted following the strategy and rubrics presented in the methods section of this chapter (Table 7.2), seeking to provide a referential qualitative assessment of the current state-of-the-art, and specifically how each technology fares regarding different relevant aspects for façade integration. Figure 7.7 shows maps for each technology, while barriers are discussed separately.

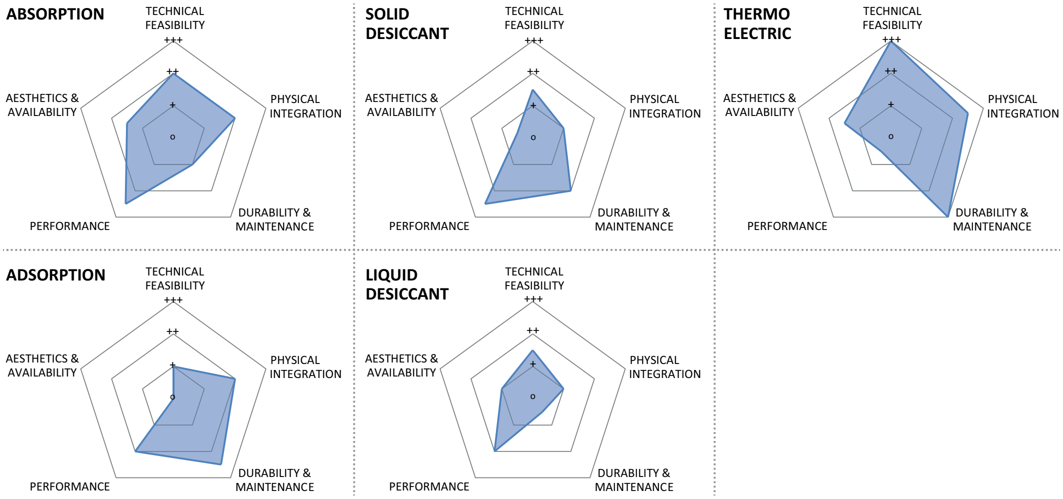


FIGURE 7.7 Qualitative assessment maps for the facade integration potential of selected solar cooling technologies.

§ 7.4.1 Technical feasibility

This refers to the overall practicability of integrating all required components for cooling in façade modules. Hence, addressing sizes of the entire system and its components, and their adequate operation in small scales. First of all, it is relevant to point out that the review showcased small scale working examples, with cooling capacities below 3 kW for all selected technologies, which, leaving efficiencies aside for the moment, shows that all of them may operate in the small capacity range.

Besides the existence of small scale concepts, the most clear proof of technical feasibility is the development of working integrated façade prototypes. In this regard, the simplicity of the cooling principle and sizes of the required components have made thermoelectric cooling the technology of choice for the development of most façade integrated concepts found in the literature. These prototypes, even in cases with underwhelming efficiencies, are regarded as evidence of the feasibility of integrated concepts for façade applications. Second to thermoelectric based systems, there are also stand-alone façade concepts based on absorption and solid desiccant principles. Both technologies are quite mature (especially absorption) but are commonly employed in larger scales, considering bulky components. The fact that compact experiences for façade integration are being developed and tested seems promising for future applications.

TOC

On the other hand, although compact systems are being designed and tested, liquid desiccant systems still need further research and development to allow for façade integrated concepts. Finally, adsorption based systems still present certain issues related to the intrinsic bulkiness of their components, and the need for another conduit for air supply, being based on closed refrigerating cycles.

§ 7.4.2 Physical integration

Barriers related to physical integration refer to externalities derived from the connection of the required components, and the compatibility of sub-systems and working materials. In these aspects, technologies based on solid-state heat transfer, such as thermoelectric cooling, have clear advantages, being based on simple direct contact between components, besides simple electrical connections to the PV array for energy input. Peltier modules are easy to handle and integrate, although further exploration is needed in order to develop ready-made building components to use in architectural designs.

For all other technologies, a basic distinction could be made between closed cycle and open cycle processes; namely absorption/adsorption, and desiccant cooling respectively. Both absorption and adsorption heat pumps commonly consist of factory sealed units, only needing connections to the heat source, heat rejection system and cooling distribution network, usually carried out throughout pipes. Of course, the fact that refrigerant is carried in a closed cycle, implies that a heat exchanger is needed for cooling delivery, commonly using fan-coils in central water-air applications. Nonetheless, these types of connections are quite common, and easy to solve, dealing with cooling and ventilation requirements through two separate but complementary channels. Furthermore, the current research and development of sorption based integrated concepts, considering a collector array, sorption heat pump, and decentralised air intake (Avesani, 2016); is pushing the boundaries on packaged systems, with no further needs than a discrete electric input for fans, following a plug & play approach.

More complex connections are present in the case of desiccant technologies, mostly due to the fact that a complementary system is needed to take care of sensible loads. While desiccants account for latent loads, evaporative cooling is commonly used to provide sensible cooling. Solid desiccant installations have been judged as slightly complicated (Goetzler et al., 2014; Mujahid et al., 2015), while liquid desiccant units present the added challenge of handling liquid material for dehumidification on a separate hydronic

TOC

circuit, with the associated pumps and storage tanks. Future applications of liquid desiccant enhanced evaporative cooling systems largely depend on the simplification and compatibility of their components. Early experiences of natural convection driven units (Fazilati et al., 2017), membrane based systems (Elmer et al., 2016), and the use of photovoltaic electrodyalisis for regeneration purposes (Cheng & Zhang, 2013) are steps in the right direction, but further research & development is still needed to advocate for the application of liquid desiccant based cooling systems in buildings.

§ 7.4.3 Durability & Maintenance

This refers to both the durability of required components over time, and maintenance requirements that have an impact on operational costs associated to each technology. Following the aforementioned simplicity associated with the technology, and the lack of moving parts nor the use of refrigerants; thermoelectric components are regarded as the most durable, being virtually maintenance free besides basic electrical maintenance. However, their lifetime within building components has not been fully tested. Regarding thermal driven technologies, durability of components and maintenance requirements highly depend on the working materials used in the cooling process. Liquid desiccant and absorption cooling rely on liquid dehumidification materials, while the principles behind solid desiccant and adsorption cooling are based on the use of solid materials on carrier surfaces.

The most common liquid desiccants currently used are aqueous halide salts, such as lithium bromide (LiBr) and lithium chloride (LiCl). These salts are highly corrosive and are subject to crystallisation at high concentrations, so careful maintenance must be conducted to assure that there is no corrosion in components nor carry-over to the supply air stream, assuring optimal operational conditions. This is more troublesome for liquid desiccant systems, based on open refrigerant cycles, although further exploration of indirect contact membrane based systems could lead to carry-over free products. An alternative option to overcome these issues is further exploration of other non-corrosive materials, but experiences are still in early stages.

On the other hand, solid materials such as silica gel and zeolites do not present any hazard and are corrosion free. This fact, plus the lack of moving parts in their inner mechanism, makes adsorption heat pumps virtually maintenance free. Solid desiccant systems, comprising more complex connections but simple and robust components, require periodic but simple maintenance.

TOC

§ 7.4.4 Performance

The performance of the selected technologies was mainly addressed in terms of cooling output and efficiency values reported by the reviewed experiences, besides considering potential hazardous externalities for indoor comfort. The aforementioned hazard risk by carry-over associated to liquid desiccant materials is the only health concern worth mentioning, being solved by means of indirect contact with the air stream. On the other hand, the use of desiccant materials (solid or liquid) to deal with latent loads may prove beneficial for indoor comfort by avoiding condensation derived from re-heating the air stream to comfort temperatures.

The reported cooling power and the coefficient of performance (COP) of the reviewed systems and prototypes are shown in the graph below (Figure 7.8). The COP refers to the input energy so it is electrical efficiency in the case of thermoelectric cooling, and thermal COP for solar thermal driven technologies. Moreover, this only considers the efficiency of the cooling system for purposes of the comparison, so the efficiencies of PVs or solar thermal collectors are not accounted for. Regarding cooling power, only experiences below 10 kW were considered. Also, the graph shows the range of cooling design capacities for a single office in different orientations, based on the simulations conducted in Chapter 6 (Prieto et al., 2018b), with dark and light grey marking the design values for an office with low and high cooling demands respectively.

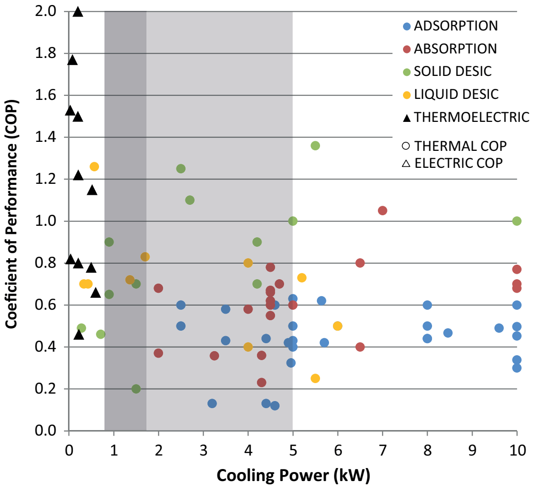


FIGURE 7.8 Cooling power (kW) and coefficient of performance of reported small-scale solar cooling prototypes.

TOC

First of all, it is possible to see that although thermoelectric concepts may reach high COP values, they are out of range for the cooling power required for a single room. Thus, current integrated thermoelectric concepts do not seem to be able to meet decentral cooling demands by lack of cooling power, requiring a back-up system. Further development and testing of larger concepts is needed to fully assess their in-range efficiencies, keeping in mind that there is a trade-off between the efficiency of the system and its cooling output.

Discussing thermal driven technologies, possibilities greatly open up. Closed-cycle systems, and particularly adsorption heat pumps (N=36), comprise the majority of the reviewed small-scale experiences. The performance of closed systems seems to be consistent among the sample, usually reaching thermal COP values of 0.6 and 0.8 for adsorption and absorption systems, respectively. The high amount of adsorption based experiences follows current research trends aimed to boost the development of small scale systems for residential application, considering several prototypes in the 3-5 kW range. Regarding absorption, most experiences are higher than 4 kW, with smaller capacities only tailored to façade integrated purposes in the aforementioned sorption collector unit (Avesani, 2016).

In general, desiccant based cooling systems discussed in the review comprise lower cooling capacities than closed-cycle systems. However, this does not seem to present a problem due to their close match with the required range for the design of cooling systems. Regarding efficiency, these technologies reach higher in-range thermal COP values, especially in the case of solid desiccants. Nonetheless, more research is required to ensure reliable results following the maturity achieved by closed-cycle technologies.

§ 7.4.5 Aesthetics & Availability

Aesthetics is a highly complex topic of discussion not only regarding façade integration, but in architecture and the arts in the wider sense, opening different trends of thought that fall out of the scope of the present research. Hence, it is necessary to constrain its understanding for the evaluation at hand. Moreover, the external appearance of façade integrated solar cooling concepts will be heavily, if not totally, influenced by the solar energy conversion system utilised, namely photovoltaics or solar thermal collectors. While there are several options to choose for any given design or preferred appearance, they do not make any difference for the evaluation of the solar cooling systems driven by them. Therefore, for the purpose of addressing this aspect in the evaluation of the

TOC

selected solar cooling technologies, the aesthetical potential is understood as the potential to allow for flexibility and variability in façade design.

Sizes and overall complexity of the components and overall current systems are regarded as a relevant hindrance for design flexibility, limiting the application of adsorption and desiccant technologies respectively. The lack of standardised components, or plug & play modular systems; limits the applicability of these technologies at best to tailor-made solutions under an integral façade design. The development of integrated compact solutions are steps in the right direction in order to develop building products for architects and facade designers to use, but further efforts need to be conducted in the field. This is also true in the case of thermoelectric components. Due to their dimensions and low complexity, they do not greatly restrict design choices, but exploration and research should eventually conduct to the development of architectural products, easy to integrate in early stages of façade design, while ensuring reliable operation.

§ 7.4.6 General assessment: charting a roadmap for the development of facade integrated concepts

The qualitative assessment of solar cooling technologies in terms of their potential for façade integration, clearly shows what is currently possible, but at the same time serves to identify shortcomings and bottlenecks related to each technology, if façade integration is the final goal. Table 7.10 shows recommendations for further development of all assessed technologies, drafting a roadmap for future R&D experiences focusing on key aspects to overcome for façade integration. Furthermore, the most pressing issues to solve per technology are highlighted, following the lower ranked aspects at the assessment (below ++).

In general, it is quite evident that these technologies are not ready yet for façade application, with all of them ranking low in 'aesthetics & availability' aspects. 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 been more recently explored, compared to other thermal driven systems, gives them a disadvantage in development level and maturity, needing further research in most aspects to be up to date. In any case, the rate of new developments in the field is seen as highly promising. Although the conducted assessment only considers current possibilities, it is the author's opinion that liquid desiccant cooling technologies have large unexplored potential, with auspicious opportunities for application in the built environment.

TOC

TABLE 7.10 Recommendations for further development of solar cooling technologies, to overcome identified barriers for façade integration.

BARRIERS	SOLAR COOLING TECHNOLOGIES				
	THERMO ELECTRIC	ABSORPTION	ADSORPTION	SOLID DESICCANT	LIQUID DESICCANT
TECHNICAL FEASIBILITY	Prototype testing and experimental measurement of facade 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	Standardise connections and components for product development.	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	Durability testing of TE modules in building components over time and different climates.	**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.**

In the case of technologies that consider solid desiccants as basis of their operation (adsorption, solid desiccant cooling), the main current bottlenecks are related to the size of components and generation of compact integrated systems. Even considering latest developments of compact desiccant units (SolarInvent, n.d.), they still need to be field tested and thoroughly validated under different working conditions. The technologies that currently seem closer to commercial façade applications are thermoelectric cooling and absorption based systems. However, important bottlenecks still remain regarding performance issues and the development of compact units with durable components and working materials, respectively.

The assessment above has shown current possibilities and bottlenecks for façade integration of selected technologies, drafting recommendations for further development. However, the discussed topics also allow to debate façade integration itself, defining

TOC

different paths for product development depending on the understanding of integration and its implications. Authors have proposed the distinction between 'integral' and 'modular' construction as two ways to integrate extra functions into the building envelope. The former considers functions embedded in a multifunctional component, while the latter refers to different mono-functional parts, connected to form a multifunctional whole (Klein, 2013). Following this distinction, there are two clear product development paths for façade integration: (a) the development of integral building components for architectural design, and (b) the development of modular packaged systems ready to be installed if the required connections are space are provided.

Current strengths and shortcomings of each assessed solar cooling technology make them more suitable for either one of these product development paths, defining potential product types worth exploring. Based on the review and assessment, the most viable options for the development of distinct façade integrated products are depicted in Figure 7.9, using the chart for the categorisation of solar cooling technologies for façade integration purposes, proposed in Chapter 2 of the present dissertation.

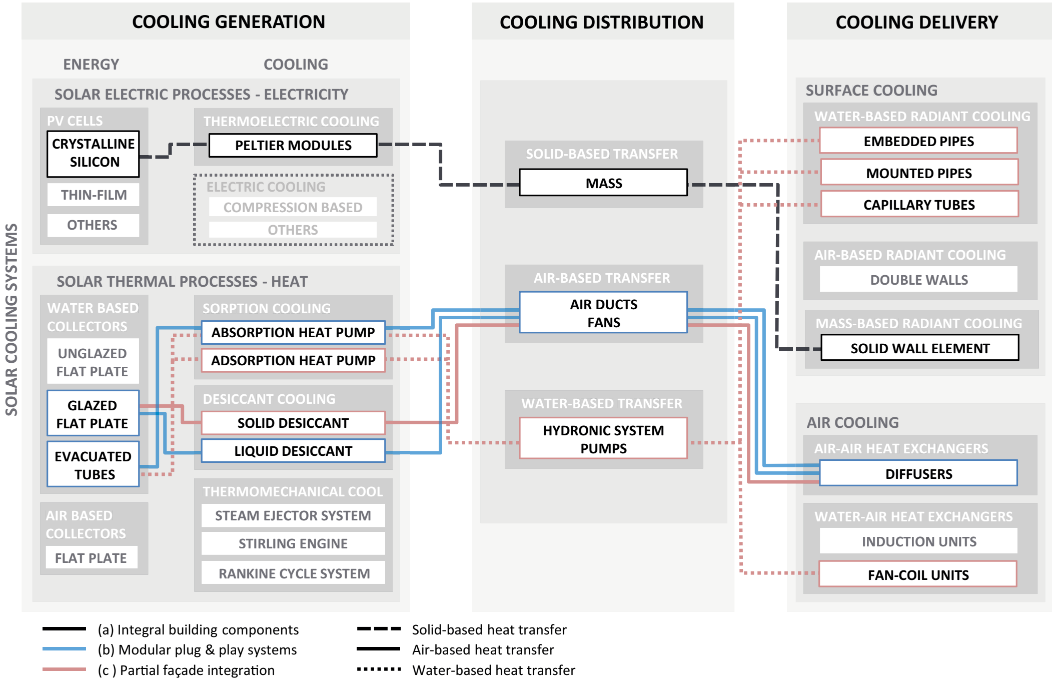


FIGURE 7.9 Research and development paths for the generation of distinct architectural products for façade integration.

Performance issues aside, thermoelectric cooling technologies are regarded as the most suitable for developing integral building components. The compact dimensions of their basic elements, and the simplicity of their connections and operation principles give them an important advantage for the design of active building components at different scales, ranging from window elements (Vasquez et al., 2001; Xu & Van Dessel, 2008b) to radiant walls and façade units (Ibañez-Puy et al., 2018; Luo et al., 2018). On the other hand, the sorption collector integrated with decentral ventilation (Avesani, 2016) is regarded as the best current example for the development of self-sufficient compact systems under absorption processes. In this case, the challenge for designers would be how to plan the connection of these modular packaged units, while assimilating them into the façade composition. Similarly, future developments on liquid desiccant units should follow this path, taking advantage of the flexibility given by the use of liquids as working material.

Finally, a third possible path for product development is added to the discussion, as partial façade integration (c). This refers to the facade integration of certain components of a solar cooling system, such as the solid desiccant based facade ventilation unit, with decoupled solar regeneration (thermal collectors located in the roof) developed by SolarInvent. Also, even if small-scale absorption/adsorption chillers remain too big for façade integration, cooling distribution may be conducted through especially designed façade elements for central or semi-decentral applications (various rooms or an entire floor). Furthermore, façade integrated water-based systems may be alternatively connected to cooling delivery elements far from the façade, such as cooled ceilings or beams, through an hydronic system, providing more application possibilities for deep plan buildings. Based on current possibilities, solid desiccant cooling and sorption chillers seem to be apt for partial façade integration. While breakthroughs may come in the future, for the time being, the generation of self-sustaining solar cooling facades based on these technologies seems unlikely. Thus, in this case, it seems logical to promote façade integration of certain key components to seek new applications based on the comparative strengths of these technologies.

§ 7.5 Conclusions

This chapter sought to discuss the potential for façade integration of selected solar cooling technologies, based on a state-of-the-art review of technology-specific attributes and the assessment of their capability to respond to previously identified barriers for façade integration of building services. The review focused on small-scale systems and concepts, exploring current boundaries and development level of compact units for integration

TOC

purposes. Moreover, the evaluation tackled the aforementioned barriers, categorised in five groups of aspects to overcome for façade integration: technical feasibility, physical connections, durability & maintenance, performance; and aesthetics & availability.

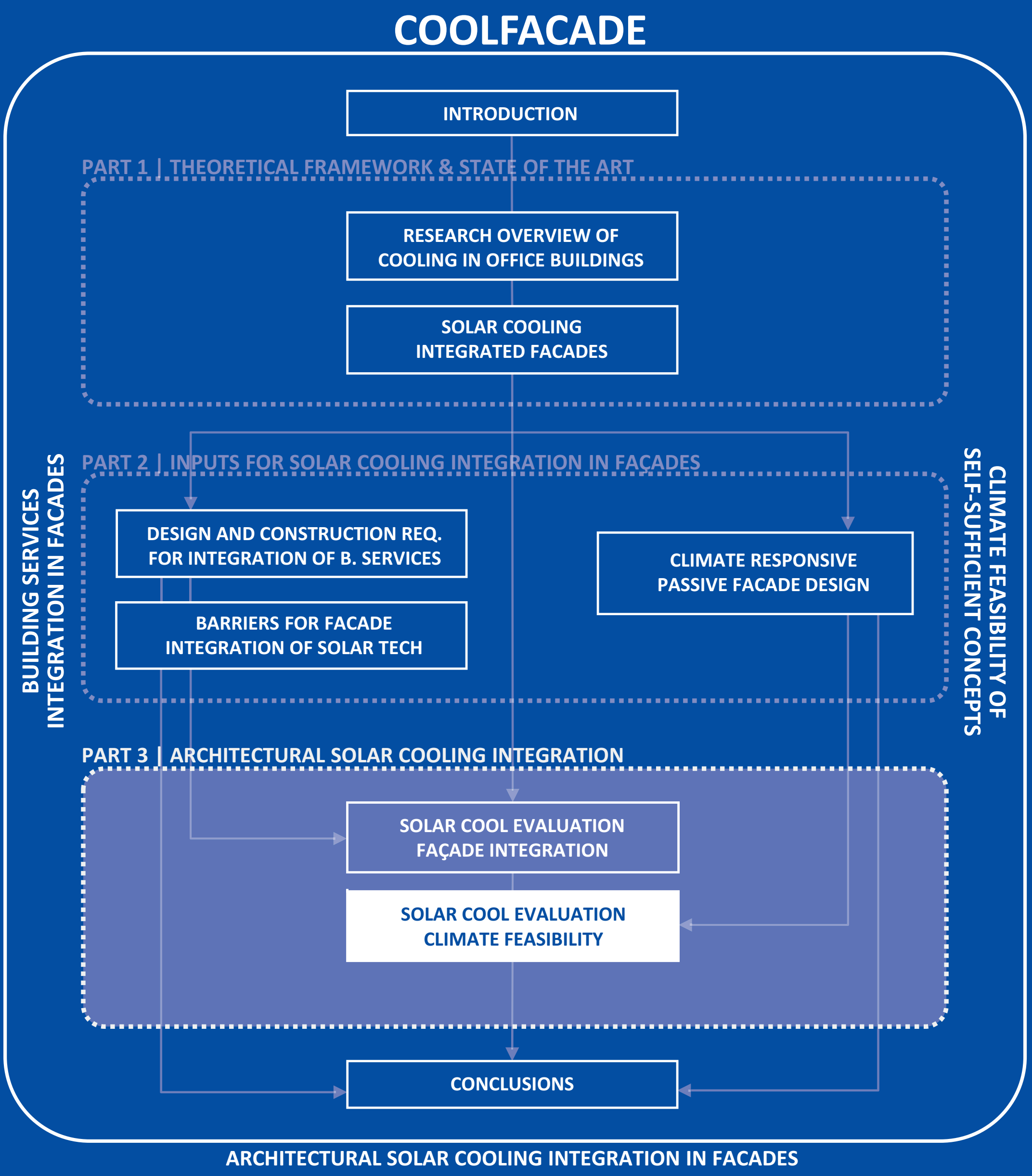
The review showcased examples of small-scale units for all technologies; and even façade integrated concepts for some of them. However, the assessment showed that the suitability of the selected technologies varies according to each particular barrier for façade integration. Hence, no technology currently fits all required aspects. Further research and development are needed for all technologies to enable the widespread use of integrated concepts, and future commercialisation of architectural products. Therefore, current possibilities were mapped, identifying certain bottlenecks and drafting recommendations for further development, focusing on key aspects to solve per technology.

Although they are not ready for widespread application yet, the use of thermoelectric modules and compact units based on absorption technologies, are regarded as the most promising ones for the development of either integral building components, or modular plug & play systems for façade integration. In the case of thermoelectric cooling concepts, the main constraint is their comparative performance in terms of cooling output; requiring the development and testing of scaled-up units that maintain high efficiencies reported by systems out of the required range. For absorption units, the main challenges are the exploration of non-corrosive working materials, and further development and testing of compact packaged units under a modular design approach. On a separate note, liquid desiccant cooling technologies are deemed as potentially promising, based on the rate of new developments and the flexibility given by liquid working materials. Nevertheless, they are less mature compared to the rest, so more research is needed to explore their potential.

Finally, it is recommended that further explorations on compact adsorption and solid desiccant cooling systems focus on partial façade integration, promoting an alternative development path based on the strengths and shortcomings of these technologies. Specific challenges are size reduction and simplification of cooling processes, however, the integration of only certain components mitigates size constraints, while opens new possibilities for semi-decentral applications, and cooling distribution to the building core.

The presented assessment and recommendations aim to coordinate future efforts and explorations in the field, charting paths for the development of a variety of architectural products and new building applications; and specific challenges to overcome. This supports a general vision for further promotion and widespread integration of renewable energy sources and environmentally friendly cooling processes in the built environment; however, this has to be thoroughly combined with campaigns and measures to reduce our energy demands, and the climate responsive design of buildings and cities, particularly in warm climate contexts.

TOC



COOLFACADE

INTRODUCTION

PART 1 | THEORETICAL FRAMEWORK & STATE OF THE ART

RESEARCH OVERVIEW OF COOLING IN OFFICE BUILDINGS

SOLAR COOLING INTEGRATED FACADES

PART 2 | INPUTS FOR SOLAR COOLING INTEGRATION IN FAÇADES

DESIGN AND CONSTRUCTION REQ. FOR INTEGRATION OF B. SERVICES

BARRIERS FOR FACADE INTEGRATION OF SOLAR TECH

CLIMATE RESPONSIVE PASSIVE FACADE DESIGN

PART 3 | ARCHITECTURAL SOLAR COOLING INTEGRATION

SOLAR COOL EVALUATION FAÇADE INTEGRATION

SOLAR COOL EVALUATION CLIMATE FEASIBILITY

CONCLUSIONS

BUILDING SERVICES INTEGRATION IN FACADES

CLIMATE FEASIBILITY OF SELF-SUFFICIENT CONCEPTS

ARCHITECTURAL SOLAR COOLING INTEGRATION IN FACADES

TOC

8 Solar cooling evaluation – Climate feasibility

Application potential of self-sufficient cooling facades on different warm climates[7]

Small-scale systems and integrated concepts are currently being explored by researchers to promote widespread application of solar cooling technologies in buildings. Chapter 7 presented a qualitative evaluation of these technologies in terms of their potential for façade integration. Moreover, this chapter expands the assessment of application possibilities by *exploring the feasibility of solar cooling integrated façades, as decentralised self-sufficient cooling modules, on different warm climate contexts*. The climate feasibility of solar electric and solar thermal concepts is evaluated based on solar availability and local cooling demands to be met by current technical possibilities.

Numerical calculations are employed for the evaluation, considering statistical climate data; cooling demands per orientation from scenarios simulated in Chapter 6; and state-of-the-art efficiency values as reference for current performance limits of solar cooling technologies, from Chapter 7. Main results show that in general, warm-dry climates and east/west orientations are more suited for solar cooling façade applications. Results from the base scenario show promising potential for solar thermal technologies, reaching a theoretical solar fraction of 100% in several cases. Application possibilities expand when higher solar array area and lower tilt angle on panels are considered, but these imply aesthetical and constructional constraints for façade design. Finally, recommendations are drafted considering prospects for the exploration of suitable technologies for each location, and façade design considerations for the optimisation of the solar input per orientation.

