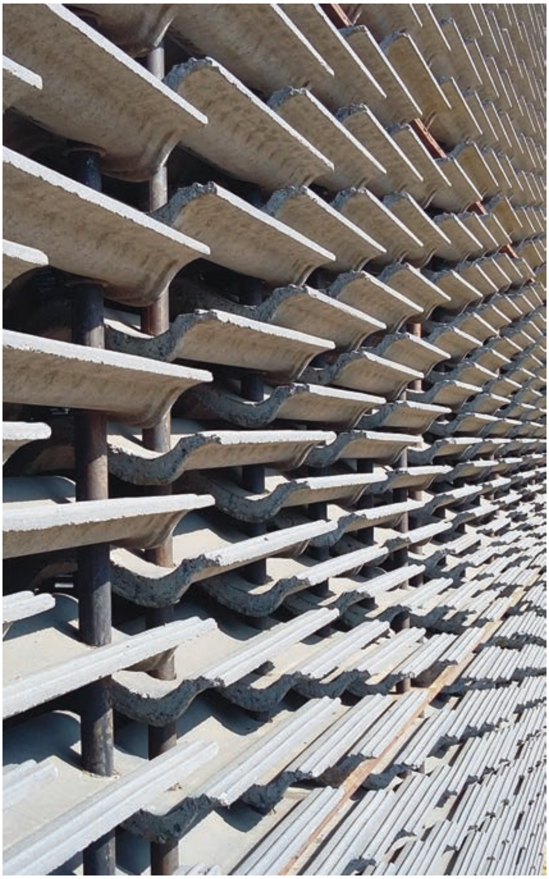
Jacopo Gaspari

Climate responsive building envelopes

From façade shading systems to adaptive shells



Ricerche di tecnologia dell'architettura
FRANCOANGELI

RICERCHE DI TECNOLOGIA DELL'ARCHITETTURA

diretta da Giovanni Zannoni (Università di Ferrara)

La collana *Ricerche di tecnologia dell'architettura* tratta prevalentemente i temi della progettazione tecnologica dell'architettura e del design con particolare attenzione alla costruibilità del progetto. In particolare gli strumenti, i metodi e le tecniche per il progetto di architettura alle scale esecutive e quindi le modalità di realizzazione, trasformazione, manutenzione, gestione e recupero dell'ambiente costruito.
I contenuti scientifici comprendono la storia e la cultura tecnologica della progettazione e della costruzione; lo studio delle tecnologie edilizie e dei sistemi costruttivi; lo studio dei materiali naturali e artificiali; la progettazione e la sperimentazione di materiali, elementi, componenti e sistemi costruttivi.
Nel campo del design i contenuti riguardano le teorie, i metodi, le tecniche e gli strumenti del progetto di artefatti e i caratteri produttivi-costruttivi propri dei sistemi industriali.
I settori nei quali attingere per le pubblicazioni sono quelli dei progetti di ricerca nazionali e internazionali specie di tipo sperimentale, le tesi di dottorato di ricerca, le analisi sul costruito e le possibilità di intervento, la progettazione architettonica cosciente del processo costruttivo.
In questi ambiti la collana pubblica progetti che abbiano finalità di divulgazione scientifica e pratica manualistica e quindi ricchi di spunti operativi per la professione di architetto.

La collana nasce sotto la direzione di Raffaella Crespi e Guido Nardi nel 1974.
I numerosi volumi pubblicati in questi anni delineano un efficace panorama dello stato e dell'evoluzione della ricerca nel settore della Tecnologia dell'architettura con alcuni testi che sono diventati delle basi fondative della disciplina.
A partire dal 2012 la valutazione delle proposte è stata affidata a un Comitato scientifico, diretto da Giovanni Zannoni, con lo scopo di individuare e selezionare i contributi più interessanti nell'ambito della Tecnologia dell'architettura e proseguire l'importante opera di divulgazione iniziata quarant'anni prima.

