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SUSTAINABLE BUILDINGS

development of low energy and eco-friendly constructions

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SUSTAINABLE BUILDINGS
DEVELOPMENT OF LOW ENERGY AND ECO-FRIENDLY CONSTRUCTIONS

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Dorota Anna Krawczyk

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Contents

Abbreviations	Description
AEC	Architecture, Engineering, and Construction
AISI	American Iron and Steel Institute
BER	Building Energy Rating
BIM	Buildings Information Modelling
BPIE	Buildings Perfomaces Institute Europe
CAM	Minimum Environmental Criteria
CDD	Cooling Degree Days
CHP	Combined Heat and Power System
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CPD	Construction Products Directive
DHW	Domestic Hot Water
DSF	Double Skin Facade
EC	European Commission
EE	Energy Efficiency
EEW	Energy Efficiency Watch
EP	Energy Performance Index
EPBD	Energy Perfomance of Building Directive
EPC	The Energy Performance Certification
EPDM	Ethylene Propylene Diene Monomer
EPP	Expanded Polypropylene
EPS	Expanded Polystyrene
ETICS	External Thermal Insulation Composite System
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning Systems
HWBD	Hot Water Boiler Directive
ICFs	Insulating Concrete Forms
ITACA	Institute for Procurement Innovation and Transparency and Environmental Compliance
LCA	Life Cycle Assessment
LEEARE	Laboratory of Energy Efficient Architecture and Renewable Energy
LEED	Leadership in Energy and Environmental Design
LSG	Light to Solar Gains Ratio
MS	Member State
NASA	National Aeronautics and Space Administration

Abbreviations	Description
NZCB	Net Zero Carbon Building
NZEB	Net Zero Energy Building
nZEB	nearly Zero Energy Buildings
OSB	Oriented Strand Board
PCM	Phase Change Material
PEF	Primary Energy Factor
PH	Passive House
PIR	Polyisocyanurate
PUR	Polyurethane
PV	Photovoltaic
PVB	Polyvinyl Butyral
PVC	Polyvinyl Chloride
RER	Renewable Energy Ratio
RES	Renewable Energy Source
S/V	Surface/Volume Ratio
SDG	Sustainable Development Goals
SHGC	Solar Heat Gain Coefficient
SIPs	Structural Insulated Panels
SSG	Structural Sealant Glazing
TSC	Thermal Solar Collectors
U	Thermal Transmittance, Heat Transfer Coefficient
UN	United Nations
UNI	Italian National Agency of Unification
UV	Ultraviolet
VIPs	Vacuum Insulation Panels
VT	Visible Transmittance
WEB	World Wide Web
WWR	Window-to-Wall Ratio
XPS	Extruded Polystyrene

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Preface

The monograph "Sustainable buildings – development of low energy and eco-friendly constructions" has been developed as the result of scientific cooperation between lecturers and researchers from five European universities: Bialystok University of Technology (Poland), the University of Cordoba (Spain), the University of Florence (Italy), Rezekne Academy of Technologies (Latvia) and Vilnius College of Technologies and Design (Lithuania). The authors' team includes professors with recognized scientific achievements, teachers who cooperate with the industrial sector as well as PhD students starting their career path. The cooperation was possible thanks to joint work in the ADD_ON_SKILLS project (Advanced Digital Design course ON modern buildings developing SKILLS for young engineers, 2020-1-PL01-KA226-HE-095244) carried out within the framework of Erasmus+ programme.

In recent years, we have been observing significant changes in the energy and construction sectors. Both, legal requirements and users' expectations in the field of energy reduction as well as the application of eco-friendly materials and solutions, result in a new approach to new and existing buildings.

In the first chapter changes in regulations regarding energy usage in buildings and their energy performance are discussed. The second chapter describes the main development trends trends of countries on their way to achieve sustainability.

Chapter three shows types of sustainable buildings, taking as examples houses and offices. Authors of chapter four analyse a model low-energy building and discuss its energy factors in various climatic locations. In turn, chapters five to eight are dedicated to modern building materials and their possible applications.

In conclusion, thanks to the joint work of the international and interdisciplinary team this book presents trends in constructions and opportunities available due to continuous development of low energy and eco-friendly constructions

The monograph, published in open access, is targeted at students, scientists, engineers, as well as house owners or occupants who are interested in new trends in sustainable development.

Dorota Anna Krawczyk, Chief Editor

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1. FROM TRADITIONAL BUILDINGS TO NEARLY ZERO-ENERGY BUILDINGS

1.1. Background of Evaluation in a Building Sector

Climate change is becoming an increasingly serious concern, both in Europe and around the world. The effects of global warming are transforming our environment, increasing the intensity and frequency of extreme weather events. Scientific evidence shows that human-induced global warming has already reached 1°C above preindustrial levels and is increasing at a rate of about 0.2°C per decade. This means, that without accelerated and coordinated international climate action, as well as unprecedented political agreement, the global average temperature could rise by 2°C soon after 2060 (Di Foggia, 2018; EC 2018; Mishra et al. 2021). Nowadays, European Union (EU) policy promotes energy efficiency and renewable energy production in order to achieve climate neutrality of the continent by 2050. Following the European Green Deal (WEB–6), meeting such an ambitious goal requires maximizing energy efficiency and renewable production, especially in the building sector, which is responsible for up to 40% of total energy consumption and 36% of greenhouse emissions, and shows significant potential for reducing energy consumption (D'Agostino et al., 2021; Ionescu et al., 2015; WEB–5). Currently, the key role in this direction play nearly-zero energy buildings (nZEBs), which combine energy efficiency with the deployment of renewables (D'Agostino et al., 2021).

In order to understand new strategies and technologies improving the energy efficiency on the buildings, it is important to know the history of their development. It is also essential to better comprehend the changes made over time to optimize energy consumption and improve thermal comfort (Ionescu et al., 2015).

Beginning in the 1970s and continuing to the present day, European energy policy has evolved, both in terms of scope, ambition and scale. Initially, as a result of the oil crisis, legislation focused mainly on ensuring the security of energy supply in Europe. This was followed by general requirements for construction products (1989) (Council of the European Union, 1989) or boilers (1992) (Council of the European Union, 1992), to create over time a set of comprehensive energy standards and requirements for the energy performance of entire buildings (2002) (European Parliament, Council of the European Union, 2002) and 2010 (European Parliament, Council of the European Union, 2010). The next step was to strengthen these policies to meet climate change commitments under the UNFCCC (United Nations Framework Convention on Climate Change) and to improve the security of energy supply (Economidou et al., 2020). The adoption of more ambitious building standards and boiler requirements, has contributed to a decrease in heating energy consumption (WEB–3).

In the case of the last decade, it can be noticed that along with energy requirements, the concept of buildings has also changed. The shift from prescriptive requirements, such as U-values for building walls, to energy performance requirements enabled the introduction of cost optimization concepts in building codes and the implementation of some important definitions, such as: high performance buildings, zero emission buildings, zero carbon buildings, net zero energy buildings, and near zero energy buildings. Accordingly, nZEB became the new official EU definition (EPDB 2010 recast), which defined how buildings should consume near-zero energy and use renewable energy, adopt cost-optimal technological choices and guarantee a healthy and comfortable environment (Cao et al., 2016; Economidou et al., 2020).

The Energy Performance of Buildings Directive (EPBD) continues to be considered as the centerpiece of EU policy on improving the energy efficiency of buildings. According to it, a "nearly zero energy building" (nZEB) is a building that has very high energy performance and the required nearly zero or very low amount of energy, should be covered to a very significant extent by renewable energy sources (RES), including renewable energy generated on site or nearby (European Parliament, Council of the European Union, 2010). The Directive stipulated, that after 31 December 2020, all new buildings should meet nearly-zero energy buildings' requirements (Cao et al., 2016; Economidou et al., 2020).

As no specific numerical thresholds or ranges are defined in the EPBD, these requirements left room for interpretation and allowed the Member States the flexibility to define near-zero energy buildings, taking into account climatic conditions, ambition levels, primary energy factors, calculation methodologies, as well as country-specific building traditions (WEB–7). Therefore, Member States were required to develop nZEB definitions according to the above factors, as well as the primary energy consumption rate (in kWh/(m^2 year)). Furthermore, they had to implement targeted policies and provide funding to support the transition to nZEB by gradually increasing their number. In doing so, requirements were to be differentiated for different building categories (D'Agostino et al., 2021).

In addition to the financial instruments, policies and strategic measures implemented by approximately 70% of the Member States to facilitate the uptake of energy-efficient houses (European Commission, 2016), the 8th European Framework Programme for Research and Innovation – "Horizon 2020" (WEB–8) was launched by the EU. It promotes smart, sustainable, and inclusive growth in the scientific, industrial, and social sectors and includes several projects that aim to improve the skills and knowledge of designers in the field of construction and work toward the ultimate goal of creating new buildings or renovating existing ones with energy efficiency according to the standards of the nZEB (Magrini et al., 2020).

Observing how national requirements for the energy performance of buildings have evolved during the EPBD period (from 2006 to the beginning of 2021) (López-Ochoa et al., 2021a; López-Ochoa et al., 2021b; Vaquero, 2020), it can be seen that the minimum primary energy demand for buildings called nZEBs has decreased on average by about 67% (Economidou et al., 2020). This shows that significant improvements have been achieved in countries where the EPBD was in force. Important changes have also been observed in the tools and measures used in energy efficiency policy. While it is true that the SAVE Directive covered many thematic areas that are still relevant today, such as metering, billing, energy certificates, financing, etc., it was the legal framework set out in the 2002 EPBD, the 2006 ESD, and the 2012 EED that recommended the implementation of a wide range of policy instruments at the national level. The EPBD required member states to develop complete requirements in their building codes, while introducing information tools such as thermal system inspection programs and energy performance certification schemes, while the Energy Efficiency Directive mandated energy audits in industry, among others, introduced provisions for metering and billing, and urged the creation of energy efficiency funds. Despite some shortcomings, these measures, ranging from regulations and information tools to campaigns and training programs, to financial instruments, still form an important part of all national policy packages today (Economidou et al., 2020).

In addition to individual policy measures, comprehensive policy packages including clearly defined targets have played an extremely important role. Although no specific target has been set for the sector itself so far, looking at the goals for 1995, 2020, 2030 and 2050 (WEB–4), it can be seen that buildings have always played an important role in achieving energy efficiency (Economidou et al., 2020; European Commission, Directorate-General for Energy, 1997).

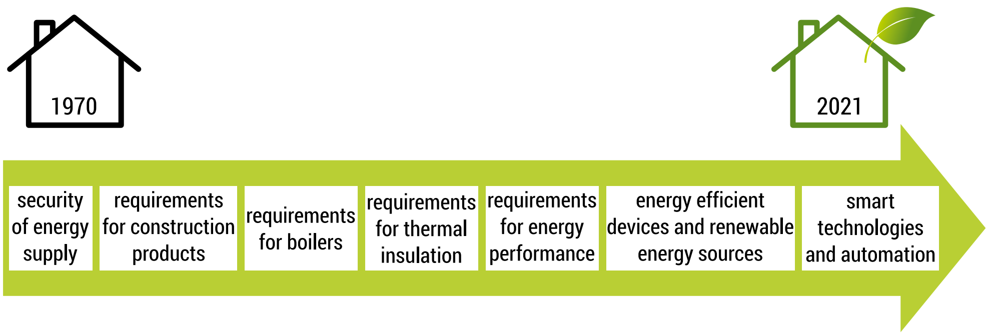

FIG. 1.1. Variability of building energy efficiency requirements over the years (Source: own elaboration)

The introduction of more recent national energy and climate plans through the adoption of the 2018 recast (European Parliament, Council of the European Union, 2018) of the Energy Performance of Building Directive, as well as the regulation "Governance of the Energy Union", has strengthened the role that energy efficiency must play in the overall efforts to mitigate climate change and achieve the 2030 and 2050 goals, as well as allowing links between different policies, such as renewable energy and decarbonization policies (Economidou et al., 2020; Rosenow et al., 2017).

The aim of all these regulations and legislation in relation to buildings, was to implement solutions that would reduce energy waste and promote the idea of energy efficient houses. Unfortunately, about 35% of the buildings in Europe are still over 50 years old (Boemi et al., 2016).

Energy-efficient buildings, whether they are renovated to improve efficiency or built with energy efficiency in mind, have a significant number of benefits. They are less expensive to operate, more comfortable to live in, and more environmentally friendly. They also help reduce greenhouse gas (GHG) emissions [40] and realize two goals of sustainable development such as saving primary resources and reducing emissions to the environment (Di Foggia, 2018; Ionescu et al., 2015).

Based on many years of observation and research, as well as guidelines set by directives, standards, and regulations in the field of energy efficiency, the most important factors that affect the energy efficiency of buildings have been specified, along with the ways to increase it.

Thus, among the most relevant solutions are the following:

- using adequate insulation thickness of the building envelope, taking into account national and European standards,
- adapting the building to climatic conditions by using adequate building materials,
- removing the thermal bridges and leaks,
- proper orientation of the building,
- purchasing high-quality windows and doors (with low-emission coatings, gas fillings, efficient glazing, and frames made of eco-friendly materials),
- the use of high-efficiency HVAC systems and equipment (heat pumps, radiant ceiling heating/cooling systems, heat recovery ventilation, etc.),
- using high-efficiency lighting systems and full use of natural light,
- rational using of water resource (rain water collection, graywater treatment, water saving appliances),
- using an intelligent control and metering systems,
- using passive solar systems,
- monitoring and verifying performance, in order to inform occupants about their habits and encourage energy conservation measures (D'Agostino et al., 2021; WEB–2; Yi & Bing, 2017).

Also important for energy efficiency is the regulation of indoor temperature and the use of automatic control devices (WEB–2). Reducing the energy consumed for space heating and cooling is highly dependent on improving the performance of the building envelope (Yi & Bing, 2017). The problems of energy efficiency in residential buildings or their impact on the environment were outlined in (Attia et al., 2022; Baniassadi et al., 2022; Dakwale et al., 2011), while the factors that influence it were discussed by Chen (Chen et al., 2020). Figure 1.2 summarizes the most important elements affecting the energy efficiency of the building.