---

[7] Published as: Prieto, A.; Knaack, U.; Auer, T.; Klein, T. (2018). Feasibility study of self-sufficient solar cooling façade applications in different warm regions. Energies; 11(6):1475. doi: 10.3390/en11061475.

TOC

§ 8.1 Introduction

Solar cooling technologies have gained increasing attention in the last decades, being explored as potential alternatives to conventional systems, in order to cope with rising cooling requirements in the built environment (OECD/IEA, 2012; Prieto, Knaack, Klein, et al., 2017). Global cooling demands are growing due to several factors such as higher standards of life, temperature in the urban environment, and climate change (Santamouris, 2016), so there is a pressing need for environmentally friendly technologies, driven by renewable energy sources. Solar cooling technologies are driven by solar radiation, throughout thermal or electric processes; using no refrigerants, nor working materials with low global warming potential (Henning, 2007; Prieto et al., 2017a). Common vapour-compression systems commercially available are highly efficient, compared to current solar cooling systems, but rely on the use of hydrofluorocarbons (HFCs), with global warming potential 1,430 times that of CO_2 (IPCC/TEAP, 2005). So, even though they could be driven by solar-generated electricity, are not considered within the range of environmentally friendly alternatives addressed under solar cooling systems.

These systems have been researched and developed, mostly focusing on their performance, but their application in the built environment remains mostly limited to large demonstration projects and pilot experiences (Balaras et al., 2007). In that regard, small-scale designs and prototypes are being developed by researchers, in order to promote widespread architectural application of these technologies in buildings, under the concept of solar cooling facades (Prieto et al., 2017a). These integrated concepts seize economic and functional benefits derived from the integration of decentralised components in the façade, while using the available exposed area for direct and diffuse solar collection. Economic benefits from façade integration refer to construction cost savings and extra leasable space from avoiding complex distribution systems and large equipment (Franzke et al., 2003; Prieto, Klein, et al., 2017), and functional advantages range from efficient energy usage by identifying local demands, to increased comfort due to personal control (Mahler & Himmler, 2008). On the other hand, the façade not only comprises available external surface, but also directly influences indoor comfort. In warm climates, peak solar irradiance in façades usually match peak cooling demands in the adjacent offices, so it makes sense to harvest that radiation to drive a cooling system; while blocking solar heat gains under a climate responsive façade design.

Solar cooling façade concepts found in the literature are based either on solar electric processes, using thermoelectric modules (Ibañez-Puy et al., 2018; Liu et al., 2015); or solar thermal processes, integrating sorption (Avesani, 2016; Bonato et al., 2016) or desiccant cooling (SolarInvent, n.d.) systems. Nonetheless, although they are regarded as relevant experiences, pushing current technical boundaries; they are standalone concepts or prototypes developed in a specific climate. This, at best, allows for proof of concept under similar climatic conditions; but does not directly allow for replicability on other climates; nor gives information about the overall suitability of said climate, for the development and application of solar cooling technologies in the first place.

In broad terms, the application of a decentralised solar cooling system depends on two main factors, heavily dependent of the climate context where the system operates: (a) solar availability; and (b) cooling demands. The solar availability determines the potential energy input of the system, which, combined with the overall efficiency of the particular cooling process, provides the theoretical cooling output of the unit. While the efficiency of the process is given by the technical maturity and operational limits of the equipment associated with a cooling principle, solar availability depends on façade orientation, relative position to the equator, and climate conditions of any given location. On the other hand, cooling demands largely depend on the climate, and secondarily on the design of the building and particularly its façade. Thus, cooling requirements may be greatly reduced under a climate responsive design through the application of passive strategies. Whilst solar availability is beneficial for power and heat generation, passive cooling design strategies aim to protect the interior space from solar radiation, and dissipate heat generated indoors, thus avoiding overheating.

This chapter explores the potential for application of solar cooling integrated facades, as decentralised self-sustaining cooling modules, on different climate contexts, based on solar availability and cooling requirements to be met by current technical possibilities. The climate feasibility of the integrated concepts is assessed throughout numerical calculations based on climate data and building scenarios simulated with specialised software. Technical issues to solve associated to each addressed technology are out of the scope of the present document. Hence, the evaluation focuses on identifying climate suitability for selected solar cooling technologies, while assessing certain façade design parameters and their impact on the overall feasibility, discussing broad possibilities and constraints for the design of façade concepts for different locations and orientations.

§ 8.2 Strategy and methods: experimental setup and parameters involved in the assessment

This chapter evaluates the application feasibility of self-sustaining solar cooling façade modules on office or commercial buildings. It focuses on the current performance of selected solar cooling technologies; and their potential to cope with indoor cooling demands by themselves, hence, without the need for complementary building services. Therefore, the main unit for the analysis is the daily solar fraction of the system (SF), theoretically calculated according to eq. 8.1. $COOL_{req}$ refers to the cooling demands of a specific interior space, while $SCOOL_{out}$ refers to the 'cooling effect' delivered indoors by the solar cooling system. So, a solar fraction of 100% or more, means that the system is capable of handling the cooling demands of a given space by itself, provided that all evaluating parameters and conditions are met in reality. The assessment will consider then, the solar availability and cooling demands for a representative summer day as a simplified basis for the evaluation.

$$SF = \frac{SCOOL_{out}}{COOL_{req}} \qquad \text{(eq. 8.1)}$$

Both the cooling demands and the cooling output of the system highly depend on the climate context, especially on temperature distribution and availability of solar radiation at any given location. Thus, the analysis is conducted in six different locations, representing several warm climate zones across the northern hemisphere. Table 8.1 shows the selected cities, along with the Koppen–Geiger climate zones they represent and the severity of the climate in terms of cooling degree days (CDD). The analysis considers three warm dry and three warm humid locations, each with one example of an extreme climate and two temperate climates of different severity, to account for a wide range of climatic scenarios.

TABLE 8.1 Cities selected for the assessment, representing several warm climate zones.

CITY	LATITUDE/LONGITUDE	CLIMATE ZONES	CDD (26 °C)
Riyadh	24.70 / 46.73	Hot desert (BWh)	1583
Athens	37.90 / 23.73	Hot-summer mediterranean (Csa)	212
Lisbon	38.72 / -9.15	Hot-summer mediterranean (Csa)	69
Singapore	1.37 / 103.98	Tropical rainforest (Af)	992
Hong-Kong	22.30 / 114.17	Humid Subtropical (Cwa)	602
Trieste	45.65 / 13.75	Humid Subtropical (Cfa)	88

§ 8.2.1 Cooling requirements (*COOL*$_{req}$) and base case for the evaluation

Cooling demands were obtained though the dynamic energy simulation software DesignBuilder v4.7, as the graphical interface of EnergyPlus v8.3 (NREL, n.d.-a). The base case used for the assessment is a single office room of 16 m^2, considered adiabatic for the purpose of the evaluation. The assessment was carried out for all orientations, with the simulation parameters depicted in Table 8.2. Passive design strategies such as a reduced window-to-wall ratio, the application of sun shading, solar control glazing and the use of ventilation for cooling purposes are judged as a necessary step to decrease cooling demands, before integrating active systems into the building envelope. The parameters defined for the simulation were derived from the results from Chapter 6, resulting on virtually similar base cases for all climate zones, with the only exemption being the restriction of ventilation for solely hygienic purposes in Singapore and Hong Kong, following the most favourable design solutions per climate zone.

TABLE 8.2 Design and operational parameters for the dynamic energy simulation of the base case defined for the assessment.

SIMULATION PARAMETERS	ALL OTHER LOCATIONS	SINGAPORE & HONG KONG
Office dimensions	4.0 x 4.0 x 2.7 m (width x depth x height) + plenum of 0.7 m	
Thermal comfort range	Maximum temp. of 26 °C and relative humidity between 25%-55%	
Occupant loads	0.1 people/m^2	
Equipment loads	11.77 W/m^2	
Lighting loads	(on demand) 12 W/m^2 for a target illuminance of 400 lux	
Ventilation (hygienic purposes)	10 L/s per person	
Ventilation (cooling purposes)	5 ACH max when it's thermodynamically feasible (external temperature below internal temperature).	NO
Window-to-wall ratio	25% (Wall U-value: 0.26 W/m^{2}K)	
Sun shading system	Dynamic exterior shading on operation over 100 W/m^2 of solar irradiance on facades.	
Glazing type	Double clear glass (6-13-6 mm with air in cavity) U-value: 2.7 W/m^{2}K / SHGC: 0.7	

The cooling demands for all scenarios are shown in Table 8.3. It is important to point out that these serve as reference for the assessment at hand and do not claim to be fully passively optimised scenarios. Hence, while they consider important cooling savings compared to a scenario with no strategies, they could probably reach further savings under a thorough design optimisation process. Several results were obtained from the simulations. Firstly, yearly cooling demands per square meter are depicted as

TOC

reference of the overall performance of the office room under normalised units, for every orientation and selected location. Annual demands of a base case without any passive strategies (no solar control strategies, window-to-wall ratio of virtually 100%, and ventilation only for hygienic purposes) are shown in comparison to the improved base case used for the analysis as further evidence of the high impact of passive strategies on decreasing cooling loads.

TABLE 8.3 Simulated cooling demands for all orientations and locations considered in the assessment.

LOCATION	SUMMER DESIGN WEEK	ORIENTATION	BASE CASE (NO PASSIVE STRATEGIES)	IMPROVED BASE CASE (WITH PASSIVE STRATEGIES)		
			Cooling yearly demands (kWh/m^2 year)	Cooling yearly demands (kWh/m^2 year)	Cooling Design Capacity (kW)	AVG daily cooling in summer design week (kWh day)
Riyadh	July 20-26th	South	298.92	92.67	1.19	11.69
		West	336.43	95.11	1.23	12.26
		East	342.14	91.56	1.21	12.26
		North	175.93	84.36	1.16	11.34
Athens	August 3-9th	South	231.28	56.00	1.10	10.95
		West	190.69	57.02	1.10	11.27
		East	210.57	54.70	1.08	10.94
		North	94.44	50.21	1.03	10.25
Lisbon	July 15-21st	South	224.37	33.01	0.92	7.73
		West	148.25	33.13	0.91	7.86
		East	227.47	33.56	0.90	7.72
		North	72.72	27.65	0.85	7.27
Singapore	June 4-10th	South	334.30	223.96	1.59	14.11
		West	385.16	228.49	1.64	14.38
		East	398.33	219.72	1.59	13.82
		North	349.13	215.12	1.57	13.72
Hong Kong	July 22-28th	South	246.53	143.99	1.61	13.76
		West	255.69	144.34	1.67	14.15
		East	247.97	135.87	1.62	13.77
		North	186.29	130.87	1.57	13.38
Trieste	July 20-26th	South	140.68	40.74	1.26	9.75
		West	110.38	41.12	1.26	9.88
		East	115.28	37.87	1.22	9.51
		North	66.74	36.13	1.18	8.80

TOC

The assessment considers daily cooling demands and solar availability as main input, so the average daily cooling demands were calculated for each orientation and location, based on their respective summer design week. This week consists of the most critical summer period and is defined by DesignBuilder based on the information on the weather file corresponding to each location. The average values shown above consider only the five working days of said week, when the cooling system is designed to operate. Similarly, the cooling design capacity is the highest resulting cooling load at a given amount of time, multiplied by a factor of 1.15 in order to provide a margin for sizing the cooling system. The summer design week was also considered to obtain the average solar irradiance per orientation at each selected location.

§ 8.2.2 Solar cooling output ($SCOOL_{out}$) and boundary conditions for the assessment

The cooling output (heat removed by the solar cooling system) is theoretically calculated through the simplified equation below (eq. 8.2), where SOL_{input} refers to the availability of solar radiation on a specific location/orientation, SOL_{array} refers to the area destined for collection, and $COP_{solarsys}$ refers to the efficiency of the system implemented for said collection, either PV-panels or solar thermal collectors for electricity and heat respectively. On the other hand, $COP_{coolsys}$ refers to the coefficient of performance of current solar cooling technologies and systems. This simplified equation does not consider transmission and parasitic losses, nor additional equipment such as storage units, serving a comparative purpose between technical possibilities to assess the broad feasibility of self-sustaining solar cooling facades in different climate contexts. Hence, detailed calculations would be needed in order to delve into the required specifics in real life applications.

$$SCOOL_{out} = SOL_{input} * SOL_{array} * COP_{solarsys} * COP_{coolsys} \qquad \text{(eq. 8.2)}$$

Daily solar irradiance values (SOL_{input} - kWh/m^2 day) for all locations were obtained from the EnergyPlus weather files used for the cooling demand simulations, through System Advisor Model v.2017.9.5, a software developed by the National Renewable Energy Laboratory (NREL) of the US. Department of Energy (NREL, n.d.-b). Monthly average daily solar radiation was obtained for south, west and east orientations, considering a 90° tilted plane as worst case scenario for solar collection on facades (vertical application). The values used for the assessment correspond to the months that contain the summer design week, as depicted in Table 8.4.

TOC

TABLE 8.4 Daily average solar irradiance in facades in all orientations and locations for the summer design month.

LOCATION	LATITUDE/ LONGITUDE	MONTH	DAILY AVG SOLAR IRRADIANCE IN 90° TILTED PLANE (KWH/M²/DAY)			
			SOUTH	WEST	EAST	NORTH
Riyadh	24.70 / 46.73	July	1.71	3.62	3.75	2.02
Athens	37.90 / 23.73	August	3.49	3.43	3.47	1.50
Lisbon	38.72 / -9.15	July	2.87	3.47	4.68	2.08
Singapore	1.37 / 103.98	June	1.51	2.28	2.19	2.72
Hong Kong	22.30 / 114.17	July	1.35	2.40	2.46	1.64
Trieste	45.65 / 13.75	July	2.84	2.81	2.81	1.64

The base case for the assessment considers a solar array (SOL_{array} - m^2) that occupies 50% of the façade area, which equals 6.8 m^2 in the defined office room. This area for solar collection may be used with PV panels or thermal collectors, to provide input for solar electric or thermal driven cooling systems respectively. For purposes of the assessment, this is represented by the coefficient of performance associated with each technology type ($COP_{solarsys}$). For photovoltaics, current performance values were obtained from the 8th edition of the International Technology Roadmap for Photovoltaic (ITRPV), developed by over 50 research institutions and companies in the field. Crystalline silicon modules largely dominate the market, with a share of about 90%, over thin film and organic PV cells, which also consider lower efficiencies. The stabilised efficiency values for (single and poly-crystalline) silicon solar cells are currently between 18.5 and 23%, range considered for the assessment, with prospect ranges for 2027 circling around 20%-26% (VDMA, 2017). Current values also comply with the predictions stipulated at the last Technology Roadmap elaborated by the International Energy Agency (OECD/IEA, 2014), evidencing systematic and continuous technological improvements.

Regarding solar thermal collectors, their nominal efficiency follows the curves shown in Figure 8.1, being highly dependent of the temperature differential between ambient and working temperatures in the collector. For solar cooling applications, driving temperatures are in the range of 50-90 °C (desiccant), 65-90 °C (adsorption), and 80-110 °C (absorption) (SOLAIR, 2009), resulting on a temperature differential range of approx. 20-80 °C considering a base ambient temperature of 30. Using this range as reference, resulting nominal efficiencies are around 40-75% and 60-75% for flat plate and evacuated tubes collectors respectively (OECD/IEA, 2012). On the other hand, experimental measurements of solar collectors coupled to solar cooling systems have shown slightly lower efficiencies in practice. For evacuated tube collectors (ETC), values around 55-60% have been consistently obtained (Crofoot & Harrison, 2012; Reda et al.,

TOC

2016), with peaks up to 78% (Reda et al., 2017). In the case of flat plate collectors, there are cases with relative high efficiencies, around 50-65% (Abdel-Salam et al., 2014; Enteria & Mizutani, 2011; Henning et al., 2001), and others with low reported values circling 20-30% (Chang et al., 2009; Selke et al., 2016). Considering all of the above, it was decided to use thermal efficiencies in the range of 55-65% for the purpose of the assessment.

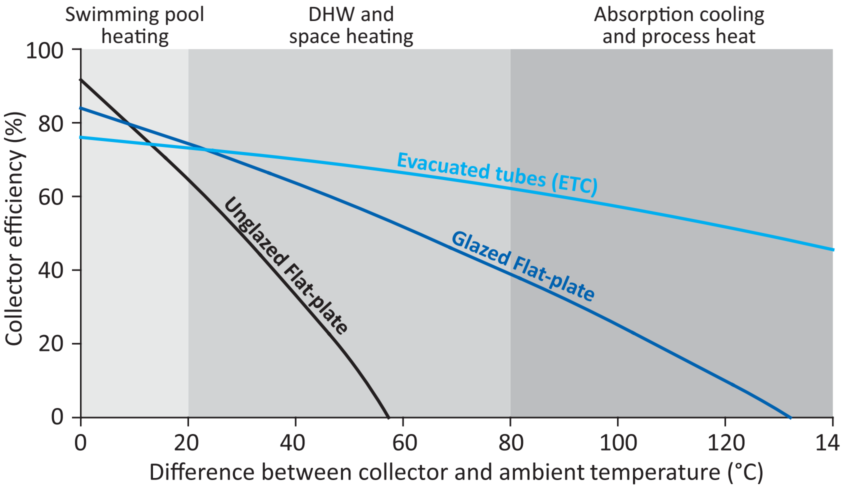


FIGURE 8.1 Graph of solar thermal collector (STC) efficiency vs temperature differential.

The last parameter refers to the coefficient of performance of the solar cooling system ($COP_{coolsys}$). The solar cooling technologies considered in the assessment are depicted in Table 8.5, along with their general expected performance ranges, based on the specialised literature (Kohlenbach & Jakob, 2014; SOLAIR, 2009). Additionally, efficiencies for solar cooling concepts and prototypes over 0.5 kW and under 5 kW are shown, based on the state-of-the-art review conducted in Chapter 7. The specific performance of these experiences is highly relevant due to the low capacities to be met by the façade integrated systems, ranging from 0.8 to 1.8 kW in the assessed scenarios. The highest registered values (Elmer et al., 2016; Finocchiaro, Beccali, Brano, et al., 2016; Irshad et al., 2017; Jaehnig, 2009; Reda et al., 2017) are used as reference of the current limits of the technology for small-scale applications, but evidently further research is needed to ensure these values under real continuous operation.

TABLE 8.5 Solar cooling technologies considered in the assessment and performance ranges reported in the literature.

ENERGY INPUT	COOLING TECHNOLOGIES	GENERAL $COP_{COOLSYS}$	COP 0.5 - 5 KW
Solar Electric	Thermoelectric cooling	-	0.66 - 1.15
Solar Thermal	Absorption cooling	0.50 - 0.75	0.23 - 0.78
	Adsorption cooling	0.50 - 0.70	0.12 - 0.63
	Solid desiccant ccoling	0.50 - 1.00	0.20 - 1.25
	Liquid desiccant cooling	≈1.00	0.40 - 1.26

Each coefficient of performance refers to the main energy input, so they correspond to thermal and electrical efficiency for solar thermal and solar electric respectively. In the case of thermoelectric cooling, space cooling application is in early R&D stages, so further developments are needed to come up with general COP values. Also, as mentioned before, these values account for the main cooling process, providing a simplified assessment without considering other types of energy to power up additional equipment, such as pumps for absorption heat pumps, or evaporative cooling units for desiccant systems. On the other hand, thermoelectric cooling is driven by direct current, so an inverter and subsequent losses derived by do not need to be considered in the calculations (Prieto et al., 2017a).

The assessment is carried out in two stages. Firstly, electrical and thermal solar fractions for all orientations and locations are shown and described, discussing the climate related application feasibility of the selected cooling technologies. Secondly, further optimisation of the results is carried out, exploring the impact on the solar fraction following higher exposed collector area, and a lower tilt angle on PV panels and thermal collectors. The discussion then will revolve around certain design constraints for façade integration, along with application possibilities in other climates not fully covered under the first assessed scenario.

§ 8.3 Results and discussion

§ 8.3.1 Climate feasibility for the application of solar cooling integrated façades

As explained before, the first stage of the evaluation sought to explore the climatic potential of different locations, for the application of solar cooling integrated façade concepts. Local solar availability and cooling demands were considered as the differentiating parameters between the addressed climate contexts for the evaluation. The results, depicted in graphs under Figures 8.2 and 8.3 for warm dry and warm humid climates respectively, are presented in terms of resulting solar fraction (SF) compared to the coefficient of performance of any given solar cooling system (COP_{coolsys}). This allowed for the exploration of the local circumstances and climatic potential of all addressed locations in general, before discussing the applicability of specific solar cooling systems. Furthermore, the graphs serve as charts to check how efficient should a system be in order to reach a solar fraction of 100% in the defined scenarios.

The graphs consider thermal COP and electric COP separately, based on the efficiencies of solar thermal collectors (STC) and photovoltaic panels (PV) respectively. Moreover, each one is depicted by two trend lines, representing the maximum and minimum efficiencies considered in the evaluation for STC (55-65%) and PV (18.5-23%). Consequentially, from a performance standpoint, solar electric cooling systems start with a disadvantage, needing higher COPs to account for the lesser efficiencies of PV panels compared to STCs.

Taking a general look at the results, there is a clear trend in favour of warm dry climates, making them more generally suited for solar cooling applications. This is not surprising, considering the overall higher solar availability and relative lower cooling demands compared to humid climate contexts. Evidence of this is the fact that Lisbon comprises the best results in all orientations, while the worst results are reported in either Singapore or Hong Kong, due to less solar availability and the highest calculated cooling demands for the simulated scenario.

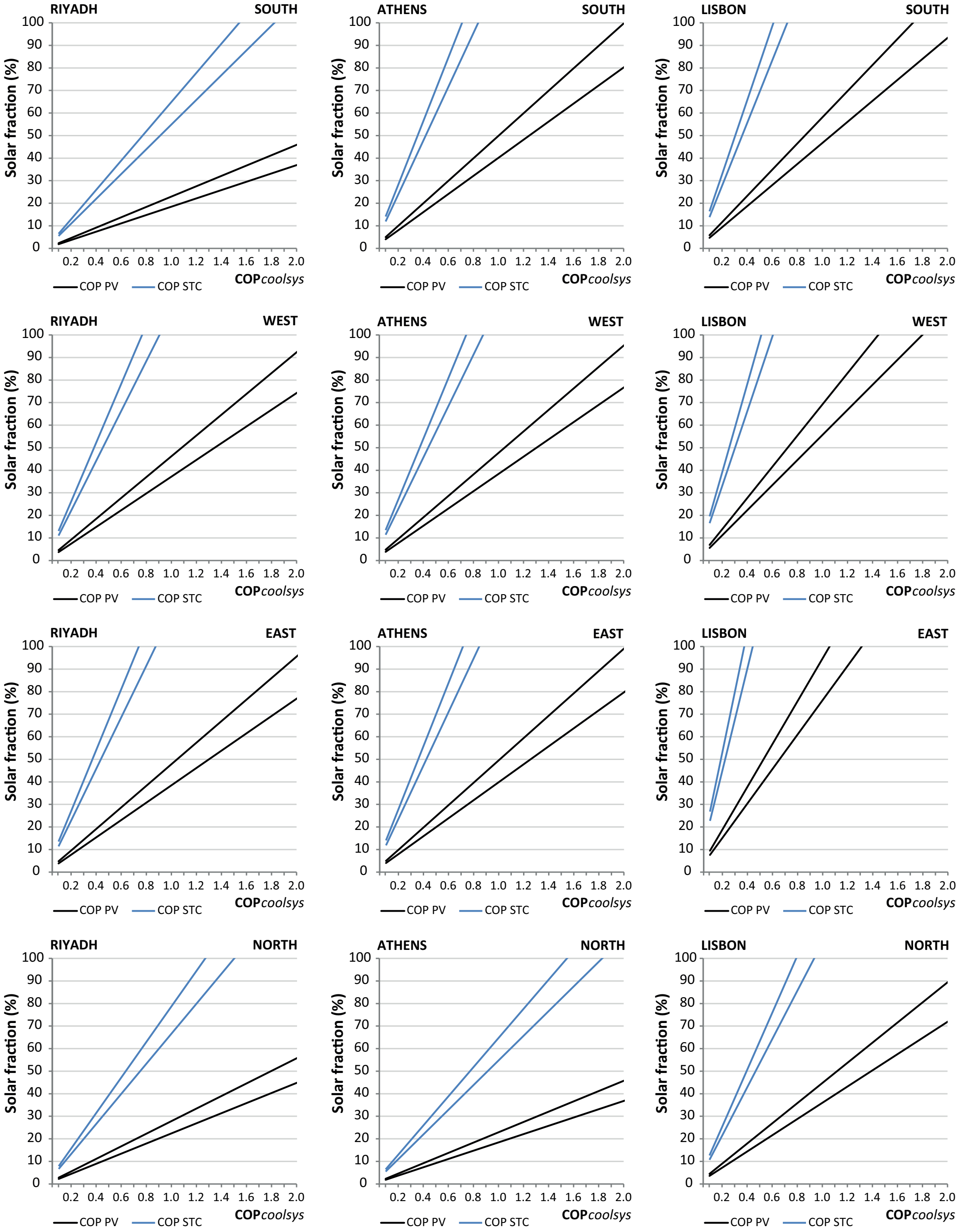


FIGURE 8.2 Comparison between solar fraction and COP (electric and thermal) of a given solar cooling system in warm dry climates.

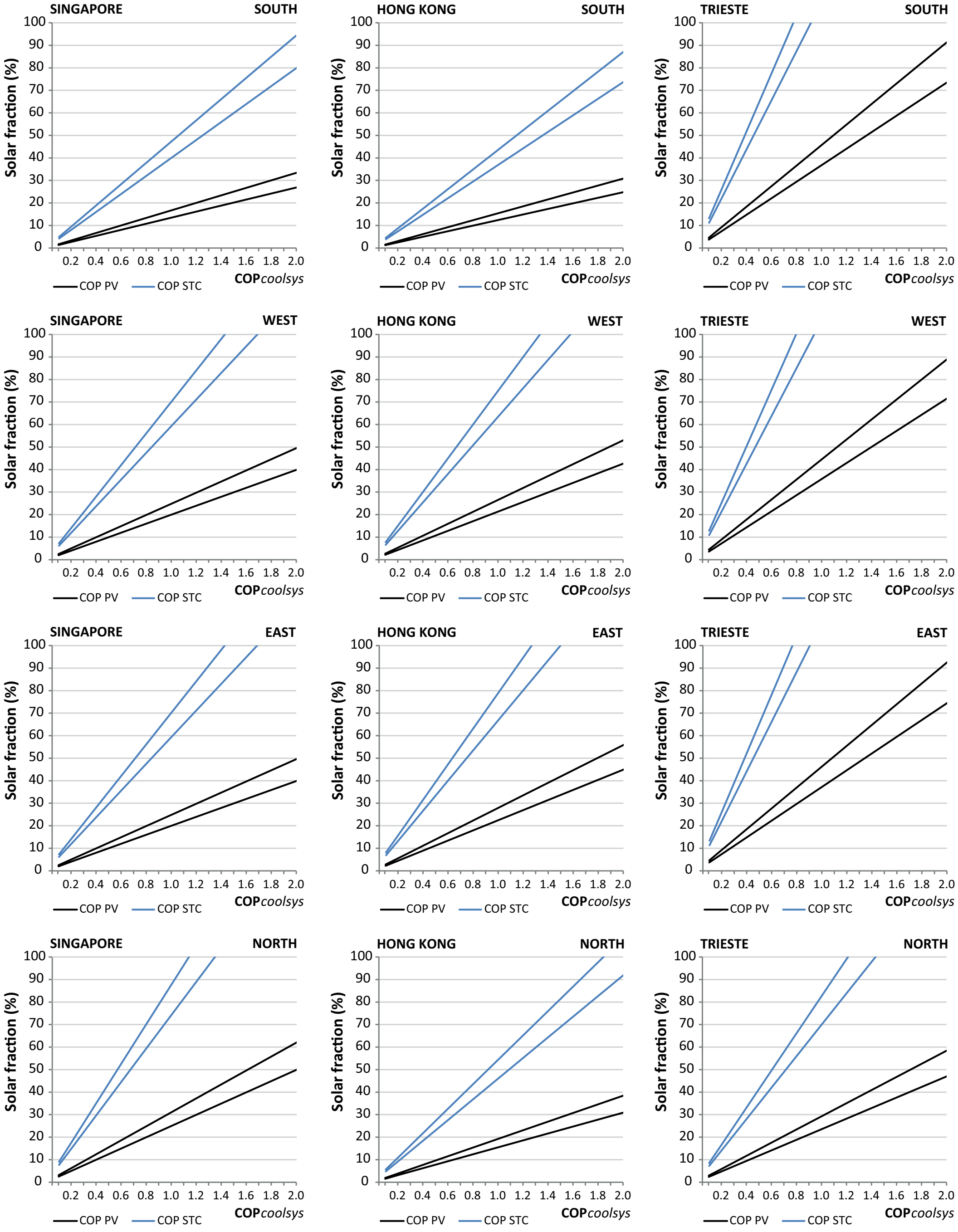


FIGURE 8.3 Comparison between solar fraction and COP (electric and thermal) of a given solar cooling system in warm humid climates.