Jacopo Gaspari

Climate responsive building envelopes

From façade shading systems to adaptive shells

Ricerche di tecnologia dell'architettura
FRANCOANGELI

Il volume è stato pubblicato con il contributo dell'Alma Mater Studiorum – Università di Bologna – Dipartimento di Architettura.

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI ARCHITETTURA

Laddove non espressamente esplicitato, le immagini sono di Jacopo Gaspari.

Where not expressly mentioned the images are by Jacopo Gaspari.

Questo volume è stato oggetto di peer review come previsto a partire dal n. 87 della collana.
ISBN: 978-88-351-0941-9

Contents

Foreword

Giovanni Zannoni

Architecture, and more generally the act of building, is basically connected with the need to provide an adequate microclimate for hosting human activities where the environmental context is quite often characterized by unfavourable conditions. Natural forces strongly contribute in creating the habit for human life but they are also the same agents that may generate unfriendly and extreme conditions that we are totally unable to control. The power of solar radiation is a good example of this concept: it represents an essential component for life and a lethal force at the same time. The scope behind any kind of construction is indeed to try to partially control these immense forces within some specific functional objectives protecting the final users from their extreme expressions.

A number of different tools have been developed to clearly determine the influence of solar radiation, from shading masks on solar diagrams to simulation models for properly considering the impacts of long distance, medium field and close field obstacles (i.e. mountains, vegetation, surrounding buildings, respectively) as well as those deriving by shading systems with relation to the building orientation.

Shading systems certainly represent the most effective solution to adjust the building behaviour with reference to daily and seasonal variations allowing to obtain both acceptable conditions during summer and passive solar gains during winter.

However, the lesson learned from some renowned examples like the *Institut du Monde Arabe* – whose diaphragms never properly worked – is to avoid the use of electro-mechanical solutions. A mechanical device can solve any kind of design problem as an outboard engine can transform any floating object into a boat without any specific design action.

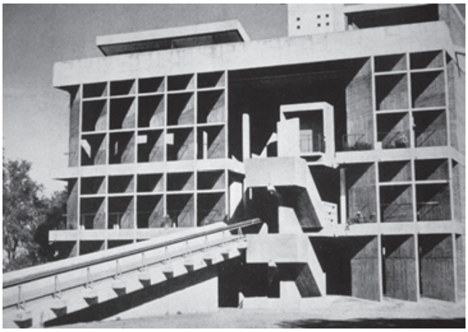
However, sustainable design is more likely close to the conceptualization of a sailboat where any single component is optimized for ensuring the best possible performance and where the users are themselves elements to keep the boat in balanced conditions. This mind-set shift suggests to reduce the unlimited confidence given to a technological capacity which often leads to provide the same technical answer in very different environmental contexts and to approach the design challenge carefully taking into account the site specific features, the optimal building configuration and the related maintenance activities.

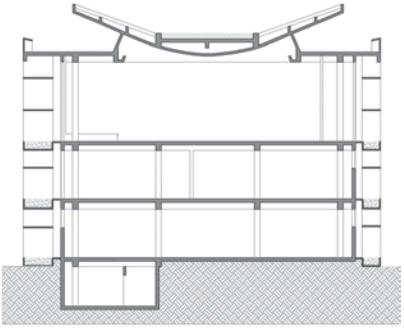
Solar shields and shading systems strongly characterize the building envelope, influencing the architectural language, the building performances with their shape and materials. Their reflectance, thermal insulation capacity, mass and thermal inertia mediate the light transmission and the thermal conduction so that they do not exceed acceptable or suitable levels without affecting transparency but limiting an external view and the related privacy issues.

These systems reflect their cultural background: walking in the streets of the great cities across Europe like Berlin or Paris it can be easily noted that in the neighbourhoods populated by the foreigner communities coming from the Mediterranean countries (Greece, Italy, Turkey, etc.) jalousie or venetian blinds are largely installed as a legacy of conditions more exposed to solar radiation while people from the northern regions seek for larger windows with light internal curtain for maximizing solar and light gains.