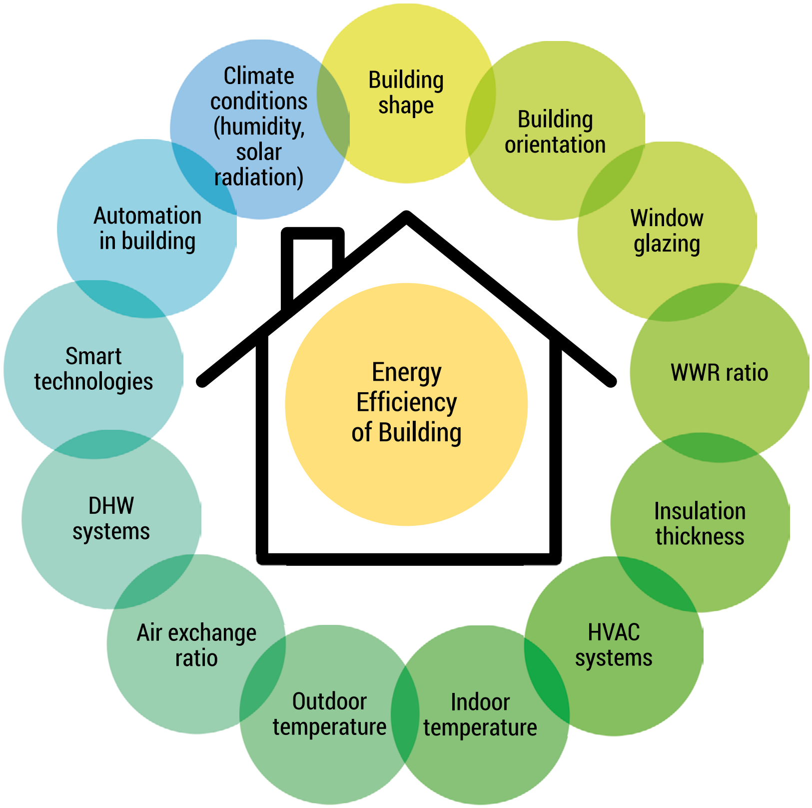

FIG. 1.2. Factors influencing energy efficiency of a building (Source: own elaboration based on Chen et al., 2020)

In the following section I will present details on how building energy efficiency policies, regulations, and laws have changed over the past 50 years, with special regard to the past 20 years, when the changes have been the most intense.

1.2. European Energy Policy

1.2.1. Beginnings

Initially, in the 1970s-80s, as a result of the oil embargo, energy policy emphasized primarily the security of energy supply. In the face of a sudden shortage of fuel, the priority became energy conservation and energy efficiency, which began to emerge as a policy response to the need for energy security, associated with the "security of oil supply". Moreover, the first and most drastic measure introduced in the 70's, relating directly to buildings, was the thermal insulation of their envelope. Next, a concept to focus on another energy sources evolved. Research on natural gas and renewable energy has been intensified (Economidou et al., 2020; WEB–10). In 1974 the European Council adopted a resolution (Council of the European Union, 1974) promoting energy saving which aimed at reducing the rate of energy consumption growth, i.e. reaching a level 15% lower than in 1973 by 1985. In 1980, the European Council implemented an energy intensity target and approved policies that included energy pricing measures. The Council Resolution of 1986, involved new Community targets for 1995 and emphasized the need to implement the "concept of Community solidarity", as well as the search for sustainable environmental and energy solutions, i.e. the use of the best available and economically viable technologies and the improvement of energy efficiency. The Council Resolution represented the first policy initiative of the European Union with the objective of greater energy efficiency in all sectors, as well as the use of various possibilities for saving energy. The Energy Efficiency (EE) target was defined as a minimum 20% improvement in efficiency of "final energy demand" by 1995. In 1987, the Commission published a communication entitled "Toward a Permanent Energy Efficiency Policy for the European Community" offering Member States fourteen energy efficiency measures to help achieve the 1995 target. In 1990, the issue of climate change began to emerge, and that same year the European Council of Environment and Energy Ministers agreed that total CO_2 emissions would stabilize at 1990 levels by the year 2000. According to the first report by the Intergovernmental Panel on Climate Change (IPCC), as well as the resolutions of the Rio Summit in 1992, the mitigation of climate change has become a key element of EU energy policy, along with the competitiveness of energy users and the security of energy supply. The concept of energy performance of buildings has varied considerably within Member States, especially in terms of assumed levels and standards, resulting in political actions at the European level. The first policies on energy efficiency of buildings were: "Construction Products Directive" in 1989, "Boiler Directive" in 1992 and "SAVE Directive" in 1993 (Economidou et al., 2020; Maltby, 2013; Papadopoulos, 2016).

1.2.2. Construction Products Directive

The Construction Products Directive (CPD) aimed at increasing the reliability of information on the performance of construction products used in buildings. It consisted of four main elements, including the CE marking of the products. The requirements introduced by CE marking included "energy conservation and heat retention", but the CPD itself did not explicitly refer to the energy performance of buildings. It merely directed that building structures and their cooling, heating, and ventilation systems be designed and built to ensure "low" energy consumption. The CPD was repealed and then replaced by the Con-struction Products Regulation (CPR 15) (Economidou et al., 2020).

1.2.3. Hot Water Boiler Directive

The first technical appliances to be covered by EU legislation were heating boilers and hot water heaters, specified in the Council Directive of 1978 on the efficiency of heat generators for space heating and the production of domestic hot water.

Due to the very low level of energy efficiency of boilers, in 1992 the Commission presented a legislative initiative on the energy efficiency of these devices. The document was called the Hot Water Boiler Directive (HWBD) and introduced common efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels in all Member States. The directive was applicable to standard boilers, low-temperature boilers, and condensing boilers of 4 to 400 kW (Council of the European Union, 1992 ; Economidou et al., 2020).

A key objective of the HWBD was to use clear and consistent energy labels on boilers in all Member States, to make them easily comparable. A similar directive was adopted in 1996 and introduced efficiency requirements for domestic refrigerators and freezers. Both directives were predecessors to Directive 2005/32/EC that established efficiency requirements for energy-using products (Economidou et al., 2020).

1.2.4. Directive 93/76/EEC of 13 September 1993 to Limit Carbon Dioxide Emissions by Improving Energy Efficiency (SAVE)

The EU's first energy efficiency policy is considered to be the "SAVE" di-rective (Council of the European Union, 1993). Earlier policies, such as the 1976 and 1979 Council Recommendations, contained only policy suggestions for improving the efficiency of electrical devices, heating systems and thermal insulation, while the "SAVE" Directive obliged Member States not only to promote the rational use of energy, but also to develop and implement energy efficiency improvement programmes to reduce carbon dioxide emissions (Economidou et al., 2020).

At the time, EU and national policy makers believed that energy efficiency standards for buildings, expressed mainly as insulation requirements (such as "U" values) should be implemented at the national level. However, to counteract situations where some EU member states had already adopted mandatory building standards with different levels of restriction, whereas several European countries did not have building codes in force, the SAVE Directive required all member states to develop and implement programs to introduce unified regulations for thermal insulation in new buildings (Economidou et al., 2020).

The main building requirements included in the Directive are:

- building certification with a description of the energy performance;
- cost settlement of heating, air-conditioning and hot water needs to be calculated on the basis of actual consumption;
- thermal insulation of buildings;

regular inspection of heating systems with a capacity > 15 kW (Economidou et al., 2020; Sands & Galizzi, 2006).

The implementation of the SAVE Directive has not been as smooth and efficient as hoped, which has not allowed the aforementioned potential to be satisfactorily tapped. This was partly due to the fact that member states did not adopt efficiency requirements or standards in their countries or adopted lax national standards. This, in turn, has provided a rationale for increasing thermal insulation in existing buildings, extending certification or licensing, and installing energy-efficient equipment. The SAVE Directive was partially replaced by the Energy Performance of Buildings Directive in 2002 and the remaining articles were replaced by the Directive on Energy End-Use Efficiency and Energy Services in 2006 (European Parliament, Council of the European Union, 2006).

In 1998 the Commission presented a communication identifying a potential for energy efficiency improvements of 22% by 2010 compared to 1995 (Commission of the European Communities, 1998). The communication em-phasized the need for more action at the European, Member State, and Re-gional level, presented both the successes and failures of the policies, as well as analyzed the barriers to achieving this potential, reviewed the programmes adopted and proposed elements of strategy and priorities to realize it (Commission of the European Communities, 1998; Economidou et al., 2020).

Since 2000, the Commission has published several Energy Efficiency Action Plans, covering future strategies and actions such as new policies or strengthening existing measures.

Following the adoption of the Kyoto Protocol in 1997, the EU committed itself to a binding target of an 8% reduction in greenhouse gas (GHG) emissions between 2008 and 2012 compared to 1990 (European Parliament, Council of the European Union, 2006; Poulopoulos, 2016). This became the driving force for the implementation of stronger climate and energy policies. The Kyoto agreement on reducing greenhouse gas emissions reiterated the need to engage and promote energy efficiency in an even more proactive way. The 2000 Action Plan proposed several intensified actions, building on the provisions of the SAVE Directive. While recommending a more coordinated approach, it emphasized the freedom of Member States to set their own efficiency requirements. However, this Action Plan served as a key stimulus, shaping the policy cycle that led to EPBD in 2002 (Economidou et al., 2020).

1.2.5. Energy Performance of Buildings Directive

The Energy Performance of Buildings Directive (EPBD) implemented in 2002, was the first coherent European legislation on energy policy in buildings. This document, aimed at taping into the sector's high potential for cost-effective savings (specifically 22% over a 10-year period). The EPBD policy framework provided the background for, among other things, setting the minimum energy performance standards in the new or existing but renovated buildings (Economidou et al., 2020).

The assumption of minimum requirements for the energy performance of buildings, represented a major step forward. Under the provisions of the EPBD, the energy performance of a building was to be defined as the amount of energy calculated or consumed (monitored), usually measured in kWh/m^2, reflected in one or more numerical indicators, taking into account the following:

- external and internal climatic conditions;
- the orientation and location of the building;
- the thermal characteristics of the building envelope;
- the presence of passive solar systems and solar protection;
- the presence of natural ventilation and passive strategies;
- type of heating, domestic hot water, ventilation or cooling systems;
- type of lighting installations (especially for the nonresidential sector);
- energy generation for our own use (Economidou et al., 2020; European Parliament, Council of the European Union, 2002).

Furthermore, another important point in EPBD was the regular inspection and performance evaluation of boilers and air conditioning systems, both to ensure safety and to reduce energy consumption. According to the Directive, boilers with a rated output of more than 10 kW should be regularly inspected to improve their operating conditions. Similar measures had to be implemented for the first time also for cooling systems, in particular in larger service buildings (Economidou et al., 2020; European Parliament, Council of the European Union, 2002).

In 2006, the European Commission published the second Energy Efficiency Action Plan. Its contents included reducing and controlling energy needs and taking action to effectively save 20% of annual primary energy consumption by 2020, compared to baseline consumption forecasts. This meant achieving around 1.5% savings per year by 2020. The measures and policies in the 2006 Action Plan were developed on consultations initiated by the 2005 Green Paper on Energy Efficiency, which emphasized the need to build up the EU energy efficiency policy (Economidou et al., 2020).

The plan defines an energy savings potential of 27% compared to existing energy consumption in residential buildings and 30% in commercial buildings. It proposes an overall energy savings target of 20% to be achieved by 2020 through the development of existing policies and the use of new measures. The plan addresses the issue of lowering the EPBD threshold for mandatory energy efficiency improvements in existing buildings and mandating very low energy levels for new buildings. This resulted in a revision of the EPBD in 2010 (Economidou et al., 2020).

Following the 2006 Action Plan, in March 2007, the EU committed itself to becoming a highly energy-efficient part of continent with a low-carbon economy (Economidou et al., 2020). According to the 2007 Directive, objectives known as the ‘20-20-20’ targets, should be achieved by 2020, such as:

- 20% reduction in GHG emissions compared to 1990 levels;
- an increase in the share of energy from renewable energy sources to 20%;
- improving energy efficiency leading to 20% primary energy savings in the EU (D'Agostino & Mazzarella, 2019; Economidou et al., 2020; Ionescu et al., 2015).

In 2009, the European Commission presented a recast of the EPBD (in force from 2010) to improve some of the original regulations and achieve additional energy savings in line with the 2006 Action Plan. The main objective of the recast was to ensure that the national minimum energy performance requirements adopted by Member States had a similar level of restriction in terms of GHG reductions and energy savings. This was due to insufficiently ambitious and cost-effective standards adopted by some countries.

The Directive's therefore distinguished a cost-optimal methodology as a guiding principle for setting energy requirements for buildings. It also introduced the concept of "nearly zero energy buildings" (nZEBs), under which all new private buildings will have to meet nationally defined nZEB standards by January 2021.

Furthermore, the directive required all EU countries to specify how thermal bridges will be taken into account in the energy performance of a building, as well as introduced energy performance requirements for technical building systems (heating, domestic hot water, ventilation, cooling, and air condition-ing). The Energy Performance Certification (EPC) and inspection provisions for heating and air-conditioning systems have been strengthened especially to increase their effectiveness (Economidou et al., 2020; Papadopoulos, 2016).

In 2011, the new Commission presented a roadmap for achieving a low-carbon economy by 2050, which outlined far-reaching new energy and environmental targets. The target is to reduce greenhouse gas emissions by 40% by 2030, by 60% by 2040 and ultimately by 80-95% by 2050, compared to the 1990 levels.

In 2014, the EU implemented energy and climate targets for 2030. They also assumed a minimum of 27% share of energy from renewable energy sources (RES) and 27% energy savings. In 2018, as a result of discussions to establish the legal basis for the targets, they were modified in terms of RES to 32%, as well as energy savings to 32.5% (Economidou et al., 2020).

In February 2015, the Energy Union Strategy was adopted, namely "The Energy Union Package: A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy". The strategy emphasized the need to promote and provide greater support for secure, sustainable, competitive and affordable energy, focusing on five core issues.

1. security and solidarity;
2. a fully integrated internal energy market;
3. energy efficiency;
4. climate action, decarbonization of the economy;
5. research, innovation and competitiveness.

In order to implement the Energy Union Strategy and align the EED and EPBD with the new 2030 climate and energy targets, in 2016, the European Commission adopted a package of measures, the so-called "Winter Package". In proposing amendments to the EPBD as part of the "Winter Package", the Commission sought to simplify existing legislation and ensure consistency with other policy areas (i.e. the EED). The proposed changes addressed long-term renovation strategies, a vision for decarbonizing buildings by 2050, the introduction of a building intelligence indicator, and the mobilization of financial resources (Economidou et al., 2020).