This fact is especially clear in west and east orientations, where an arrangement of best to worst results puts Lisbon, Athens and Riyadh (warm dry climates), ahead of Trieste, Hong Kong and Singapore (warm humid climates). Within each climate group, locations are also neatly arranged following the severity of the context, from mild to extremes. Hence, for these orientations, temperate climates are more suited for solar cooling façade application than extreme climates, although extreme dry contexts (desert) are more suited than temperate humid ones. In the case of south applications, locations between the equator and the tropic of cancer (Singapore, Hong Kong and Riyadh) have the worst results, due to the severity of the climate and less solar radiation being harvested by a 90° tilted south facing plane because of the high solar irradiance incidence angle. At the same time, Singapore has the second best results for north orientations (only after Lisbon), benefiting of direct irradiance on north facing façades by being virtually on the equator.

Discussing applicability potential on each specific context and orientation, four distinct trends were found in the evaluation of the six locations. In the cases of Riyadh and Hong Kong (a), results for east and west applications are the best, and very similar to each other. Then north applications, and finally south ones. This is explained by the low latitudes of these locations, as argued before. Secondly, in the cases of Athens and Trieste (b), east, south and west applications have very close results, being virtually tied with a minor advantage for east façades, while north application is markedly underwhelming in comparison.

Façade applications in Lisbon (c) favour east orientation with difference, steadily declining for west, south and north (best to worst). Finally, Singapore (d) is regarded as a special case due to its particularities already discussed, showing best results for north applications, with east/west following and south far behind. Interestingly, with the sole exemption of Singapore, east orientation seems to be the most suitable for the general application of façade integrated solar cooling systems. This is explained by the good solar availability on a 90° tilted plane on both east and west orientations, plus the lower cooling demands on east facing rooms, compared to west offices.

The next step after assessing the climatic and solar potential of each selected location, was to evaluate the feasibility of the application of self-sufficient solar cooling façade modules in their different orientations, based on reported performance values associated to currently available technologies. Based on the graphs above, Table 8.6 shows the COP values that a solar cooling system ($COP_{coolsys}$) should meet, in order to reach a solar fraction of 100% at every location and orientation. These values are calculated assuming maximum efficiencies for STC and PVs (65% and 23% respectively), to draw the line at the minimum $COP_{coolsys}$ required for every scenario.

TOC

TABLE 8.6 Minimum COP values required for a solar cooling system ($COP_{coolsys}$) in order to reach a solar fraction of 100% per orientation and location.

SOLAR COOLING	LOCATION	REQUIRED MINIMUM $COP_{COOLSYS}$ FOR SF=100%			
		SOUTH	WEST	EAST	NORTH
Electric $COP_{solarsys}$ = 0.23	Riyadh	4.36	**2.17**	**2.09**	3.59
	Athens	**2.01**	**2.10**	**2.02**	4.37
	Lisbon	**1.72**	**1.45**	**1.05**	**2.24**
	Singapore	5.99	4.04	4.04	**3.23**
	Hong Kong	6.50	3.78	3.58	5.21
	Trieste	**2.19**	**2.25**	**2.16**	**3.43**
Thermal $COP_{solarsys}$ = 0.65	Riyadh	1.54	**0.77**	**0.74**	1.27
	Athens	**0.71**	**0.74**	**0.71**	1.55
	Lisbon	**0.61**	**0.51**	**0.37**	**0.79**
	Singapore	2.12	1.43	1.43	**1.14**
	Hong Kong	2.30	1.34	1.27	1.84
	Trieste	**0.78**	**0.80**	**0.76**	**1.21**

The required minimum $COP_{coolsys}$ values were then compared to the COP ranges registered in Table 8.5, for small-scale application of current solar cooling technologies. The cases that meet the calculated requirements for a solar fraction of 100% are highlighted in colour in Table 8.6, showing the theoretical feasibility of solar electric or solar thermal integrated façade units, based on the assumed scenarios.

As mentioned before, discussing performance limits, solar electric systems have a disadvantage due to the lower conversion efficiencies of PV panels compared to STCs. This is evident by looking at Table 8.6, showing that thermoelectric cooling technologies are only capable to meet the cooling requirements in an east oriented room in Lisbon, while required COP values in south and west orientations are above the 1.15 maximum reported for the technology. The lower efficiencies of PV panels, ask for very high efficiencies from the solar cooling system to compensate in most locations. This drawback remains even considering the hypothetical use of vapour compression cooling systems coupled to PV panels for energy input, with markedly higher COP compared to thermoelectric cooling units. Nominal Energy Efficiency Ratios (EER) of commercial small residential units circle around of 12-13, which translate to electric COP values of 3.5-3.8 (Goetzler et al., 2014), or 3.15-3.4 for the entire system considering an inverter (90% efficiency) to change the current from DC to AC for the operation of the cooling unit. These COP values mean that small-scale vapour compression heat pumps could deliver sufficient cooling in all orientations for Lisbon and Trieste, west and east in Riyadh, west, east and south in Athens, and only north in Singapore (bold but black in

Table 8.6). This shows that even the most efficient cooling technology currently available in the market cannot meet cooling demands in challenging climates by means of purely solar energy input. Hence, besides on-going explorations in the field of thermoelectrics, further development of PV technologies is needed in order to promote general solar electric façade integrated concepts.

On the other hand, thermal technologies have higher potential for application, judged solely by their reported efficiencies. Firstly, adsorption cooling systems, with maximum reported COP values circling 0.65, only seem to cope with cooling requirements in south, east and west orientations in Lisbon, being the most constrained solar thermal technology. Nonetheless, the maximum thermal COP around 0.8 reported for small-scale absorption heat pumps, would be enough to back their application in south, west and east orientations of Trieste and Athens, east/west orientations in Riyadh, and all orientations in Lisbon. Finally, desiccant cooling technologies (solid and liquid), with higher reported COP values up to 1.25, may also meet the cooling demands of north facing rooms in Singapore and Trieste, besides being close to the required COP for east and west orientations in Hong Kong. It is worth mentioning that the orientations and locations where the cooling demands are potentially covered entirely by solar thermal systems, are the same cases that could be potentially covered with integrated small-scale vapour compression heat pumps. Hence, even though the latter technologies have higher COP values, regarded as more efficient, solar thermal systems may potentially achieve the same goal, through environmentally friendly cooling processes with low Global Warming Potential (GWP) refrigerants.

§ 8.3.2 Impact of façade design on solar collection and resulting solar fraction

Undoubtedly, improvements on the performance of solar cooling systems and solar energy conversion technologies would increase the applicability of integrated façade concepts. However, the design of the façade system itself may improve its potential for solar collection, providing higher energy input to the cooling system and therefore higher cooling output, even if current COP values are maintained. Therefore, the second evaluation stage explored the impact of the solar array on the overall performance, discussing constraints and possibilities for facade design.

Further optimisation of the solar fraction per location/orientation was sought by exploring two parameters: dimension of the solar array, and tilt of the PV or STC panels. The impact of a larger solar array is evident, with a direct correlation between its dimensions and the solar radiation harvested by it. The impact of panel tilt on the other

TOC

hand, largely depends on each orientation and location. The graphs in Figure 8.4 show the relation between solar irradiance on a exposed plane facing all orientations, and the tilt of said plane referring to the horizontal; on every addressed location. The graphs start with a 90° tilt, corresponding to a vertical wall, reaching an inclination of 60° to establish a trend. It is clear that the effect of the tilt is particularly relevant in south oriented facades, as well as some north orientations.

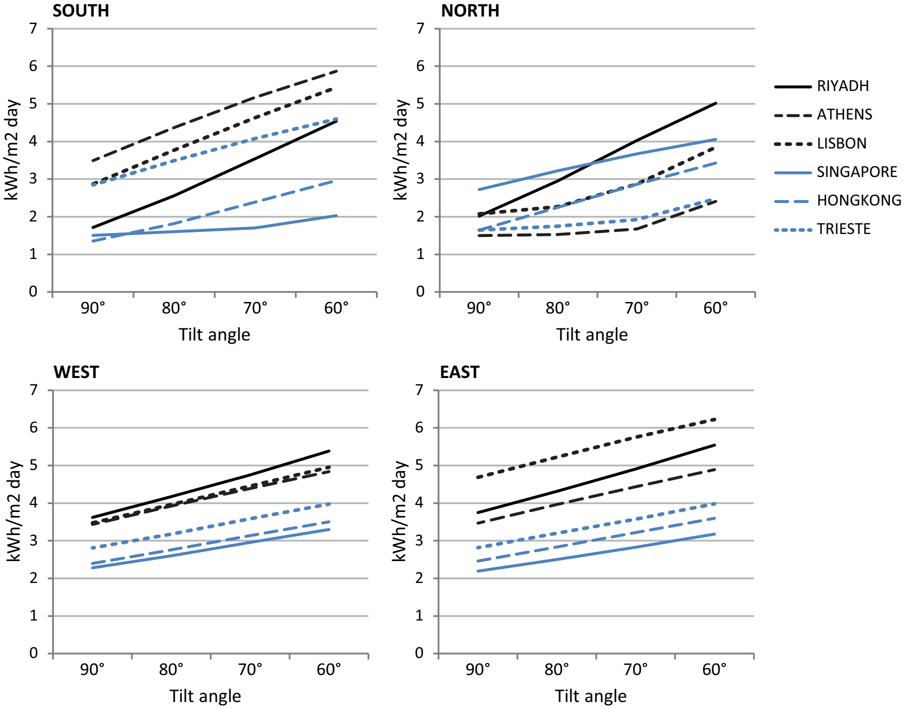


FIGURE 8.4 Relation between solar irradiance and the tilt of the receiving surface, for every orientation and location.

Higher solar yields certainly increase the application possibilities of self-sustaining solar cooling façade concepts. However, larger sizes and panel tilt potentially required for the solar array also imply design constraints for façade composition. These design implications and potential improvements in the performance of the systems are discussed by means of different scenarios for the evaluation, showcasing broad formal solutions derived by performance based decisions. Four scenarios were considered, based on the combination of array size and panel tilt, shown in Figure 8.5. Scenario A is the base case used in the first evaluation stage, comprising 50% of the façade area for a vertical solar array (90° panel tilt). Scenario B maintains the tilt, but increases the size of the solar array up to 75% of total façade area. On the opposite, under scenario C, tilt angle is lowered to 60° while the initial array size is maintained. Finally, scenario D's solar array spans 75% or the total façade area, with a slight tilt of 80°, which allows its use as façade cladding preventing self-shading. These selected scenarios are presented for discussion purposes as possible variations within an infinite amount of combinations and design choices. Nonetheless, their level of abstraction means that detailed analyses are required in order to move forward for hypothetical real applications under a finalised façade design concept.

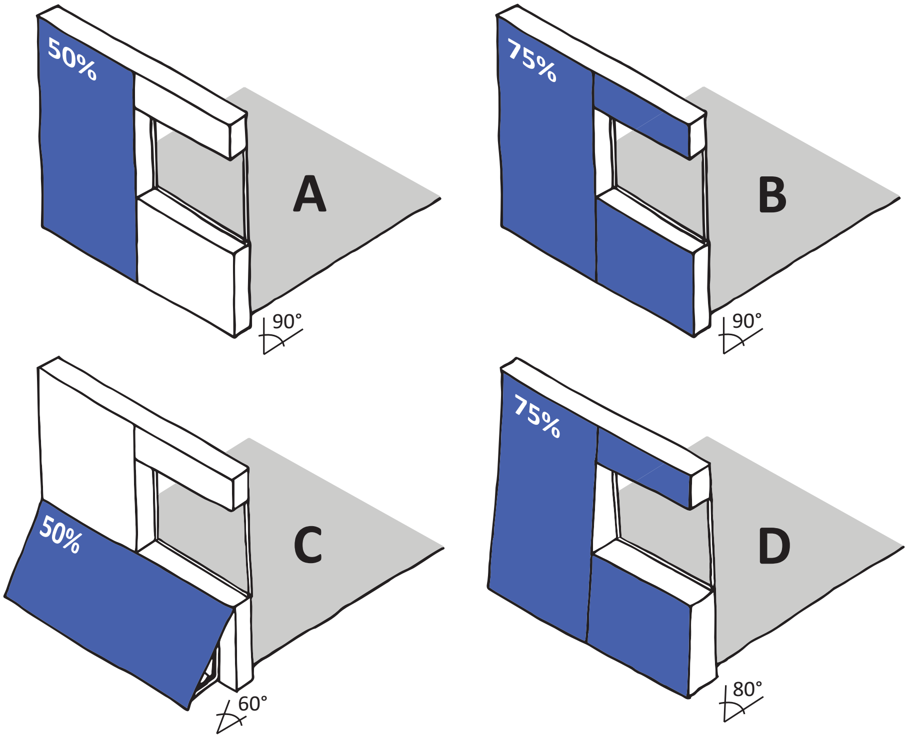


FIGURE 8.5 Scenarios considered in the assessment, combining array size and panel tilt possibilities.

Reference COP values for the solar array and solar cooling systems were defined for the purpose of the evaluation, considering thermoelectric, sorption and desiccant technologies (Table 8.7). The last two groups combine absorption and adsorption; and solid and liquid desiccants respectively, due to the closeness of their performance, to simplify the assessment. Moreover, maximum efficiencies of PV and STCs are assumed for thermoelectric and desiccant systems respectively. The fact that sorption technologies require higher input temperatures to properly operate (Prieto et al., 2017a) was considered by assuming a lower $COP_{solarsys}$ in the calculations.

TABLE 8.7 Reference COP values for solar array and solar cooling systems used in the assessment.

SOLAR COOLING TECHNOLOGIES	$COP_{SOLARSYS}$	$COP_{COOLSYS}$
Thermoelectric (TE)	0.23	1.15
Sorption (ABS-ADS)	0.55	0.75
Desiccant (SDEC-LDEC)	0.65	1.25

The results are presented in Table 8.8 and Table 8.9, in terms of the calculated solar fraction (SF) for every scenario, in each location and orientation. Evidently, scenarios with tilted panels generate higher solar fractions compared to scenarios with same solar array dimensions, in a fully vertical position; so regarding solar fraction, scenario C will always be better than scenario A (50% façade area), and results from scenario D will always surpass the results from scenario B (75% façade area). However, the optimal case varies from C to D, depending on the orientation, with general improvements in the range of 133%-265% compared to the results from the base case (A).

For east and west applications, scenario D is always the best. Moreover, in these cases, scenario B has also better (Lisbon, Athens and Trieste) or equal (Riyadh, Hong Kong and Singapore) results than scenario C. Hence, in east and west orientations, more panel area is preferable to tilted applications. In the cases of north and south orientations, results differ according to each location. In Riyadh and Hong Kong, both orientations have better results by scenario C, thus less tilt angle is preferable than more panel area. On the contrary, scenario D is the best for both orientations in Singapore and Trieste, benefiting from more exposed surface. Finally, in Athens and Lisbon, higher solar fractions for south applications are obtained with scenario D, while scenario C is better for north orientations.

For all cases, the best results are obtained either under scenario C or D, with the sole exemption of Singapore, where best scenarios are either D or B. In this case, lower panel tilt is not rewarded, possibly due to the higher percentage of diffuse radiation in the global solar irradiance, in a location characterised by high cloud coverage along the year.

TABLE 8.8 Solar fraction for scenarios A & B in all locations and orientations.

LOCATION	SOLAR COOLING	A (%)				B (%)			
		SOUTH	WEST	EAST	NORTH	SOUTH	WEST	EAST	NORTH
Riyadh	TE	26	53	55	32	40	80	82	48
	ABS/ADS	41	83	86	50	62	**124**	**129**	75
	SDEC/LDEC	-	-	-	-	-	-	-	-
Athens	TE	57	55	57	26	86	82	85	39
	ABS/ADS	89	85	89	41	**134**	**128**	**133**	62
	SDEC/LDEC	**176**	**168**	**175**	81	**264**	**252**	**263**	**121**
Lisbon	TE	67	80	**109**	51	**100**	**119**	**164**	77
	ABS/ADS	**104**	**124**	**170**	80	**156**	**186**	**255**	**120**
	SDEC/LDEC	**205**	**244**	**335**	**158**	**307**	**366**	**503**	**237**
Singapore	TE	19	28	28	36	29	43	43	53
	ABS/ADS	30	44	44	56	45	67	67	83
	SDEC/LDEC	59	87	88	**110**	88	**131**	**131**	**164**
Hong Kong	TE	18	30	32	22	27	46	48	33
	ABS/ADS	28	47	50	34	41	71	75	52
	SDEC/LDEC	54	**94**	**99**	68	82	**140**	**148**	**102**
Trieste	TE	52	51	53	34	79	77	80	50
	ABS/ADS	82	80	83	52	**123**	**120**	**124**	79
	SDEC/LDEC	**161**	**157**	**163**	**103**	**242**	**235**	**245**	**155**

The identification and discussion of the best results is useful to understand the impact of panel tilt and solar array size on the selected locations, establishing priorities for the design of optimal solar integrated facades per orientation, based on the resulting solar fraction of the overall system. However, the feasibility of a self-sufficient solar cooling façade, based on a specific technology, depends on said technology being able to provide a solar fraction of 100%. The cases that result on solar fractions over 100% are highlighted in blue in Tables 8.8 and 8.9, and cases over 90% are marked in bold.

Thermoelectric systems reach a solar fraction of 100% in Lisbon for south, east and west orientations under scenarios B, C and D; and in Athens only for south application in scenario D (east/west showing 94%-98%). Maximum values for north orientation in Lisbon reach 95% in scenario C. Results for other locations show maximum values of 87%-95% for east/west and 70%-97% for south orientations in Riyadh and Trieste. In Singapore and Hong Kong, east/west applications centre around 49%-56%, while south results are in the range 31%-39%. Maximum results for north oriented façades, excluding Lisbon, revolve around 42% and 80% (Athens and Riyadh, respectively).

TOC

TABLE 8.9 Solar fraction for scenarios C & D in all locations and orientations.

LOCATION	SOLAR COOLING	C (%)				D (%)			
		SOUTH	WEST	EAST	NORTH	SOUTH	WEST	EAST	NORTH
Riyadh	TE	70	79	81	80	59	**92**	**95**	70
	ABS/ADS	**109**	**123**	**127**	**124**	**92**	**143**	**148**	**110**
	SDEC/LDEC	-	-	-	-	-	-	-	-
Athens	TE	**96**	77	80	42	**108**	**94**	**98**	40
	ABS/ADS	**150**	**120**	**125**	66	**168**	**146**	**152**	63
	SDEC/LDEC	**296**	**237**	**247**	**130**	**331**	**288**	**300**	**124**
Lisbon	TE	**126**	**113**	**145**	**95**	**132**	**136**	**182**	84
	ABS/ADS	**197**	**177**	**226**	**148**	**205**	**212**	**284**	**131**
	SDEC/LDEC	**388**	**348**	**445**	**292**	**404**	**418**	**560**	**259**
Singapore	TE	26	41	41	53	31	49	49	63
	ABS/ADS	40	64	64	83	48	76	76	**99**
	SDEC/LDEC	80	**127**	**127**	**163**	**94**	**150**	**150**	**195**
Hong Kong	TE	39	45	47	46	36	53	56	45
	ABS/ADS	60	69	73	72	56	82	87	71
	SDEC/LDEC	**119**	**137**	**144**	**141**	**109**	**162**	**171**	**139**
Trieste	TE	85	72	75	51	**97**	87	**91**	54
	ABS/ADS	**132**	**113**	**117**	79	**151**	**135**	**141**	84
	SDEC/LDEC	**260**	**222**	**231**	**155**	**297**	**267**	**279**	**165**

Sorption based cooling achieves a SF over 100% in all orientations in Riyadh (C), and Lisbon (B, C, D). Application in south, east and west oriented façades in possible in Athens (B, C, D), Lisbon (A), and Trieste (B, C, D). Besides Riyadh and Lisbon, north application is only barely possible in Singapore (D), where SF reaches 99%. Apart from this, solar fractions in Hong Kong and Singapore reach 60% and 48% respectively for south orientations, while east/west applications reach up to 87% and 76%.

Finally, the higher COP of desiccant cooling systems increases their chances of application in different contexts. Riyadh was exempted due to the operational inapplicability of desiccant cooling in its climate. These systems work by enhancing the operation of evaporative coolers by taking care of the latent loads, through dehumidification of incoming fresh air. Riyadh experiences only sensible cooling loads, so the application of solar based dehumidification does not make sense (evaporative cooling is advised, though). Based on the assumed COP for desiccant technologies, these systems could reach a SF of 100% at all orientations in Athens (B, C, D), Lisbon (all scenarios), Trieste (all scenarios), and Hong Kong (C, D). In Singapore, only east, west

TOC

and north orientations are entirely covered, with a maximum south solar fraction of 94% (scenario D).

TABLE 8.10 Recommendations for further development of integrated façade concepts in each assessed location/climate context.

CLIMATE ZONES	LOCATION	RECOMMENDED SOLAR COOLING TECHNOLOGY	RECOMMENDATIONS FOR INTEGRATED FAÇADE DESIGN
Hot desert (BWh)	Riyadh	Sorption cooling (ABS/ADS)	Application in all orientations is potentially feasible. North and South applications depend on tilt, while East/West ones have more flexibility, being solved by either panel tilt or higher panel area.
Hot summer mediterr. (Csa)	Athens	Sorption cooling (ABS/ADS) & Thermoelectric cooling (TE)	South, East and West orientations are potentially suitable for TE application, reaching SF values close to 100% under high design constraints (panel tilt and high panel/façade ratio are required). The same orientations may be covered by sorption systems by means of either panel tilt or higher panel area.
	Lisbon	Thermoelectric cooling (TE)	South, East and West orientations are suitable for TE application, using either tilted panels or higher panel/façade ratio. For north applications, SF values close to 100% are reached through lower tilts.
Tropical rainforest (Af)	Singapore	Desiccant cooling (DEC)	Suitable for north application in all scenarios. East and west application feasible, by lower panel tilt or higher panel/façade ratio. South application highly constrained, requiring optimisation of both parameters to reach SF: 94%
Humid Subtropical (Cwa/Cfa)	Hong Kong	Desiccant cooling (DEC)	Desiccant cooling can provide sufficient SF for west and east orientations in virtually all scenarios (base case: 94%-99%). South orientation requires panel tilt and north applications may be solved by either panel tilt or higher panel area.
	Trieste	Sorption cooling (ABS/ADS) & Desiccant cooling (DEC)	Desiccant cooling application is feasible for all orientations in all scenarios. Sorption cooling is feasible for south, east and west application, by means of either panel tilt or higher panel/façade ratio.

Based on the assessment, some recommendations for the development of integrated façade concepts are drafted and depicted in Table 8.10, considering prospects for the assessed technologies in all selected locations, and design considerations for the optimisation of the solar radiation input. It is worth pointing out that applications on all orientations on virtually every addressed location are possible, under current performance values assumed in the evaluation. Hence, this is regarded as evidence of current opportunities for the development of integrated façade concepts, even

TOC

considering important design constraints. Further improvements on the performance and efficiency of compact solar cooling systems, especially designed for façade integration, will undoubtedly increase façade design variety and flexibility. Nevertheless, the numerical feasibility obtained by the assessment shows that solar driven cooling systems do not necessarily need to reach the same COP values of vapour compression heat pumps, in order to be a competitive alternative in specific locations.

§ 8.4 Conclusions

This chapter sought to assess the potential for the application of self-sufficient solar cooling facades in several warm climates across the northern hemisphere. The assessment focused on numerical calculations of the general efficiencies required by solar cooling technologies to meet cooling demands in several locations; exploring prospects in different climate contexts and orientations, while discussing certain design constraints for façade composition. The calculations were mainly based on solar availability, from statistical climate data; cooling requirements per orientation/location, from dynamic simulations; and reported efficiencies of state-of-the-art solar cooling concepts as reference of current limits of the technology. Different scenarios were explored to discuss the impact of certain design parameters (panel tilt and panel/façade area ratio) on the performance of the façade configurations, per orientation and location.

Unsurprisingly, warm-dry climates were found to be more suited for solar cooling façade applications, due to their higher solar availability and relative lower cooling demands, compared to humid climates. Regarding orientations, the use of vertical solar panels as a base case shows that with minor exemptions, east/west applications are the best suited, favouring dry over humid climates, and temperate climates over extreme environments. For south applications, locations between the tropics have the worst results, due to both climate severity and low solar incidence angle in facades. Contrarily, locations near the equator present better opportunities for north façade applications.

Regarding the feasibility of particular solar cooling technologies, solar electric processes are more constrained due to the lower efficiencies of PV panels compared to solar thermal collectors, and limited efficiencies of thermoelectric modules. Hence, self-sufficient façade modules are only theoretically feasible on east orientations in Lisbon. Based purely on performance values, solar thermal technologies have a wider range for application, reaching a solar fraction of 100% in all orientations in Lisbon and Trieste,

TOC

and in some orientations in Riyadh, Athens and Singapore. Application possibilities expand when considering more area for the solar array and lower tilt angle on the panels, but they imply aesthetical and constructional constraints for façade design. Based on this, recommendations for the development for integrated façade concepts were drafted, considering prospects for the exploration of suitable technologies for specific locations, and façade design considerations for the optimisation of the solar input per orientation.

Further development of thermoelectric façade concepts is recommended for application on the temperate dry climates of Lisbon and Athens. The former allows for more design flexibility, but either panel tilt or a solar array over 50% are required to fully cover cooling demands in most orientations. Results showed that application in Athens is potentially feasible, but the design is heavily constrained. In any case, the simplicity associated with the technology makes it worth exploring for clear feasibility on mild dry locations.