One of the major problems in contemporary architecture, beside energy saving, is planning feasible maintenance and renovation actions during the lifecycle, otherwise the risk is that buildings may quickly lose their functionality and architectural aesthetic values.

Le Corbusier, Mill Owners' Association Building, Ahmedabad (1952-56). Double solar shielding consisting of exposed concrete oriented walls are used in west façade to address the prevailing wind inside the building while cantilevered wings (vented roof) are used to trigger a stack effect facilitating heat extraction and to protect the waterproofing surface of the roof.





Introduction

The building envelope has always played a very relevant role, not simply providing a protection against outdoor environmental conditions, but also expressing the formal intention, the constructive thinking and the cultural background that generated its design. During the last decades the rising attention given to the energy saving issue, with the imperative aim to reduce greenhouse gas emissions, has led to invest huge efforts in evolving the traditional concept of building envelope at functional, technical and formal level. This is not basically related to figurative reasons, that even occur as a consequence of a more complex conceptual transition, it is mainly connected with the need to widen the functional response of a technical system that has been considered almost coincident with the structural one for centuries. In massive envelopes the structural capacity and the complementary attitude to confine the indoor environment were assigned to the same construction elements usually arranged in one main layer, the external wall, that also expresses its own features through the façade layout. Despite the intrinsic differences regarding the use of materials and the assembling process, even traditional dry construction systems are not so far from this core concept.

The conceptual shift towards a more articulated and multi-layer building envelope is mainly due to the more recent demand for effective energy saving solutions largely based on the adoption of adequate insulation layers, highly performing windows and appropriate details to avoid both dispersions and thermal bridges. This strongly contributed in evolving the building envelope design in a quite fast time articulating the system in a wider range of technical and functional options. Once high energy efficiency standards have been achieved, fulfilling the national and international regulations that were introduced and constantly updated in the while, new complementary design issues dealing with the indoor comfort levels and the control of airflow exchange emerged. Many involved parameters are strictly dependant on daily and seasonal cycles that are undergoing radical variations due to the effects of climate change. Despite these impacts have been largely investigated in the last decades and many evidences have been collected to sustain the need to adopt corrective measures to contain the actual trends, the climate change issue raised an adequate global attention only quite recently. However, the increasing recurrence of extreme climate events in the recent years has contributed in creating a collective awareness of the impacts that climate change may have on the built environment in the near future and in driving a further evolution of building envelope design.

This book is the result of a study, spread over a period of ten years, regarding the use of shading and shielding systems adopted to improve the building envelope response to climate conditions with the purpose to achieve a more efficient and sustainable design. During this period a number of different solutions were selected, collected, and analysed considering both the technical and functional aspects as well as production and market implications in order to obtain a comprehensive overview of the available solutions. The research has been then addressed to understand how the effects of varying conditions and of standards updating could influence the design of the involved systems from conventional solutions to innovative adaptive shells. Accordingly, the book is structured in five chapters: the first describing the main drivers for changing and their influence on design paradigms; the second providing a synthesis of the main involved physical parameters; the third describing the proposed classification methodology and the related outcomes; the fourth explaining innovation pathways towards adaptive building shells and describing the main design options; the fifth exploring a possible application of self-sufficient adaptive solution.

The study has not the intent to provide any conclusive positions, but to offer a systematic approach for working on a quite heterogeneous field of research, where many conceptual assumptions and theoretical analyses still lack of shared definitions and common tools, where many experiences are still driven by innovative elements and experimental solutions, where the use of simulation tools and validation methodologies are not consolidated by a long practice within the scientific community. Thus the main scope is to provide an organized vision of the available knowledge according to its different understanding and to offer a small step forward in exploring how to possibly apply innovative approaches in ordinary market conditions. On the background, the main challenge evocated by this book is the capacity to evolve design strategies taking into account the complex interrelation between different factors according to a simple but ambitious vision that is able to face the unpredictable changes of the time we are all living in.

1. *The role of building envelope in sustainable architecture*

1.1. Building envelope and energy efficiency

The building envelope is often associated with the image or the "formal architectural language" of the building itself, that for a long time in the history of Architecture was directly influenced by the availability of materials, the construction techniques and structural limitations until the progress in architectural technology allowed a certain freedom originating a number of styles and results.