In mid-2018, a new EPBD was published. The amendment implemented changes to accelerate cost-effective renovation of existing buildings, with the aim of decarbonizing the building stock by 2050, as well as strengthening smart technologies and systems and automation in buildings (including building controls and indoor temperature control devices) by implementing an assessment of buildings for their smart grid readiness capabilities (Witczak, 2018). An important point was also to increase the promotion of health and well-being of building occupants by paying more attention to air quality and ventilation systems.

On December 15, 2021, the European Commission published a proposal for substantial revisions (recast) to the Energy Performance of Buildings Directive (EPBD), as part of the "Fit for 55" package. The document consists of several legislative proposals aimed at meeting the EU's new goal of reducing green-house gas (GHG) emissions by a minimum of 55% by 2030 compared to 1990. The proposed changes will include the introduction of new energy per-formance standards for buildings, changes to the definitions of energy per-formance standards, changes to national building renovation plans, and new requirements for calculating emissions throughout the life cycle of new build-ings. There are also to be revised definitions of terms such as: "Zero-emission building", "Nearly-zero energy building", and "Deep renovation" (WEB–14, WEB–15).

New buildings will have to be zero-emission by 2030 (2027 for public build-ings), and the life cycle global warming potential (GWP) will be calculated for new large buildings starting in 2027, and for all new buildings by 2030. The calculations will take into account carbon emissions from the entire life cycle of a building - from production and construction, through use and decommis-sioning. Other regulations will introduce, among other things, building renova-tion passports and a smart readiness indicator, as well as will end all financial support for fossil fuel boilers, and promote building control or automation systems. The EPBD recast aims to accelerate the pace of building renovation, reduce energy consumption and greenhouse gas emissions, and promote the use of renewable energy (WEB–14, WEB–15).

1.2.6. Energy Efficiency Directive

At the end of 2012, the Energy Efficiency Directive (EED) (European Parliament, Council of the European Union, 2012; WEB–4) was adopted as part of the European energy and climate package. It set a target of a 20% reduction in primary and final energy consumption levels by 2020 and required member states to set their own energy efficiency challenges, as well as develop building energy efficiency strategies and implement energy efficiency obligation systems. In addition, Article 7. of the Directive required an annual reduction in the final energy consumption of 1.5% (Economidou et al., 2020; Rosenow, 2017). To provide a legal framework for the 2030 energy efficiency targets, the EED was updated in 2018.

One of the goals set out in the updated directive was the need to achieve an energy efficiency of 32.5% by 2030. It also stressed that strategies must facilitate the cost-effective transformation of existing buildings into nearly-zero energy buildings (Economidou et al., 2020).

Figure 1.3 shows the level of primary energy consumption in Europe, with reference to the targets set for 2020 and 2030, as an example of the effects of achieving the goals set by the directive.

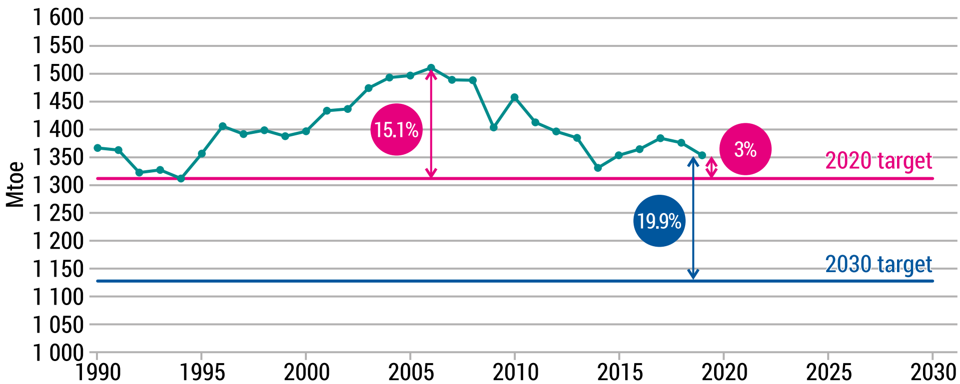

FIG. 1.3. Primary energy consumption in the EU, distance to 2020 and 2030 targets (Source: WEB–9)

To promote energy savings through behavioral change, the EED introduced a mandatory requirement for consumption-based billing for heating, cooling, and domestic hot water in multifamily buildings equipped with collective heating/cooling systems. The implementation of this legislation was intended to provide energy users with feedback on their consumption, which, in turn, was expected to reduce final energy consumption by up to 10% on average (Economidou et al., 2020).

Actions to limit global warming have been accelerated in recent years, and United Nations Climate Change Conferences (COPs) are considered the latest major milestones in global climate change debates (Economidou et al., 2020).

At the recent COP26 summit of world leaders, a new global agreement was reached – the Glasgow Climate Pact, whose main findings include reducing the use of coal (which accounts for 40% of annual CO_2 emissions), moving away from fossil fuels, limiting methane emissions by 30% by 2030 (compared to 2020), as well as the need to increase funding to help poor countries cope with the effects of climate change and switch to clean energy (WEB–1; WEB–11).

The development of energy efficiency requirements and policy instruments has also been discussed in (Geller et al., 2006; Reuter et al.; 2021; Shen et al., 2016).

As can be seen, none of the above-described European legal acts specified unambiguously precise and uniform requirements for all Member States regarding the internal systems or installations in buildings, as well as their structure (thickness of insulation, materials used). This happened and still happens because the energy efficiency of a building is influenced by various factors, depending among others on the location and climatic or social conditions of the country. The evolution of buildings over the years has been driven by the challenges of increasing energy efficiency or reducing atmospheric emissions, which in themselves have become the driving force for European countries to implement their own individual regulations tailored to the characteristics and possibilities of each country, in order to achieve their objectives. It is appropriate to apply the phrase that in the case of the development of energy-efficient buildings, "necessity is the mother of invention".

However, with increasing demands on energy efficiency and in parallel with rising indoor environmental quality standards, the building envelope has come to play a more important role in climate regulations. As a result, numerous requirements have been placed on them 2 The Figure 1.4 shows the variation of requirements concerning the heat transfer coefficient "U" of selected building partitions between 1983-2021, on the example of Poland.

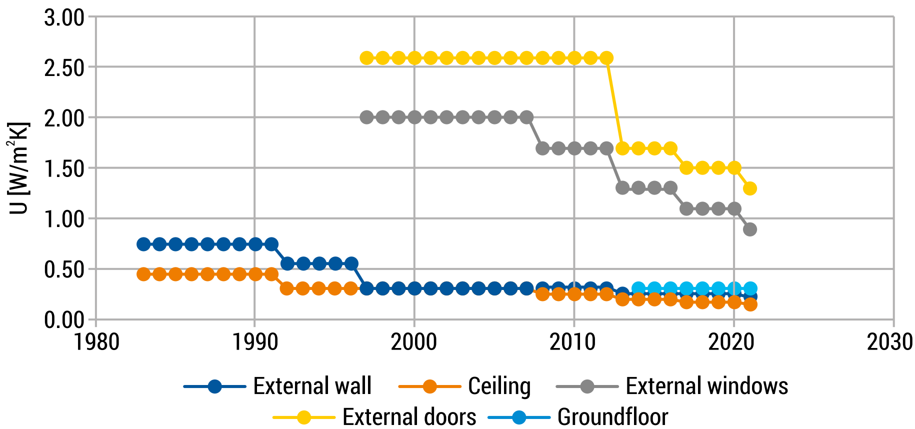

FIG. 1.4. Variability of heat transfer coefficient "U" requirements between 1983-2021 (Source: own elaboration based on Tatara et al., 2017)

It can be seen that in almost 30 years, the heat transfer coefficient requirements for external walls for new buildings have changed by as much as 73%, while for roofs and flat roofs – by about 67%, what indicates considerable progress.

1.3. Evolution of Buildings

The first energy efficiency regulations for buildings were not really aimed at reducing energy demand, but at providing adequate heating conditions. This was done by promoting the use of traditional architectural features that helped increase the thermal resistance of the envelope, such as a layer of air in the cavity of a double brick wall or in a two-layer wood floor (Papadopoulos, 2016).

The need to improve the energy efficiency of buildings emerged as a consequence of the oil crisis in the 1970s and was primarily expressed in the desire to reduce the energy demand of HVAC systems while improving indoor environmental performance. It has been a long way from those days to the zero or near-zero energy buildings required today. However, significant technological developments in buildings have been achieved through intensive, systematic deepening of interdisciplinary theoretical knowledge and regulatory frameworks such as directives and European standards (Papadopoulos, 2016). Successive and ever more stringent regulations have driven the development of efficient insulation materials and intelligent airtight buildings.

For many years, the greatest environmental importance was attributed to the building operation phase, as the longest period in its life cycle [3]. Therefore, people became more concerned with super-insulation, tightness of the building envelope, heat recovery from ventilation, the use of triple-glazed windows and passive technologies that relied on solar thermal energy. Definitions of “self-sufficient houses”, “autonomous houses” and “green houses” were developed (Ionescu et al., 2015; Papadopoulos, 2016).

After the crisis, when the environmental consequences of the other phases of building began to grow (reduced reserves of raw materials, difficulties in managing and disposing of construction waste), a holistic approach was adopted, taking into account the impact of all stages of a building’s “life”. The building sector adopted the sustainability goals, as an innovative concept in structures, that began to be considered when defining new design strategies, creating new definition of “sustainable buildings” (Cao et al., 2016; Ionescu et al., 2015).

In 1974, research on the effect of air exchange on heat loss in buildings began. The concept of the “zero-energy house,” which is very popular today, also emerged at that time (Ionescu et al., 2015).

With the dynamic development of technology in the building industry, the first “intelligent building” was developed in the early 1980s. During this time, Wolfgang Feist promoted the idea of the “Low Energy House” and, at the end of the 1980s, developed the concept of the “Passive House”, combining all relevant design theories or algorithms. The first passive house was built in 1991 in Darmstadt (Germany) (Ionescu et al., 2015).

In 1992, the first autonomous energy house was developed, which was able to meet its own energy needs thanks to excellent insulation and solar energy technology (Ionescu et al., 2015).

In 1994, the first positive energy house designed by Rolf Disch and built in Freiburg was commissioned. It was the first house in which the amount of energy produced was greater than the amount consumed. All technologies used in it used only renewable energy (Ionescu et al., 2015).

In 1995, in turn, Wolfgang Feist developed the passive house standard on the basis of the experience gained. This was an important step in the evolution of buildings, as the idea of Passive Houses is popular up to the present day (Martinez-de-Alegria et al., 2021) and as shown in (Di Foggia, 2018) in the residential sector, currently the incremental costs of achieving Passive House standards range from 6% to 16% of the cost compared to standard constructions'.

Recent technological advances that affect the development of building techniques allow easy integration of energy-efficient ideas into building design, providing improvements in comfort, utility, energy efficiency, and even aesthetics. Environmental evaluation and analysis efforts also have been intensified. However, it must be remembered that 40 years after the first thermal insulation requirements were introduced and more than ten years after the first Energy Performance of Buildings Directive was established, thermal loads still account for almost two-thirds of building loads. Consequently, reducing them further is becoming an increasingly difficult task and requires increasingly advanced building materials and techniques, but also a more ambitious, integrated regulatory approach (Papadopoulos, 2016).

In recent decades, researchers in the field of low-energy house design are continually focused on creative solutions and thermal design principles, as well as ways to overcome barriers that prevent energy efficiency gains in buildings (Ionescu et al., 2015).

1.4. Energy Indicators of the nZEB

As mentioned, the concept of the nZEB is defined in the Directive EPBD 2010/31/UE as a building that has very high energy performance and in which the required nearly zero or very low amount of energy, should be covered to a very significant extent by renewable energy sources (RES) produced on-site or nearby. This concept must be differenced from other stricter concepts related to efficient buildings:

- Net Zero Energy Building (NZEB), where the energy consumed in the building is equal to the energy produced on-site;
- Positive Energy Building, that produces more energy than consumed;
- Net Zero Carbon Building (NZCB), when the amount of carbon emis-sion associated with the building operation during one year is zero

Nowadays, with the present technology, all the above criteria are not economically profitable. So, the EU has decided to set the nZEB concept in its Directives and recommendations.

The EU required from the Member States (MS) to stablish their nZEB requirements in their national regulations based on different factors: climate, heating system used, the building geometry, etc. It follows, therefore, that there is no common criterion and each state defines its own requirements.

In 2016, the Recommendations EU 2016/1318 considered 4 climatic zones (Mediterranean, Oceanic, Continental, and Nordic) and published the reference values for the primary energy consumption of the resident and non-residential buildings (Table 1.1) (European Commission, 2016). This means that the percentage of renewable energy ranges between 32 and 87%, depend-ing on the climatic zone.

TABLE 1.1. EU recommendations of the Primary Energy Consumptions [kWh/(m^2 year)] (Source: own elaboration based on European Commission, 2016)

	Residence Building			Offices		
	Total Primary Energy [kWh/(m^2 year)]	Renewable Energy Source [kWh/(m^2 year)]	Net Primary Energy [kWh/(m^2 year)]	Total Primary Energy [kWh/(m^2 year)]	Renewable Energy Source [kWh/(m^2 year)]	Net Primary Energy [kWh/(m^2 year)]
Mediterranean	50-65	50	0-15	80-90	60	20-30
Oceanic	50-65	35	15-30	85-100	45	40-55
Continental	50-70	30	20-40	85-100	45	40-55
Nordic	65-90	25	40-65	85-100	30	55-70

Recently, the European Commission published a draft of the revision of the Energy Performance of Building Directive to be approved in 2022 (European Commission, 2021). This revision is more oriented towards the Zero Emission Building than the current regulation. The new values of the proposed total primary energy use are given in Table 1.2. To avoid carbon emissions from fossil fuels, this energy should be fully covered, in an annual balance, by:

- renewable energy generated on-site;
- renewable energy provided from a renewable energy community;
- renewable or waste energy from an efficient district heating and cooling system.

Only in exceptional cases established at the national level may the primary energy consumption also be covered from the grid.

Table 1.3 presents the values used in some MS regulations for building energy performance (BPIE, 2021). Not all states consider the kWh/(m^2 year) in their regulations. This table shows the wide disparity in the way the EU directive about nZEB is implemented.

