# 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.

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[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

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## § 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 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.

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## § 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).

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## § 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.

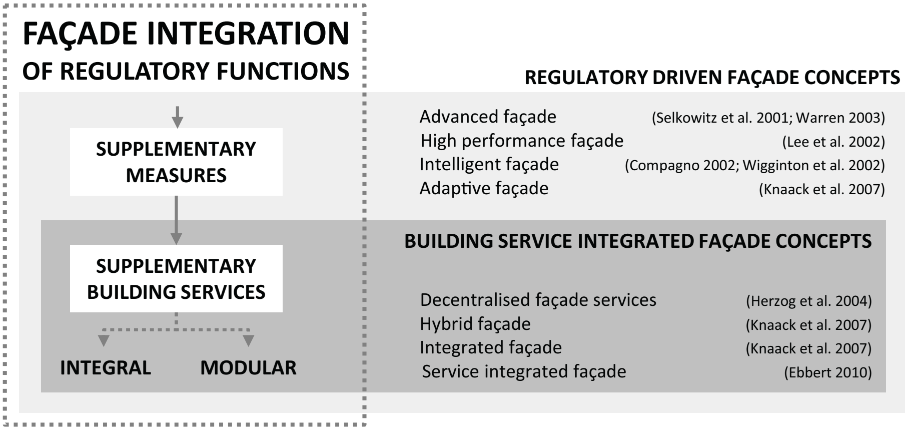

FIGURE 3.1 Scheme for façade integration of regulatory functions

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.

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## § 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 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 |

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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/hydrochloro/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,<br>Lithium-Chloride/water |
| | | Adsorption heat pump | Silica gel, zeolites |
| | Desiccant cooling | Solid desiccant | Silica gel, zeolites |
| | | Liquid desiccant | Lithium-Bromide/water,<br>Lithium-Chloride/water |
| | Thermomechanical cooling | Steam ejector system | Water |
| | | Stirling engine | Water |
| | | Rankine cycle heat pump | Organic fluids, water |

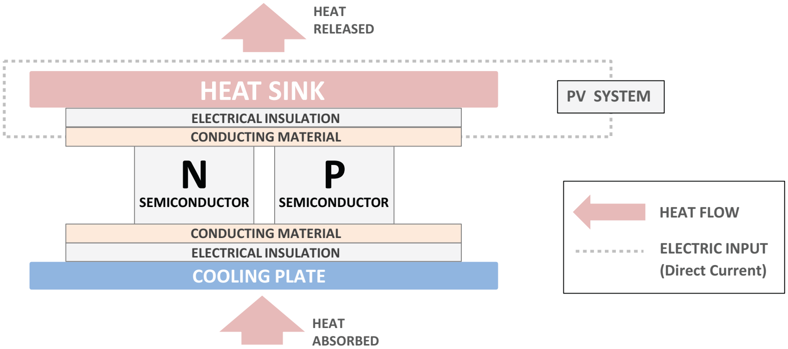

FIGURE 3.2  Functioning scheme of a thermoelectric cooling module

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 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).