However, the building envelope or building enclosure can be defined – first of all – as the architectural system separating the conditioned and unconditioned environment of a building, the indoor spaces from the surrounding environment ensuring the resistance to air, water, heat, light, noise transfer (Cutler et al., 2009; Sayed, 2012; Stazi, 2019; Straube, 2005, 2006). The building envelope often (but not necessarily) includes structural elements that can be embedded in the enclosure or coincident with it and can be divided in different elements according to the roof, walls, foundation, doors/windows classification (UNI 8290).

The building enclosure may contain, but it is not the same as, the so-called thermal envelope, which is used to define the thermal insulation layer. The increasing complexity of the functions associated to each element is leading to a multilayer structure of the enclosure where the synergy among the several components tries to provide an answer to the different climate solicitations. An appropriate design of this barrier is a crucial factor to improve a building's thermal performance that mainly influences the current consumption and therefore it can positively contribute in energy savings. In order to avoid thermal loss, the building envelope has to ensure air tightness (with the consequence that fresh air inflows must be controlled) and protect from strong winds. At the same time, it has to be designed to possibly benefit of passive solar gains (figure 1.1) in rigid climates and to prevent overheating in hot climates that often means to exploit the effects of thermal inertia (Sala Lizarraga et al., 2020; Stazi, 2017), of ventilated façades (Aparicio-Fernández et al., 2014; Bikas et al., 2017) and – of course – of shielding systems.

Fig. 1.1 – The building envelope is often designed to increase passive solar gains during winter, however this may create overheating during summer if not adequately controlled.

The effectiveness of solutions depends on a number of factors including various climates (mild or extreme) and seasons, building typologies, mode of use of indoor spaces, heating profiles and cross-ventilation, but an appropriate combination of design options can lead to a significant reduction of energy consumption and to achieve thermal comfort and low environmental impact.

All these considerations put an increasing attention on the outer layers of the building envelope and on their potential contribute in successfully achieving energy savings.

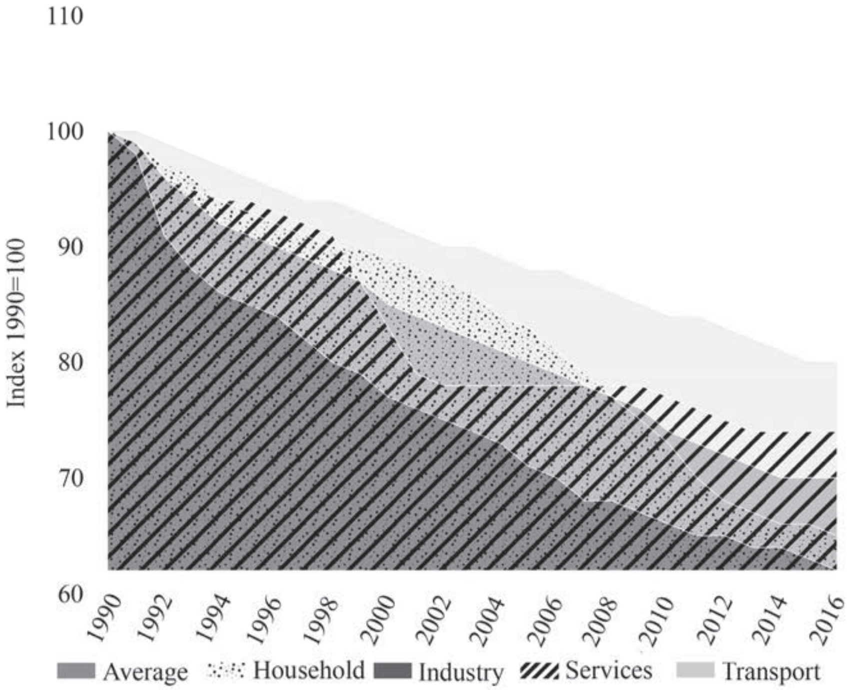
Energy efficiency represents a key priority in the European Union [EU] agenda towards 2030 and 2050 especially if the future achievement of United Nations [UN] Sustainable Development Goal [SDG] 7 "Affordable and Clean Energy" (https://sustainabledevelopment.un.org/) is considered in its broader impacts. In the publication "Progress on energy efficiency in Europe", the European Environment Agency [EEA] reports that over the period between 1990 and 2016 the energy efficiency of end-use sectors improved by 30% in the EU-28 countries at an annual average rate of 1.4%/year according to the energy efficiency ODEX indicator (which is calculated weighting the energy consumption trends observed by sector and for all final consumers).