TABLE 1.2. Proposal Primary Energy Consumptions [kWh/(m^2 year)] in the draft of the new EU directive about the energy performance of building (Source: own elaboration based on European Commission, 2021)

EU Climatic Zone	Residence Building [kWh/(m^2 year)]	Offices	Other non-residential build-ing
Mediterranean	< 60	< 70	< NZEB requirements at national level
Oceanic	< 60	< 85	< NZEB requirements at national level
Continental	< 65	< 85	< NZEB requirements at national level
Nordic	< 75	< 90	< NZEB requirements at national level

TABLE 1.3. Total Primary Energy requirements [kWh/(m^2 year)] in the regulations of some EU Member States (Source: own elaboration based on data of BPIE, 2021)

	Residental Building [kWh/(m^2 year)]	Offices [kWh/(m^2 year)]
Denmark	27	33
Croatia	40	30
Ireland	42	66
France	50	50
Netherlands	50	40
Greece	53	125
Slovakia	54	61
Lithuania	60	80
Belgium	63	93
Spain	63	143
Poland	70	45
Sweden	70	50
Malta	73	290
Estonia	74	62
Slovenia	75	51
Bulgaria	95	140
Latvia	95	110
Cyprus	100	125
Hungary	100	90
Czechia	130	130
Finland	131	100
Romania	158	67

– More demand than EU recommendation

– Less demand than EU recommendation

The REHVA (Federation of European heating, Ventilation and Air Conditioning association) worked for a uniformed implementation of EPBD recast (Kurnitski, 2013). This common definition was based on the imported and exported primary energy according to EPBD recast and prEN 15603:2013. In these regulations, the Non-renewable Primary Energy ($E_{P,nRE}$) is defined as summatory for all energy types:

$$E_{P,nRE} = \Sigma_i (E_{i,imp} f_{i,imp.nRE} - E_{i,exp} f_{i,exp.nRE}) \tag{1.1}$$

where $E_{i,imp}$ and $E_{i,exp}$ are the annual imported and exported energies of type i on site or nearby, respectively, and $f_{i,imp.nRE}$ and $f_{i,exp.nRE}$ are the non-renewable imported and exported energy (type i) factors on site or nearby, respectively. If the national regulations do not define them otherwise, these factors can be considered similar.

The Energy Primary Indicator can be calculated by Eq. 1.1 and the useful floor area A_{net}, according to national definitions:

$$EP_p = \frac{E_{P,nRE}}{A_{net}} \tag{1.2}$$

This indicator uses the concept of *Primary Energy*, that can be defined as the energy that has not been subjected to any transformation. Subsequently, this energy must be managed by different energy chains before it is delivered to the building in the form of electricity, gas, heat (conversion, transport, etc.). These processes require additional energy consumption. The energy primary factor is the conversion factor that relates the delivery energy to the required primary energy.

The values of Primary Energy Factor are collected in the national standards of each Member State (MS). These values can vary from one standard to another because the transformation and transportation processes can be different in each country and different conventions can also be used for the estimation of these factors. Table 1.4 shows the range of values of the Primary Energy Factors of the EU states' standards (Hitchin, 2019).

TABLE 1.4. Range of the Primary Energy Factors in the EU states (Source: own elaboration based on data of Hitchin, 2019)

	Coal	Gas	Oil	Wood	Biomass	Grid Electricity	District heating
PEFs' range in EU states	1.00-1.46	1.00-1.26	1.00-1.23	0.01-1.26	0.01-1.12	1.50-3.45	0.15-1.50

Also, the EU calls for distinguishing between renewable and non-renewable energy with regard to energy consumption in buildings (see Eq. 1.2). So, PEFs for total and non-renewable factors are defined in the national standards.

Other indicator, that indicates the percentage of renewable energy shared, is the Renewable Energy Ratio (RER), that is the ratio of the net renewable energy consumed in the building to the total used energy. Using the energy flows shown in Fig 1.5, this indicator is defined by (Kurnitski, 2013):

$$RER = \frac{\Sigma_i [E_{i,RE} + (f_{i,imp.tot} - f_{i,imp.nRE})\, E_{i,imp}]}{\Sigma_i [E_{i,RE} + f_{i,imp.tot}\, E_{i,imp} - f_{i,exp.tot}\, E_{i,exp}]} \tag{1.3}$$

where $E_{i,RE}$ is the renewable energy of type i produced on site or nearby and $f_{i,imp,tot}$ and $f_{i,exp,tot}$ are the total primary energy factors for the imported and exported energy, respectively.

The definitions of Eqs. 1.1. and 1.3 include the concepts of 'on site' and 'nearby' to consider the possibility of energy production, for example an energy plant, near and linked to the building. Figure 1.5 shows an example of the energy flows considered in Eqs. 1.1 and 1.3).

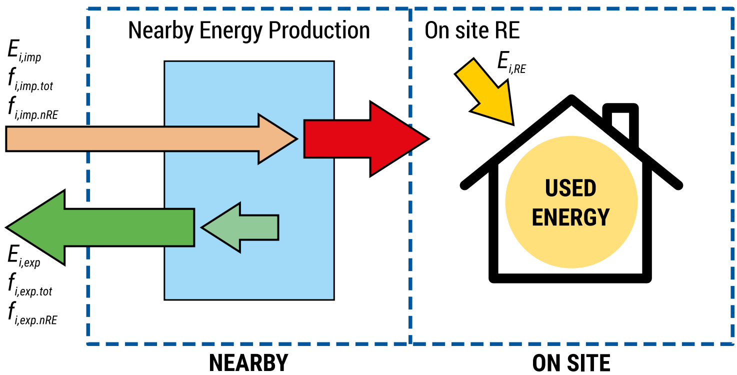

FIG. 1.5. Example of the energy flows of the equations 1.1 and 1.2 (Source: own elaboration)

Not all the countries have a requirement for renewable energy to contribute to the total primary energy demand. Table 1.5 shows the minimum renewable requirements in the countries that have implemented this condition.

TABLE 1.5. Minimum percentage of renewable energy in the regulations of some Member States of EU (Source: own elaboration based on data of BPIE, 2021)

Country	Minimum percentage of renewable energy [%]
Ireland	20
France	20-30
Hungary	25
Croatia	30

Country	Minimum percentage of renewable energy [%]
Netherlands	30-40
Lithuania	50
Portugal	50
Bulgaria	55
Austria	80% heating or hot water or 20% electricity from PV
Germany	15% solar energy (PV or solar thermal) 50% (geothermal, biomass and/or waste heat)
Portugal	50
Spain	60%–70% Domestic Hot Water DHW

1.5. Solutions of nZEBs

A proper design is crucial to reach the nZEB requirements. This design is based on a triple strategy:

- Passive solutions, oriented to reduce the energy demand of the building by architecture design. These solutions must be considered the priority in this design;
- Active solutions with the use of more efficient systems;
- The use of renewable systems meet most of the building's demand.

A priority scheme of these solutions in the design is shown in Figure 1.6.

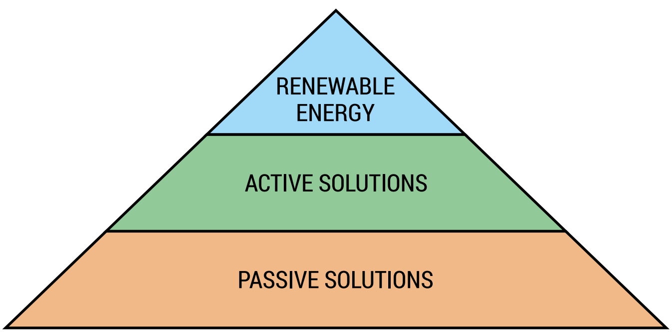

FIG. 1.6. Scheme of the triple strategy to nZEB design (Source: own elaboration)

A more detailed descriptions of these three solutions is given in this section.

Passive Solutions:

These types of solutions can reduce the heating and cooling energy consumption by about 90% compared to a conventional building. Some factors considered in this strategy are:

1. **Optimization of thermal insulation** of the building, with the selection of efficient material for wall, roof, etc.

2. **Selection of windows with high quality glazing.** Typically, these are tripple glazed windows. Also, the orientation of widows can have a positive effect. South-facing windows receive more direct radiation. Additionally, a canopy over the window pre-vents from overheating in hot season.
3. **Reduction of thermal bridges:** The thermal bridges produce the transmission of the heat from a part of the building to another. The reduction of thermal bridges in the building construction allows to reduce unnecessary energy losses.
4. **Natural ventilation** is also a good strategy for cooling in hot climate.

Other modern technologies for passive solutions of nZEBs are also being developed or are in the first stages of implementation. Some researchers are studying the application of nanomaterials, such as aerogels or Vacuum Insula-tion Panels, to improve the thermal insulation of the building with thinner lay-er dimensions. On the other hand, the Phase Change Materials (PCMs) are investigated for these purposes. These materials are paraffins or salts that al-low to store the solar radiation by phase changes from solid to liquid and vice versa. Their use in the external envelope leads to reduction of energy demand.

Special attention is also being paid to improving glazing. The study of "smart" glazing, with dynamic room darkening using different technologies: photo-chromic, thermo-chromatic, electrochromic, etc., allows to increase the win-dows-to-wall ratio (WWR) without reducing the building performance.

ZEBRA2020 project studied the strategies considered in 253 nZEBs in different countries located in three climate zones: Cold, Mild, and Warm climates (ZEBRA2020, 2016). The main characteristic of the passive solutions in these buildings are summarized in Table 1.6.

The stone wool and expanded polystyrene are the materials most commonly used for the walls of the building, which allow for isolation with an average thermal transmittance between 0.11 and 0.16 W/(m^2 K).

Triple glazed windows are used in more than 57% of the nZEB cases studied.

Sunshade, natural ventilation, and thermal mass are other passive systems commonly used.

TABLE 1.6. Most often used passive solutions in a selection of nZEBs (Source: own elaboration based on data of ZEB-RA2020, 2016)

	Cold Climate		Mild Climate		Warm Climate	
	Resident building	Offices	Resident building	Offices	Resident building	Offices
Average $U_{tramit.}$ of walls [W/m^{2}K]	0.18	0.14	0.14	0.14	0.17	0.14

	Cold Climate		Mild Climate		Warm Climate	
	Resident building	Offices	Resident building	Offices	Resident building	Offices
Typical wall material	expanded polystyrene in 27% of the nZBEs.	stone wool in 19% of the nZEBs.	expanded polystyrene in 27% of the nZBEs	stone wool in 28% of the nZEBs	expanded polystyrene in 25% of the nZBEs	stone wool in 19% of the nZEBs
Average $U_{tramit.}$ of roofs [W/m^{2}K]	0.11	0.16	0.13	0.12	0.24	0.15
Typical roof material	stone wool in 19% of the nZEBs.	stone wool in 14% of the nZEBs.	stone wool in 18% of the nZEBs.	expanded polystyrene in 28% of the nZBEs.	Wood fiber in 35% of the nZEBs.	expanded polystyrene in 14% of the nZBEs.
Average $U_{tramit.}$ of windows	0.84	0.85	0.99	0.87	1.16	1.17
Typical windows material	Triple glass in 57% of then ZEBs	Triple glass in 57% of then ZEBs	Triple glass in 57% of then ZEBs	Triple glass for 61% of then ZEBs	Triple glass in 47% of then ZEBs	Triple glass in 29% and doble glass in 29% of then ZEBs
Passive cooling	• sunshade (24%) • natural ventilation (16%) • thermal mass (16%) • night cooling (15%)	• sunshade (18%) • natural ventilation (8%) • evaporative cooling (4%) • night cooling (2%) • thermal mass (2%);	• sunshade (27%) • natural ventilation (23%) • thermal mass (20%)	• sunshade (17%) • night cooling (17%) • natural ventilation (11%) • thermal mass (11%)	• natural ventilation (55%) • sunshade (55%) • night cooling (49%) • thermal mass (47%)	• sunshade (50%) • natural ventilation (43%) • night cooling (36%) • thermal mass (36%)

Active Solutions:
These solutions aim to increase the energy efficiency of the building systems, such as lighting or HAVC systems.

The active energy efficiency solutions include:

- improving the lighting systems with low energy consumption lamp (LED), advanced lighting control (photoelectric cells, presence detec-tor), a daylight design;
- including ventilation systems: fan coils, displacement diffusers;
- increasing the efficiency of heating/cooling systems (HVAC and DWH), such as boilers (gas, biomass...), heat pumps, district heating, etc.;
- using automatic or manual shading devices.

The report ZEBRA2020 presents also the results of the most commonly used active solutions adopted in the studied nZEBs (ZEBRA2020, 2016). The summary of these results is presented in Table 1.7.

The air and water heat pump is the heating and cooling system most common-ly used, followed by district heating and condensing boiler.

For heating of DHW, the system is the same as the HVAC system in 50% of studied cases in the cold zones, the percentage decreases in warmer zones.

TABLE 1.7. Most often used active solutions in a selection of nZEBs (Source: own elaboration based on data of ZEBRA2020, 2016)

	Cold Climate		Mild Climate		Warm Climate	
	Residential building	**Offices**	**Residential building**	**Offices**	**Residential building**	**Offices**
Ventilation systems	Mechanical ventilation with heat recovery in 80% of the nZEBs	Mechanical ventilation with heat recovery in 80 % of the nZEBs	Mechanical ventilation with heat recovery in 86% of the nZEBs	Mechanical ventilation with heat recovery in 78% of the nZEBs	Mechanical ventilation with heat recovery in 90% of the nZEBs	Mechanical ventilation with heat recovery in 90% of the nZEBs
Heating systems	• heat pumps (31%) • district heating (21%) • condensing boiler (17%).	• heat pumps (32%) • district heating (27%) • condensing boiler (11%).	• heat pump (40%) • condensing boiler (20%) • stove (20%).	• heat pump (40%) • boiler (33%).	• heat pumps (57%) • boiler (15%).	• heat pumps (57%) • boiler (14%).
Domestic Hot Water	• 50% of nZEBs is the same system as HVAC	• 31% of nZEBs is the same system as HVAC.	• 40% nZEBs is the same system as HVAC (partly solar ther-mal energy)	• 44% nZEBs has separate system	• 31% nZEBs is the same system as HVAC (partly solar thermal energy)	• 36% of the nZEBs has separate system

	Cold Climate		Mild Climate		Warm Climate	
	Residential building	Offices	Residential building	Offices	Residential building	Offices
Cooling System					• 53% of the nZEBs use cooling systems: • air source heat pump (22%) • soil source heat pump (7%) • water source heat pump (7%)	• 79% of the nZEBs use cooling systems: • air source heat pump (36%) • soil source heat pump (21%) • water source heat pump (14%)

Use of Renewable Energy in nZEBs:
The incorporation of renewable energy in the nZEB designs is mandatory according to the Directive EPBD 2010/31/UE that encourages Member States to increase the RER in the building energy consumption.