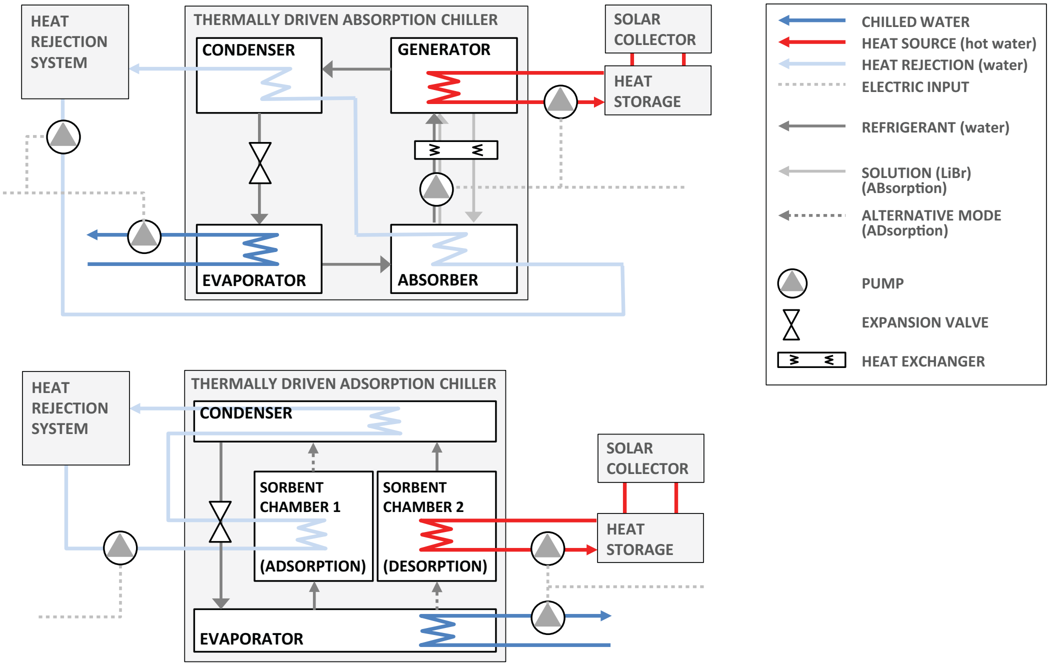

FIGURE 3.3 Required components for the operation of solar driven absorption and adsorption chillers.

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

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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).

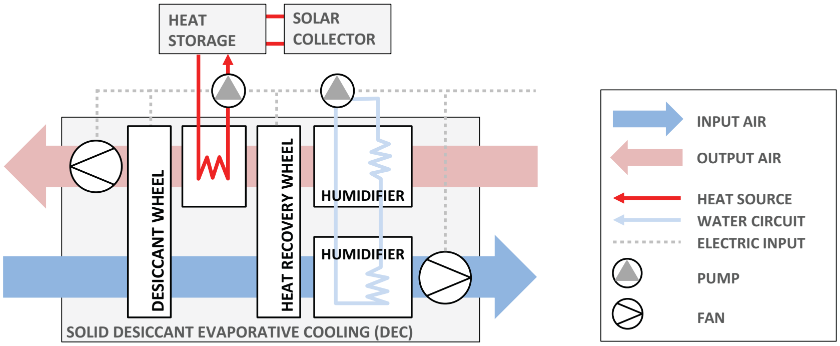

FIGURE 3.4 Operation of a solid desiccant cooling system (DEC).

## 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).

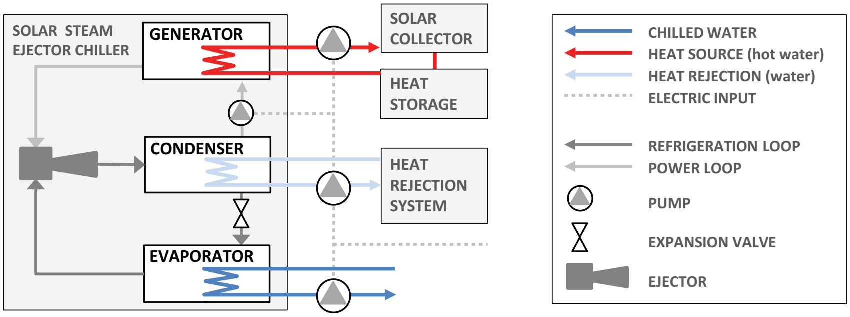

FIGURE 3.5 Operation of a solar steam ejector chiller.

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).

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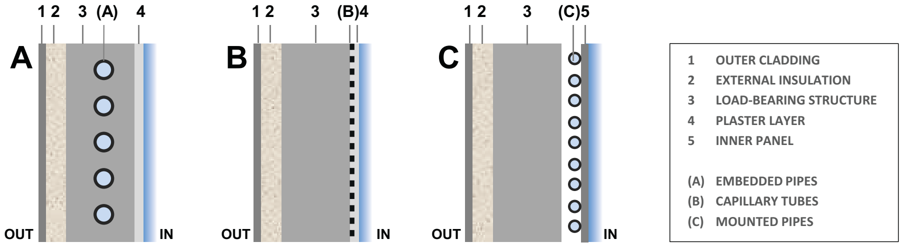

FIGURE 3.6 Water-based surface cooling systems: embedded pipes (A), capillary tubes (B) and panel systems (C)

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

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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.