Discussing solar thermal, sorption cooling systems are recommended for application in Riyadh, Trieste and Athens. All orientations on temperate climates are potentially covered with minor extra design constraints, compared to the base scenario; which also extends to east/west application in Riyadh. Application on north/south façades in Riyadh requires lower panel tilt to reach a solar fraction of 100%. The higher reported performances of desiccant cooling technologies and their particular handling of latent loads, make them especially suited for humid environments. Thus, the development of desiccant integrated façade units is recommended for Trieste, Hong Kong and Singapore. On temperate environments, reported COP values are theoretically enough to allow for application on all orientations with minor design constraints. On Hong Kong and Singapore, west, east and north applications are feasible with either lower panel tilt or higher panel area; but south applications are heavily constrained, particularly in tropical contexts.

The numerical assessment has shown that the application of solar cooling integrated façade concepts is theoretically feasible in virtually all climate contexts and orientations, although based on the upper limits of performance reported for the involved technologies and components; and important design constraints in some cases. Hence, further research on the performance of integrated and compact units is needed, in order to ensure reliable efficiencies and hopefully increase them to provide more flexibility for the design of façade systems. The fact that not every climate was found suitable for the application of every addressed solar cooling technology is not seen as a limitation, but rather as an opportunity to explore distinct integrated concepts with technology that responds better to the particularities of each climate context. In any case, regardless of future developments on the performance of the systems, the application of integrated façade concepts heavily relies on the optimisation of the solar input, and the reduction

TOC

of cooling demands through passive cooling strategies. Hence, a climate responsive approach to façade design is a basic condition; allowing for the integration of cooling systems only if still needed. Finally, it is important to reiterate that this assessment purely focused on numerical calculations and broad climate data to discuss application potential, but detailed calculations and dynamic performance simulations would be needed for the design of a façade unit for a particular building in a specific context. Moreover, extensive research is still needed to solve technical issues for the operation of compact units, and to cope with architectural requirements for façade integration of required components and systems.

TOC

TOC

9 Conclusions

This dissertation aimed to explore the possibilities and constraints for the façade integration of solar cooling systems, in order to support the design of climate responsive architectural products for office buildings as an alternative to conventional AC systems. This final chapter summarises and discusses the main outcomes of the dissertation. Firstly, responses to the research questions are showcased, starting with the sub-questions and their particular findings, leading to a comprehensive answer to the main research question driving the research project. Then, general conclusions are drafted, outlining the scientific contribution and limitations of the study to finalise with recommendations for further developments in the field.

TOC

§ 9.1 Introduction

This thesis aimed to explore the possibilities and constraints for the façade integration of solar cooling systems, in order to support the design of climate responsive architectural products for office buildings as an alternative to conventional AC systems. The exploration was conducted through diverse qualitative and quantitative assessments, in order to provide a comprehensive answer to the main research question, and the sub-questions that build up to it. Following the discussion of these answers, this chapter finalises with general conclusions, highlighting the scientific contribution and limitations of the study, besides outlining recommendations for further development and final remarks.

§ 9.2 Answers to the research questions

The responses to the sub-questions are presented first, as partial outcomes that lead to a comprehensive response to the main research question, featured directly after. The sub-questions outline the thesis chapters, hence the conclusions summarise the main findings of each chapter.

§ 9.2.1 Sub-questions

What is the available knowledge on façade related cooling strategies for office buildings? (Chapter 2)

This first sub-question aimed to present a panorama of cooling research in office buildings as a start point for the thesis, identifying relevant research trends and current knowledge gaps to expand the background of the research project. This panorama of the available knowledge in the field was the outcome of systematic data gathering, categorisation of reported research experiences, and the detailed review and discussion of relevant findings. Peer reviewed scientific articles published from 1990 to 2014 were the source of the study, generating a journal article database for referential purposes of the thesis. Chapter 2 showed an initial exploration of this database, conducted at the beginning of the research project (2014). Nonetheless, the database kept

TOC

growing during the course of the study, adding new experiences and state-of-the-art developments.

The initial exploration conducted in 2014 showed that cooling research follows an increasing trend over time, which remains true for different climates (temperate, hot-arid, hot-humid) and cooling sources (passive, active, solar). Interestingly, solar cooling research related to building applications has experienced steady growth from 2008 onwards. This trend has been maintained until today with current explorations of integrated façade concepts, thermoelectric based prototypes in particular, published in the last three years. This evidences increasing interest and current relevance of the topics studied in this dissertation. Regarding research content, most experiences deal with passive cooling, and especially heat prevention strategies. Simulations are the preferred evaluation tool by far, although there is an increasing amount of on-site monitoring studies and prototype testing of new technologies, as validation of previous simulations. Moreover, further tests under real conditions are encouraged when possible. Besides this clear knowledge gap, other identified gaps are the need for more research on heat dissipation cooling principles, such as ground , evaporative, and solar cooling; and the exploration of the architectural integration of active/hybrid low-energy cooling equipment and systems, a challenge that defined the focus of this research project.

What are the conceptual issues and state-of-the-art components and systems to consider for solar cooling façade integration? (Chapter 3)

This question sought to define the concept of solar cooling integrated facades, and the components and technical possibilities comprised by it. Firstly, they are defined as façade systems that consider all necessary equipment to self-sufficiently provide solar driven cooling to a particular indoor environment. From an architectural point of view, the façade integration of building services is regarded as a second step in the design of climate responsive or adaptive façades. Hence, this definition acknowledges a necessary first step of design optimisation through passive strategies or supplementary measures to take care of regulatory façade functions. Moreover, from a constructive standpoint, building services integration can follow either an integral or a modular approach, with different impacts on façade design possibilities and construction and assembly processes.

Discussing solar cooling technological possibilities, a first important distinction to make is between solar electric and solar thermal processes, which will have a great impact on the external appearance of the façade unit. The former rely on photovoltaic panels (PV) and batteries, while the latter deal with solar thermal collectors (STC) and heat storage units. Various cooling principles derive from this major distinction: thermoelectric, sorption, desiccant and thermomechanical cooling, along with sub-principles and systems within them. Nonetheless, self-sufficient decentralised cooling modules need to consider all necessary equipment to remove heat from indoor spaces and release it outdoors. Therefore, all these components are categorised in three main groups, charting the most common possibilities for cooling generation, distribution, and delivery. Although talking in terms of 'cooling generation' or 'delivery' are not physically correct, these categories were preferred for their simplicity.

Cooling generation comprises solar cooling principles, and their corresponding energy conversion technologies (PV or STC). Cooling distribution discusses general technology based on different heat transfer mediums (air, water or mass); while finally, under cooling delivery, several systems for heat exchange with the indoor air are showcased. The integration of technological components from all three groups is regarded as a condition for the development of self-sufficient cooling façade modules. Furthermore, while distribution and delivery basically cover all general possibilities; new alternative cooling processes could be added in the 'generation' tab, further expanding the proposed framework for design and development of self-sufficient cooling facades.

What are the main perceived problems for building services integration in facades at different stages of the façade design process? (Chapter 4)

The answers to questions 3 and 4 are derived from the analysis of the results from the questionnaire exhibited as Appendix A. In general, barriers related to the overall process are perceived as more pressing issues to solve than issues about the end product itself, to allow for widespread façade integration of building services. In particular, problems related to the coordination among professionals from different areas are perceived as the most relevant ones, which holds true in all three defined stages of façade development (design, production and assembly). Discussing other highly mentioned process related problems, lack of technical knowledge seems to be especially relevant during design and assembly stages. The fact that this did not appear as a major problem during the production stage, is regarded as evidence of the experience and maturity of façade building companies, at least in the European context, where most responses came from. Nonetheless, several logistical issues were pointed out 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 usual underestimation of cost projections during design phases. Finally, other mentioned problems, of minor compared reference, 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,

TOC

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 identified product related barriers, albeit with lower mentions in 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 have the same importance than process related aspects, they represent basic requirements and relevant challenges to overcome in the path for the development of components and systems for façade integration.

What are the main perceived barriers for façade integration of solar collection technologies? (Chapter 5)

Regarding the particular integration of solar collection technologies in facades, 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.

On a side note, the classification of responses from this section of the questionnaire followed slightly different categories compared to the assessed barriers for building services integration. In that case, the barriers were identified solely based on the provided responses, while in the case of solar technologies it was decided to use pre-defined categories already validated in the literature, allowing for the comparison and discussion of the findings against previous experiences in the topic.

A further exploration of product related barriers was conducted, based on the gathered responses, in order to freely identify key aspects to draft recommendations for future developments. Hence, detailed product related barriers refer to performance, technical complexity of the systems, aesthetics, durability, and product availability; which unsurprisingly closely match the identified key product related aspects for building services integration. In this case though, performance and aesthetics are the main perceived issues to overcome, which makes sense considering the strong impact of solar collectors and PV panels on the outer finishing of the façade and thus, the external appearance of buildings.

What is the potential impact of the application of passive cooling strategies on the cooling demands of office buildings in different warm climates? (Chapter 6)

To answer this question, an assessment of the effectiveness of selected passive strategies was conducted, based on a statistical analysis of published data from previous research experiences, and additional cooling demand simulations under a controlled

TOC

setup. The assessment focused on the most common heat prevention and heat dissipation strategies applied on buildings, avoiding hybrid systems of more complexity, to provide referential performance ranges for early design stages. Thus, the effectiveness of solar control (shading, glazing type, window-to-wall ratio) and ventilation strategies (when external conditions allow) was assessed in several locations from warm-dry (Riyadh, Athens, Lisbon) and warm-humid (Singapore, Hong Kong, Trieste) climates of different severity.

In general terms, the results showed that the potential impact of these strategies is quite relevant in all climates, affirming the importance of a climate responsive design approach for buildings. As expected, this impact is larger in warm dry climates than in warm humid ones. Maximum cooling savings obtained from the application of combined strategies on a worst case scenario, reach up to 80% in Lisbon and 70% in Riyadh and Athens; compared to 40% and 65% in Singapore / Hong Kong and Trieste, respectively. Nevertheless, it was found that the mere inclusion of passive strategies is not enough to guarantee these savings. Hence, they need to be carefully considered within a conscious design process to not only optimise their effectiveness, but even more importantly, to avoid counterproductive effects.

Regarding particular strategies, lower window-to-wall ratio (down to 25%) was found to be a highly effective strategy in all events and every climate zone. Similarly, natural ventilation is an important complement to solar control, leading to relevant extra savings in all locations except Hong Kong and Singapore, where its use increased cooling demands due to the high humidity (latent loads) of incoming air. Finally, the use of external shading devices or reflective glazing showed potentially good results as standalone strategies, but counterproductive effects when used in combination, due to their redundant action. Therefore, the choice between one or the other should follow local particularities of the climate context, users' preferences, and other architectural considerations.

What are the current possibilities and technical barriers for the architectural integration of solar cooling technologies in façade systems? (Chapter 7)

This question was answered through the qualitative assessment of the current façade integration potential of main solar cooling technologies, based on an exhaustive state-of-the-art review. Hence, thermoelectric, sorption, and desiccant technologies were assessed in terms of the main product related barriers for façade integration of building services, identified in Chapter 4. This showed what is currently possible for each assessed technology, while identifying bottlenecks and technical barriers to overcome. Furthermore, different paths for the development of distinct façade integrated products were recommended, based on the strengths and shortcomings of each technology.

TOC

First of all, no technology currently meet 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. The detailed assessment is showcased in Chapter 7. Nevertheless, in summary, 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. 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. Liquid desiccant systems are potentially promising, but the overall technology is less mature compared to the others. Finally, a partial integration approach is recommended for further explorations on compact adsorption and solid desiccant cooling systems, acknowledging certain technical barriers while promoting the alternative development of products for semi-decentral application and cooling distribution to areas far from the façade.

What is the potential for the application of self-sufficient solar cooling façades in different warm climate contexts, and what is the impact of the climate conditions on façade design possibilities? (Chapter 8)

Results from numerical calculations show that the application of self-sufficient façade concepts could be feasible on virtually all orientations from every assessed location. Even though these outcomes follow 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 the dimensions of the solar array, and panel tilt. These design constraints are more pressing in south and north facades, making east and west orientations more generally suited for solar cooling applications. Regarding climatic application potential of the assessed technologies, there are clear research and development paths. Although solar electric processes present clear advantages for façade integration, as discussed in Chapter 7, their overall performance is an important barrier, allowing for application at most in temperate dry climates, under medium to strong design constraints. Solar thermal offers more possibilities, recommending further research 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. On Hong Kong and Singapore, west, east and north applications are theoretically feasible with medium design constraints, but south applications are heavily hindered.

The discussed design constraints 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, BIST and 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 are 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.

§ 9.2.2 Main research question

To what extent can solar cooling technologies be integrated into the building envelope, in order to meet local thermal requirements through climate responsive integrated façade units, as an alternative to conventional centralised mechanical cooling in office buildings?

The driving force of the research project was the intention to test the limits of solar cooling integration in façades, showcasing current possibilities while identifying technical constrains and barriers to overcome for the widespread application of integrated façade concepts. A short and simple answer to the main research question is that self-sufficient integrated façade concepts based on solar cooling technologies are still far from widespread application, based on current possibilities. Although interesting prospects were identified in this dissertation, important technical constraints need to be solved to conceive a façade component fail-tested for application in buildings. Furthermore, several barriers related to the façade design and development process would need to be tackled in order to introduce architectural products such as these into the building market.

TOC

In spite of this, there is potential for further development, aiming to overcome the constraints and barriers identified throughout the research project. This brings us to a second, lengthier version of the answer provided above, in order to fully address the extents of current possibilities for façade integration. Seeking an answer to the main research question proved to be a complex task, due to several requirements of diverse nature. The answers to the sub-questions discussed above, address the different types of requirements to meet, focusing on specific aspects of the main research problem. However, they present a fragmented panorama of current possibilities for façade integration. Therefore, an effort to summarise all findings was conducted, in the form of the chart showed in Figure 9.1. This chart is regarded as a collated representation of the main outcomes of this dissertation, acting as graphical answer to the main research question, and a compass to guide further explorations in the topic.

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 depend then, 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. This is regarded as the main focus of the dissertation, exploring the suitability of solar driven cooling generation technology, for the development of self-sufficient integrated cooling façade units. Therefore, this ring shows the outcomes from the evaluation conducted in Chapters 7 and 8, showcasing the potential for façade integration of each technology [Chapter 7] based on their response to several product related barriers for integration of building services [Chapter 4]; and the climate contexts where their self-sufficient application is theoretically feasible [Chapter 8], within a climate responsive design approach [Chapter 6].

Outside of the ring, there are barriers that do not respond to a specific technology, but are essential for the application of integrated products nonetheless. The list on the left down side showcases the main identified barriers for the integration of solar collection technologies in façades, namely PV & STC [Chapter 5]. The application of these technologies in façades is conditioned in particular by economic barriers and performance issues that require further explorations. Finally, the list on the upper right corner showcases perceived problems for façade integration of building services in general, related both to the façade design and development process, and the façade products themselves [Chapter 4]. Even if the assessed technologies meet all the technical requirements for façade integration, coordination is greatly needed to make this a reality. Moreover, the involved professionals need to understand the intricacies behind these systems; while the building industry ultimately needs to turn these concepts into architectural products, for different potential applications following the strengths and shortcomings of each solar cooling technology.

TOC

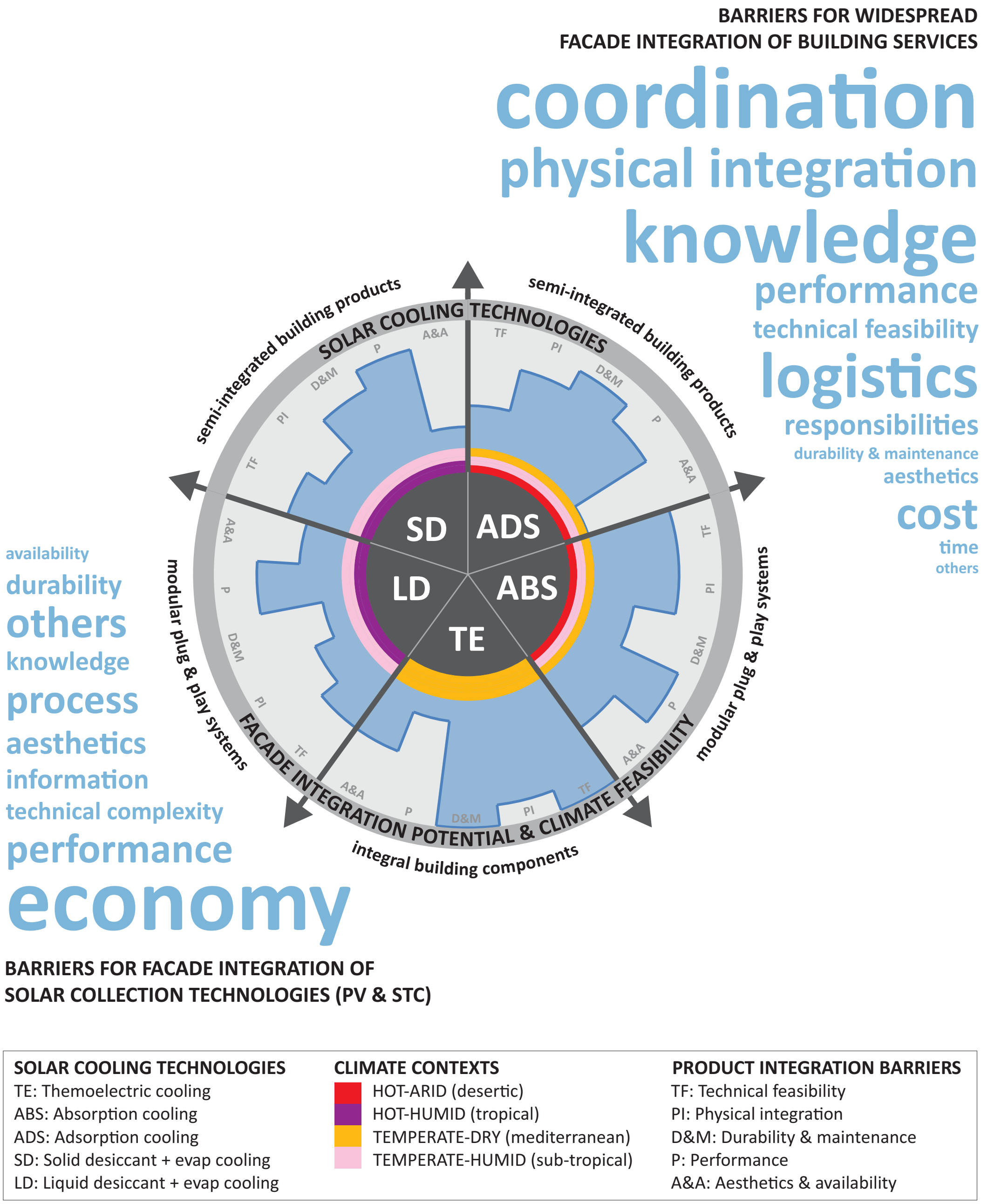


FIGURE 9.1 Chart of current possibilities and identified barriers for the development of solar cooling integrated facades.

§ 9.3 General conclusions

§ 9.3.1 Scientific contribution

Besides specific outcomes from each chapter, aiming at particular knowledge gaps; the main scientific contribution of this dissertation is the identification of the main barriers and constraints to overcome for the development of solar cooling integrated facades, based on current possibilities. The aforementioned chart, or compass, aims to serve as a graphical representation of a guide for further research and development, based on a comprehensive assessment of technical possibilities related to each evaluated technology, and state-of-the-art research in the field. Furthermore, the systematic approach developed in order to assess the façade integration potential of solar cooling technologies, could be further expanded to explore façade integration potential of new technologies in general, promoting the development of high-performance architectural products under a climate responsive façade design approach.

§ 9.3.2 Limitations of the research

The interpretation of the outcomes presented throughout this dissertation follows the focus and aim defined in the introductory chapter. Hence, while the results provide comprehensive answers to the research questions, certain limitations of the study need to be discussed in order to define their validity on a wider sense, as issues to be addressed to allow for replicability. Three main limitations are identified throughout the study, discussed as follows.

Firstly, the study consciously focused on commonly reported solar cooling technologies, for their environmental benefits in contrast to the use of harmful refrigerants in current air-conditioning systems. Therefore, widespread vapour compression systems were out of the scope of the study, to give room for the exploration of alternative cooling processes. Nonetheless, the main problem associated with current systems lies with the refrigerants used as working materials, rather than vapour compression technology itself. This technology is greatly mature, so it could potentially be a more promising choice for integrated concepts, if (and only if), environmentally friendly refrigerants are developed throughout research in chemical and material sciences, fields far from the scope of the present study, established within the boundaries of architectural engineering and climate design. In any case, if progress is indeed achieved on those areas, vapour compression technologies could be added into the proposed framework, coupled to PV panels as a solar electric process. Although for sure there would be specific technical issues to solve, the general barriers for façade integration and identified design possibilities will remain valid.

Secondly, the assessment of cooling demands was based on scenarios that considered a typical office room in an abstract building and site, without accounting for the potential impact of climate responsive design strategies at building level. While this followed a focus on the building envelope, façade design should not be isolated from the particularities of the building and the microclimate surrounding it. A conscious design approach should comprehend strategies at different scales to optimise the operation of buildings, and lower their energy consumption as much as possible. Furthermore, this also applies to the use and operation of buildings, and perceived comfort by users. Even though these aspects fall out of the scope of this dissertation, their correct assessment could help decrease cooling demands even further than the results showcased in this study.

Finally, economic aspects related to the potential cost of solar cooling integrated facades could not be directly assessed, due to the development level of current examples. Integrated façade concepts are still in early development stages; and small-scale solar cooling systems, designed for integration purposes are not yet market-ready. This is a highly relevant aspect, that could impede introduction to the market and widespread application. The potential for cost-effectiveness was indirectly addressed in the assessment in terms of the performance, technical complexity of the cooling process and required components for each technology, but specialised studies will be required in the future. All technologies assessed need to be further developed, and production chains need to be optimised in order to promote the application of competitive integrated concepts.

§ 9.3.3 Recommendations for further development

The main recommendations for further research and development in the field follow the different rings depicted in the chart from Figure 9.1, containing different barriers and thus, specific challenges for diverse disciplines.

First of all, there is 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 by the main addressed principles would enhance the potential for application at a base technological level. Furthermore, experimental and applied research on 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, to tackle technology-specific challenges identified in Chapter 7.

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 further manufacturing of cost-effective products for integration by system developers; technical improvements on electricity and heat storage technologies; and the exploration of new business models and subsidy schemes to incentivise their application. Moreover, the introduction of new players in the market, such as Tesla's solar venture, may increase market competition, lowering costs and promoting innovative solutions.

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 by 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.

§ 9.3.4 Final remarks

This dissertation explored the potential for façade integration and widespread application of solar cooling technologies as a response to rising cooling demands and the widespread use of environmentally harmful refrigerants in the built environment. However, this is regarded as a potential alternative to cope with the situation and not a definitive solution to the problem. Furthermore, the climate feasibility assessment conducted as part of the study, showed that, technical issues aside, the application of self-sufficient integrated façade concepts is heavily conditioned by achieving an important reduction of cooling demands throughout the use of passive design strategies. Therefore, the need to decrease cooling demands at base level remains to be the most logical starting point for a responsible design of sustainable buildings and cities.

A responsible approach to architectural design then, implies that all low-tech and passive options should be exhausted, considering the climate design of buildings, and operational measures involving buildings' users, before considering the integration of complex technologies into the building and particularly the façade. Most probably, if this were to be strongly enforced and taken to the limit, there would be no need for integrated systems for cooling in several temperate contexts. Although this may seem to hinder some prospects for application identified in this dissertation, this final remark aims to deliver a clear message for the understanding of the outcomes from this study. Technological developments will not solve current environmental challenges by themselves. They will merely provide an increasing array of possibilities, whose application needs to be carefully assessed during the development of sustainable buildings, under an overall environmentally conscious and responsible design approach.

TOC

Appendix Questionnaire: requirements for facade integration of building services

The purpose of this questionnaire is to gather information about **design and construction requirements for the architectural integration of building services in facades**, as a way to promote the development of new cost-effective multifunctional façade products for office buildings. The questionnaire is addressed to professionals with practical experience in the development of façade systems for office buildings, situated at any stage of the design and construction process. Hence, architects, façade consultants, system and building services suppliers and façade builders are welcome to participate.

This questionnaire is part of the ongoing PhD research project titled *COOLFACADE: Architectural integration of solar cooling technologies in the building envelope*, developed within the Architectural Façades & Products Research Group (AF&P) of Delft University of Technology (TU Delft).

All information will be treated as confidential and will be used only for research and dissemination purposes, in activities related with the development of the PhD project.

Questionnaire

Introduction

This questionnaire is divided in three main sections: (I) Basic Information, (II) Design process of building services integrated facades, and (III) Integration of solar technologies in the building façade. Filling this form takes about 10 minutes. Please provide only one answer for multiple choice questions unless specifically stated otherwise.

TOC

I. BASIC INFORMATION

1. Which alternative represents your background more closely?

- A) Architecture
- B) Engineering
- C) Material Science
- D) Other: _______________________________________

2. Which alternative represents the role that you have mostly taken within façade development processes?

- A) Architect / Façade Consultant (Designer)
- B) Façade builder
- C) System supplier
- D) Other: _______________________________________

3. How many years of experience do you have in the field?

- A) Less than 5 years
- B) Between 5 to 20
- C) More than 20

4. Where are your projects mostly located? (name up to three countries)

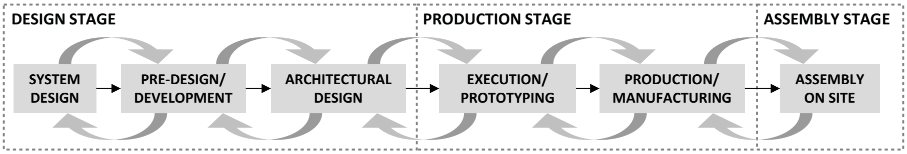
_____________________ | _____________________ | _____________________

5. Have you been part of a project involving the integration of building services in the façade? (heating, cooling or ventilation systems)

- A) YES
- B) NO

II. DESIGN PROCESS OF BUILDING SERVICES INTEGRATED FACADES

NOTE: To answer the following questions, please refer to the scheme below, which contains the stages of design and construction process for façade products (based on scheme in Klein, T. 2013):



Stages of development process for façade products (based on scheme in Klein, T. 2013).

6. In your experience, what is the importance of the following variables when discussing the possibilities for building services integration in facades during the design stage (pre-design and architectural concept) of the development process? (Please mark with an "X" the corresponding level of importance)

VARIABLES	NOT RELEVANT	RELEVANT	HIGHLY RELEVANT
AESTHETICS	-	-	-
PERFORMANCE	-	-	-
COST	-	-	-
TECHNICAL FEASIBILITY	-	-	-
USER CONTROL & INTERACTION	-	-	-
OTHER:	-	-	-

7. What are in your opinion the main problems associated with building services integration in facades encountered during the **DESIGN STAGE**? (mention up to three problems starting from the most relevant)

1st _

2nd _

3rd _

8. What are in your opinion the main problems associated with building services integration in facades encountered during the **PRODUCTION STAGE**? (mention up to three problems starting from the most relevant)

1st _

2nd _

3rd _

9. What are in your opinion the main problems associated with building services integration in facades encountered during the **ASSEMBLY STAGE**? (mention up to three problems starting from the most relevant)

1st ____
2nd ____
3rd ____

III. INTEGRATION OF SOLAR TECHNOLOGIES IN THE BUILDING FAÇADE

10. Have you had practical experience integrating any of the following solar technologies in façade systems? (you may check more than one alternative)

- A) YES, I have worked with integrated solar thermal collectors in façade systems
- B) YES, I have worked with integrated Photovoltaic cells (PV) in façade systems
- C) YES, I have worked with integrated solar cooling technologies in façade systems
- D) NO, I haven't worked with solar technologies.