As figure 1.2 shows, the main contributors to the observed energy efficiency improvement are the industry sector (1.8%/year) and the households sector (1.6%/year). The industry sector accounts for 38% of increased efficiency during the observed period with a greater progress registered during the 1990s (2.6%/year) and a net slowdown after 2005 as a consequence of the market fluctuations and of the financial crisis. The increase of energy efficiency in the households sector is about 35% at an average rate of 1.6%/year.

These results are mostly due to the improvements in space heating. New buildings and renovated existing buildings must fulfil higher energy efficiency standards introduced by specific EU Directives (especially Ecodesign in 2005 and 2009, the Energy Performance in Buildings Directive in 2002 and 2010, the Effort Sharing Decision in 2006 and the Energy Efficiency Directive in 2012) supported by dedicated measures at national level. This is reflected by an increase of 2.4%/year since 2005 compared to the 1.4%/year from 1990 to 2005.

Minor contributions come from the transport sector (20%) and the services sector (26%). The EEA observes that in recent years the energy consumption per employee decreased due to more efficient buildings, however space heating represents the majority of the use of fossil fuels.

Fig. 1.2 – Energy efficiency index (ODEX) for final consumers in the EU.

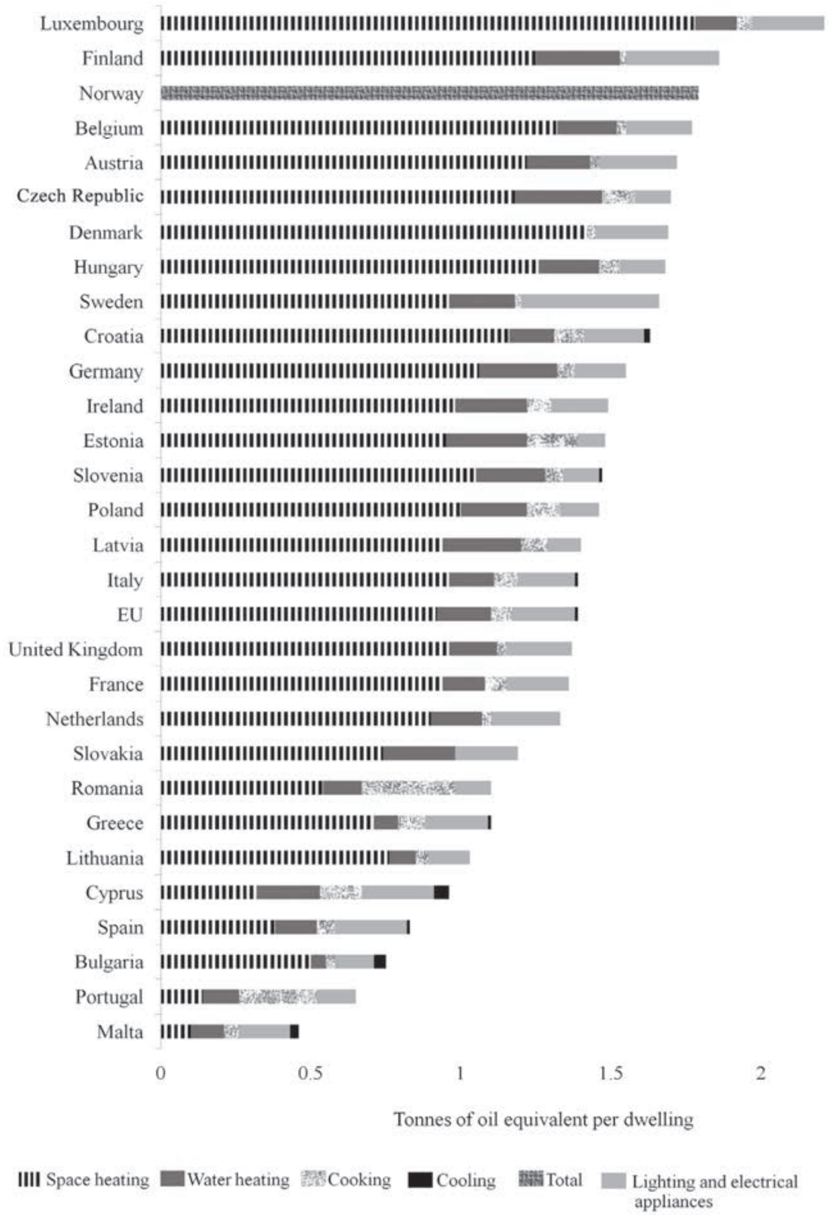


Source: Author's elaboration based on European Environment Agency, Progress on energy efficiency in Europe.

The final energy consumption across EU-28 is estimated in more than 1,100 million tonnes of oil equivalent [Mtoe], with the building sector (households and services) accounting approximately around 41% (depending on calculation methodology and limitations) of the total demand with a share of 27% related to residential buildings and 14% related to services (IEA, 2008; Dol & Haffner, 2010). In 2016, at the EU level, the average annual specific energy consumption per square metre for all types of building was around 200 kWh/m^2.