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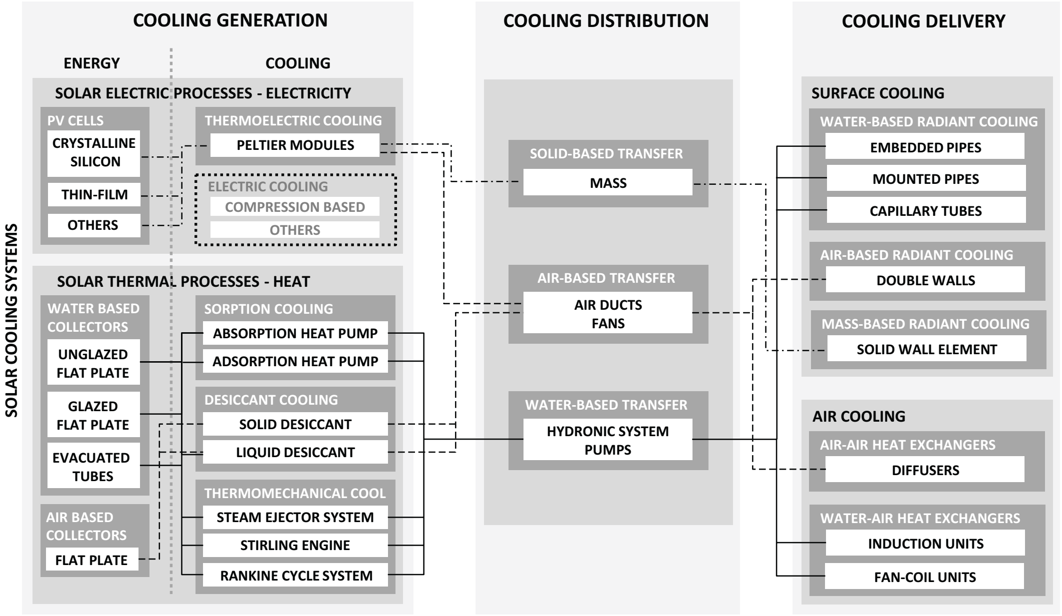

FIGURE 3.7 Chart for the categorisation of cooling technologies for façade integration purposes.

## § 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.

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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)<br>Xu & Van Dessel (2008)<br>Xu & Van Dessel (2008) | Thermoelectric modules for active building envelopes (ABE) | Thermoelectric cooling | Water-based transfer | Surface cooling (Mounted pipe) | -Visual contact (window)<br>-Heating<br>-Heat storage | MODULAR |
| 2 | Gibson (2008) | Active thermoelectric manifold double façade | Thermoelectric cooling | Air-based transfer | Air cooling (Diffusers) | -Heating<br>-Visual contact<br>-Ventilation | MODULAR |
| 3 | Ruschenburg et al. (2011)<br>Kuhn (2013) | Solar-assisted heat pump for decentral applications | Vapour compression heat pump (Solar assisted) | Water-based transfer | Air cooling (Induction Unit) | -Heating<br>-Visual contact (window)<br>-Sun shading | INTEGRAL |
| 4 | Streefkerk (2011) | Stirling solar cooling for office facades | Thermo-mechanical cooling (duplex stirling engine) | Water-based transfer | NO | -Heating<br>-Visual contact (window)<br>-Sun shading<br>-Power generation | MODULAR |
| 5 | Chan et al. (2012) | Solar façade for space cooling | Indirect evaporative cooling | Air-based transfer | NO | -Heating<br>-Ventilation<br>-Insulation (external wall) | INTEGRAL |
| 6 | Ibanez-Puy et al. (2013)<br>Ibanez-Puy et al. (2014) | Active façade envelope with Peltier cells | Thermoelectric cooling | Air-based transfer | Air cooling (Diffusers) | -Heating<br>-Ventilation<br>-Insulation | INTEGRAL |
| 7 | Avesani et al. (2014)<br>Hallstrom et al. (2014)<br>Hallstrom et al. (2015)<br>Blackman et al. (2014) | Metal-glass façade + Sorption collector (FP7 EU iNSPiRe Project) | Absorption cycle | Air-based transfer | Air cooling (Diffusers) | -Heating<br>-Visual contact (window)<br>-Sun shading<br>-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<br>-Ventilation<br>-Insulation | INTEGRAL |

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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<br>-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<br>-Visual contact (window)<br>-Sun shading<br>-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).