11. Do you see potential for developing architecturally integrated façade products considering solar technologies?

- A) YES
- B) NO
- C) NOT SURE / If so, why not? ____

12. In your opinion, is there market currently for commercial application of solar integrated architectural products?

- A) YES
- B) NO
- Please specify ____

13. In your opinion, what would be the most important constraints to overcome in order to promote widespread integration of solar technologies into the façade? (mention up to three constraints starting from the most relevant)

1st ____
2nd ____
3rd ____

TOC

14. Would you be open to discuss your answers in more detail by means of an in-depth interview? If so, please write your full name, affiliation and contact information. If not, you may skip this question (all information will be treated as confidential and will be used only for research and dissemination purposes)

NAME: ____
AFFILIATION: ____
E-MAIL: ____

THANK YOU!

TOC

References

Abdallah, A. S. H., Yoshino, H., Goto, T., Enteria, N., Radwan, M. M., & Eid, M. A. (2013). Integration of evaporative cooling technique with solar chimney to improve indoor thermal environment in the New Assiut City, Egypt. International Journal of Energy and Environmental Engineering, 4(1), 1-15.

Abdel-Salam, A. H., Ge, G., & Simonson, C. J. (2013). Performance analysis of a membrane liquid desiccant air-conditioning system. Energy and Buildings, 62(0), 559-569. doi: http://dx.doi.org/10.1016/j.enbuild.2013.03.028

Abdel-Salam, A. H., Ge, G., & Simonson, C. J. (2014). Thermo-economic performance of a solar membrane liquid desiccant air conditioning system. Solar Energy, 102, 56-73. doi: 10.1016/j.solener.2013.12.036

Abdel-Salam, A. H., & Simonson, C. J. (2016). State-of-the-art in liquid desiccant air conditioning equipment and systems. Renewable and Sustainable Energy Reviews, 58, 1152-1183. doi: 10.1016/j.rser.2015.12.042

Abdullah, A. H., Meng, Q., Zhao, L., & Wang, F. (2009). Field study on indoor thermal environment in an atrium in tropical climates. Building and Environment, 44(2), 431-436. doi: 10.1016/j.buildenv.2008.02.011

Abu Khadra, A., & Chalfoun, N. (2014). Development of an integrated passive cooling façade technology for office buildings in hot arid regions. WIT Transactions on Ecology and the Environment, 190 VOLUME 1, 521-534.

Advantix announces exclusive Rep. agreement with Trane in Southeast. (2014). ACHR News. https://www.achrnews.com/articles/128003-advantix-announces-exclusive-rep-agreement-with-trane-in-southeast [accessed on Dec 13th 2017]

Advantix Systems' Dehumidification & Cooling System reduces energy consumption in schools by more than 40 percent. (2010). Business Wire. https://www.businesswire.com/news/home/20101109006478/en/Advantix-Systems%E2%80%99-Dehumidification-Cooling-System-Reduces-Energy [accessed on Dec 13th 2017]

Agyenim, F., Knight, I., & Rhodes, M. (2010). Design and experimental testing of the performance of an outdoor LiBr/H2O solar thermal absorption cooling system with a cold store. Solar Energy, 84(5), 735-744. doi: 10.1016/j.solener.2010.01.013

Ahmed, N. A., & Wongpanyathaworn, K. (2012). Optimising Louver Location to Improve Indoor Thermal Comfort based on Natural Ventilation. Procedia Engineering, 49, 169-178. doi: 10.1016/j.proeng.2012.10.125

Ala-Juusela, M. e. (2003). LowEx guidebook: low-exergy systems for heating and cooling of buildings. Guidebook to IEA ECBCS annex 37. Birmingham, UK: ECBCS Bookshop.

Alahmer, A. (2016). Thermal analysis of a direct evaporative cooling system enhancement with desiccant dehumidification for vehicular air conditioning. Applied Thermal Engineering, 98, 1273-1285. doi: 10.1016/j.applthermaleng.2015.12.059

Alahmer, A., Wang, X., Al-Rbaihat, R., Amanul Alam, K. C., & Saha, B. B. (2016). Performance evaluation of a solar adsorption chiller under different climatic conditions. Applied Energy, 175, 293-304. doi: 10.1016/j.apenergy.2016.05.041

Aldawoud, A. (2013a). Conventional fixed shading devices in comparison to an electrochromic glazing system in hot, dry climate. Energy and Buildings, 59(0), 104-110. doi: http://dx.doi.org/10.1016/j.enbuild.2012.12.031

Aldawoud, A. (2013b). The influence of the atrium geometry on the building energy performance. Energy and Buildings, 57(0), 1-5. doi: http://dx.doi.org/10.1016/j.enbuild.2012.10.038

Aliane, A., Abboudi, S., Seladji, C., & Guendouz, B. (2016). An illustrated review on solar absorption cooling experimental studies. Renewable and Sustainable Energy Reviews, 65, 443-458. doi: 10.1016/j.rser.2016.07.012

Allouhi, A., Kousksou, T., Jamil, A., Bruel, P., Mourad, Y., & Zeraouli, Y. (2015). Solar driven cooling systems: An updated review. Renewable and Sustainable Energy Reviews, 44, 159-181. doi: 10.1016/j.rser.2014.12.014

Allouhi, A., Kousksou, T., Jamil, A., El Rhafiki, T., Mourad, Y., & Zeraouli, Y. (2015). Optimal working pairs for solar adsorption cooling applications. Energy, 79, 235-247. doi: 10.1016/j.energy.2014.11.010

TOC

Amos-Abanyie, S., Akuffo, F. O., & Kutin-Sanwu, V. (2011). Parametric study of effect of thermal mass, window size and night-time ventilation on peak indoor temperature in the warm-humid climate of Ghana. Paper presented at the 7th International Symposium on Heating, Ventilating and Air Conditioning - Proceedings of ISHVAC 2011.

Anand, S., Gupta, A., & Tyagi, S. K. (2015). Solar cooling systems for climate change mitigation: A review. Renewable and Sustainable Energy Reviews, 41(0), 143-161. doi: http://dx.doi.org/10.1016/j.rser.2014.08.042

Angrisani, G., Minichiello, F., Roselli, C., & Sasso, M. (2010). Desiccant HVAC system driven by a micro-CHP: Experimental analysis. Energy and Buildings, 42(11), 2028-2035. doi: http://dx.doi.org/10.1016/j.enbuild.2010.06.011

Angrisani, G., Minichiello, F., & Sasso, M. (2016). Improvements of an unconventional desiccant air conditioning system based on experimental investigations. Energy Conversion and Management, 112, 423-434. doi: 10.1016/j.enconman.2016.01.013

Appelfeld, D., McNeil, A., & Svendsen, S. (2012). An hourly based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems. Energy and Buildings, 50(0), 166-176. doi: http://dx.doi.org/10.1016/j.enbuild.2012.03.038

Arenas, A., Palacios, R., Rodriguez-Pecharroman, R., & Pagola, F. (2008). Full-size prototype of active thermal windows based on thermoelectricity. Paper presented at the ECT2008 - 6th European Conference on Thermoelectrics, Paris, France.

Argiriou, A. A., Balaras, C. A., Kontoyiannidis, S., & Michel, E. (2005). Numerical simulation and performance assessment of a low capacity solar assisted absorption heat pump coupled with a sub-floor system. Solar Energy, 79(3), 290-301. doi: http://dx.doi.org/10.1016/j.solener.2004.11.001

Artmann, N., Manz, H., & Heiselberg, P. (2007). Climatic potential for passive cooling of buildings by night-time ventilation in Europe. Applied Energy, 84(2), 187-201. doi: http://dx.doi.org/10.1016/j.apenergy.2006.05.004

ASHRAE. (2010). ANSI/ASHRAE Standard 55-2010. Atlanta, USA: ASHRAE.

ASHRAE. (2011). Advanced Energy Design Guide for Small to Medium Office Buildings. Atlanta, USA.

Assem, E. O., & Al-Mumin, A. A. (2010). Code compliance of fully glazed tall office buildings in hot climate. Energy and Buildings, 42(7), 1100-1105. doi: http://dx.doi.org/10.1016/j.enbuild.2010.02.001

Aste, N., Compostella, J., & Mazzon, M. (2012). Comparative energy and economic performance analysis of an electrochromic window and automated external venetian blind. Energy Procedia, 30(0), 404-413. doi: http://dx.doi.org/10.1016/j.egypro.2012.11.048

Audah, N., Ghaddar, N., & Ghali, K. (2011). Optimized solar-powered liquid desiccant system to supply building fresh water and cooling needs. Applied Energy, 88(11), 3726-3736. doi: 10.1016/j.apenergy.2011.04.028

Avesani, S. (2016). Design of a solar façade solution with an integrated sorption collector for the systemic retrofit of the existing office buildings. (Doctoral thesis), Leopold-Franzens-Universität Innsbruck, Innsbruck, Austria.

Avesani, S., Hallstrom, O., & Fuldner, G. (2014). Integration of sorption collector in office curtain wall: Simulation based comparison of different system configurations. Paper presented at the Eurosun 2014, Aix-les-Bains, France.

Azcarate-Aguerre, J., Klein, T., & den Heijer, A. (2016). A business-oriented roadmap towards the implementation of circular integrated facades: Merging the interests of suply and demand stakeholders in the construction industry through long-term collaboration models. Paper presented at the 9th International Conference Improving Energy Efficiency in Commercial Buildings and Smart Communities, Frankfurt, Germany.

Badache, M., Rousse, D. R., Hallé, S., & Quesada, G. (2013). Experimental and numerical simulation of a two-dimensional unglazed transpired solar air collector. Solar Energy, 93(0), 209-219. doi: http://dx.doi.org/10.1016/j.solener.2013.02.036

Bahaj, A. S., James, P. A. B., & Jentsch, M. F. (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. Energy and Buildings, 40(5), 720-731. doi: http://dx.doi.org/10.1016/j.enbuild.2007.05.006

Bakker, E. J., & de Boer, R. (2010). Development of a new 2,5kW adsorption chiller for heat driven cooling. The Netherlands: ECN.

Balaras, C. A., Grossman, G., Henning, H.-M., Infante Ferreira, C. A., Podesser, E., Wang, L., & Wiemken, E. (2007). Solar air conditioning in Europe—an overview. Renewable and Sustainable Energy Reviews, 11(2), 299-314. doi: 10.1016/j.rser.2005.02.003

Baldinelli, G. (2009). Double skin façades for warm climate regions: Analysis of a solution with an integrated movable shading system. Building and Environment, 44(6), 1107-1118. doi: http://dx.doi.org/10.1016/j.buildenv.2008.08.005

Baldwin, C. Y., & Clark, K. B. (2004). Modularity in the Design of Complex Engineering Systems: Division of Research, Harvard Business School.

Banham, R. (2013). The Architecture of the Well-Tempered Environment: Elsevier Science.

Baniyounes, A. M., Ghadi, Y. Y., Rasul, M. G., & Khan, M. M. K. (2013). An overview of solar assisted air conditioning in Queensland's subtropical regions, Australia. Renewable and Sustainable Energy Reviews, 26, 781-804. doi: 10.1016/j.rser.2013.05.053

Baniyounes, A. M., Liu, G., Rasul, M. G., & Khan, M. M. K. (2013). Comparison study of solar cooling technologies for an institutional building in subtropical Queensland, Australia. Renewable and Sustainable Energy Reviews, 23, 421-430. doi: 10.1016/j.rser.2013.02.044

Bansal, V., Mishra, R., Agarwal, G. D., & Mathur, J. (2012). Performance analysis of integrated earth–air-tunnel-evaporative cooling system in hot and dry climate. Energy and Buildings, 47(0), 525-532. doi: http://dx.doi.org/10.1016/j.enbuild.2011.12.024

Bataineh, K., & Taamneh, Y. (2016). Review and recent improvements of solar sorption cooling systems. Energy and Buildings, 128, 22-37. doi: 10.1016/j.enbuild.2016.06.075

BBVA. (2016). Emerging and Growth Leading Economies (EAGLEs). Economic Outlook. Annual Report 2016: BBVA.

Belarbi, R., & Allard, F. (2001). Development of feasibility approaches for studying the behavior of passive cooling systems in buildings. Renewable Energy, 22(4), 507-524. doi: http://dx.doi.org/10.1016/S0960-1481(00)00094-X

Bell, L. (2008). Addressing the challenges of commercializing new thermoelectric materials. Paper presented at the International conference on thermoelectrics, Oregon, USA.

Belleri, A., Lollini, R., & Dutton, S. M. (2014). Natural ventilation design: an analysis of predicted and measured performance. Building and Environment(0). doi: http://dx.doi.org/10.1016/j.buildenv.2014.06.009

Bellia, L., De Falco, F., & Minichiello, F. (2013). Effects of solar shading devices on energy requirements of standalone office buildings for Italian climates. Applied Thermal Engineering, 54(1), 190-201. doi: 10.1016/j.applthermaleng.2013.01.039

Ben-David, T., & Waring, M. S. (2016). Impact of natural versus mechanical ventilation on simulated indoor air quality and energy consumption in offices in fourteen U.S. cities. Building and Environment, 104, 320-336. doi: 10.1016/j.buildenv.2016.05.007

Bergero, S., & Chiari, A. (2011). On the performances of a hybrid air-conditioning system in different climatic conditions. Energy, 36(8), 5261-5273. doi: http://dx.doi.org/10.1016/j.energy.2011.06.030

Blackman, C., Hallstrom, O., & Bales, C. (2014). Demonstration of Solar Heating and Cooling System using Sorption Integrated Solar Thermal Collectors. Paper presented at the EuroSun, Aix-les-Bains, France.

Blismas, N., Pendlebury, M., Gibb, A., & Pasquire, C. (2005). Constraints to the use of off-site production on construction projects. Architectural Engineering and Design Management, 1(3), 153-162.

Bluyssen, P. M. (2009). The Indoor Environment Handbook: How to Make Buildings Healthy and Comfortable: Earthscan LLC.

Bolocan, S., Chiriac, F., Serban, A., Dragomir, G., & Nastase, G. (2015). Development of a Small Capacity Solar Cooling Absorption Plant. Energy Procedia, 74, 624-632. doi: 10.1016/j.egypro.2015.07.796

Bonato, P., D'Antoni, M., & Fedrizzi, R. (2016). Integration of a sorption collector coupled with a decentralized mechanical ventilation unit in curtain wall module. Paper presented at the Advance Building Skins, Bern, Switzerland.

Bong, T., Ng, K., & Tay, A. (1987). Performance study of a solar-powered air-conditioning system. Solar Energy, 39(3), 173-182.

Bongs, C., Morgenstern, A., & Henning, H.-M. (2012). Advanced performance of an open desiccant cycle with internal evaporative cooling. Energy Procedia, 30, 524-533. doi: 10.1016/j.egypro.2012.11.062

BP. (2016). BP Energy Outlook, 2016 edition. London, United Kingdom.

Brinkmann, P. (2012). Growing Advantix Systems relocates HQ to Sunrise. South Florida Business Journal. https://www.bizjournals.com/southflorida/news/2012/08/02/growing-company-advantix-systems.html [accessed on Dec 13th 2017]

Broad. (n.d.). BROAD Group. Retrieved April 6th, 2018, from http://en.broad.com/.

Brown, D. R., Fernandez, N., Dirks, J. A., & Stout, T. B. (2010). The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications. USA: Pacific Northwest National Laboratory (PNNL). Prepared for the U.S. DOE under contract DE-AC05-76RL01830.

Brown, J. S., & Domanski, P. A. (2014). Review of alternative cooling technologies. Applied Thermal Engineering, 64(1-2), 252-262. doi: 10.1016/j.applthermaleng.2013.12.014

Buker, M. S., Mempouo, B., & Riffat, S. B. (2015). Experimental investigation of a building integrated photovoltaic/thermal roof collector combined with a liquid desiccant enhanced indirect evaporative cooling system. Energy Conversion and Management, 101, 239-254. doi: 10.1016/j.enconman.2015.05.026

Buker, M. S., & Riffat, S. B. (2015). Recent developments in solar assisted liquid desiccant evaporative cooling technology—A review. Energy and Buildings, 96, 95-108. doi: 10.1016/j.enbuild.2015.03.020

Bustamante, W., Vera, S., Prieto, A., & Vasquez, C. (2014). Solar and Lighting Transmission through Complex Fenestration Systems of Office Buildings in a Warm and Dry Climate of Chile. Sustainability, 6(5), 2786-2801. doi: 10.3390/su6052786

Buyadgie, D., Nichenko, S., & Schenyh, V. (2010). Solar Ejector Refrigerating And Air-Conditioning System (SERAS) Working on Zeotropic Mixtures. International Refrigeration and Air-Conditioning Conference.

Campaniço, H., Hollmuller, P., & Soares, P. M. M. (2014). Assessing energy savings in cooling demand of buildings using passive cooling systems based on ventilation. Applied Energy, 134(0), 426-438. doi: http://dx.doi.org/10.1016/j.apenergy.2014.08.053

Cândido, C., de Dear, R., & Lamberts, R. (2011). Combined thermal acceptability and air movement assessments in a hot humid climate. Building and Environment, 46(2), 379-385. doi: http://dx.doi.org/10.1016/j.buildenv.2010.07.032

Cappel, C., Streicher, W., Lichtblau, F., & Maurer, C. (2014). Barriers to the Market Penetration of Façade-integrated Solar Thermal Systems. Energy Procedia, 48, 1336-1344. doi: 10.1016/j.egypro.2014.02.151

Carrier. (n.d.). Carrier. Retrieved April 6th, 2018, from https://www.carrier.com.

Castro, J., Oliva, A., Perez-Segarra, C. D., & Oliet, C. (2008). Modelling of the heat exchangers of a small capacity, hot water driven, air-cooled H2O–LiBr absorption cooling machine. International Journal of Refrigeration, 31(1), 75-86. doi: 10.1016/j.ijrefrig.2007.05.019

Cejudo, J. M., Fernández, F., Domínguez, F., & Carrillo, A. (2013). The optimization of the operation of a solar desiccant air handling unit coupled with a radiant floor. Energy and Buildings, 62(0), 427-435. doi: http://dx.doi.org/10.1016/j.enbuild.2013.03.030

Chaiwiwatworakul, P., Matuampunwong, D., & Chirarattananon, S. (2012). Energy Saving Potential from daylighting through External Multiple-Slat Shaded Window in the Tropics. International Journal of Renewable Energy Research, 2(3).

Chan, H. Y., Zhu, J., & Riffat, S. (2012). Solar facade for space cooling. Energy and Buildings, 54, 307-319. doi: 10.1016/j.enbuild.2012.07.033

Chan, Y.-C., & Tzempelikos, A. (2013). Efficient venetian blind control strategies considering daylight utilization and glare protection. Solar Energy, 98, Part C(0), 241-254. doi: http://dx.doi.org/10.1016/j.solener.2013.10.005

Chang, W. S., Wang, C. C., & Shieh, C. C. (2009). Design and performance of a solar-powered heating and cooling system using silica gel/water adsorption chiller. Applied Thermal Engineering, 29(10), 2100-2105. doi: 10.1016/j.applthermaleng.2008.10.021

Chekirou, W., Boukheit, N., & Karaali, A. (2016). Performance improvement of adsorption solar cooling system. International Journal of Hydrogen Energy, 41(17), 7169-7174. doi: 10.1016/j.ijhydene.2016.02.140

Chen, Z., Zhu, J., & Bai, H. (2017). Performance assessment of a membrane liquid desiccant dehumidification cooling system based on experimental investigations. Energy and Buildings, 139, 665-679. doi: 10.1016/j.enbuild.2017.01.046

Chen, Z., Zhu, J., Bai, H., Yan, Y., & Zhang, L. (2017). Experimental study of a membrane-based dehumidification cooling system. Applied Thermal Engineering, 115, 1315-1321. doi: 10.1016/j.applthermaleng.2016.10.153

Cheng, Q., & Zhang, X. (2013). Review of solar regeneration methods for liquid desiccant air-conditioning system. Energy and Buildings, 67, 426-433. doi: 10.1016/j.enbuild.2013.08.053

Cheng, T.-C., Cheng, C.-H., Huang, Z.-Z., & Liao, G.-C. (2011). Development of an energy-saving module via combination of solar cells and thermoelectric coolers for green building applications. Energy, 36(1), 133-140. doi: 10.1016/j.energy.2010.10.061

Chiesa, G., & Grosso, M. (2015). Geo-climatic applicability of natural ventilative cooling in the Mediterranean area. Energy and Buildings. doi: http://dx.doi.org/10.1016/j.enbuild.2015.08.043

Choudhury, B., Saha, B. B., Chatterjee, P. K., & Sarkar, J. P. (2013). An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling. Applied Energy, 104, 554-567. doi: http://dx.doi.org/10.1016/j.apenergy.2012.11.042

Chunnanond, K., & Aphornratana, S. (2004). Ejectors: applications in refrigeration technology. Renewable and Sustainable Energy Reviews, 8(2), 129-155. doi: http://dx.doi.org/10.1016/j.rser.2003.10.001

CIBSE. (2012). Guide F: Energy Efficiency in Buildings. UK: CIBSE.

CICA. (2002). Industry as a partner for sustainable development-Refrigeration: Confederation of International Contractors' Associations.

Clausse, M., Alam, K. C. A., & Meunier, F. (2008). Residential air conditioning and heating by means of enhanced solar collectors coupled to an adsorption system. Solar Energy, 82(10), 885-892. doi: 10.1016/j.solener.2008.04.001

ClimaSol. (2002). ClimaSol - Promoting Solar Air Conditioning: Technical overview of active techniques. ALTENER Project Number 4.1030/Z/02-121/2002.

Compagno, A. (2002). Intelligent Glass Facade: Birkhauser.

Cool innovation: an upstart hopes to make rival cooling companies sweat. (2012). The Economist. http://www.economist.com/node/21559655

Corgnati, S. P., & Kindinis, A. (2007). Thermal mass activation by hollow core slab coupled with night ventilation to reduce summer cooling loads. Building and Environment, 42(9), 3285-3297. doi: http://dx.doi.org/10.1016/j.buildenv.2006.08.018

Cosnier, M., Fraisse, G., & Luo, L. (2008). An experimental and numerical study of a thermoelectric air-cooling and air-heating system. International Journal of Refrigeration, 31(6), 1051-1062. doi: 10.1016/j.ijrefrig.2007.12.009

Crofoot, L., & Harrison, S. (2012). Performance Evaluation of a Liquid Desiccant Solar Air Conditioning System. Energy Procedia, 30, 542-550. doi: 10.1016/j.egypro.2012.11.064

CustomChill. (n.d.). CustomChill - Innovative cooling solutions. Retrieved April 6th, 2018, from http://www.customchill.com/

Daniels, K. (2003). Advanced Building Systems: A Technical Guide for Architects and Engineers: Birkhäuser.

Daou, K., Wang, R., & Xia, Z. (2006). Desiccant cooling air conditioning: a review. Renewable and Sustainable Energy Reviews, 10(2), 55-77. doi: 10.1016/j.rser.2004.09.010

Das, R. S., & Jain, S. (2017). Experimental investigations on a solar assisted liquid desiccant cooling system with indirect contact dehumidifier. Solar Energy, 153, 289-300. doi: 10.1016/j.solener.2017.05.071

De Boer, R., Smeding, S. F., & Mola, S. (2009). Silicagel-water adsorption cooling prototype system for mobile air conditioning. Paper presented at the Heat Powered Cycles Conference '09. 7-9 September 2009., Berlin.

de Lieto Vollaro, R., Botta, F., de Lieto Vollaro, A., & Galli, G. (2014). Solar cooling system for buildings: Thermal analysis of solid absorbents applied in low power adsorption system. Energy and Buildings, 80, 436-440. doi: 10.1016/j.enbuild.2014.05.039

DehuTech. (n.d.). DehuTech AB. Retrieved April 6th, 2018, from http://dehutech.com/.

Deng, Y., Zhao, Y., Wang, W., Quan, Z., Wang, L., & Yu, D. (2013). Experimental investigation of performance for the novel flat plate solar collector with micro-channel heat pipe array (MHPA-FPC). Applied Thermal Engineering, 54(2), 440-449. doi: http://dx.doi.org/10.1016/j.applthermaleng.2013.02.001

Desideri, U., Proietti, S., & Sdringola, P. (2009). Solar-powered cooling systems: Technical and economic analysis on industrial refrigeration and air-conditioning applications. Applied Energy, 86(9), 1376-1386. doi: 10.1016/j.apenergy.2009.01.011

Dimoudi, A., & Tompa, C. (2008). Energy and environmental indicators related to construction of office buildings. Resources, Conservation and Recycling, 53(1-2), 86-95. doi: 10.1016/j.resconrec.2008.09.008

DOE. (n.d.). U.S. Department of Energy. Retrieved Sept 13th, 2016, from http://energy.gov/

DOE/EIA. (2016). International Energy Outlook 2016. Washington, DC, USA: US Energy Information Administration, US Department of Energy.

Eames, P. C. (2008). Vacuum glazing: Current performance and future prospects. Vacuum, 82(7), 717-722. doi: http://dx.doi.org/10.1016/j.vacuum.2007.10.017

Ebbert, T. (2010). Re-Face: Refurbishment Strategies for the Technical Improvement of Office Façades. (PhD), Delft University of Technology, Delft, The Netherlands.

ECN. (n.d.). SmartBox: Energy facade. Retrieved March 3rd, 2017, from www.smartfacade.nl

TOC

ECOHEATCOOL. (2006). The European cold market, final report. Ecoheatcool and Euroheat & Power 2005-2006. Brussels.: Euroheat & Power.

Egan, J. (1998). Rethinking Construction: The Report of the Construction Task Force to the Deputy Prime Minister. London.

EIA. (2015). EU F-Gas Regulation Handbook: Keeping ahead of the curve as Europe phases down HFCs. London, UK: Environmental Investigation Agency.

Eicker, U., Colmenar-Santos, A., Teran, L., Cotrado, M., & Borge-Diez, D. (2014). Economic evaluation of solar thermal and photovoltaic cooling systems through simulation in different climatic conditions: An analysis in three different cities in Europe. Energy and Buildings, 70, 207-223. doi: 10.1016/j.enbuild.2013.11.061

Eicker, U., & Dalibard, A. (2011). Photovoltaic–thermal collectors for night radiative cooling of buildings. Solar Energy, 85(7), 1322-1335. doi: http://dx.doi.org/10.1016/j.solener.2011.03.015

Eicker, U., Pietruschka, D., Haag, M., & Schmitt, A. (2014). Energy and Economic Performance of Solar Cooling Systems World Wide. Energy Procedia, 57(0), 2581-2589. doi: http://dx.doi.org/10.1016/j.egypro.2014.10.269

Eicker, U., Pietruschka, D., Haag, M., & Schmitt, A. (2015). Systematic design and analysis of solar thermal cooling systems in different climates. Renewable Energy, 80, 827-836. doi: http://dx.doi.org/10.1016/j.renene.2015.02.019

Eicker, U., Schneider, D., Schumacher, J., Ge, T., & Dai, Y. (2010). Operational experiences with solar air collector driven desiccant cooling systems. Applied Energy, 87(12), 3735-3747. doi: http://dx.doi.org/10.1016/j.apenergy.2010.06.022

El-Sharkawy, I. I., AbdelMeguid, H., & Saha, B. B. (2014). Potential application of solar powered adsorption cooling systems in the Middle East. Applied Energy, 126, 235-245. doi: 10.1016/j.apenergy.2014.03.092

El Fadar, A. (2016). Novel process for performance enhancement of a solar continuous adsorption cooling system. Energy, 114, 10-23. doi: 10.1016/j.energy.2016.07.149

Elmer, T., Worall, M., Wu, S., & Riffat, S. (2016). An experimental study of a novel integrated desiccant air conditioning system for building applications. Energy and Buildings, 111, 434-445. doi: 10.1016/j.enbuild.2015.11.065

Enteria, N., & Mizutani, K. (2011). The role of the thermally activated desiccant cooling technologies in the issue of energy and environment. Renewable and Sustainable Energy Reviews, 15(4), 2095-2122. doi: 10.1016/j.rser.2011.01.013

European Commission. DIRECTIVE 2002/91/EC: EUR-Lex (2002).