The renewable energy solutions that are often used:

- for electricity production: photovoltaic panels integrated or non-integrated in the building, mini-wind turbines, co-generation.
- for thermal energy production (heating/cooling and domestic hot water) systems using solar thermal collectors, solar absorption machine, geothermal energy, biomass.

Table 1.8 shows the summary of the results obtained from the ZEBRA2020 project for the 253 studied nZEBs located in the three climates zones.

TABLE 1.8. Most often used renewable energies in a selection of nZEBs (Source: own elaboration based on data of ZEB-RA2020, 2016)

	Cold Climate		Mild Climate		Warm Climate	
	Residential building	Offices	Residential building	Offices	Residential building	Offices
PV system	Used in 30% of the nZEBs	Used in 27% of the nZEBs	Used in 33% of the nZEBs	Used in 44% of the nZEBs	Used in 55% of the nZEBs	Used in 43% of the nZEBs
Solar thermal system	Used in 31% of the nZEBs	Used in 24% of the nZEBs	Used in 44% of the nZEBs	Used in 22% of the nZEBs	Used in 44% of the nZEBs	Used in 29% of the nZEBs

The most commonly used technologies in nZEBs are PV and solar thermal, with similar percentages. The tendency is to increase the use of these technol-ogies in the climate zones where the solar radiation is higher. In general, the renewable energy is more often used in the residential building than in non-residential ones (offices).

1.6. Example of nZEB

In this section, three of examples of nZEB have been presented to show the strategies used in each case. The selected buildings are located in countries with different climate: cold, mild and warm. Special attention was paid to the performance of these nZEBs with the passive, active and renewable energy solutions selected in their designs. The primary energy indicator and RER are determined, in order to compare with national requirements in each country.

Cold Zone (Sandvika-NORWAY)

The example selected for cold zone is the *Powerhouse Kjørbo*, located in Sandvika (Norway) (Erhorn, 2014). This group of buildings is a retrofitting of four old office buildings adapted to produce energy (positive energy build-ing). The total area of these offices is 5200 m^2. The construction project is divided into in two stages. Nowadays, the first stage (2 buildings) has been completed (see Fig. 1.7).

FIG. 1.7. Photo of the Project *Powerhouse Kjørbo buildings* (Source: photo from 3D-view of Google Map)

Passive Solutions:
The old concrete structure of the walls is preserved, but its insulation properties are renovated. These concrete walls are covered with timber frames to reduce the thermal transmittance U= 0.13 W/(m^2K).

Triple glazing with aluminum frame is used in the windows with a U value equal to 0.80 W/(m^2K).

Natural light is optimized by a better design of the window arrangements.

Active Solutions
The heating, hot water and cooling energy is produced by a geothermal heat pump with the district heating network as an external supply.

A ventilation system with low pressure drop, heat recovery, and displacement diffuser was installed, which allows to increase its cooling efficiency.

Lighting is controlled by automatic system with presence sensor. And the ex-ternal sunscreens are also automated.

Renewable Energy Solutions
Solar PV panels placed in the roof surface (1400 m^2 per building) can produce 41 kWh/(m^2 year) electricity. This amount is enough to cover the electricity demand of building and to sell surplus electricity back to the grid.

As mentioned, geothermal heat pump with 10 wells is also used to supply energy for heating, hot water, and cooling.

The Building Energy Consumption
The electricity consumption of the building is dividing as following:

- lighting by efficient LED with sensors: 7.7 kWh/(m^2 year);
- heating supplied by the geothermal heat pump: 5.9 kWh/(m^2 year);
- ventilation: 2.3 kWh/(m^2 year);
- hot water supplied by the geothermal heat pump: 1.4 kWh/(m^2 year);
- cooling supplied by the geothermal heat pump: 1.3 kWh/(m^2 year);
- other household equipment: 0.8 kWh/(m^2 year).

The total electricity consumption is 19.4 kWh/(m^2 year).

The Energy Sources
The electricity produced by the PV system cover all the energy needs of these office buildings, including the energy necessary to operate the geothermal heat pump. The production capacity of this PV system is 41 kWh/(m^2 year).

Thus, a theoretical surplus electricity of 21.6 kWh/m^2 year can be obtained, which would be sold back to the Grid. Such building can then be considered an Energy-plus building.

An energy balance in the *Powerhouse Kjørbo* is shown in the figures 1.8:

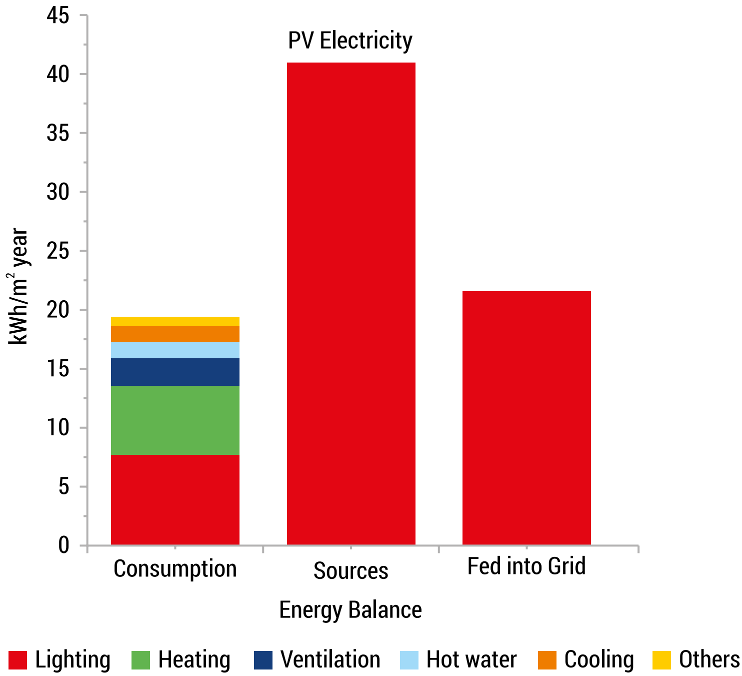

FIG. 1.8. Energy Balance in the *Powerhouse Kjørbo* (Source: own elaboration based on data of Erhorn, 2014)

The nZEB Indicators

The Primary Energy Indicators EP_P for this example can be calculated from Eqs. 1.1 and 1.2, considering the primary energy indicator of the national regulations. In Norway, there are not official values. An estimated value of this factor considering the contribution of renewable energy to the national energy mix is 1.46. Thus, the calculated EP_P is 28.3 kWh/(m^2 year).

Mild Zone (Berlin-GERMAN)

As example of nZEBs in Mild climate zone, *the Efficiency House Plus with E-mobility*, located in the Berlin city near Technical University of Berlin, is pre-sented (see Fig. 1.9). This is a prototype building built in 2011 with the aims to test its performance in real working conditions. It has an area of 150 m^2 and is design for a family of 4. This nZEB is a smart glass building with two floors that generate electricity for its own use and residents' vehicles (Erhorn, 2014; WEB–12).

FIG. 1.9. Photo of the building of the Project Efficiency House Plus with E-mobility in Berlin (Source: photo from https://www.solarwende-berlin.de/allgemein/masterplan-solarcity-berlin/wettbewerb-architektur Free License)

Passive Solutions:

The main envelope material was cellulose insulation. Timber panels 360-420 mm thick were used for the construction of walls, roof and floor. The thermal transmittances of this elements were similar about U=0.11 W/(m^{2}K).

A triple glazing was used for the windows with U=0.7 W/(m^{2}K).

Photovoltaic panels were covering the roof and façade.

The thermal bridges were reduced to avoid heat losses.

Active Solutions

The chosen heating system was an efficient heat pump with air-to-water heat source. The energy was distributed to the rooms by floor heating system.

A mechanical ventilation system with heat recovery of efficiency 80% was installed in the house.

All equipments are controlled by an automated system that monitors and manages its operation on-line.

Renewable Energy Solutions

As mentioned, the roof is cover by 98 m^2 of photovoltaic monocrystalline panels with an efficiency of 15%, and the façade is cover by 73 m^2 of thin-film panels with a efficiency of 12%. The total electricity production can reach 16 MWh that is it enough for the electricity consumption of the building and the electric vehicles.

The PV system is connected to a battery storage tank to store solar energy. A total of 7250 single second-hand car batteries with the capacity of 40 kWh was used to this purpose.

The Building Energy Consumption

All power equipment and systems require electricity. Beneath is a summary of the demand for electricity:

- heating supplied by a heat pump system: 20.8 kWh/(m^2 year);

- hot water supplied by a heat pump system: 8.1 kWh/(m^2 year);
- lighting by LED: 2.5 kWh/(m^2 year);
- ventilation: 15.3 kWh/(m^2 year);
- electrical household equipment: 14.3 kWh/(m^2 year).

Then the total annual energy consumption of the building is 61.1 kWh/(m^2 year). Additionally, the electrical automation can consume up to 19.6 kWh/(m^2 year).

The Energy Sources:
The solar PV panels covering the building is the main source of the energy, but the house is also connected to the grid from which energy is taken during the months when there is no radiation. The balance of the energy supply is as follow:

- Renewable PV energy: 65,6 kWh/(m^2 year). Part of this energy is used by the building itself, 32.3 kWh/(m^2 year), and the rest is fed into grid, 33,3 kWh/(m^2 year).
- Energy taken from the grid: 28.8 kWh/(m^2 year).

The figure 1.10 shows a scheme of the energy balance in this nZEB:

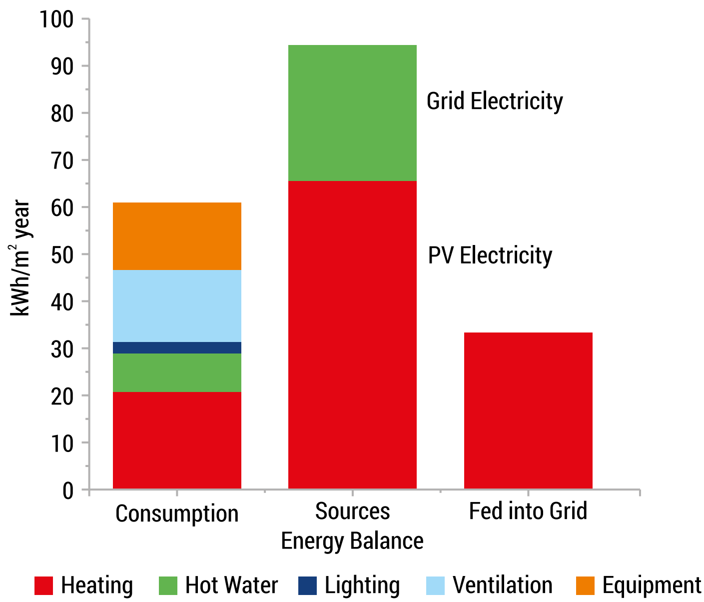

FIG. 1.10. Energy Balance in the Efficiency House Plus with E-mobility building in Berlin (Source: own elaboration based on data of Erhorn, 2014)

The net surplus energy produced by the renewable sources is 4.5 kWh/(m^2 year).

The nZEB Indicators
The Primary Energy Indicator, considering a primary energy factor of 2.5 for electricity, is: -24.1 kWh/(m^2 year).

The Renewable Energy Ratio is 1.07 (107%).

These data indicate that the building has an improvement of 78% above the national requirements.

Warm Zone (Valladolid-SPAIN)

The *LUCIA* building is advanced nZEB which belongs to the University of Valladolid (Rey-Hernández, 2018). With an area of 7500 m^2 (Figs. 1.11 a) and b)), it is used for research purposes, and it houses offices, laboratories, etc. This building has received one of the best ratings in the international rankings for efficient energy. It presents innovative passive and active solutions for the reduction of the energy consumption through the joint use of several different renewable energy sources.

a) b)

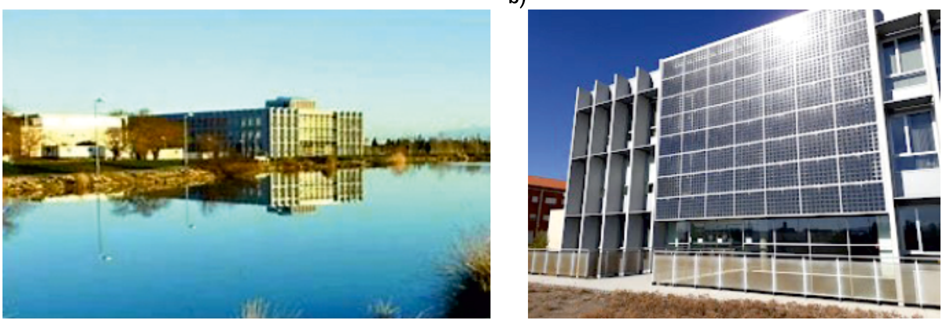

FIG. 1.11. Photos of the building of LUCIA in Valladolid (Spain). a) Source: photo by Rey-Hernández, 2018 with CC BY 4.0; b) Source: photo by D.Krawczyk

Passive Solutions:

The building presents different passive solutions that allow for the reduction of energy consumption by 50% compared to a standard building. The first is its orientation with south facing to increase the solar radiation in winter and to reduce it in summer. This effect is enhanced with a zigzag concrete structure in the external façade of the building, that causes a self-shading. Parts of the external wall and roof are also cover by PV panels with translucent glass that causes additional shading.

The walls are plastered with an internal insulation of thermal transmittance: U = 0.157 W/(m^2 K).

The windows are doble glazing filled with argon gas, U = 1.2 W/(m^2 K).

The building has also a natural ventilation with geothermal and heat recovery.

Active Solutions

The most innovative improvement of this design is the use of a biomass fueled combined heat and power system (CHP) to produce electricity and heat. The heating system is based on the heat generated by the CHP boiler with a nominal power of 328 kW and efficiency of 0.88. This system works in cooperation with heat recovery with efficiency of 61%.

There are two cooling systems. An absorption cooling system with the power of 176 kW and 232.7 kW conventional air system. A cooling tower located on the roof of the building is used to deliver the heat generated by the absorption system.

A triple ventilation system has been implemented. Free-cooling, heat recovery and earth-air heat exchanger with Canadian wells can work together or independently.

In terms of lighting, this building makes maximum use of the natural light. Big windows and tubular skylight aid the use of this light. For dark conditions, artificial light with efficient LEDs is used, which is controlled by automatic systems with presence detectors.