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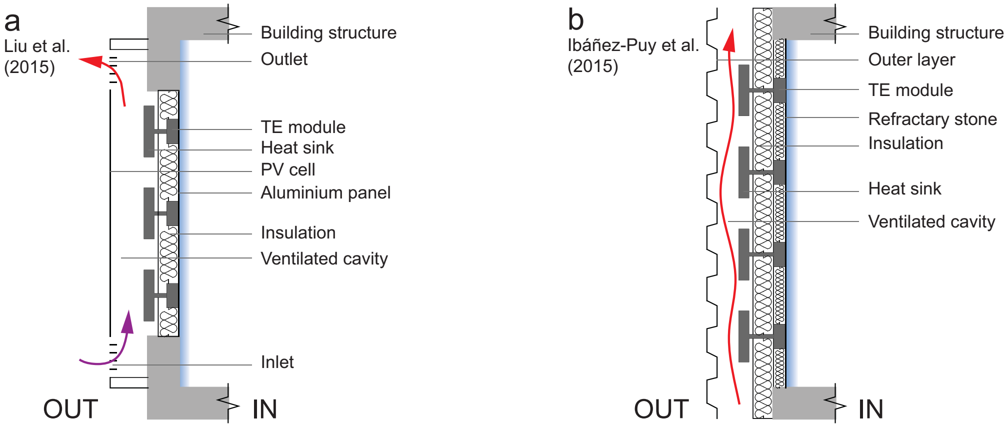

FIGURE 3.8 Solid-based thermoelectric facades. Schemes based on Liu et al. (2015) and Ibanez-Puy et al. (2015).

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

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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).

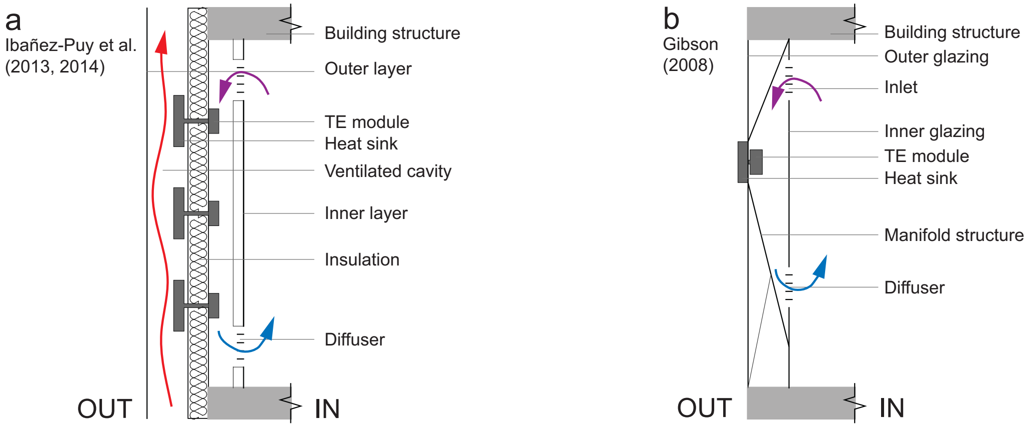

FIGURE 3.9 Air-based thermoelectric facades. Schemes based on Ibanez-Puy et al. (2013, 2014) and Gibson (2008).

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).

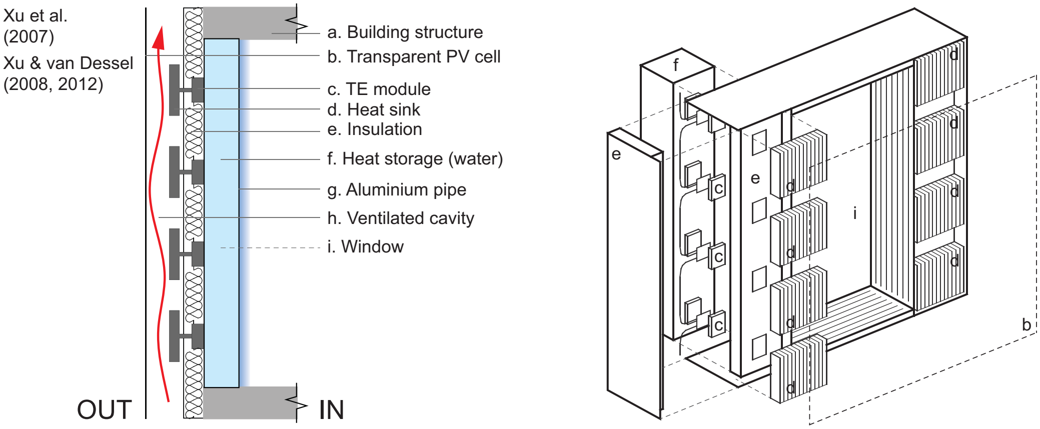

FIGURE 3.10 Water-based thermoelectric facade. Schemes based on Xu et al. (2007, 2008a, 2008b).