European Commission. DIRECTIVE 2010/31/EU: Energy Performance of Buildings - Recast (2010) (2010).

Escarré, J., Li, H.-Y., Sansonnens, L., Galliano, F., Cattaneo, G., Heinstein, P., . . . Perret-Aebi, L.-E. (2015). When PV modules are becoming real building elements: White solar module, a revolution for BIPV. Paper presented at the Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd, New Orleans, LA.

Eskin, N., & Türkmen, H. (2008). Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey. Energy and Buildings, 40(5), 763-773. doi: http://dx.doi.org/10.1016/j.enbuild.2007.05.008

Evident. (n.d.). Evident Thermoelectrics. Retrieved April 6th, 2018, from http://evidentthermo.com/

Ezzeldin, S., & Rees, S. J. (2013). The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates. Energy and Buildings, 65(0), 368-381. doi: http://dx.doi.org/10.1016/j.enbuild.2013.06.004

Fadar, A. E., Mimet, A., & Pérez-García, M. (2009). Modelling and performance study of a continuous adsorption refrigeration system driven by parabolic trough solar collector. Solar Energy, 83(6), 850-861. doi: http://dx.doi.org/10.1016/j.solener.2008.12.003

Fahrenheit. (n.d.). FAHRENHEIT. Retrieved April 6th, 2018, from https://fahrenheit.cool/.

Farkas, K., & Horvat, M. (2012). T.41.A.1: Building integration of Solar Thermal and Photovoltaics - Barriers, Needs and Strategies: IEA SHC Task 41: Solar Energy and Architecture.

Fasfous, A., Asfar, J., Al-Salaymeh, A., Sakhrieh, A., Al_hamamre, Z., Al-bawwab, A., & Hamdan, M. (2013). Potential of utilizing solar cooling in The University of Jordan. Energy Conversion and Management, 65, 729-735. doi: 10.1016/j.enconman.2012.01.045

Fathoni, A. M., Chaiwiwatworakul, P., & Mettanant, V. (2016). Energy analysis of the daylighting from a double-pane glazed window with enclosed horizontal slats in the tropics. Energy and Buildings, 128, 413-430. doi: 10.1016/j.enbuild.2016.06.034

TOC

Favoino, F., Overend, M., & Jin, Q. (2015). The optimal thermo-optical properties and energy saving potential of adaptive glazing technologies. Applied Energy, 156, 1-15. doi: http://dx.doi.org/10.1016/j.apenergy.2015.05.065

Fazilati, M. A., Alemrajabi, A. A., & Sedaghat, A. (2017). Liquid desiccant air conditioning system with natural convection. Applied Thermal Engineering, 115, 305-314. doi: 10.1016/j.applthermaleng.2016.12.111

Fernández-Hernández, F., Cejudo-López, J. M., Domínguez-Muñoz, F., & Carrillo-Andrés, A. (2015). A new desiccant channel to be integrated in building façades. Energy and Buildings, 86(0), 318-327. doi: http://dx.doi.org/10.1016/j.enbuild.2014.10.009

Ferrari, S., & Zanotto, V. (2012). Office Buildings Cooling Need in the Italian Climatic Context: Assessing the Performances of Typical Envelopes. Energy Procedia, 30(0), 1099-1109. doi: http://dx.doi.org/10.1016/j.egypro.2012.11.123

Fiaschi, D., & Manfrida, G. (2013). Model to predict design parameters and performance curves of vacuum glass heat pipe solar collectors. Energy, 58(0), 28-35. doi: http://dx.doi.org/10.1016/j.energy.2012.12.028

Finocchiaro, P., Beccali, M., Brano, V. L., & Gentile, V. (2016). Monitoring Results and Energy Performances Evaluation of Freescoo Solar DEC Systems. Energy Procedia, 91, 752-758. doi: 10.1016/j.egypro.2016.06.240

Finocchiaro, P., Beccali, M., Calabrese, A., & Moreci, E. (2015). Second Generation of Freescoo Solar DEC Prototypes for Residential Applications. Energy Procedia, 70, 427-434. doi: 10.1016/j.egypro.2015.02.144

Finocchiaro, P., Beccali, M., & Gentile, V. (2016). Experimental results on adsorption beds for air dehumidification. International Journal of Refrigeration, 63, 100-112. doi: 10.1016/j.ijrefrig.2015.10.022

Fischer, S., Tomlinson, P., & Hughes, P. (1994). Energy and global warming impacts of not-in-kind and next generation CFC and HCFC alternatives: ORNL.

Fong, K. F., Chow, T. T., Lee, C. K., Lin, Z., & Chan, L. S. (2010a). Comparative study of different solar cooling systems for buildings in subtropical city. Solar Energy, 84(2), 227-244. doi: 10.1016/j.solener.2009.11.002

Fong, K. F., Chow, T. T., Lee, C. K., Lin, Z., & Chan, L. S. (2010b). Solar hybrid air-conditioning system for high temperature cooling in subtropical city. Renewable Energy, 35(11), 2439-2451. doi: http://dx.doi.org/10.1016/j.renene.2010.02.024

Fong, K. F., Chow, T. T., Lee, C. K., Lin, Z., & Chan, L. S. (2011). Solar hybrid cooling system for high-tech offices in subtropical climate − Radiant cooling by absorption refrigeration and desiccant dehumidification. Energy Conversion and Management, 52(8-9), 2883-2894. doi: 10.1016/j.enconman.2011.04.005

Franchini, G., Notarbartolo, E., Padovan, L. E., & Perdichizzi, A. (2015). Modeling, Design and Construction of a Micro-scale Absorption Chiller. Energy Procedia, 82, 577-583. doi: 10.1016/j.egypro.2015.11.874

Franzke, U., Heidenreich, R., Ehle, A., & Ziller, F. (2003). Comparison between decentralised and centralised air conditioning systems. Dresden, Germany: ILK Dresden.

Freewan, A. A. Y. (2014). Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. Solar Energy, 102(0), 14-30. doi: http://dx.doi.org/10.1016/j.solener.2014.01.009

Frontini, F. (2011). Daylight and solar control in building: A new angle selective see-thorough PV-façade for solar control. Paper presented at the PLEA 2011 - Architecture and Sustainable Development, Conference Proceedings of the 27th International Conference on Passive and Low Energy Architecture.

Fung, T. Y. Y., & Yang, H. (2008). Study on thermal performance of semi-transparent building-integrated photovoltaic glazings. Energy and Buildings, 40(3), 341-350. doi: http://dx.doi.org/10.1016/j.enbuild.2007.03.002

Gang, W., Wang, S., Xiao, F., & Gao, D.-c. (2016). District cooling systems: Technology integration, system optimization, challenges and opportunities for applications. Renewable and Sustainable Energy Reviews, 53, 253-264. doi: 10.1016/j.rser.2015.08.051

Gasparella, A., Cappelletti, F., Pernigotto, G., & Romagnonj, P. (2012). Long-term evaluation of internal thermal comfort with different kinds of glazing systems and window sizes: From energetic considerations to users' comfort. Paper presented at the ASHRAE Transactions.

Ge, G., Xiao, F., & Xu, X. (2011). Model-based optimal control of a dedicated outdoor air-chilled ceiling system using liquid desiccant and membrane-based total heat recovery. Applied Energy, 88(11), 4180-4190. doi: http://dx.doi.org/10.1016/j.apenergy.2011.04.045

Ge, T. S., Dai, Y. J., Wang, R. Z., & Li, Y. (2008). Experimental investigation on a one-rotor two-stage rotary desiccant cooling system. Energy, 33(12), 1807-1815. doi: 10.1016/j.energy.2008.08.006

Ge, T. S., Li, Y., Wang, R. Z., & Dai, Y. J. (2009). Experimental study on a two-stage rotary desiccant cooling system. International Journal of Refrigeration, 32(3), 498-508. doi: 10.1016/j.ijrefrig.2008.07.001

Ge, T. S., Ziegler, F., Wang, R. Z., & Wang, H. (2010). Performance comparison between a solar driven rotary desiccant cooling system and conventional vapor compression system (performance study of desiccant cooling). Applied Thermal Engineering, 30(6-7), 724-731. doi: 10.1016/j.applthermaleng.2009.12.002

Gea. (2012). Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Geetha, N. B., & Velraj, R. (2012). Passive cooling methods for energy efficient buildings with and without thermal energy storage – A review. Energy Education Science and Technology Part A: Energy Science and Research, 29(2), 913-946.

Geros, V. S., M; Tsangrasoulis, A; Guarracino, G. (1999). Experimental evaluation of night ventilation phenomena. Energy and Buildings, 29, 141-154.

Gibson, M. (2008). The Active Thermal Manifold Skin: Feasibility, Prototyping, and Performance Studies of a Wall System Integrating Distributed Solid State, Solar Powered Cooling and Heating Technology. Collegue of Architecture and Planning, Ball State University. Muncie, IN, USA.

Givoni, B. (1994). Passive Low Energy Cooling of Buildings: Wiley.

Goetzler, W., Zogg, R., Young, J., & Johnson, C. (2014). Energy savings potential and RD&D opportunities for non-vapor-compression HVAC technologies. USA: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office.

Goia, F. (2016). Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential. Solar Energy, 132, 467-492. doi: 10.1016/j.solener.2016.03.031

Goldsworthy, M., & White, S. (2011). Optimisation of a desiccant cooling system design with indirect evaporative cooler. International Journal of Refrigeration, 34(1), 148-158. doi: 10.1016/j.ijrefrig.2010.07.005

Gommed, K., & Grossman, G. (2007). Experimental investigation of a liquid desiccant system for solar cooling and dehumidification. Solar Energy, 81(1), 131-138. doi: 10.1016/j.solener.2006.05.006

Goulding, J. S., Pour Rahimian, F., Arif, M., & Sharp, M. D. (2014). New offsite production and business models in construction: priorities for the future research agenda. Architectural Engineering and Design Management, 11(3), 163-184. doi: 10.1080/17452007.2014.891501

Gratia, E., & De Herde, A. (2004a). Natural ventilation in a double-skin facade. Energy and Buildings, 36(2), 137-146. doi: http://dx.doi.org/10.1016/j.enbuild.2003.10.008

Gratia, E., & De Herde, A. (2004b). Optimal operation of a south double-skin facade. Energy and Buildings, 36(1), 41-60.

Gratia, E., & De Herde, A. (2007a). Greenhouse effect in double-skin facade. Energy and Buildings, 39(2), 199-211.

Gratia, E., & De Herde, A. (2007b). Guidelines for improving natural daytime ventilation in an office building with a double-skin facade. Solar Energy, 81(4), 435-448.

Gratia, E., & De Herde, A. (2007c). The most efficient position of shading devices in a double-skin facade. Energy and Buildings, 39(3), 364-373. doi: 10.1016/j.enbuild.2006.09.001

Haase, M., & Amato, A. (2006). Ventilated façade design in hot and humid climate. Paper presented at the PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Conference Proceedings.

Haase, M., Andresen, I., & Helge Dokka, T. (2009). The role of advanced integrated facades in the design of sustainable buildings. Journal of Green Buildings, 4(1), 76-98.

Habib, K., Saha, B. B., & Koyama, S. (2014). Study of various adsorbent–refrigerant pairs for the application of solar driven adsorption cooling in tropical climates. Applied Thermal Engineering, 72(2), 266-274. doi: 10.1016/j.applthermaleng.2014.05.102

Hallström, O. (2016). Design Optimization of a Sorption Integrated Sydney Type Vacuum Tube Collector. Journal of Solar Energy Engineering, 139(2), 021007. doi: 10.1115/1.4034912

Hallstrom, O., & Füldner, G. (2015). Integration of Sorption Modules in Sydney Type Vacuum Tube Collector with Air as Heat Transfer Fluid. Energy Procedia, 70, 445-453. doi: 10.1016/j.egypro.2015.02.146

Hallström, O., Füldner, G., Spahn, H.-J., Schnabel, L., & Salg, F. (2014). Development of Collector Integrated Sorption Modules for Solar Heating and Cooling: Performance Simulation. Energy Procedia, 48, 67-76. doi: 10.1016/j.egypro.2014.02.009

Hammad, F., & Abu-Hijleh, B. (2010). The energy savings potential of using dynamic external louvers in an office building. Energy and Buildings, 42(10), 1888-1895. doi: http://dx.doi.org/10.1016/j.enbuild.2010.05.024

Hamza, N. (2008). Double versus single skin facades in hot arid areas. Energy and Buildings, 40(3), 240-248. doi: http://dx.doi.org/10.1016/j.enbuild.2007.02.025

Hanby, V. I., & Smith, S. T. (2012). Simulation of the future performance of low-energy evaporative cooling systems using UKCP09 climate projections. Building and Environment, 55(0), 110-116. doi: http://dx.doi.org/10.1016/j.buildenv.2011.12.018

He, W., Zhou, J., Chen, C., & Ji, J. (2014). Experimental study and performance analysis of a thermoelectric cooling and heating system driven by a photovoltaic/thermal system in summer and winter operation modes. Energy Conversion and Management, 84(0), 41-49. doi: http://dx.doi.org/10.1016/j.enconman.2014.04.019

He, W., Zhou, J., Hou, J., Chen, C., & Ji, J. (2013). Theoretical and experimental investigation on a thermoelectric cooling and heating system driven by solar. Applied Energy, 107, 89-97. doi: 10.1016/j.apenergy.2013.01.055

Hee, W. J., Alghoul, M. A., Bakhtyar, B., Elayeb, O., Shameri, M. A., Alrubaih, M. S., & Sopian, K. (2015). The role of window glazing on daylighting and energy saving in buildings. Renewable and Sustainable Energy Reviews, 42(0), 323-343. doi: http://dx.doi.org/10.1016/j.rser.2014.09.020

Hellmann, H.-M., & Grossman, G. (1995). Simulation and analysis of an open-cycle dehumidifier-evaporator-regenerator (DER) absorption chiller for low-grade heat utilization. International Journal of Refrigeration, 18(3), 177-189.

Henning, H.-M. (2007). Solar assisted air conditioning of buildings – an overview. Applied Thermal Engineering, 27(10), 1734-1749. doi: http://dx.doi.org/10.1016/j.applthermaleng.2006.07.021

Henning, H.-M., & Döll, J. (2012). Solar Systems for Heating and Cooling of Buildings. Energy Procedia, 30, 633-653. doi: 10.1016/j.egypro.2012.11.073

Henning, H.-M., Erpenbeck, T., Hindenburg, C., & Santamaria, I. S. (2001). The potential of solar energy use in desiccant cooling cycles. International Journal of Refrigeration, 24, 220-229.

Hepbasli, A. (2012). Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies. Renewable and Sustainable Energy Reviews, 16(1), 73-104. doi: 10.1016/j.rser.2011.07.138

Herzog, T., Krippner, R., & Lang, W. (2004). Facade Construction Manual: Birkhauser.

Hitachi. (n.d.). Hitachi Group. Retrieved April 6th, 2018, from http://www.hitachi.com/.

Hollmuller, P., & Lachal, B. (2014). Air–soil heat exchangers for heating and cooling of buildings: Design guidelines, potentials and constraints, system integration and global energy balance. Applied Energy, 119(0), 476-487. doi: http://dx.doi.org/10.1016/j.apenergy.2014.01.042

Hsieh, H. F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. Qual Health Res, 15(9), 1277-1288. doi: 10.1177/1049732305276687

Huang, B. J. C., J.M.; Petrenko, V.A.; Zhuk, K.B. (1998). A solar ejector cooling system using refrigerant R141b. Solar Energy, 64(4-6), 223-226.

Huang, K. T., & Lin, H. T. (2007). Development of simplified estimation method of chiller energy use for office buildings in Taiwan. Paper presented at the ASHRAE Transactions.

Huang, Y., & Niu, J.-l. (2015). Application of super-insulating translucent silica aerogel glazing system on commercial building envelope of humid subtropical climates – Impact on space cooling load. Energy(0). doi: http://dx.doi.org/10.1016/j.energy.2015.02.027

Hwang, R.-L., Cheng, M.-J., Lin, T.-P., & Ho, M.-C. (2009). Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot–humid regions. Building and Environment, 44(6), 1128-1134. doi: http://dx.doi.org/10.1016/j.buildenv.2008.08.001

Hwang, R.-L., & Shu, S.-Y. (2011). Building envelope regulations on thermal comfort in glass facade buildings and energy-saving potential for PMV-based comfort control. Building and Environment, 46(4), 824-834. doi: 10.1016/j.buildenv.2010.10.009

Ibañez-Puy, M., Martín-Gómez, C., Bermejo-Busto, J., Sacristán, J. A., & Ibañez-Puy, E. (2018). Ventilated Active Thermoelectric Envelope (VATE): Analysis of its energy performance when integrated in a building. Energy and Buildings, 158, 1586-1592. doi: 10.1016/j.enbuild.2017.11.037

Ibáñez-Puy, M., Martín-Gómez, C., Vidaurre-Arbizu, M., & Sacristán-Fernández, J. A. (2014). Theoretical Design of an Active Façade System with Peltier Cells. Energy Procedia, 61, 700-703. doi: 10.1016/j.egypro.2014.11.946

Ibáñez-Puy, M., Sacristán-Fernández, J. A., & Martín-Gómez, C. (2013). Construction of an Active Facade Envelope with Peltier Cells. Paper presented at the 39th World Congress on Housing Science - Changing Needs, Adaptive Buildings, Smart Cities, Milan, Italy.

Ibáñez-Puy, M., Sacristán Fernández, J. A., Martín-Gómez, C., & Vidaurre-Arbizu, M. (2015). Development and construction of a thermoelectric active facade module. Journal of Facade Design and Engineering, 3(1), 15-25. doi: 10.3233/fde-150025

IEA-SHC. (2016). IEA Solar Heating & Cooling Programme. Retrieved Sept 13th, 2016, from https://www.iea-shc.org/

Infante Ferreira, C., & Kim, D.-S. (2014). Techno-economic review of solar cooling technologies based on location-specific data. International Journal of Refrigeration, 39, 23-37. doi: 10.1016/j.ijrefrig.2013.09.033

InvenSor. (n.d.). InvenSor. Retrieved April 6th, 2018, from http://invensor.com/.

IPCC/TEAP. (2005). Special Report: Safeguarding the Ozone Layer and the Global Climate System.

Irshad, K., Habib, K., Basrawi, F., & Saha, B. B. (2017). Study of a thermoelectric air duct system assisted by photovoltaic wall for space cooling in tropical climate. Energy, 119, 504-522. doi: 10.1016/j.energy.2016.10.110

Islam, M. P., & Morimoto, T. (2016). Thermodynamic performances of a solar driven adsorption system. Solar Energy, 139, 266-277. doi: 10.1016/j.solener.2016.09.003

Izquierdo, M., Marcos, J. D., Palacios, M. E., & González-Gil, A. (2012). Experimental evaluation of a low-power direct air-cooled double-effect LiBr–H2O absorption prototype. Energy, 37(1), 737-748. doi: 10.1016/j.energy.2011.10.004

Jaehnig, D. (2009). D-A1: Market available components for systems for Solar Heating and Cooling with a Cooling Capacity <20 kW / A technical report of subtask A of IEA SHC Task 38: Solar Air-Conditioning and Refrigeration. Austria: AEE Intec.

Jain, S., Tripathi, S., & Das, R. S. (2011). Experimental performance of a liquid desiccant dehumidification system under tropical climates. Energy Conversion and Management, 52(6), 2461-2466. doi: http://dx.doi.org/10.1016/j.enconman.2010.12.052

Jakob, U., & Mittelbach, W. (2008). Development and investigation of a compact silica gel/water adsorption chiller integrated in solar cooling systems. Paper presented at the VII Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators, Power Sources", Minsk, Belarus.

James, P. A. B., & Bahaj, A. S. (2005). Smart glazing solutions to glare and solar gain: a 'sick building' case study. Energy and Buildings, 37(10), 1058-1067. doi: http://dx.doi.org/10.1016/j.enbuild.2004.12.010

Jani, D. B., Mishra, M., & Sahoo, P. K. (2016). Solid desiccant air conditioning – A state of the art review. Renewable and Sustainable Energy Reviews, 60, 1451-1469. doi: 10.1016/j.rser.2016.03.031

Jeong, E. S. (2014). A new approach to optimize thermoelectric cooling modules. Cryogenics, 59, 38-43. doi: 10.1016/j.cryogenics.2013.12.003

Ji, Y., Lomas, K. J., & Cook, M. J. (2009). Hybrid ventilation for low energy building design in south China. Building and Environment, 44(11), 2245-2255. doi: 10.1016/j.buildenv.2009.02.015

Jia, C. X., Dai, Y. J., Wu, J. Y., & Wang, R. Z. (2007). Use of compound desiccant to develop high performance desiccant cooling system. International Journal of Refrigeration, 30(2), 345-353. doi: 10.1016/j.ijrefrig.2006.04.001

Jiru, T. E., Tao, Y.-X., & Haghighat, F. (2011). Airflow and heat transfer in double skin facades. Energy and Buildings, 43(10), 2760-2766. doi: http://dx.doi.org/10.1016/j.enbuild.2011.06.038

Jochem, E., & Schade, W. (2009). 2-degree scenario for Europe - policies and impacts. ADAM: Adaptation and mitigation strategies: supporting European climate policy. Karlsruhe, Germany: Fraunhofer Institute for Systems and Innovation Research (Fraunhofer-ISI).

Joly, M., Antonetti, Y., Python, M., Gonzalez, M., Gascou, T., Scartezzini, J.-L., & Schüler, A. (2013). Novel black selective coating for tubular solar absorbers based on a sol–gel method. Solar Energy, 94(0), 233-239. doi: http://dx.doi.org/10.1016/j.solener.2013.05.009

Kabeel, A. E. (2007). Solar powered air conditioning system using rotary honeycomb desiccant wheel. Renewable Energy, 32(11), 1842-1857. doi: 10.1016/j.renene.2006.08.009

Kaiser, A. S., Zamora, B., Mazón, R., García, J. R., & Vera, F. (2014). Experimental study of cooling BIPV modules by forced convection in the air channel. Applied Energy, 135(0), 88-97. doi: http://dx.doi.org/10.1016/j.apenergy.2014.08.079

Kalogirou, S. A. (2013). Solar Energy Engineering: Processes and Systems: Elsevier Science.

Kalz, D., & Pfafferott, J. (2014). Thermal Comfort and Energy-Efficient Cooling of Nonresidential Buildings: Springer International Publishing.

Kathabar. (n.d.). Alfa Laval Kathabar. Retrieved April 6th, 2018, from http://www.kathabar.com/.

KeepCool. (2005). Service buildings KeepCool: Promotion of sustainable cooling in the service building sector. Final Report. In F. Unterpertinger (Ed.). Vienna, Austria: Austrian Energy Agency.

Keniar, K., Ghali, K., & Ghaddar, N. (2015). Study of solar regenerated membrane desiccant system to control humidity and decrease energy consumption in office spaces. Applied Energy, 138(0), 121-132. doi: http://dx.doi.org/10.1016/j.apenergy.2014.10.071

Khattab, N. M., Sharawy, H., & Helmy, M. (2012). Development of Novel Solar Adsorption Cooling Tube. Energy Procedia, 18, 709-714. doi: 10.1016/j.egypro.2012.05.086

Khire, R. A., Messac, A., & Van Dessel, S. (2005). Design of thermoelectric heat pump unit for active building envelope systems. International Journal of Heat and Mass Transfer, 48(19–20), 4028-4040. doi: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2005.04.028

Kim, M. K., Leibundgut, H., & Choi, J.-H. (2014). Energy and exergy analyses of advanced decentralized ventilation system compared with centralized cooling and air ventilation systems in the hot and humid climate. Energy and Buildings, 79(0), 212-222. doi: http://dx.doi.org/10.1016/j.enbuild.2014.05.009

Klein, T. (2013). Integral Facade Construction: Towards a new product architecture for curtain walls: TU Delft.

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007). Facades: Principles of Construction: Birkhauser Verlag GmbH.

Kohlenbach, P., & Jakob, U. (2014). Solar Cooling: The Earthscan Expert Guide to Solar Cooling Systems: Taylor & Francis.

Kolokotroni, M., & Aronis, A. (1999). Cooling-energy reduction in air-conditioned offices by using night ventilation. Applied Energy, 63(4), 241-253. doi: http://dx.doi.org/10.1016/S0306-2619(99)00031-8

Kolokotroni, M., Giannitsaris, I., & Watkins, R. (2006). The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. Solar Energy, 80(4), 383-392. doi: http://dx.doi.org/10.1016/j.solener.2005.03.010

Kolokotroni, M., Webb, B. C., & Hayes, S. D. (1998). Summer cooling with night ventilation for office buildings in moderate climates. Energy and Buildings, 27(3), 231-237. doi: http://dx.doi.org/10.1016/S0378-7788(97)00048-0

Konis, K. (2013). Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California. Building and Environment, 59(0), 662-677. doi: http://dx.doi.org/10.1016/j.buildenv.2012.09.017

Kozubal, E., Woods, J., Burch, J., Boranian, A., & Merrigan, T. (2011). Desiccant enhanced evaporative air-conditioning (DEVap): evaluation of a new concept in ultra efficient air conditioning. Colorado, US: National Renewable Energy Laboratory (NREL).

Kuhn, T. E. (2017). State of the art of advanced solar control devices for buildings. Solar Energy, 154, 112-133. doi: 10.1016/j.solener.2016.12.044

Kuhn, T. E. (2013). Cost-Effective - Deliverable D0.1.4: Final summary report.