The control and regulation of the energy consumption of all building systems is another important issue of the building's energy efficiency. A connection protocol ModBus is used to this purpose.

Renewable Energy Solutions

As mentioned, two renewable energy sources are used: Biomass and solar energy.

Biomass is burnt in CHP boiler to produce heat. This heat is used for heating, hot water, and cooling. After a gasification process, the produced gas is com-busted in 5 modified engines to produce electricity, which is used for cooling, ventilation, and lighting.

Additionally, the solar PV panels located in the façade and roof allows to produce additional electricity.

The Building Energy Consumption

In this nZEB, there are two types of energies: thermal energy and electricity. Each of them is used as follows:

1. thermal Energy from the CHP system and heat recovery:
   - heating: 23.10 kWh/(m^2 year),
   - domestic Hot Water: 0.9 kWh/(m^2 year),
   - cooling Absorption: 4.56 kWh/(m^2 year),
2. Electricity from CHP system, PV panels and grid.
   - ventilation 9.2 kWh/(m^2 year),
   - lighting 10.42 kWh/(m^2 year),
   - cooling: 16.29 kWh/(m^2 year),
   - household equipment (Cooling tower, Flow system.): 23.27 kWh/(m^2 year).

Thus, the total annual energy consumption of the house is 28.56 kWh/(m^2 year) of thermal energy and 59.18 kWh/(m^2 year) of electricity.

The Energy Sources:

The thermal energy (heating, hot water and cooling) of LUCIA building is pro-duced by Biomass, 41.65 kWh/(m^2 year).

The electricity comes from the CHP system, the PV panels and the grid:

- heat from the CHP system (Biomass): 21.8 kWh/(m^2 year);
- PV panels: 2.97 kWh/(m^2 year);
- delivered by Grid: 34.4 kWh/(m^2 year).

Figures 1.12 a) and b) summarize the energy consumed by *LUCIA* building and the origin of the energy used to produce heat and electricity, respectively.

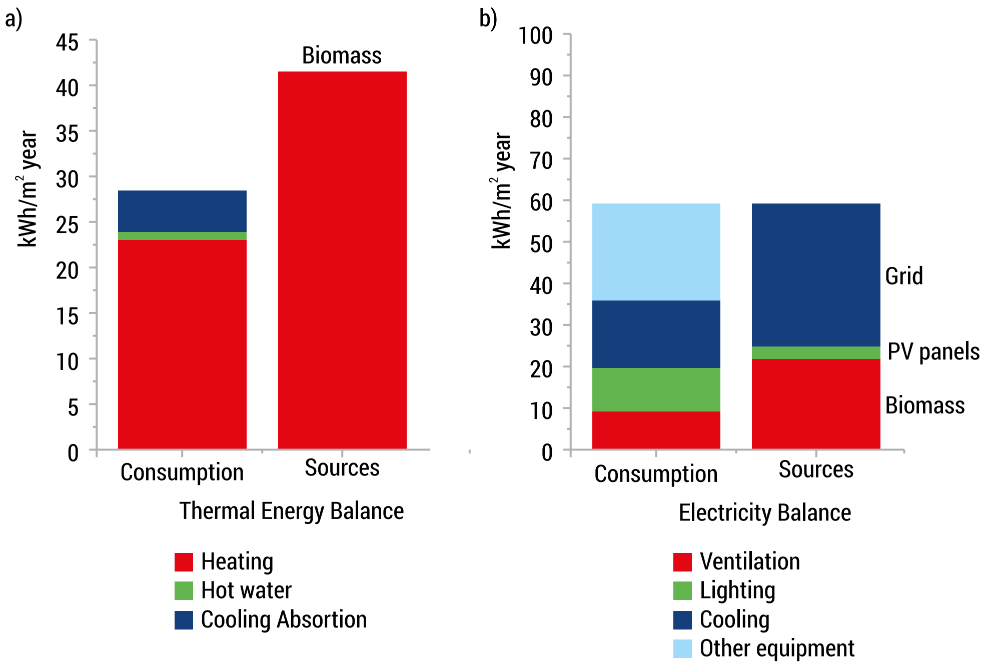

FIG. 1.12. Energy Balance in the LUCIA Building for a) heat and b) electricity (Source: own elaboration based on Rey-Hernández, 2018)

The nZEB Indicators

The Primary Energy Indicator can be calculated from Eqs. 1.1 and 1.2 using the primary energy factors defined in the national spanish regulation that are:

- for electricity from the Grid: $f_{i,nonRE} = 1.954$ and $f_{i,RE} = 0.414$;
- for electricity on-site: $f_{i,nonRE} = 0$ and $f_{i,RE} = 1$;
- for biomass on-site: $f_{i,nonRE} = 0$ and $f_{i,RE} = 1$.

The obtained values is:

$$EP_P = 67.2 \frac{\text{kWh}}{\text{m}^2\text{year}}$$

which is lower than the EU requirement for continental zone that is between 85-100 kWh/(m^2 year).

On the other hand, the renewable energy ratio RER is obtained from Eq. 1.2, with the contribution of the on-site renewable energy and the percentage of the renewable energy of the grid. The RER value for LUCIA building is 0.66 (66%).

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References

[1] Attia, S., Kosiński, P., Wójcik, R., Węglarz, A., Koc, D., Laurent, O. (2022) Energy efficiency in the Polish residential building stock: A literature review. *Journal of Building Engineering*, 45, 103461.

[2] Baniassadi, A., Heusinger, J., Gonzalez, P.I., Weber, S., Samuelson, H.W. (2022) Co-benefits of energy efficiency in residential buildings. *Energy*, 238, Part B, 121768.

[3] Buildings Performance Institute Europe (BPIE) (2021) Report *Nearly zero: a review of EU member state implementation of new build requirements*. Available from https://www.bpie.eu/publication/nearly-zero-a-review-of-eu-member-state-implementation-of-new-build-requirements/ [Accessed 01.05.2022].

[4] Boemi, S-N., Irulegi, O., Santamouris, M. (2016) Energy Performance of Building Energy Efficiency and Built Environment in Temperate Climates. *Springer*.

[5] Cao, X., Dai, X., Liu, J. (2016) Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy and Buildings*, 128, 198-213.

[6] Chen, S., Zhang, G., Xia, X., Setunge, S., Shi, L. (2020) A review of internal and external influencing factors on energy efficiency design of buildings. *Energy and Buildings*, 216, 109944.

[7] Commission of the European Communities. (1998) Communication from the Commission: Energy Efficiency in the European Community – Towards a Strategy for the Rational Use of Energy.

[8] Council of the European Union. (1974) Council Resolution of 17 September 1974 concerning a new energy policy strategy for the Community.

[9] Council of the European Union. (1989) Council Directive 89/106/EEC of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products.

[10] Council of the European Union. (1992) Council Directive 92/42/EEC of 21 May 1992 on efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels.

[11] Council of the European Union. (1993) Council Directive 93/76/EEC of 13 September 1993 to limit carbon dioxide emissions by improving energy efficiency (SAVE).

[12] D'Agostino, D., Mazzarella, L. (2019) What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *Journal of Building Engineering*, 21, 200-212.

[13] D'Agostino, D., Tzeiranaki, S.T., Zangheri, P., Bertoldi, P. (2021) Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe. *Energy Strategy Reviews*, 36, 100680.

[14] Dakwale, V.A., Ralegaonkar, R.V., Mandavgane, S. (2011) Improving environmental performance of building through increased energy efficiency: A review. *Sustainable Cities and Society*, 1, 4, 211-218.

[15] Di Foggia, G. (2018) Energy efficiency measures in buildings for achieving sustainable development goals. *Heliyon*, 4.

[16] Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., Castellazzi, L. (2020) Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings*, 225, 110322.

[17] Erhorn, H. and Heike Erhorn-Kluttig H. (2014) Report *Selected Examples of Nearly Zero-Energy Buildings* of Concerted Action ENERGY PERFOMANCE OF BUILDING. Available from www.epbd-ca.eu [Accessed 01.05.2022].

[18] European Commission. (2016) Commission Recommendation (EU) 2016/1318 of 29 July 2016 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings.

[19] European Commission. (2018) A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.

[20] European Commission, Directorate-General for Energy. (1997) Communication from the Commission – Energy for the future: renewable sources of energy – White Paper for a Community strategy and action plan.

[21] European Commission (2021) Proposal for a Directive of the European Par-liament and of the Council on the Energy Performance of Building (re-cast). Document 52021PC0802. December 2021 (draft).

[22] European Commission (2021) Proposal for a Directive of the European Par-liament and of the Council on the Energy Performance of Buildings (re-cast). Document 52021PC0802. December 2021 (draft).

[23] European Parliament, Council of the European Union. (2002) Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings.

[24] European Parliament, Council of the European Union. (2006) Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC (Text with EEA relevance).

[25] European Parliament, Council of the European Union. (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).

[26] European Parliament, Council of the European Union. (2012) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance.

[27] European Parliament, Council of the European Union. (2018) Directive (EU) 2018-844 of the European Parliament and the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

[28] Geller, H., Harrington, P., Rosenfeld, A.H., Tanishima, S., Unander, F. (2006) Polices for increasing energy efficiency: Thirty years of experience in OECD countries. *Energy Policy*, 34, 5, 556-573.

[29] Hitchin, R. (2019) Primary Energy Factors and the primary energy intensity of delivered energy: An overview of possible calculation conventions. *Building Services Engineering Research and Technology*, 40(2), 198-219.

[30] Ionescu, C., Baracu, T., Vlad, G-E., Necula, H., Badea, A. (2015) The historical evolution of the energy efficient buildings. *Renewable and Sustainable Energy Reviews*, 49, 243-253.

[31] Kurnitski, J. (2013) Technical definition for nearly zero energy buildings. *REHVA Journal*, 22-28.

[32] López-Ochoa, L.M., Las-Heras-Casas, J., López-González, L.M., Olasolo-Alonso, P. (2021) Towards nearly zero-energy buildings in Mediterranean countries: Energy Performance of Buildings Directive evolution and the energy rehabilitation challenge in the Spanish residential sector. *Energy*, 176, 335-352.

[33] López-Ochoa, L.M., Las-Heras-Casas, J., Olasolo-Alonso, P., López-González, L.M. (2021) Towards nearly zero-energy buildings in Mediterranean countries: Fifteen years of implementing the Energy Performance of Buildings Directive in Spain (2006–2020) *Journal of Building Engineering*, 44, 102962.

[34] Magrini, A., Lentini, G., Cuman, S., Bodrato, A., Marenco, L. (2020) From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge – The most recent European trends with some notes on the energy analysis of a forerunner PEB example. *Developments in the Built Environment*, 3, 100019.

[35] Maltby, T. (2013) European Union energy policy integration: A case of European Commission policy entrepreneurship and increasing supranationalism. *Energy Policy*, 55, 435-444.

[36] Martinez-de-Alegria, I., Rio, R-M., Zarrabeitia, E., Álvareza, I. (2021) Heating demand as an energy performance indicator: A case study of buildings built under the passive house standard in Spain. *Energy Policy*, 159, 112604.

[37] Mishra, S., Ghosh, A., Rai, K., Jaiswal, B., Yadav, D.S., Agrawal, M., Agrawal S.B. (2021) 6 – Dimensions of climate change and its consequences on ecosystem functioning. *Global Climate Change*, 109-149

[38] Papadopoulos, A.M. (2016) Forty years of regulations on the thermal performance of the building envelope in Europe: Achievements, perspectives and challenges. *Energy and Buildings*, 127, 942-952.

[39] Poulopoulos, S.G. (2016) Chapter 2 – Atmospheric Environment. *Environment and Development. Basic Principles, Human Activities and Environmental Implications*, 45-136.

[40] Reuter et al. (2021) Linking energy efficiency indicators with policy evaluation – A combined top-down and bottom-up analysis of space heating consumption in residential buildings. *Energy and Buildings*, 244, 110987.

[41] Rey-Hernández, J.M., Velasco-Gómez E., San José-Alonso, J. F., Tejero-González, A. and Rey-Martínez, F.J. (2018), Energy Analysis at a Near Zero Energy Building. A Case-Study in Spain. *Energies*, 11, 857; doi:10.*3390*/en11040857

[42] Rosenow, J., Cowart, R., Bayer, E., Fabbri, M. (2017) Assessing the European Union's energy efficiency policy: Will the winter package deliver on 'Efficiency First'? *Energy Research & Social Science*, 26, 72-79.

[43] Sands, P., Galizzi, P. (2006) Documents in European Community Environmental Law. *Cambridge University Press.*

[44] Shen, L., He, B., Jiao, L., Song, X., Zhang, X. (2016) Research on the development of main policy instruments for improving building energy-efficiency. *Journal of Cleaner Production*, 112, Part 2, 1789-1803.

[45] Tatara, T., Fedorczak-Cisak, M., Furtak, M., Surówka, M., Steidl, T., Knap-Miśniakiewicz, K., Kozak, E., Kawalec, W. (2017) Ekspertyza na temat: Przegląd przepisów określających minimalne wymagania dotyczące charakterystyki energetycznej budynków. *Małopolskie Centrum Budownictwa Energooszczędnego, Politechnika Krakowska.*

[46] Vaquero, P. (2020) Buildings Energy Certification System in Portugal: Ten years later. *Energy Reports*, 6, 1, 541-547.

[47] WEB–1: BBC News. Science. (2021) *COP26:* What was agreed at the Glasgow climate conference? [Online] Available from: https://www.bbc.com/news/science-environment-56901261 [Accessed 14.02.2022]

[48] WEB–2: Boechler, E., Hanania, J., Jenden, J., Stenhouse, K., Yyelland, B., Donev, J. (2021) *Energy efficient building design*. Available from: https://energyeducation.ca/encyclopedia/Energy_efficient_building_design [Accessed 21.11.2021].

[49] WEB–3: EEA. (2021) Progress on energy efficiency in Europe. [Online] Available from: https://www.eea.europa.eu/data-and-maps/indicators/progress-on-energy-efficiency-in-europe-3/assessment [Accessed 21.11.2021].

[50] WEB–4: European Commission. (2019) Energy efficiency directive. [Online] Available from: https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive_en [Accessed 21.11.2021].

[51] WEB–5: European Commission. (2020) In focus: Energy efficiency in buildings. [Online] Availablefrom:https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-feb-17_en [Accessed 21.11.2021].

[52] WEB–6: European Commission. (2021) European Green Deal. [Online] Available from: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_pl [Accessed 21.11.2021].