## § 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).

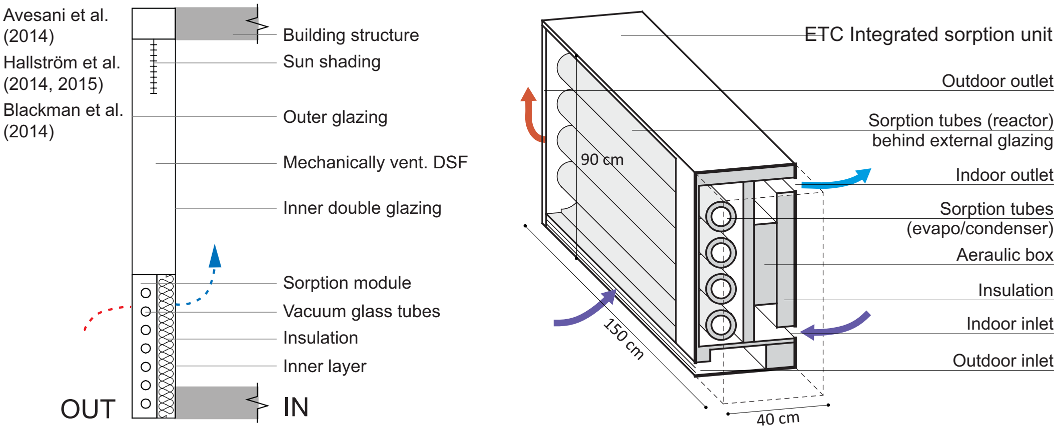

FIGURE 3.11 Sorption based facade. Scheme based on Avesani et al.(2014), Hallström et al.(2015) and Blackman et al.(2014).

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

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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.

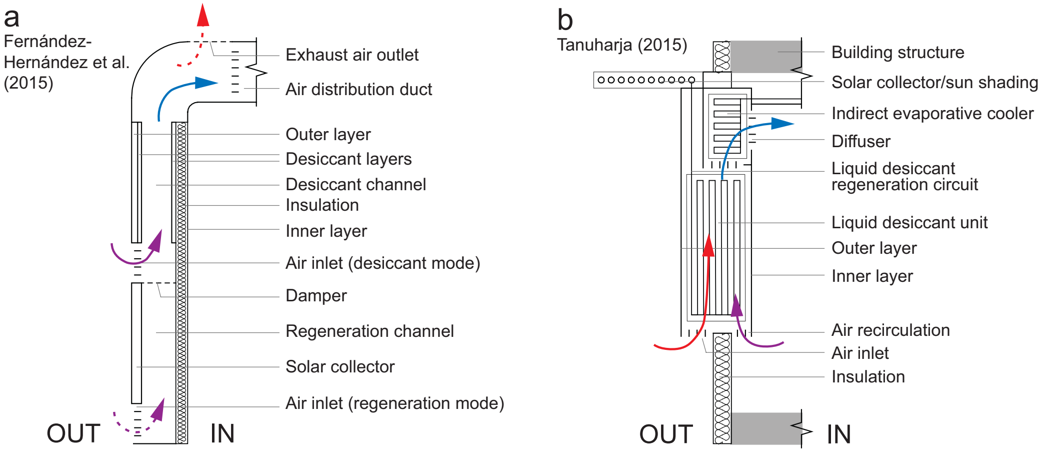

FIGURE 3.12 Desiccant facades. Schemes based on Fernandez-Hernandez et al. (2015) and Tanuharja (2015).

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).