La, D., Dai, Y. J., Li, Y., Wang, R. Z., & Ge, T. S. (2010). Technical development of rotary desiccant dehumidification and air conditioning: A review. Renewable and Sustainable Energy Reviews, 14(1), 130-147. doi: 10.1016/j.rser.2009.07.016

Labus, J., Bruno, J. C., & Coronas, A. (2013). Performance analysis of small capacity absorption chillers by using different modeling methods. Applied Thermal Engineering, 58(1–2), 305-313. doi: http://dx.doi.org/10.1016/j.applthermaleng.2013.04.032

Lam, J. C., & Hui, S. C. M. (1995). Outdoor design conditions for HVAC system design and energy estimation for buildings in Hong Kong. Energy and Buildings, 22(1), 25-43. doi: http://dx.doi.org/10.1016/0378-7788(94)00900-5

Lam, J. C., Li, D. H. W., & Cheung, S. O. (2003). An analysis of electricity end-use in air-conditioned office buildings in Hong Kong. Building and Environment, 38(3), 493-498. doi: http://dx.doi.org/10.1016/S0360-1323(02)00132-4

Lapisa, R., Bozonnet, E., Salagnac, P., & Abadie, M. O. (2018). Optimized design of low-rise commercial buildings under various climates – Energy performance and passive cooling strategies. Building and Environment, 132, 83-95. doi: 10.1016/j.buildenv.2018.01.029

Lau, A. K. K., Salleh, E., Lim, C. H., & Sulaiman, M. Y. (2016). Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: The case of Malaysia. International Journal of Sustainable Built Environment, 5(2), 387-399. doi: 10.1016/j.ijsbe.2016.04.004

Lazzarin, R. M. (2014). Solar cooling: PV or thermal? A thermodynamic and economical analysis. International Journal of Refrigeration, 39, 38-47. doi: 10.1016/j.ijrefrig.2013.05.012

TOC

Le Pierrès, N., Cosnier, M., Luo, L., & Fraisse, G. (2008). Coupling of thermoelectric modules with a photovoltaic panel for air pre-heating and pre-cooling application; an annual simulation. International Journal of Energy Research, 32(14), 1316-1328. doi: 10.1002/er.1439

Lechner, N. (2014). Heating, Cooling, Lighting: Sustainable Design Methods for Architects: Wiley.

Ledbetter, S. (2001). Barriers to the integration of cladding and building services. Paper presented at the 22nd Annual AIVC Conference, Bath, UK.

Lee, E., Selkowitz, S., Bazjanac, V., Inkarojrit, V., & Kohler, C. (2002). High Performance Commercial Building Facades. Berkeley, USA: LBNL, University of California.

Lee, J. W., Jung, H. J., Park, J. Y., Lee, J. B., & Yoon, Y. (2013). Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. Renewable Energy, 50, 522-531. doi: 10.1016/j.renene.2012.07.029

Leenknegt, S., Wagemakers, R., Bosschaerts, W., & Saelens, D. (2012). Numerical sensitivity study of transient surface convection during night cooling. Energy and Buildings, 53(0), 85-95. doi: http://dx.doi.org/10.1016/j.enbuild.2012.06.020

Li, D. H. W., Lam, J. C., Lau, C. C. S., & Huan, T. W. (2004). Lighting and energy performance of solar film coating in air-conditioned cellular offices. Renewable Energy, 29(6), 921-937. doi: http://dx.doi.org/10.1016/j.renene.2003.10.006

Li, D. H. W., Lam, T. N. T., Chan, W. W. H., & Mak, A. H. L. (2009). Energy and cost analysis of semi-transparent photovoltaic in office buildings. Applied Energy, 86(5), 722-729.

Li, D. H. W., Lam, T. N. T., Wong, S. L., & Tsang, E. K. W. (2008). Lighting and cooling energy consumption in an open-plan office using solar film coating. Energy, 33(8), 1288-1297. doi: http://dx.doi.org/10.1016/j.energy.2008.03.002

Li, H., Yu, Y., Niu, F., Shafik, M., & Chen, B. (2014). Performance of a coupled cooling system with earth-to-air heat exchanger and solar chimney. Renewable Energy, 62, 468-477. doi: 10.1016/j.renene.2013.08.008

Li, Z., Ye, X., & Liu, J. (2014). Performance analysis of solar air cooled double effect LiBr/H2O absorption cooling system in subtropical city. Energy Conversion and Management, 85(0), 302-312. doi: http://dx.doi.org/10.1016/j.enconman.2014.05.095

Liu, Z., Zhang, L., & Gong, G. (2014). Experimental evaluation of a solar thermoelectric cooled ceiling combined with displacement ventilation system. Energy Conversion and Management, 87(0), 559-565. doi: http://dx.doi.org/10.1016/j.enconman.2014.07.051

Liu, Z., Zhang, L., Gong, G., & Han, T. (2015). Experimental evaluation of an active solar thermoelectric radiant wall system. Energy Conversion and Management, 94(0), 253-260. doi: http://dx.doi.org/10.1016/j.enconman.2015.01.077

Liu, Z., Zhang, L., Gong, G., Li, H., & Tang, G. (2015). Review of solar thermoelectric cooling technologies for use in zero energy buildings. Energy and Buildings(102), 207-216. doi: http://dx.doi.org/10.1016/j.enbuild.2015.05.029

Lizarte, R., Izquierdo, M., Marcos, J. D., & Palacios, E. (2012). An innovative solar-driven directly air-cooled LiBr–H 2 O absorption chiller prototype for residential use. Energy and Buildings, 47, 1-11. doi: 10.1016/j.enbuild.2011.11.011

Lof, G. O. G. (1955). Cooling with solar energy. Paper presented at the Congress on Solar Energy, Tucson, Arizona, USA.

Loncour, X., Deneyer, A., Blasco, M., Flamant, G., & Wouters, P. (2004). Ventilated Double Facades. Classification & illustration of facade concepts. Belgium: Belgian Building Research Institute (BBRI).

Loonen, R. C. G. M., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. Renewable and Sustainable Energy Reviews, 25, 483-493. doi: 10.1016/j.rser.2013.04.016

López-Villada, J., Ayou, D. S., Bruno, J. C., & Coronas, A. (2014). Modelling, simulation and analysis of solar absorption power-cooling systems. International Journal of Refrigeration, 39, 125-136. doi: 10.1016/j.ijrefrig.2013.11.004

Lorenz, W. (1998). Design guidelines for a glazing with a seasonally dependent solar transmittance. Solar Energy, 63(2), 79-96. doi: http://dx.doi.org/10.1016/S0038-092X(98)00053-X

Louajari, M., Mimet, A., & Ouammi, A. (2011). Study of the effect of finned tube adsorber on the performance of solar driven adsorption cooling machine using activated carbon–ammonia pair. Applied Energy, 88(3), 690-698. doi: http://dx.doi.org/10.1016/j.apenergy.2010.08.032

Lowenstein, A., Slayzak, S., & Kozubal, E. (2006). A zero carryover liquid-desiccant air conditioner for solar applications. Paper presented at the ISEC2006 ASME International Solar Energy Conference, Denver, CO, USA.

Lu, Z., Wang, R., Xia, Z., & Gong, L. (2013). Experimental investigation adsorption chillers using micro-porous silica gel–water and compound adsorbent-methanol. Energy Conversion and Management, 65, 430-437. doi: 10.1016/j.enconman.2012.09.018

Luo, H., Wang, R., & Dai, Y. (2010). The effects of operation parameter on the performance of a solar-powered adsorption chiller. Applied Energy, 87(10), 3018-3022. doi: 10.1016/j.apenergy.2010.03.013

Luo, Y., Zhang, L., Liu, Z., Wang, Y., Meng, F., & Wu, J. (2016). Thermal performance evaluation of an active building integrated photovoltaic thermoelectric wall system. Applied Energy, 177, 25-39. doi: 10.1016/j.apenergy.2016.05.087

Luo, Y., Zhang, L., Liu, Z., Wu, J., Zhang, Y., & Wu, Z. (2018). Numerical evaluation on energy saving potential of a solar photovoltaic thermoelectric radiant wall system in cooling dominant climates. Energy, 142, 384-399. doi: 10.1016/j.energy.2017.10.050

Luo, Y., Zhang, L., Liu, Z., Wu, J., Zhang, Y., Wu, Z., & He, X. (2017). Performance analysis of a self-adaptive building integrated photovoltaic thermoelectric wall system in hot summer and cold winter zone of China. Energy, 140, 584-600. doi: 10.1016/j.energy.2017.09.015

Ma, Y., Saha, S., Miller, W., & Guan, L. (2017). Comparison of Different Solar-Assisted Air Conditioning Systems for Australian Office Buildings. Energies, 10(10), 1463. doi: 10.3390/en10101463

Mach, T., Grobbauer, M., Streicher, W., & Müller, M. J. (2015). MPPF - The multifunctional plug & play approach in facade technology: Verlag d. Technischen Universität Graz.

Maerefat, M., & Haghighi, A. P. (2010). Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney. Renewable Energy, 35(10), 2316-2324. doi: 10.1016/j.renene.2010.03.003

Maestre, I. R., Blázquez, J. L. F., Gallero, F. J. G., & Cubillas, P. R. (2015). Influence of selected solar positions for shading device calculations in building energy performance simulations. Energy and Buildings, 101, 144-152. doi: 10.1016/j.enbuild.2015.05.004

Mahesh, A. (2017). Solar collectors and adsorption materials aspects of cooling system. Renewable and Sustainable Energy Reviews, 73, 1300-1312. doi: 10.1016/j.rser.2017.01.144

Mahler, B., & Himmler, R. (2008). Results of the evaluation study DeAL - Decentralized facade integrated ventilation systems. Paper presented at the 8th International Conference for Enhanced Building Operations, Berlin, Germany.

Makaremi, N., Salleh, E., Jaafar, M. Z., & Ghaffarian, A. H. (2012). Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia. Building and Environment, 48, 7-14. doi: 10.1016/j.buildenv.2011.07.024

Mallick, T. K., Eames, P. C., Hyde, T. J., & Norton, B. (2004). The design and experimental characterisation of an asymmetric compound parabolic photovoltaic concentrator for building façade integration in the UK. Solar Energy, 77(3), 319-327. doi: http://dx.doi.org/10.1016/j.solener.2004.05.015

Mandalaki, M., Zervas, K., Tsoutsos, T., & Vazakas, A. (2012). Assessment of fixed shading devices with integrated PV for efficient energy use. Solar Energy, 86(9), 2561-2575. doi: http://dx.doi.org/10.1016/j.solener.2012.05.026

Manzan, M. (2014). Genetic optimization of external fixed shading devices. Energy and Buildings, 72, 431-440. doi: 10.1016/j.enbuild.2014.01.007

Marc, O., Praene, J.-P., Bastide, A., & Lucas, F. (2011). Modeling and experimental validation of the solar loop for absorption solar cooling system using double-glazed collectors. Applied Thermal Engineering, 31(2-3), 268-277. doi: 10.1016/j.applthermaleng.2010.09.006

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P. A., Möller, B., . . . Hvelplund, F. K. (2015). Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy, 145, 139-154. doi: 10.1016/j.apenergy.2015.01.075

Maurer, C., Gasnier, D., Pflug, T., Plešec, P., Hafner, J., Jordan, S., & Kuhn, T. E. (2014). First Measurement Results of a Pilot Building with Transparent Façade Collectors. Energy Procedia, 48, 1385-1392. doi: 10.1016/j.egypro.2014.02.156

Maurer, C., Pflug, T., Di Lauro, P., Hafner, J., Knez, F., Jordan, S., . . . Kuhn, T. E. (2012). Solar Heating and Cooling with Transparent Façade Collectors in a Demonstration Building. Energy Procedia, 30(0), 1035-1041. doi: http://dx.doi.org/10.1016/j.egypro.2012.11.116

Mayring, P. (2014). Qualitative content analysis. Theoretical foundation, basic procedures and software solution. Klagenfurt, Austria.

TOC

McNevin, C., & Harrison, S. J. (2017). Multi-stage liquid-desiccant air-conditioner: Experimental performance and model development. Building and Environment, 114, 45-55. doi: 10.1016/j.buildenv.2016.12.011

Mei, L., Infield, D., Eicker, U., Loveday, D., & Fux, V. (2006). Cooling potential of ventilated PV façade and solar air heaters combined with a desiccant cooling machine. Renewable Energy, 31(8), 1265-1278. doi: http://dx.doi.org/10.1016/j.renene.2005.06.013

Melendo, J. M. A., & La Roche, P. (2008). Effects of window size in daylighting and energy performance in buildings. Paper presented at the American Solar Energy Society - SOLAR 2008, Including Proc. of 37th ASES Annual Conf., 33rd National Passive Solar Conf., 3rd Renewable Energy Policy and Marketing Conf.: Catch the Clean Energy Wave.

Mirzaei, P. A., Paterna, E., & Carmeliet, J. (2014). Investigation of the role of cavity airflow on the performance of building-integrated photovoltaic panels. Solar Energy, 107(0), 510-522. doi: http://dx.doi.org/10.1016/j.solener.2014.05.003

Monné, C., Alonso, S., Palacín, F., & Serra, L. (2011). Monitoring and simulation of an existing solar powered absorption cooling system in Zaragoza (Spain). Applied Thermal Engineering, 31(1), 28-35. doi: 10.1016/j.applthermaleng.2010.08.002

Montagnino, F. M. (2017). Solar cooling technologies. Design, application and performance of existing projects. Solar Energy. doi: 10.1016/j.solener.2017.01.033

Moretti, E., & Belloni, E. (2015). Evaluation of energy, thermal, and daylighting performance of solar control films for a case study in moderate climate. Building and Environment. doi: http://dx.doi.org/10.1016/j.buildenv.2015.07.031

Morgado, I., Melero, S., Neila, J., & Acha, C. (2011). Evaporative cooling efficiency according to climate conditions. Procedia Engineering, 21, 283-290. doi: 10.1016/j.proeng.2011.11.2016

Mujahid Rafique, M., Gandhidasan, P., Ibrahim, N. I., & Bahaidarah, H. M. (2017). Recent Developments in Liquid Desiccant-Based Cooling Systems. 441-453. doi: 10.1016/b978-0-12-409548-9.10146-0

Mujahid Rafique, M., Gandhidasan, P., Rehman, S., & Al-Hadhrami, L. M. (2015). A review on desiccant based evaporative cooling systems. Renewable and Sustainable Energy Reviews, 45, 145-159. doi: 10.1016/j.rser.2015.01.051

MultiChill. (n.d.). MultiChill Technologies Inc. Retrieved April 7th, 2018, from http://multichilltech.com/.

Munari-Probst, M. C., Roecker, C., & Schueler, A. (2005). Architectural integration of solar thermal collectors: results of a european survey. Paper presented at the ISES Solar World Congress, Orlando, USA.

Munari-Probst, M. C., & Roecker, C. e. (2012). Solar energy systems in architecture. Report T.41.A.2 IEA SHC Task 41 Solar energy and Architecture.

Munari Probst, M. C., & Roecker, C. (2007). Towards an improved architectural quality of building integrated solar thermal systems (BIST). Solar Energy, 81(9), 1104-1116. doi: 10.1016/j.solener.2007.02.009

Munters. (n.d.-a). DesiCool air conditioning - product brochure. Retrieved March 15th, 2018, from https://www.munters.com/.

Munters. (n.d.-b). Munters. Retrieved April 6th, 2018, from https://www.munters.com/.

Nadim, W., & Goulding, J. S. (2009). Offsite Production in the UK: The Construction Industry and Academia. Architectural Engineering and Design Management, 5(3), 136-152. doi: 10.3763/aedm.2008.0094

Nakahara, N., Miyakawa, Y., & Yamamoto, M. (1977). Experimental study on house cooling and heating with solar energy using flat plate collector. Solar Energy, 19, 657-662.

Nicol, F., Humphreys, M., & Roaf, S. (2012). Adaptive Thermal Comfort: Principles and Practice: Taylor & Francis.

NIOSH. (n.d.). The National Institute for Occupational Safety and Health (NIOSH). Retrieved November 16th 2017, from https://www.cdc.gov/niosh/index.htm.

Nkwetta, D. N., & Smyth, M. (2012). Performance analysis and comparison of concentrated evacuated tube heat pipe solar collectors. Applied Energy, 98(0), 22-32. doi: http://dx.doi.org/10.1016/j.apenergy.2012.02.059

Noro, M., & Lazzarin, R. M. (2014). Solar cooling between thermal and photovoltaic: An energy and economic comparative study in the Mediterranean conditions. Energy(0). doi: http://dx.doi.org/10.1016/j.energy.2014.06.035

NREL. (n.d.-a). EnergyPlus. Retrieved September 16th, 2016, from https://energyplus.net/.

NREL. (n.d.-b). System advisor model (SAM). Retrieved January 24th, 2018, from https://sam.nrel.gov/.

OECD/IEA. (2012). Technology Roadmap - Solar Heating and Cooling.

OECD/IEA. (2014). Technology Roadmap - Solar Photovoltaic Energy.

TOC

OECD/IEA. (2015). Energy and climate change / World Energy Outlook Special Report. Paris, France: IEA - International Energy Agency.

Olgyay, V., & Olgyay, A. (1963). Design With Climate: Bioclimatic Approach to Architectural Regionalism: Princeton University Press.

Orel, B., Spreizer, H., Šurca Vuk, A., Fir, M., Merlini, D., Vodlan, M., & Köhl, M. (2007). Selective paint coatings for coloured solar absorbers: Polyurethane thickness insensitive spectrally selective (TISS) paints (Part II). Solar Energy Materials and Solar Cells, 91(2–3), 108-119. doi: http://dx.doi.org/10.1016/j.solmat.2006.07.012

Ortiz, M., Barsun, H., He, H., Vorobieff, P., & Mammoli, A. (2010). Modeling of a solar-assisted HVAC system with thermal storage. Energy and Buildings, 42(4), 500-509. doi: http://dx.doi.org/10.1016/j.enbuild.2009.10.019

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials, 23(1), 28-39. doi: 10.1016/j.conbuildmat.2007.11.012

Otanicar, T., Taylor, R. A., & Phelan, P. E. (2012). Prospects for solar cooling – An economic and environmental assessment. Solar Energy, 86(5), 1287-1299. doi: 10.1016/j.solener.2012.01.020

Overduin, J. (2016). Facade for wind and stack driven ventilation in tropical high-rise office. (Master Thesis), Delft University of Technology, Delft, The Netherlands.

Palmero-Marrero, A. I., & Oliveira, A. C. (2006). Evaluation of a solar thermal system using building louvre shading devices. Solar Energy, 80(5), 545-554. doi: http://dx.doi.org/10.1016/j.solener.2005.04.003

Pampuri, L., Cereghetti, N., Strepparava, D., & Caputo, P. (2016). Analysis of the electricity consumptions: A first step to develop a district cooling system. Sustainable Cities and Society, 23, 23-36. doi: 10.1016/j.scs.2016.02.015

Panchabikesan, K., Vellaisamy, K., & Ramalingam, V. (2017). Passive cooling potential in buildings under various climatic conditions in India. Renewable and Sustainable Energy Reviews, 78, 1236-1252. doi: 10.1016/j.rser.2017.05.030

Pando Martínez, G. E., Sauceda Carvajal, D., Velázquez Limón, N., Luna León, A., & Moreno Hernandez, S. (2014). Simulation and Comparative Study of a Hybrid Cooling Solar – Gas with Heat Storage. Energy Procedia, 57(0), 2646-2655. doi: http://dx.doi.org/10.1016/j.egypro.2014.10.276

Pardo, N., Montero, Á., Martos, J., & Urchueguía, J. F. (2010). Optimization of hybrid – ground coupled and air source – heat pump systems in combination with thermal storage. Applied Thermal Engineering, 30(8–9), 1073-1077. doi: http://dx.doi.org/10.1016/j.applthermaleng.2010.01.015

Paricio, I. (2000). La Proteccion Solar. Barcelona, Spain: Bisagra.

Peng, J., Lu, L., & Yang, H. (2013). An experimental study of the thermal performance of a novel photovoltaic double-skin facade in Hong Kong. Solar Energy, 97(0), 293-304. doi: http://dx.doi.org/10.1016/j.solener.2013.08.031

Pérez-Grande, I., Meseguer, J., & Alonso, G. (2005). Influence of glass properties on the performance of double-glazed facades. Applied Thermal Engineering, 25(17–18), 3163-3175. doi: http://dx.doi.org/10.1016/j.applthermaleng.2005.04.004

Pfafferott, J., Herkel, S., & Wambsganß, M. (2004). Design, monitoring and evaluation of a low energy office building with passive cooling by night ventilation. Energy and Buildings, 36(5), 455-465. doi: http://dx.doi.org/10.1016/j.enbuild.2004.01.041

Phononic. (n.d.). Phononic.   Retrieved April 6th, 2018, from http://phononic.com/

Pino, A., Bustamante, W., Escobar, R., & Encinas, F. (2012). Thermal and lighting behavior of office buildings in Santiago of Chile. Energy and Buildings, 47(0), 441-449. doi: http://dx.doi.org/10.1016/j.enbuild.2011.12.016

Pollerberg, C., Ali, A. H. H., & Dötsch, C. (2009). Solar driven steam jet ejector chiller. Applied Thermal Engineering, 29(5-6), 1245-1252. doi: 10.1016/j.applthermaleng.2008.06.017

Preisler, A., Selke, T., Focke, H., Hartl, N., Geissegger, G., Podesser, E., & Thür, A. (2012). Development of a Technology Roadmap for Solar Thermal Cooling in Austria. Energy Procedia, 30, 1422-1431. doi: 10.1016/j.egypro.2012.11.156

Prieto, A., Klein, T., & Knaack, U. (2016). Facade integration: survey-based assessment of the main problems for the integration of building services in facade systems. Paper presented at the ID@50 Integrated Design Conference, Bath, United Kingdom.

Prieto, A., Klein, T., Knaack, U., & Auer, T. (2017). Main perceived barriers for the development of building service integrated facades: Results from an exploratory expert survey. Journal of Building Engineering, 13, 96-106. doi: 10.1016/j.jobe.2017.07.008

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2017a). Solar coolfacades: Framework for the integration of solar cooling technologies in the building envelope. Energy, 137, 353-368. doi: 10.1016/j.energy.2017.04.141

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2017b). Solar façades – Main barriers for widespread façade integration of solar technologies. Journal of Facade Design and Engineering, 5(1), 51-62. doi: 10.7480/jfde.2017.1.1398

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2018a). Feasibility Study of Self-Sufficient Solar Cooling Façade Applications in Different Warm Regions. Energies, 11(6), 1475. doi: 10.3390/en11061475

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2018b). Passive cooling & climate responsive façade design: exploring the limits of passive cooling strategies to improve the performance of commercial buildings in warm climates. Energy and Buildings, 175, 30-47. doi: 10.1016/j.enbuild.2018.06.016

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2019). COOLFACADE: State-of-the-art review and evaluation of solar cooling technologies on their potential for façade integration. Renewable and Sustainable Energy Reviews, 101, 395-414. doi: 10.1016/j.rser.2018.11.015

Prieto, A., Knaack, U., Klein, T., & Auer, T. (2017). 25 Years of cooling research in office buildings: Review for the integration of cooling strategies into the building façade (1990–2014). Renewable and Sustainable Energy Reviews, 71, 89-102. doi: 10.1016/j.rser.2017.01.012

ProFlute. (n.d.). ProFlute. Retrieved April 6th, 2018, from http://www.proflute.se/.

Purix. (n.d.). Purix. Retrieved April 6th, 2018, from http://www.purix.com/.

Qi, C. (2006). Office Building Energy Saving Potential in Singapore. (MSc Thesis), National University of Singapore (NUS), Singapore.

Qi, R., Lu, L., & Huang, Y. (2014). Energy performance of solar-assisted liquid desiccant air-conditioning system for commercial building in main climate zones. Energy Conversion and Management, 88(0), 749-757. doi: http://dx.doi.org/10.1016/j.enconman.2014.09.006

Qiu, Z., Chow, T., Li, P., Li, C., Ren, J., & Wang, W. (2009). Performance evaluation of the photovoltaic double-skin facade. Paper presented at the IBPSA 2009 - International Building Performance Simulation Association 2009.

Qu, M., Yin, H., & Archer, D. H. (2010). A solar thermal cooling and heating system for a building: Experimental and model based performance analysis and design. Solar Energy, 84(2), 166-182. doi: http://dx.doi.org/10.1016/j.solener.2009.10.010

Quoilin, S., Orosz, M., Hemond, H., & Lemort, V. (2011). Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation. Solar Energy, 85(5), 955-966. doi: http://dx.doi.org/10.1016/j.solener.2011.02.010

Radhi, H., Sharples, S., & Fikiry, F. (2013). Will multi-facade systems reduce cooling energy in fully glazed buildings? A scoping study of UAE buildings. Energy and Buildings, 56, 179-188. doi: 10.1016/j.enbuild.2012.08.030

Ralegaonkar, R. V., & Gupta, R. (2010). Review of intelligent building construction: A passive solar architecture approach. Renewable and Sustainable Energy Reviews, 14(8), 2238-2242. doi: 10.1016/j.rser.2010.04.016

Ramponi, R., Angelotti, A., & Blocken, B. (2014). Energy saving potential of night ventilation: Sensitivity to pressure coefficients for different European climates. Applied Energy, 123, 185-195.

Reda, A. M., Ali, A. H. H., Morsy, M. G., & Taha, I. S. (2016). Design optimization of a residential scale solar driven adsorption cooling system in upper Egypt based. Energy and Buildings, 130, 843-856. doi: 10.1016/j.enbuild.2016.09.011

Reda, A. M., Ali, A. H. H., Taha, I. S., & Morsy, M. G. (2017). Performance of a small-scale solar-powered adsorption cooling system. International Journal of Green Energy, 14(1), 75-85. doi: 10.1080/15435075.2016.1234380

Riffat, S. B., & Ma, X. (2004). Improving the coefficient of performance of thermoelectric cooling systems: a review. International Journal of Energy Research, 28(9), 753-768. doi: 10.1002/er.991

Roach, P., Bruno, F., & Belusko, M. (2013). Modelling the cooling energy of night ventilation and economiser strategies on façade selection of commercial buildings. Energy and Buildings, 66(0), 562-570. doi: http://dx.doi.org/10.1016/j.enbuild.2013.06.034

TOC

Rodríguez-Sánchez, D., Belmonte, J. F., Izquierdo-Barrientos, M. A., Molina, A. E., Rosengarten, G., & Almendros-Ibáñez, J. A. (2014). Solar energy captured by a curved collector designed for architectural integration. Applied Energy, 116, 66-75. doi: 10.1016/j.apenergy.2013.10.059

Rosiek, S., & Batlles, F. J. (2009). Integration of the solar thermal energy in the construction: Analysis of the solar-assisted air-conditioning system installed in CIESOL building. Renewable Energy, 34(6), 1423-1431. doi: 10.1016/j.renene.2008.11.021

RotorSource. (n.d.). RotorSource. Retrieved April 6th, 2018, from https://www.rotorsource.com/.

Rouf, R. A., Alam, K. C. A., & Khan, M. A. H. (2015). Solar Adsorption Cooling and Hot Water Supply for Climatic Condition of Dhaka. Procedia Engineering, 105, 705-712. doi: 10.1016/j.proeng.2015.05.060

Rouf, R. A., Alam, K. C. A., Khan, M. A. H., Saha, B. B., Meunier, F., Alim, M. A., & Kabir, K. M. A. (2014). Advancement of Solar Adsorption Cooling by Means of Heat Storage. Procedia Engineering, 90, 649-656. doi: 10.1016/j.proeng.2014.11.786

Ruschenburg, J., Baisch, K., Courtot, F., Oltersdorf, T., & Herkel, S. (2011). Experimental and simulation results on a solar-assisted heat pump prototype for decentral applications. Paper presented at the 10th IEA Heat Pump Conference.

Russell, J. (2003). Architectural Style and Management Ideals. AV Monographs.

RVO. (2013). Infoblad Trias Energetica en energieneutraal bouwen. The Netherlands: Rijksdienst voor Ondernemend Nederland.