Non-residential buildings are, on average, more energy intensive than residential buildings (300 kWh/m^2 compared with 180 kWh/m^2) (EEA, 2019). The total floor area of buildings across EU was estimated in about 26 billion square meters, with the household sector representing about 76% of it (EEA, 2019).

Fig. 1.3 – Energy consumption by end use per dwelling across EU.



Source: Author's elaboration based on European Environment Agency, Progress on energy efficiency in Europe.

The weight of the residential sector plays a relevant role in the challenge of increasing the energy efficiency of the building sector considering its share on the whole existing stock and its longevity compared to the tertiary and commercial sectors, becoming a priority field of investigation and experimentation (Eames et al., 2013). The average energy demand of households per dwelling is estimated in 180 kWh/m^2 year at normal climate conditions, however many differences occur especially for space heating and cooling depending on climate conditions country by country (Fleiter et al., 2016).

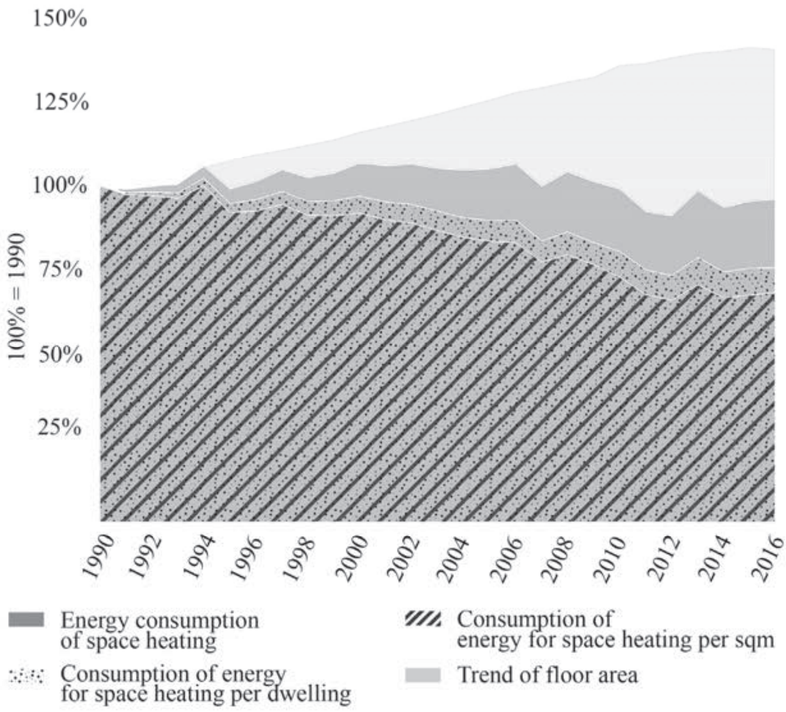
Figure 1.3 provides an overview of energy consumption by end use per dwelling. Most of the differences between southern and northern countries are due to climatic reasons, however data availability and collection method in each Member State may partially affect the results. That said, the graph reflects a quite acceptable comprehensive picture, where the energy demand for space heating decreased to 67% in 2016 compared to 69% in 2005 and 72% in 1990, while electrical appliances and water heating increased to 15% and 13% respectively against 8% and 13% in 1990. Air cooling [AC] seems to have a limited weight but its role may be underestimated considering the evolving climate conditions in many countries.