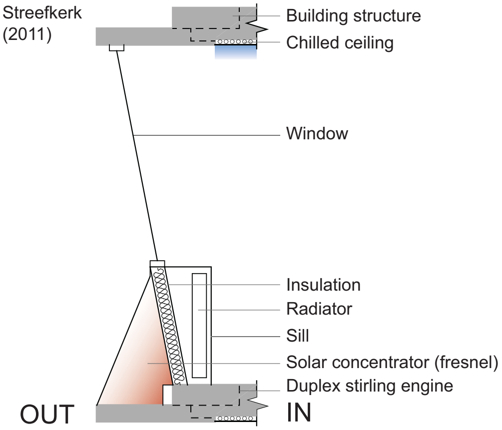

FIGURE 3.13 Stirling solar cooling facade. Scheme based on Streefkerk (2011).

## § 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 highrise 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.

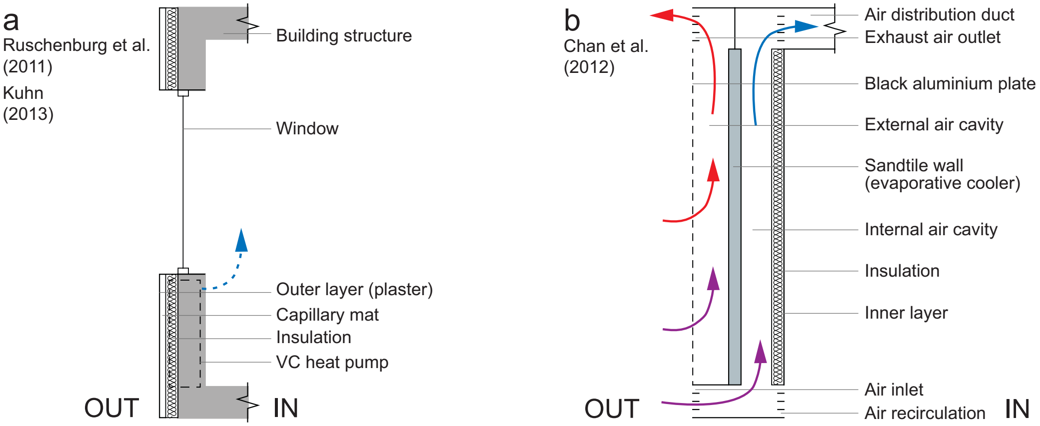

FIGURE 3.14 Other solar assisted cooling façades. Schemes based on Ruschenburg et al. (2011) and Chan et al. (2012).

## § 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).

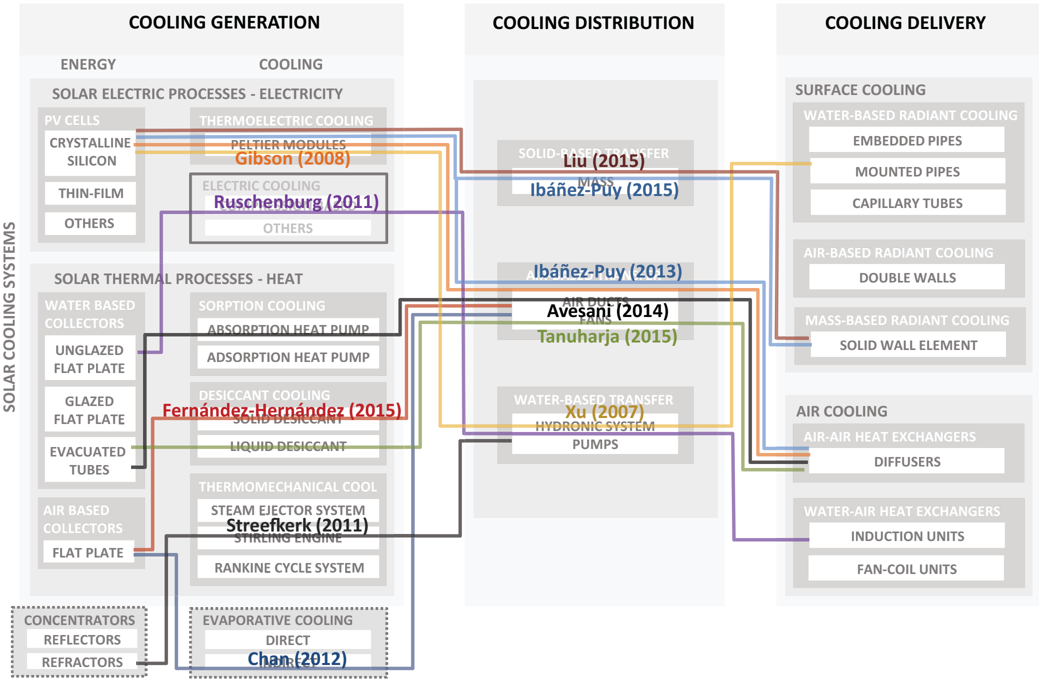

FIGURE 3.15 Categorisation of the reviewed integrated façade concepts in the proposed chart.