[53] WEB–7: European Commission. (2021) nzeb. [Online] Available from: https://ec.europa.eu/energy/content/nzeb-24_en [Accessed 21.11.2021].

[54] WEB–8: European Commission. (2021) What is Horizon 2020? [Online] Available from: https://ec.europa.eu/programmes/horizon2020/what-horizon-2020 [Accessed 21.11.2021].

[55] WEB–9: Eurostat. (2021) Energy saving statistics. [Online] Available from: https://ec.europa.eu/eurostat/statisticsexplained/index.php?title=Energy_saving_statistics [Accessed 21.11.2021].

[56] WEB–10: Rapid Transition Alliance. (2019) From oil crisis to energy revolution – how nations once before planned to kick the oil habit. [Online] Available from: https://www.rapidtransition.org/stories/from-oil-crisis-to-energy-revolution-how-nations-once-before-planned-to-kick-the-oil-habit/ [Accessed 21.11.2021].

[57] WEB–11: United Nations. Climate Action. (2021) COP26: Together for our planet. [Online] Available from: https://www.un.org/en/climatechange/cop26 [Accessed 14.02.2022]

[58] WEB–12: BUILD UP. The European Portal for Energy Efficiency in Building. Available from http://www.buildup.eu/en/practices/cases/efficiency-house-plus-berlin [Accessed 01.05.2022].

[59] WEB–13: https://www.solarwende-berlin.de/allgemein/masterplan-solarcity-berlin/wettbewerb-architektur Free Use License [Accessed 30.05.2022]

[60] WEB–14: https://epthinktank.eu/2022/02/04/revision-of-the-energy-performance-of-buildings-directive-fit-for-55-package-eu-legislation-in-progress/ [Accessed 12.07.2022]

[61] WEB–15: https://www.interregeurope.eu/news-and-events/news/updating-the-energy-performance-of-buildings-directive [Accessed 12.07.2022]

[62] Witczak, K. (2018) Nowa dyrektywa EPBD dotycząca efektywności energetycznej budynków. *Materiały Budowlane*, 1, 557.

[63] Yi, C., Bing, X. (2017) Building as Major Energy Consumer. *Encyclopedia of Sustainable Technologies*, 137-148.

[64] ZEBRA2020: NEARLY ZERO-ENERGY BUILDING STRATEGY 2020 (2016) Report Nearly Zero-Energy Building (nZEB) technology solutions, cost assessment and performance. Available from https://zebra2020.eu/ [Accessed 01.05.2022].

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2. THE ROLE OF SUSTAINABLE DESIGN IN ECO-FRIENDLY BUILDINGS

2.1. Sustainability in Construction Sector

Earth's global average surface temperature in 2020 tied with 2016 as the warmest year on record, according to an analysis by NASA (NASA, 2022). The sources show that buildings are responsible for 40% of energy consumption and more than 36% of CO_2 emissions in the EU (EEW, 2015). 80% of energy use over a building's lifecycle is from the building's operation. Construction of infrastructure and buildings is an extremely carbon-intensive process that encompasses the entire supply chain, from the extraction of natural resources to its transportation and manufacturing. Add in other infrastructure and activities, such transportation and industry, that are associated with construction or buildings, and that number will increase. There's a consensus (NASA, 2022) among the scientific community around the world that human activity is a driver of global warming. That's why we need to do something for our home as soon as possible. The mainstream trend nowadays is sustainable development of countries as well as other development theories such as: blue economy, silver economy, "donut's economy" etc.

Sustainable development is a dynamic process through the countries, which means that there is no precise definition of it and every society and city evolves over time to become better or worse. The term was popularised in the end of XX century and means "*development which meets the needs of the present without compromising the ability of future generations to meet their own needs*". The sustainability can be described as incontestable development of society and economy on a long-term basis within the framework of the carrying inclusion of the earth's ecosystems (Kamari et al, 2017).

Climate change and need for sustainable solutions are now playing a critical role in the decision-making of governments and companies all over the world. The growing importance of sustainability across the key stakeholders of government, industry and the public, compounded by the impending climate emergency, creates a need to act now (Royan, 2021). Almost half of the companies surveyed in EU in 2021 report sustainability is an important part of the strategy, or even a cornerstone of their business.

The main idea of sustainable development is making world better place for all – and some goals should be changed as soon as possible. The world is challenged not only by climate change, pollution and dwindling supplies of fossil fuels affecting all spheres of human activity. Sustainability is no longer an option we can choose or not – but a way of living which we need to rapidly adopt for our survival and sustainability of humanity. If we are building a sustainable future, the construction sector must lead the way forward.

In the centre of Sustainable development there are 17 goals – Sustainable Development Goals (SDGs) (UN, 2022):

1. No poverty;
2. Zero hunger;
3. Good health and well-being;
4. Quality education;
5. Gender equality;
6. Clean water and sanitation;
7. Affordable and clean energy;
8. Decent work and economic growth;
9. Industry, innovation and infrastructure;
10. Reduced inequalities;
11. Sustainable cities and communities;
12. Responsible consumption and production;
13. Climate action;
14. Life below water;
15. Life on land;
16. Peace, justice and strong institutions;
17. Partnerships for the goals.

Together with the SDGs, the European Green Deal is another key driver of sustainability across the architecture, engineering, and construction (AEC) and manufacturing industries in Europe (Royan, 2021). The European Green Deal is a differentiator that will catalyse the low-carbon transition and drive sustainability on the global stage. These initiatives will help transform industry sectors that are particularly challenged by environmental impact and transition to more sustainable methods.

Investment in infrastructure and innovation are crucial drivers of economic growth and development. Some of SDG are more about construction sector opportunities to change the world, some are less. Green buildings, zero-emission construction, zero-waste management in construction – can be part of the solution in combating climate change. The construction industry must make calculations and don't exceed carbon credits. Their resources should be entered accurately and with minimal waste. Some studies show, that construction has a huge impact on general economic growth and that there are definite effects of economic recessions on construction quality (Pheng, 2019). The built environment has a significant impact on many sectors of the economy, on local jobs and quality of life not only in EU, but all over the world. It requires vast amounts of resources and accounts for about 50% of all extracted materials. That's why it is so important to go forward in sustainability of the construction sector and take the leading role in this process. Figure 2.1 highlights some of the key digital enabled trends in the building sector:

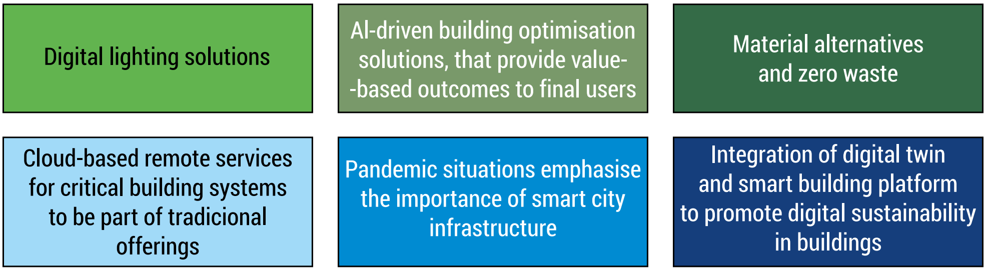

FIG. 2.1. Key trends in the building sector in EU (Source: own elaboration based on Frost & Sullivan)

The European Commission's energy efficiency and energy performance directives for buildings were updated in 2018. The directives mention installing automation and control systems and energy management systems in certain buildings, with an objective to improve energy efficiency. The directives reference long-term renovation strategies for decarbonising national building stocks by 2050 and have mandated that all new buildings must be Net Zero Energy Buildings (nZEB) from 31 December 2020 (Royan, 2021). Today the EU construction policy aims green deal's Renovation Wave Initiative – it can lead to significant improvements in energy efficiency in the region. European Union will implement the Initiative along with circular economy principles, notably optimised lifecycle performance, and longer life expectancy of built assets (EC, 2022b). As part of revising the recovery targets for construction and demolition waste, the EU has plans to pay special attention to insulation materials which generate a growing waste stream.

2.1.1. Ecological and Sustainable Cuilding Design

Sustainable architecture is the application of the principles of sustainable development in the design, construction and operation of buildings. Its main objectives are the search for energy efficiency and low environmental impact – not only by projecting and constructing, but also for the whole building life cycle. Studies show (Lavagna, 2018), that life cycle assessment (LCA) is still too little to implement. Five factors are considered for sustainability:

1. Ecosystem,
2. Energy,
3. Type of materials,
4. Waste,
5. Mobility.

On the other hand, it aims to save resources and understand the design according to the user's needs. The social side of design is the most important part that makes buildings more sustainable. With these factors and principles in mind, greater energy efficiency is achieved throughout the life cycle of a building; it is accomplished at the architecture, construction, employment and operation levels (Fig. 2.2).

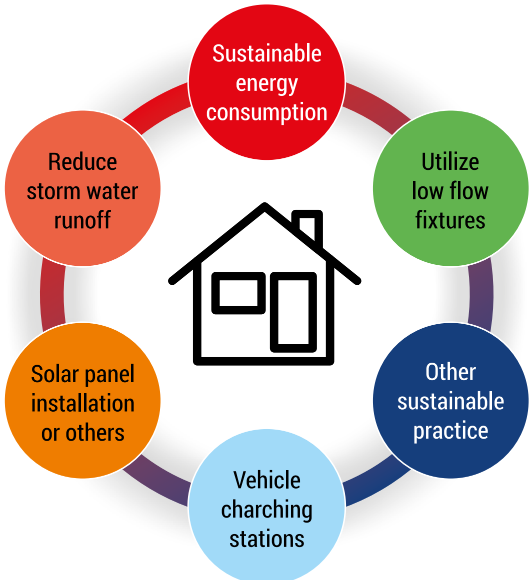

FIG. 2.2. Sustainable construction practice (Source: own elaboration)

The building as an object must contain several different common elements in order to become sustainable:

- healthy inside microclimate;
- indoor environmental quality (visual, acoustic comfort etc.);
- monitoring of energy consumption;
- A++ energy efficiency;
- carbon neutral materials;
- reuse of parts of the building;
- renewable energy;
- assembly of modules in the factory;
- rainwater harvesting for irrigation;
- vegetation of local origin;
- natural lighting;
- universal architecture;
- infrastructure outside the building.

Sustainable design aims to reduce the use of non-renewable energy and maximize the use of renewable energy (EC, 2020b). In this sense, the use of clean energy systems such as solar, wind, geothermal and hydropower is encouraged, but still used fragmentarily (Fig. 2.3):

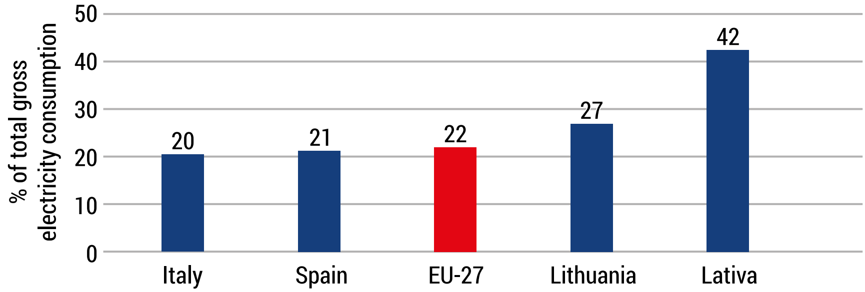

FIG. 2.3. Electricity from renewable sources in construction in the EU, 2020 (Source: EC, 2020b)

An increase in the use of renewable energy has multiple benefits for society such as mitigating climate change, reducing the emission of air pollutants and improving energy security. The EU had set the goal of ensuring that 20% of its gross final energy consumption would come from renewable sources by 2020 (EC, 2022a), increasing to 32% by 2030. Some studies show (Vita, 2019), that passive housing and decentralized renewable energy reduces carbon emissions up to 5 and 14%, respectively. The share of renewable energy in buildings (heating and cooling) also increased in the last few years, albeit at a lower rate (Fig. 2.4):

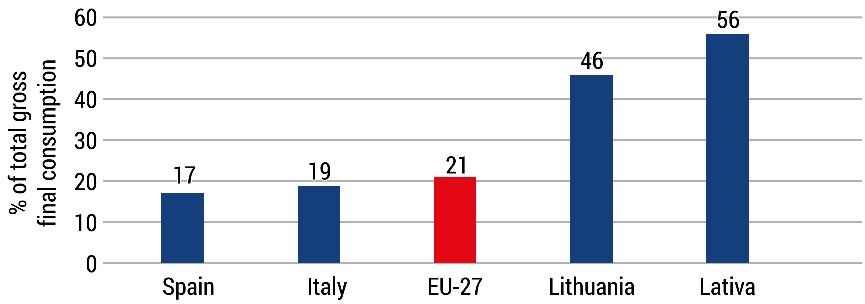

FIG. 2.4. Renewable energy used for heating and cooling in the EU (Source: EC, 2020b)

The next aim is to use water efficiently, using rainwater and recycling grey water. On the other hand, a relationship with the natural environment is essential, so it is also common to use green roofs. In Europe (Germany, France, Austria) these technologies have become very well established (however in the USA not yet, but they are starting to emerge). The most important green roofs benefits are:

- aesthetic improvements;
- energy efficiency;
- fire retardation;

- improved air quality;
- improved health and well-being;
- increased biodiversity;
- new meeting places for people;
- noise reduction;
- stormwater management;
- waste diversion;
- urban agriculture and architecture.

Sustainability in not only a trend we should fallow – its everyday life for construction sector as well. Denmark (WEB–5) is a leading country in sustainability of new building and construction projects. Port of Copenhagen is a good example of how smart decisions can change a part of a city into sustainable area (WEB–8). Nordic countries are more sustainable than other European countries for several reasons: this region has the lowest level of perceived challenges with regards to sustainability and companies in the region are most likely to leverage software and technology – design as well – to drive sustainability. There are so many decisions in construction and design that are not only about ecology but about social aspect of sustainability as well. Here ecological, social design plays an important role from education to real projects and everyday life. Another interesting example is the municipal school in Guastalla (Bailey, 2017), a little town in Italy's Emilia-Romagna region in the centre of the Po Valley – it is a highly symbolic achievement. Built to replace two similar facilities damaged by the 2012 earthquake, it stands for the area's determination to rebuild its communities but at the same time rethink the way educational spaces are organized, based on the idea that learning should be fun and that school buildings should help make that possible.