Average energy demand for space heating is between 80 and 100 kWh/m^2 year in many countries in South Europe and around the Mediterranean basin, such as Portugal, Spain, Malta, Cyprus, Greece, Bulgaria due to lower heating needs, some countries as Italy, Slovenia or France include limited areas benefitting of favourable conditions while the majority of them belongs to a continental climate as the rest of Central Europe. Colder countries from the North, such as Poland, Czech Republic, Luxemburg, Latvia, Estonia, easily reach an energy demand higher than 180 kWh/m^2 year. The achieved improvements are the results of a combination of increased thermal performance of building envelopes and of condensing boilers and heat pumps adoption according to the mandatory standards and ambitious targets fixed by the EU Directives for new constructions and for the renovation of existing buildings. By 2020 the Energy Performance of Buildings Directive [EPBD] states that all new buildings in the EU should be nearly-zero energy buildings [nZEB] with an expected reduction of energy demand ranging from 30 to 50% compared to the previous regulations. Unfortunately, a common and harmonized definition of nZEB is not available and different design approaches and assessment criteria are adopted across the European States reducing the chance to fairly compare the achieved performances country by country. According to the most shared positions the average energy demand of nZEBs is expected to be 25-30 kWh/m^2 year and not to exceed 50 kWh/m^2

year. However, according to EEA, in 2016 energy demand for space heating decreased of only 4% compared to its 1990 level.

On one side, the increase of the building envelope performances, obtained by the adoption of more appropriate technological solutions and thermal insulation layers as well as of more efficient systems, allowed to contribute in reducing the energy demand for heating (and sometimes for cooling), but on the other one, the increase of larger homes and the number of appliances and related lifestyles negatively contributed in meeting more visible results. At the same time an increase of 1.3%/year in the total floor area of dwellings has been registered, much more of the 0.9%/year of number of dwellings increase, driving the space heating consumption per m^2 to decrease more rapidly than space heating consumption per dwelling (respectively by 1.2%/year and 1%/year since 1990) as figure 1.4 displays.

Fig. 1.4 – Heating energy consumption in the EU as a whole.



Source: Author's elaboration based on European Environment Agency, Progress on energy efficiency in Europe.

The role of the building envelope in terms of thermal behaviour and related energy performance is indeed a key design element in effectively contributing to the energy savings targets. Compared to the past, building envelope design is no more simply addressed to fulfil the energy performance thresholds but it is focused on optimizing the behaviour with relation to orientation and climate parameters in order to maximise the passive gains, to reduce the demand for heating and to properly consider the possible overheating during the summer period.

Accordingly, the design process does not simply require to include an adequate insulation layer but to carefully take into account the thermal-igrometric variations within the different layers in order to prevent unsuitable effects such as condensation and related pathologies while achieving optimal indoor comfort conditions. The lesson learnt from the northern countries about passive solar gains can't be exported elsewhere without properly considering the local climate and geographical conditions. It is within this increasing complexity that in many countries building envelopes are expected to serve also as shielding surface to solar radiation during the intense hot conditions of summer with the purpose to reduce the response demand from cooling systems.