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).

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

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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.

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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.

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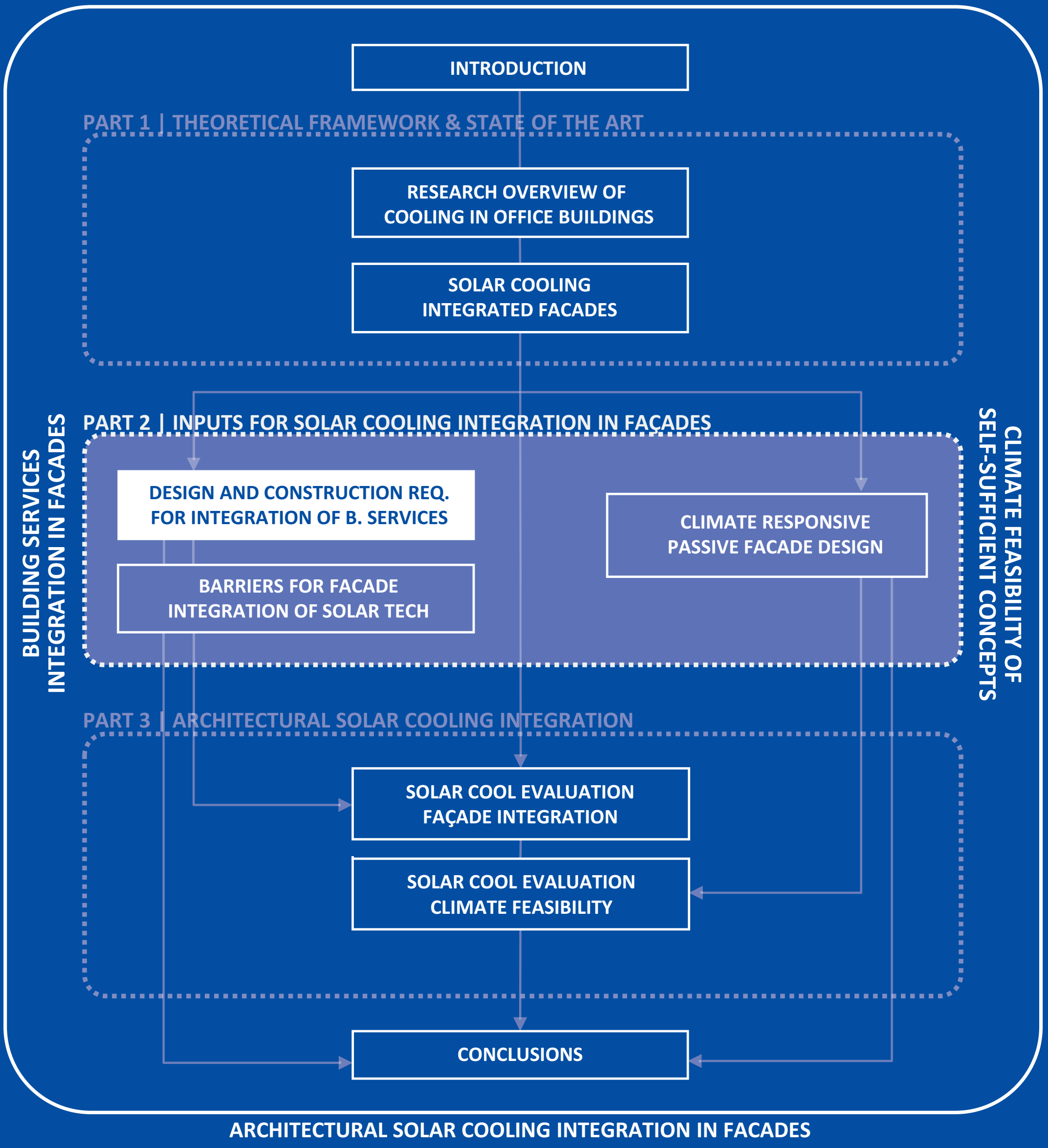
# COOLFACADE



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