SAGE (n.d.). Research methods. Retrieved July 13th, 2017, from http://methods.sagepub.com/

Sagia, Z., Rakopoulos, C., & Kakaras, E. (2012). Cooling dominated Hybrid Ground Source Heat Pump System application. Applied Energy, 94(0), 41-47. doi: http://dx.doi.org/10.1016/j.apenergy.2012.01.031

Sahlot, M., & Riffat, S. B. (2016). Desiccant cooling systems: a review. International Journal of Low-Carbon Technologies, ctv032. doi: 10.1093/ijlct/ctv032

Said, S. A. M., El-Shaarawi, M. A. I., & Siddiqui, M. U. (2012). Alternative designs for a 24-h operating solar-powered absorption refrigeration technology. International Journal of Refrigeration, 35(7), 1967-1977. doi: 10.1016/j.ijrefrig.2012.06.008

Sales, B. C. (2002). Smaller Is Cooler. Science, 295(5558), 1248-1249. doi: 10.1126/science.1069895

SaltX. (n.d.). SaltX Technology. Retrieved April 6th, 2018, from http://saltxtechnology.com/.

Samaan, M. M., Farag, O., & Khalil, M. (2016). Using simulation tools for optimizing cooling loads and daylighting levels in Egyptian campus buildings. HBRC Journal. doi: 10.1016/j.hbrcj.2016.01.001

Samuel, D. G. L., Nagendra, S. M. S., & Maiya, M. P. (2013). Passive alternatives to mechanical air conditioning of building: A review. Building and Environment, 66, 54-64. doi: 10.1016/j.buildenv.2013.04.016

Sanjuan, C., Soutullo, S., & Heras, M. R. (2010). Optimization of a solar cooling system with interior energy storage. Solar Energy, 84(7), 1244-1254. doi: 10.1016/j.solener.2010.04.001

Santamouris, M. (2016). Cooling the buildings – past, present and future. Energy and Buildings, 128, 617-638. doi: 10.1016/j.enbuild.2016.07.034

Santamouris, M., & Asimakopoulos, D. (1996). Passive Cooling of Buildings: James & James.

Santamouris, M., & Kolokotsa, D. (2013). Passive cooling dissipation techniques for buildings and other structures: The state of the art. Energy and Buildings, 57, 74-94. doi: 10.1016/j.enbuild.2012.11.002

Santamouris, M., Pavlou, K., Synnefa, A., Niachou, K., & Kolokotsa, D. (2007). Recent progress on passive cooling techniques. Energy and Buildings, 39(7), 859-866. doi: 10.1016/j.enbuild.2007.02.008

Sarbu, I., & Sebarchievici, C. (2013). Review of solar refrigeration and cooling systems. Energy and Buildings, 67, 286-297. doi: 10.1016/j.enbuild.2013.08.022

Schüco. (2009). Schüco E^2 façade: Saving Energy and Generating Energy. Germany.

Schüler, A., Boudaden, J., Oelhafen, P., De Chambrier, E., Roecker, C., & Scartezzini, J. L. (2005). Thin film multilayer design types for colored glazed thermal solar collectors. Solar Energy Materials and Solar Cells, 89(2–3), 219-231. doi: http://dx.doi.org/10.1016/j.solmat.2004.11.015

Schüler, A., Dutta, D., de Chambrier, E., Roecker, C., De Temmerman, G., Oelhafen, P., & Scartezzini, J.-L. (2006). Sol−gel deposition and optical characterization of multilayered SiO2/Ti1−xSixO2 coatings on solar collector glasses. Solar Energy Materials and Solar Cells, 90(17), 2894-2907. doi: http://dx.doi.org/10.1016/j.solmat.2006.05.003

Schüler, A., Roecker, C., Scartezzini, J. L., Boudaden, J., Videnovic, I. R., Ho, R. S. C., & Oelhafen, P. (2004). On the feasibility of colored glazed thermal solar collectors based on thin film interference filters. Solar Energy Materials and Solar Cells, 84(1–4), 241-254. doi: http://dx.doi.org/10.1016/j.solmat.2004.02.045

TOC

Schuler, M. (2002). Integrated Concepts. In J. Eisele & E. Kloft (Eds.), High-Rise Manual: Typology and Design, Construction and Technology (pp. 182-193). Berlin, Germany: Birkhauser.

Schulze, T., & Eicker, U. (2013). Controlled natural ventilation for energy efficient buildings. Energy and Buildings, 56, 221-232. doi: 10.1016/j.enbuild.2012.07.044

Selke, T., Frein, A., Muscherà, M., Sethuvenkatraman, S., Hands, S., & White, S. (2016). SHC Task 48 B2 – Three GOOD Practice Examples of Solar Heat Driven Desiccant Evaporative Cooling Systems. Energy Procedia, 91, 832-843. doi: 10.1016/j.egypro.2016.06.250

Selkowitz, S. (2001). Integrating Advanced Facades into High Performance Buildings. Paper presented at the 7th International Glass Processing Days, Tampere, Finland.

Sheetak. (n.d.). Sheetak. Retrieved April 6th, 2017, from http://www.sheetak.com/

Shen, L., Pu, X., Sun, Y., & Chen, J. (2016). A study on thermoelectric technology application in net zero energy buildings. Energy, 113, 9-24. doi: 10.1016/j.energy.2016.07.038

Shen, L., Xiao, F., Chen, H., & Wang, S. (2013). Investigation of a novel thermoelectric radiant air-conditioning system. Energy and Buildings, 59, 123-132. doi: 10.1016/j.enbuild.2012.12.041

Sherif, A., El-Zafarany, A., & Arafa, R. (2012). External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments. Energy and Buildings, 52, 1-10. doi: 10.1016/j.enbuild.2012.05.025

Shukla, D. L., & Modi, K. V. (2017). A technical review on regeneration of liquid desiccant using solar energy. Renewable and Sustainable Energy Reviews, 78, 517-529. doi: 10.1016/j.rser.2017.04.103

Sijpheer, N. C., Bakker, E. J., & De Boer, R. (2010). Testing a prototype adsorption cooler in a research dwelling. Paper presented at the 10th International Conference for Enhanced Building Operations (ICEBO), 26-28 October 2010, Kuwait.

Sim, L. F. (2014). Numerical modelling of a solar thermal cooling system under arid weather conditions. Renewable Energy, 67, 186-191. doi: 10.1016/j.renene.2013.11.032

SOLAIR. (2009). Solair Project: Increasing the market implementation of Solar Air-Conditioning Systems for small and medium applications in residential and commercial buildings. Retrieved 14 September 2014, from http://www.solair-project.eu/

Solarcombi+. (2009). SonnenKlima package solution description. Report of Solarcombi+ project: Identification of most promising markets and promotion of standardised system configurations for the market entry of small scale combined solar heating & cooling applications: Intelligent Energy Europe.

SolarInvent. (n.d.). Freescoo / SolarInvent S.r.l. Retrieved April 6th, 2018, from http://www.freescoo.com.

SolarNext. (n.d.). SolarNext. Retrieved April 6th, 2018, from http://www.solarnext.eu.

Solgi, E., Fayaz, R., & Kari, B. M. (2016). Cooling load reduction in office buildings of hot-arid climate, combining phase change materials and night purge ventilation. Renewable Energy, 85, 725-731. doi: 10.1016/j.renene.2015.07.028

Soussi, M., Balghouthi, M., Guizani, A., & Bouden, C. (2017). Model performance assessment and experimental analysis of a solar assisted cooling system. Solar Energy, 143, 43-62. doi: 10.1016/j.solener.2016.12.046

SScooling. (n.d.). Solid State cooling systems. Retrieved April 6th, 2018, from http://www.sscooling.com/

Stavrakakis, G. M., Koukou, M. K., Vrachopoulos, M. G., & Markatos, N. C. (2008). Natural cross-ventilation in buildings: Building-scale experiments, numerical simulation and thermal comfort evaluation. Energy and Buildings, 40(9), 1666-1681. doi: 10.1016/j.enbuild.2008.02.022

Stazi, F., Marinelli, S., Di Perna, C., & Munafò, P. (2014). Comparison on solar shadings: Monitoring of the thermo-physical behaviour, assessment of the energy saving, thermal comfort, natural lighting and environmental impact. Solar Energy, 105(0), 512-528. doi: http://dx.doi.org/10.1016/j.solener.2014.04.005

Stevanović, S. (2013). Optimization of passive solar design strategies: A review. Renewable and Sustainable Energy Reviews, 25, 177-196. doi: 10.1016/j.rser.2013.04.028

Streefkerk, W. (2011). Stirling Solar cooling in office facades. (Master in Building Technology), TU Delft, Delft, The Netherlands.

Szokolay, S. V., & Brisbin, C. (2004). Introduction to Architectural Science: The Basis of Sustainable Design: Architectural Press.

Tamasauskas, J., Kegel, M., & Sunye, R. (2014). An Analysis of Solar Thermal Technologies Integrated into a Canadian Office Building. Energy Procedia, 48, 1017-1026. doi: 10.1016/j.egypro.2014.02.116

Tan, G., & Zhao, D. (2015). Study of a thermoelectric space cooling system integrated with phase change material. Applied Thermal Engineering, 86, 187-198. doi: 10.1016/j.applthermaleng.2015.04.054

TOC

Tanuharja, M. (2015). Integrated Facade System in High Rise Office Buildings in Tropical Climate Condition. (Master), TU Delft, Delft, The Netherlands.

Tejero-González, A., Andrés-Chicote, M., García-Ibáñez, P., Velasco-Gómez, E., & Rey-Martínez, F. J. (2016). Assessing the applicability of passive cooling and heating techniques through climate factors: An overview. Renewable and Sustainable Energy Reviews, 65, 727-742. doi: 10.1016/j.rser.2016.06.077

Thirakomen, K. (2007). Why building has to be airtight? Paper presented at the Proceedings - 9th Asia Pacific Conference on the Built Environment 2007: "Sustainable HVAC and R Technology".

Torío, H., & Schmidt, D. (2010). Framework for analysis of solar energy systems in the built environment from an exergy perspective. Renewable Energy, 35(12), 2689-2697. doi: 10.1016/j.renene.2010.04.015

Trane. (n.d.). TRANE. Retrieved April 6th, 2018, from http://www.trane.com/.

Tsikaloudaki, K., Laskos, K., Theodosiou, T., & Bikas, D. (2012). Assessing cooling energy performance of windows for office buildings in the Mediterranean zone. Energy and Buildings, 49(0), 192-199. doi: http://dx.doi.org/10.1016/j.enbuild.2012.02.004

Tzempelikos, A., Bessoudo, M., Athienitis, A. K., & Zmeureanu, R. (2010). Indoor thermal environmental conditions near glazed facades with shading devices – Part II: Thermal comfort simulation and impact of glazing and shading properties. Building and Environment, 45(11), 2517-2525. doi: http://dx.doi.org/10.1016/j.buildenv.2010.05.014

Ullah, K. R., Saidur, R., Ping, H. W., Akikur, R. K., & Shuvo, N. H. (2013). A review of solar thermal refrigeration and cooling methods. Renewable and Sustainable Energy Reviews, 24, 499-513. doi: 10.1016/j.rser.2013.03.024

UN. (2016). Decision XXVIII/1 Further Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer. Kigali, Rwanda.

UNEP. (2017). Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer (11th edition (2017) ed.): Ozone Secretariat, United Nations Environment Programme.

Van Den Wymelenberg, K. (2012). Patterns of occupant interaction with window blinds: A literature review. Energy and Buildings, 51, 165-176. doi: 10.1016/j.enbuild.2012.05.008

Vasquez, C., Prieto, A., & Aguirre, C. (2012). Characterisation of summer thermal behaviour of 'Class A' office buildings in Santiago, Chile. Paper presented at the PLEA2012 - 28th Conference, Oportunities, Limits & Needs Towards an environmentally responsible architecture, Lima, Peru.

Vasquez, J., Sanz-Bobi, M., Palacios, R., & Arenas, A. (2001). An active thermal wall based on thermoelectricity. Paper presented at the 6th European Workshop on Thermoelectrics, Freiburg, Germany.

VDMA. (2017). International Technology Roadmap for Photovoltaic (ITRPV): 2016 Results including maturity report (8th edition ed.). Germany: VDMA.

Venkatasubramanian, R., Siivola, E., Colpitts, T., & O'Quinn, B. (2001). Thin-film thermoelectric devices with high room-temperature figures of merit. Nature, 413(6856), 597-602.

Verde, M. (2015). Modelling and optimization of an adsorption cooling system for automotive applications. (PhD), Universidad politecnica de Valencia, Valencia, Spain.

Vischer, J. (2007). Space Meets Status: Designing Workplace Performance: Taylor & Francis.

Vitte, T., Brau, J., Chatagnon, N., & Woloszyn, M. (2008). Proposal for a new hybrid control strategy of a solar desiccant evaporative cooling air handling unit. Energy and Buildings, 40(5), 896-905. doi: http://dx.doi.org/10.1016/j.enbuild.2007.07.004

Wan Nazi, W. I., Royapoor, M., Wang, Y., & Roskilly, A. P. (2017). Office building cooling load reduction using thermal analysis method – A case study. Applied Energy, 185, 1574-1584. doi: 10.1016/j.apenergy.2015.12.053

Wan Nazi, W. I., Wang, Y. D., & Roskilly, T. (2015). Methodologies to Reduce Cooling Load using Heat Balance Analysis: A Case Study in an Office Building in a Tropical Country. Energy Procedia, 75, 1269-1274. doi: http://dx.doi.org/10.1016/j.egypro.2015.07.185

Wang, F., Pichatwatana, K., Roaf, S., Zhao, L., Zhu, Z., & Li, J. (2014). Developing a weather responsive internal shading system for atrium spaces of a commercial building in tropical climates. Building and Environment, 71, 259-274. doi: 10.1016/j.buildenv.2013.10.003

Wang, H., Peterson, R., Harada, K., Miller, E., Ingram-Goble, R., Fisher, L., . . . Ward, C. (2011). Performance of a combined organic Rankine cycle and vapor compression cycle for heat activated cooling. Energy, 36(1), 447-458. doi: http://dx.doi.org/10.1016/j.energy.2010.10.020

Wang, H. H., Ge, T. S., Zhang, X. L., & Zhao, Y. (2016). Experimental investigation on solar powered self-cooled cooling system based on solid desiccant coated heat exchanger. Energy, 96, 176-186. doi: 10.1016/j.energy.2015.12.067

Wang, L., & Greenberg, S. (2015). Window Operation and Impacts on Building Energy Consumption. Energy and Buildings(0). doi: http://dx.doi.org/10.1016/j.enbuild.2015.01.060

Wang, S. K. (2001). Handbook of Air Conditioning and Refrigeration: McGraw-Hill.

Warren, P. e. (2003). Integral Building Envelope Performance Assessment - Technical Synthesis Report IEA ECBCS Annex 32. Hertfordshire, UK: IEA.

Weber, C., Berger, M., Mehling, F., Heinrich, A., & Núñez, T. (2014). Solar cooling with water–ammonia absorption chillers and concentrating solar collector – Operational experience. International Journal of Refrigeration, 39, 57-76. doi: 10.1016/j.ijrefrig.2013.08.022

Weber, C., Mehling, F., Fregin, A., Daßler, I., & Schossig, P. (2014). On Standardizing Solar Cooling – Field Test in the Small Capacity Range. Energy Procedia, 48, 1027-1035. doi: 10.1016/j.egypro.2014.02.117

Wei, Y., Guo-qiang, Z., Xiao, W., Jing, L., & San-xian, X. (2010). Potential model for single-sided naturally ventilated buildings in China. Solar Energy, 84(9), 1595-1600. doi: http://dx.doi.org/10.1016/j.solener.2010.06.011

Weiss, W., & Biermayr, P. (2009). Potential of solar thermal in Europe. Final report of RESTMAC. Brussells, Belgium.

WICONA. TEmotion: Intelligent Facade Concept.   Retrieved March 3rd 2017, from https://www.wicona.com/en/int/Product/Facade/TEmotion-Intelligent-facade-concept/

Wigginton, M., & Harris, J. (2002). Intelligent Skins: Butterworth-Heinemann.

Wong, L. T., & Mui, K. W. (2009). Efficiency assessment of indoor environmental policy for air-conditioned offices in Hong Kong. Applied Energy, 86(10), 1933-1938. doi: http://dx.doi.org/10.1016/j.apenergy.2008.12.012

Wood, A., Henry, S., & Safarik, D. (2014). Best Tall Buildings: A Global Overview of 2014 Skyscrapers. Chicago: Routledge.

Wood, A., & Salib, R. (2013). Guide to Natural Ventilation in High Rise Office Buildings: Routledge.

Woudhuysen, J., & Abley, I. (2004). Why is Construction So Backward: Wiley.

Wu, D., Aye, L., Mendis, P., & Ngo, T. (2012). Technical feasibility of a façade integrated solar cooling system for commercial buildings. Proceedings of the 50th Annual Conference Australian Solar Energy Society.

Xu, X., & Van Dessel, S. (2008a). Evaluation of a prototype active building envelope window-system. Energy and Buildings, 40(2), 168-174. doi: 10.1016/j.enbuild.2007.02.027

Xu, X., & Van Dessel, S. (2008b). Evaluation of an Active Building Envelope window-system. Building and Environment, 43(11), 1785-1791. doi: 10.1016/j.buildenv.2007.10.013

Xu, X., Van Dessel, S., & Messac, A. (2007). Study of the performance of thermoelectric modules for use in active building envelopes. Building and Environment, 42(3), 1489-1502.

Yang, B., Sekhar, C., & Melikov, A. K. (2010). Ceiling mounted personalized ventilation system in hot and humid climate—An energy analysis. Energy and Buildings, 42(12), 2304-2308. doi: http://dx.doi.org/10.1016/j.enbuild.2010.07.022

Yang, L., & Li, Y. (2008). Cooling load reduction by using thermal mass and night ventilation. Energy and Buildings, 40(11), 2052-2058. doi: http://dx.doi.org/10.1016/j.enbuild.2008.05.014

Yang, R. J. (2015). Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): hardware and software strategies. Automation in Construction, 51(0), 92-102. doi: http://dx.doi.org/10.1016/j.autcon.2014.12.005

Yapıcı, R., & Ersoy, H. K. (2005). Performance characteristics of the ejector refrigeration system based on the constant area ejector flow model. Energy Conversion and Management, 46(18–19), 3117-3135. doi: http://dx.doi.org/10.1016/j.enconman.2005.01.010

Yau, Y. H., & Pean, H. L. (2014). The performance study of a split type air conditioning system in the tropics, as affected by weather. Energy and Buildings, 72(0), 1-7. doi: http://dx.doi.org/10.1016/j.enbuild.2013.12.010

Yazaki. (n.d.). YAZAKI Corporation. Retrieved April 6th, 2018, from https://www.yazaki-group.com/.

Yeo, T. H. C., Tan, I. A. W., & Abdullah, M. O. (2012). Development of adsorption air-conditioning technology using modified activated carbon – A review. Renewable and Sustainable Energy Reviews, 16(5), 3355-3363. doi: 10.1016/j.rser.2012.02.073

Yilmazoglu, M. Z. (2016). Experimental and numerical investigation of a prototype thermoelectric heating and cooling unit. Energy and Buildings, 113, 51-60. doi: 10.1016/j.enbuild.2015.12.046

Yin, R., Xu, P., & Shen, P. (2012). Case study: Energy savings from solar window film in two commercial buildings in Shanghai. Energy and Buildings, 45, 132-140.

Yoo, S.-H., & Manz, H. (2011). Available remodeling simulation for a BIPV as a shading device. Solar Energy Materials and Solar Cells, 95(1), 394-397. doi: http://dx.doi.org/10.1016/j.solmat.2010.02.015

Yoon, Y. B., Kim, D. S., & Lee, K. H. (2014). Detailed heat balance analysis of the thermal load variations depending on the blind location and glazing type. Energy and Buildings, 75(0), 84-95. doi: http://dx.doi.org/10.1016/j.enbuild.2014.02.002

York. (n.d.). YORK. Retrieved April 6th, 2018, from http://www.york.com/.

Yu, Y., Li, H., Niu, F., & Yu, D. (2014). Investigation of a coupled geothermal cooling system with earth tube and solar chimney. Applied Energy, 114, 209-217. doi: 10.1016/j.apenergy.2013.09.038

Yun, G. Y., & Steemers, K. (2010). Night-time naturally ventilated offices: Statistical simulations of window-use patterns from field monitoring. Solar Energy, 84(7), 1216-1231. doi: http://dx.doi.org/10.1016/j.solener.2010.03.029

Zandian, A., & Ashjaee, M. (2013). The thermal efficiency improvement of a steam Rankine cycle by innovative design of a hybrid cooling tower and a solar chimney concept. Renewable Energy, 51, 465-473. doi: 10.1016/j.renene.2012.09.051

Zelenay, K., Perepelitza, M., & Lehrer, D. (2011). High-Performance Facades: Design Strategies and Applications in North America and Northern Europe. In U. o. C. Centre for the Built Environment (CBE) (Ed.). Berkeley, USA.

Zeyghami, M., Goswami, D. Y., & Stefanakos, E. (2015). A review of solar thermo-mechanical refrigeration and cooling methods. Renewable and Sustainable Energy Reviews, 51, 1428-1445. doi: 10.1016/j.rser.2015.07.011

Zhang, F., Yin, Y., & Zhang, X. (2017). Performance analysis of a novel liquid desiccant evaporative cooling fresh air conditioning system with solution recirculation. Building and Environment, 117, 218-229. doi: 10.1016/j.buildenv.2017.03.015

Zhang, L. Z., & Niu, J. L. (2003). A pre-cooling Munters environmental control desiccant cooling cycle in combination with chilled-ceiling panels. Energy, 28(3), 275-292. doi: http://dx.doi.org/10.1016/S0360-5442(02)00114-7

Zhang, T., Liu, X., Jiang, J., Chang, X., & Jiang, Y. (2013). Experimental analysis of an internally-cooled liquid desiccant dehumidifier. Building and Environment, 63(0), 1-10. doi: http://dx.doi.org/10.1016/j.buildenv.2013.01.007

Zhao, D., & Tan, G. (2014). A review of thermoelectric cooling: Materials, modeling and applications. Applied Thermal Engineering, 66(1-2), 15-24. doi: 10.1016/j.applthermaleng.2014.01.074

Zhou, J., & Chen, Y. (2010). A review on applying ventilated double-skin facade to buildings in hot-summer and cold-winter zone in China. Renewable and Sustainable Energy Reviews, 14(4), 1321-1328. doi: http://dx.doi.org/10.1016/j.rser.2009.11.017

List of Tables

List of Figures

Curriculum Vitae

1984	Born in Valparaíso, Chile.
2003-2007	Bachelor in Architecture, Pontifical Catholic University of Chile (PUC).
2008-2010	Master of Science in Architecture, PUC.
2008-2010	Architect at CVZ Architecture Studio.
2011-2012	Researcher & Lecturer at School of Architecture, PUC.
2013-2014	Assistant Professor (non-tenured) at School of Architecture, PUC.
2014-2018	PhD Researcher at Architectural Facades & Products Research Group, Faculty of Architecture and the Built Environment, TU Delft.
2018-	Senior Researcher/Research Coordinator at Chair Design of Construction, Dept. of Architectural Engineering + Technology, TU Delft.

TOC

TOC

List of Publications

Journal articles

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2019). COOLFACADE: State-of-the-art review and evaluation of solar cooling technologies on their potential for façade integration. Renewable & Sustainable Energy Reviews, 101, 395-414. doi: 10.1016/j.rser.2018.11.015.

Prieto, A., Knaack, U., Klein, T., & Auer, T. (2018). Possibilities and constraints for the widespread application of solar cooling integrated façades. Journal of Facade Design and Engineering, 6(3), 10-18. doi: 10.7480/jfde.2018.3.2468.

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2018). Passive cooling & climate responsive façade design: exploring the limits of passive cooling strategies to improve the performance of commercial buildings in warm climates. Energy and Buildings, 175, 30-47. doi: 10.1016/j.enbuild.2018.06.016

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2018). Feasibility Study of Self-Sufficient Solar Cooling Façade Applications in Different Warm Regions. Energies, 11(6), 1475. doi: 10.3390/en11061475

Prieto, A., Klein, T., Knaack, U., & Auer, T. (2017). Main perceived barriers for the development of building service integrated facades: Results from an exploratory expert survey. Journal of Building Engineering, 13, 96-106. doi: 10.1016/j.jobe.2017.07.008

Prieto, A., Knaack, U., Klein, T., & Auer, T. (2017). 25 Years of cooling research in office buildings: Review for the integration of cooling strategies into the building façade (1990–2014). Renewable and Sustainable Energy Reviews, 71, 89-102. doi: 10.1016/j.rser.2017.01.012

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. doi: 10.1016/j.energy.2017.04.141

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2017). Solar façades – Main barriers for widespread façade integration of solar technologies. Journal of Facade Design and Engineering, 5(1), 51-62. doi: 10.7480/jfde.2017.1.1398

TOC

Bustamante, W., Vera, S., Prieto, A., Vásquez, C. (2014). Solar and Lighting Transmission through Complex Fenestration Systems of Office Buildings in a Warm and Dry Climate of Chile. Sustainability, 6(5):2786-2801., DOI:10.3390/su6052786

Vásquez, C., Encinas, F., Prieto, A., Aguirre, C. (2013). Thermal and lighting perception in four fully glazed office buildings in Santiago, Chile. Journal of Façade Design and Engineering, 1(1-2):31-51., DOI:10.3233/FDE-130007

Vásquez, C., Prieto, A. (2013). The ventilated facade [La fachada ventilada]. ARQ, 84:6-9.,DOI:10.4067/S0717-69962013000200016

Prieto, A. (2012). Opening workspace [La apertura del espacio de trabajo]. ARQ, 82:12-15., DOI:10.4067/S0717-69962012000300018

Book chapters

Konstantinou, T., Prieto, A. (2018). “Environmental Design Principles for the Building Envelope and More _ Passive and Active Measures” In: T. Konstantinou, N. Cukovic, M. Zbasnik (eds.). Energy – Resources and Building Performance. TU Delft Open, pp.147-180.

Vásquez, C., Prieto, A., Aguirre, C. (2014). " Impact of shape, occupation and external parameters in the overall thermal performance of office buildings in Santiago, Chile". In: Dincer, I., Midilli, A., Kucuk, H. (eds.). Progress in sustainable energy technologies vol II: Creating sustainable development. Springer, pp. 577-589.

Conference papers

Prieto, A., Knaack, U., Klein, T., & Auer, T. (2018). Possibilities and constraints for the widespread application of solar cooling façades. Facade 2018 - Adaptive!, Lucerne, Switzerland; November 26th-27th 2018.

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2017). Main barriers for widespread façade integration of solar technologies. Powerskin 2017 Conference, Munich, Germany; January 19th 2017.

Prieto, A., Knaack, U., Auer, T., Klein, T. (2016). COOLFACADE: Design driven categorisation of solar cooling technologies for facade integration possibilities. 15th International Conference on Sustainable Energy Technologies – SET 2016, Singapore; July 19th-22nd 2016.

Prieto, A., Klein, T., Knaack, U. (2016). Façade integration: survey-based assessment of the main problems for the integration of building services in façade systems. Integrated Design Conference ID@50: Building our Future, Bath, UK; June 29th-July 1st 2016.

Vásquez, C., Prieto, A., Aguirre, C. (2012). Characterization of summer thermal behaviour of "Class A" office buildings in Santiago, Chile. PLEA2012 - 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture, Lima, Perú; November 7th-9th 2012; 11/2012, DOI:10.13140/2.1.4146.3045

TOC