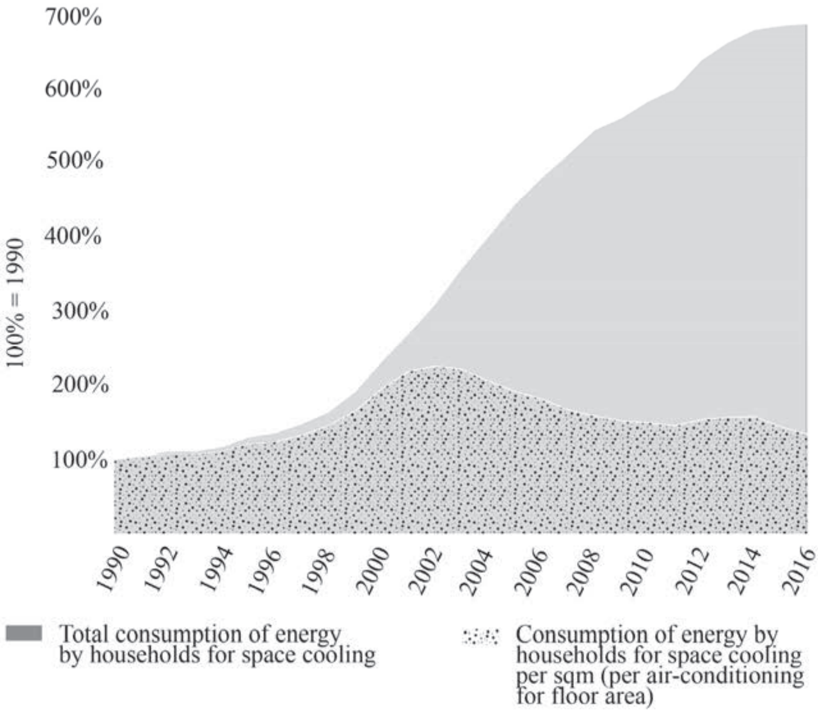
Energy demand for AC is acquiring an ever increasing relevance at EU level. The related average increase is around 8%/year since 1990, with a rate much higher than the one of space heating demand decrease as figure 1.5 shows. The average diffusion of AC equipment is still limited – 2.9% in 2016 (it was 0.8% in 1990 and 1.5% in 2005) – but it is differently distributed across the Member States with a coverage of more than 80% of dwellings equipped in Cyprus and Greece, 60% in Malta and Spain, around 35% in Bulgaria, Croatia and Italy.

The increasing number of appliances and devices (including multiple IT equipment) has led to an average increase of 1.2%/year which was partially offset by the efficiency of the installed systems as requested by the mandatory labelling introduced by the EU Directives.

It has to be observed that the specific electricity consumption includes also the demand of a number of sensors and devices adopted to increase the responsiveness of buildings functional systems and to remotely monitor their activity during operation according to the smart vision associated to the new generation of buildings.

Also the lighting consumption has to be taken into account considering both the progress in the field of more efficient lighting systems and the possible contributes from an optimization of the building envelope design in ensuring a more appropriate natural light inflow.

Fig. 1.5 – Heating energy consumption in the EU as a whole.



Source: Author's elaboration based on European Environment Agency, Progress on energy efficiency in Europe.

Again, the building envelope design plays a key role in defining effective solutions to properly consider the daily and seasonal parameters variation.

With reference to the service sector, energy demand for space heating – representing the 46% of the sector consumption (63% in 1990, 51% in 2005) – is decreasing rapidly due to the improvement of buildings energy performance introduced in the last decades (EEA, 2020). A relevant share (39%) of energy demand is associated with information and communication technologies as well as electrical appliances and lighting which play a very relevant role at functional and operational level within the service sector. Energy demand for AC represents only 5% (3% in 1990) of the total consumption but a relevant growth can be expected in the very near future considering climate trends and the rapid evolution of lifestyles.