And here we can find the most popular solution for making buildings more sustainable or greener: creating green roofs. The great benefit or green roofs is not only less air pollution, but also new social meeting places and possibilities of spend time in open areas, not only inside the buildings. The most popular examples of green roofs and walls are:

- The 8 House, Copenhagen, Denmark;
- The Biesbosch Museum Island, the Netherlands;
- The California Academy of Sciences, USA;
- The City Hall, Chicago, USA;
- The Moesgaard Museum, Højbjerg, Denmark;
- The Namba Parks, Japan;
- The ACROS Fukuoka Prefectural International Hall, Fukuoka City, Japan;
- The Daniel F. and Ada L. Rice Plant Conservation Science Center, Chicago, USA;
- The Javits Centre, NYC, USA;
- The Kö-Bogen retail and office complex in Düsseldorf, Germany;
- The landscaped green roof at Beijing airport, China;
- The Nanyang Technological University, Singapore;

- The Solaire, NYC, USA;
- The Vancouver Convention Centre, Canada;
- The Vendée History Museum Les Lucs-sur-Boulogne, France.

Another interesting example of a green roof can be seen in Italy: Salpi Plant. Enzo Eusebi's (Bailey, 2017) project for the Salpi cured meat processing plant in the open countryside – it some contradictions with the realism and pragmatism of the engineer and the vision and sense of experimentation of the architect (not only the green roof but also outer facades, ventilation at night, thermal accumulation, sun shading, elevations, plan).

Another interesting example of sustainable design – how wind turbines can be used in buildings – is The Bahrain World Trade Centre. It is the first commercial building to use wind turbines on a horizontal axis, attached to the actual building for electricity (WEB–6). In Brisbane Australia, the Kurilpa Bridge holds the title of the largest foot bridge powered by solar panels. A prime example of wastewater management is the Robert Redford Building located just outside of Los Angeles. By using low-water fixtures, waterless urinals, efficient subsurface irrigation, a grey water system for toilets and irrigation, and an effective rain harvesting system, this building sets the bar for sustainable design and function. The building was awarded a LEED (certificate of *Leadership in Energy and Environmental Design*) Platinum rating and is among the greenest buildings in the world. For more information look here (WEB–9). Torre Reforma building in Mexico City or Transoceanic Building in Santiago, Chile (WEB – 11) are other examples of structures with LEED certificate (WEB–10).

Another important aspect of sustainable decisions is construction waste management based on the rule of three ecological principles: reduction, reuse and recycling. In addition, sustainable constructions emphasize the use of materials derived from renewable or recycled natural resources. Waste can be used in the construction industry in two ways (Dachowski, 2016): by reusing (using components again) and recycling (processing waste into raw materials used in the production of building materials). Construction sector and housing must be low-carbon in both construction and use, with on-site materials reused or recycled wherever possible. Some housing items should be locally manufactured if possible. Initiatives such as rain water harvesting, grey water capturing for landscape and food production (local), communal composting and on-site wastewater treatment should be considered where appropriate. New buildings must be created for the users to feel comfortable inside and around their homes.

Today, structures that are designed, built and managed according to sustainability criteria are becoming more common (criteria include the product's recyclability level, recycled content, eco-friendliness, regional aspects, indoor air quality, life cycle impact, as well as the company's social responsibility and responsible environmental management across the product's supply chain). In this sense, there are organizations that provide certificates for sustainable buildings, such as the LEED Green Building

Councils in Lithuania, Spain, Poland and Italy or Latvian Sustainable Building Council in Latvia, and others, such as WELL, FITWEL, GREEN GLOBES, BREEAM, DGNB, GREEN STAR or BCA GREEN MARK SCHEME. The number of buildings with such certification is expected to increase significantly in the future.

2.2. The Role of Ecological Design and its Benefits

More than ever before, we need to apply the principles of circular economy and resource efficiency to buildings to reduce future resource consumption (EC, 2020c). End-users look for sustainable building concepts (Bauer et al, 2010), with low energy and smaller operating costs, which offer open, socially acceptable and communication-friendly structures made from materials that are ecologically acceptable for the building and have been left in as natural a state as possible – in the cites. Sustainable design is not only about construction – it's about architectural input: it also requires structural, mechanical and perhaps electrical design so that investors can use the buildings for as long as possible and repurpose them if needed. New technologies in construction provide the opportunity to "live" some moments in the buildings, even if they are only in the design phase – it is now easier to understand what is needed at each stage design and construction. A good design includes how the space will function.

2.2.1. The Future of Ecological Design in Sustainable Construction

Green, sustainable buildings were first promoted for environmental reasons. The projects involved high start-up costs, specialized teams and unusual equipment and construction practices. Government agencies, universities, and non-profit organisations began to adopt sustainable designs early, using subsidies and grants to offset more expensive construction costs and recoup returns from long-term use. Green buildings are buildings of any usage category that follow the principle of a conscientious handling of natural resources.

Today, sustainable design is becoming commonplace as more building developers are discovering the value that is created when low upfront capital costs and short payback times increase rental rates as well as attract and retain tenants (Pientka, 2015).

Sustainable design makes sense. For a development to become "sustainable", engineers must incorporate „sustainability" into all their planning and engineering of products and projects.

And today, the most common principles of sustainability in construction are:

- Circular economy (by using energy, water and materials – some com-panies are using CO_2 footprint calculation today as a part of general strategy);
- Lifecycle of design (the need to analyse construction processes and their impact on the environment – not only at the design stage, but also during construction

and operation. Reducing material and energy use throughout manufacturing life cycle as most important sustainable task indicates more than 41% of construction companies in EU (Royan, 2021));

- Consumer oriented design and decisions (sustainable projects must promote the interaction of people and nature. This means that preserving natural conditions must be an integral part of any urban design.
- In addition, the quality of life of the user needs to be maintained).

Sustainability must occur at all stages of the building's life cycle (design, construction, operation, maintenance and demolition). Sustainability aims such important sites of infrastructure as living quality and mobility inside the living area. And it is not only about closed areas, but about the whole cities as well. People must have access to safe, inclusive, green public spaces, especially women and children, the elderly, and people with disabilities. Systems thinking of connecting the different dots and looking at it from a different perspective in totality, which will help in reaching new levels of sustainability – that's the key to better results.

According to the United Nations, today more than half of us live in cities. By 2050, two-thirds of all humanity—6.5 billion people—will be urban dwellers. Sustainable development cannot be achieved without significantly transforming the way we build and manage our urban spaces (UN, 2022).

One of future solutions for sustainable cities is the concept of „15-minutes city" (WEB–1), whose main idea is that everyone living in a city should have quick access to essential urban services. The „15-minutes city" project is designed to help access-focused urban transformations be what they need to be: ambitious, inclusive, measurable and effectively implemented.

Sustainable cities, buildings and design depend on several key factors:

- New projects –but also older but renovated places – must stay in harmony with the ecosystem and biosphere. Both the construction process and the operation of the building are expected to have the least possible negative impact on the environment. To this end, the building and its support system (provision of services, transport routes) must be integrated as much as possible into the natural environment. One of the most incredible examples of such design is the circular eco-friendly Brondby garden city of Copenhagen in Denmark (WEB – 3). Incorporating nature into the design is a very wise and sustainable solution. Circularity—reduced use of scarce resources and an increased focus on design for reuse instead of single use (digitalisation has a key role) and design thinking from the start, with a shift in focus on material use from what needs to be built to the most efficient use of resources in a circular economy – that's the future trend (Royan, 2021).
- To force a building to produce energy for itself. The focus is on renewable energy for the air conditioning systems, which consume a lot of energy and thus reduce the building's impact on the environment. This considers the design of the building, the use of suitable materials and the orientation of the building. Ventilation

is required to lower building temperatures and adequate insulation is required for efficient heating. However, glass is a bad heat insulator, so it is necessary to reduce heat loss through the glass. Water reuse serves the same purpose.

- The materials used in the design and construction in accordance with the principle of sustainable architecture/design should have a low environmental impact. Therefore, substances whose acquisition may be harmful to the environment must be disposed of. Cement production and calcination account for 8% of global anthropogenic CO_2 emissions, which is about four times that of the aviation industry. Due to the massive consumption of carbon-intensive materials (such as concrete and steel) and its associated high emission factor, robotics and 3D printing can significantly reduce the construction sector's environmental impact (Royan, 2021). That's why today becomes popular use natural materials in construction. Interesting sustainable trend can be seen in Scandinavian (WEB – 12) countries and Lithuania as well: wooden construction or buildings from clay or raw earth (WEB – 4). All the time earth as a building material (Minke, 2015) was very important. Wooden materials (in some areas – bamboo) must have the certification too. There are a lot of new materials in construction engineering that can be reused (WEB – 7): from different waste such as plastic, gum to useful materials. More and more innovations are coming into construction sectors such 3D printing (WEB – 2), augmented reality, BIM, virtual reality, Internet of Things, artificial intelligence and others. Digital technology will drive tangible efficiency improvements in manufacturing and AEC with greater integration of design, process and operational workflows.
- There are many software tools looking to cover embodied carbon; however, the databases that support this software are not fully reliable and require many manual overrides (Royan, 2021). There is a definite role for BIM to help in supporting the reliable calculations of embodied carbon. Buildings performance management is an increasing focus of sustainability initiatives linked to energy intensive lighting and heating, ventilation and air conditioning systems (HVAC) operations, both in AEC and manufacturing. There is a growing role for building energy management systems that are expanding on the sensors and data that monitor, measure, and manage energy efficiency.
- Waste management – as a solution and guarantor for reducing environmental pollution in the construction sector. Waste management is considered in the construction process when waste is generated that has a significant impact on the environment. It therefore aims to use materials efficiently, generate less waste and reuse or recycle manufactured products. An appropriate waste management system for population must then be established. Other aspects may include waste sorting for recycling and reuse and composting of organic waste for orchards.

Never before design and construction sectors have been so interesting as they are today. New challenges give more opportunities to communicate between owners and builders and to achieve more sustainable goals than ever before – for saving our planet. Building and creating an environment is a huge responsibility (Dos Santos Gervasio, 2018), and the pursuit of sustainable design should not be the prerogative of several companies, but the commitment of all stakeholders in the construction sector.

References

[1] Bailey, K. E. and others (2017) Sustainable architecture. Contemporary architecture in detail. CUBE srl Bologna. ISBN 978-84-16504-20-6.

[2] Bauer, M., Mösle, Schwarz, P. M. (2010) Green building. Guidebook for sustainable architecture. ISBN 978-3-642-00634-0, Springer-Verlag Berlin Heidelberg.

[3] Dachowski, R., Kostrzewa, P. (2016) The Use of Waste Materials in the Construction Industry. *Procedia Engineering*, Volume 161. ISSN 1877-7058. [Online] Available from: https://www.sciencedirect.com/science/article/pii/S1877705816329939 [Accessed 08.04.2022].

[4] Dos Santos Gervasio, H. (2018) Sustainable design of buildings, EUR 29324 EN, *Publications Office of the European Union*, ISBN 978-92-79-92882-6, doi:10.2760/356384, JRC112808.

[5] Energy Efficiency Watch [EEW]. (2015) Progress in energy efficiency policies in the EU Member States – the expert's perspective. Retrieved October 25. [Online], Available from: http://www.energy-efficiency-watch.org/fileadmin/eew_documents/EEW3/Survey_Summary_EEW3/EEW3-Survey-Summary-fin.pdf [Accessed on 28.03.2022].

[6] European Commission. (2020c) Circular economy principles for building design. Final report.

[7] European Commission. (2022a) Share of energy consumption from renewable sources in Europe. [Online] Available from: https://www.eea.europa.eu/ims/share-of-energy-consumption-from [Accessed on 28.03.2022].

[8] European Commission. (2022b) Buildings and construction. [Online] Available from: https://ec.europa.eu/growth/industry/sustainability/buildings-and-construction_lt [Accessed on 08.04.2022].

[9] European Commission. (2020a) Annex: Clean Energy in Buildings. [Online] Available from: https://eur-lex.europa.eu/resource.html?uri=cellar:fa6ea15b-b7b0-11e6-9e3c01aa75ed71a1.0001.02/DOC_2&format=PDF [Accessed on 28.03.2022].

[10] European Commission. (2020b). Renewable energy for heating and cooling. [Online] Available from: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200211-1 [Accessed 28.03.2022].

[11] Kamari, A., Corrao, R., Kirkegaard, K. (2017) Sustainability focused decision-making in building renovation. *International Journal of Sustainable Built Environment*, Volume 6, Issue 2, December 2017, Pages 330-350. [Online] Available from: https://www.sciencedirect.com/science/article/pii/S221260901730064X#b0135 [Accessed on 28.03.2022].

[12] Lavagna, M., Baldassarri, C., others (2018) Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock. *Building and Environment*. Volume 145. ISSN 0360-1323. [Online] Available from: https://www.sciencedirect.com/science/article/pii/S0360132318305560 [Accessed on 08.04.2022].

[13] Minke, G. (2015) Building with earth: design and technology of a sustainable architecture. Birkhäuser. [Online] Available from: (PDF) Building with Earth: Design and Technology of a Sustainable Architecture | Gernot Minke – Academia.edu [Accessed on 28.03.2022].

[14] NASA Agency data. (2022) [Online] Available from: https://www.nasa.gov/press-release/2020-tied-for-warmest-year-on-record-nasa-analysis-shows [Accessed on 08.04.2022].

[15] NASA Agency data. (2022) Scientific Consensus: Earth's Climate Is Warming. [Online], https://climate.nasa.gov/scientific-consensus/ [Accessed on 08.04.2022]

[16] Pheng, L. S., Hou, L. S. (2019) Construction Quality and the Economy: A Study at the Firm Level. *The Economy and the Construction Industry.* 21–54. [Online] Available from: https://doi.org/10.1007/978-981-13-5847-0_2 [Accessed on 08.04.2022]

[17] Pientka, K. (2015) Investing in sustainable design. New technologies help developers and tenants save the environment – and money. [Online] Available from: https://www.ccim.com/cire-magazine/articles/investing-sustainable-design/ [Accessed on 28.03.2022]

[18] Royan, F. (2021) Digital Sustainability: The Path to Net Zero for Design & Manufacturing and Architecture, Engineering, & Construction (AEC) Industries. *Sustainability and Circular Economy, Frost & Sullivan.* [Online] Available from: https://a.storyblok.com/f/64835/x/16b57c3331/digital_sustainability_wp.pdf [Accessed on 06.05.2022]

[19] United Nations. (2022) Sustainable development goals. [Online] Available from: https://www.un.org/en/academic-impact/page/sustainable-development-goals [Accessed on 28.03.2022]

[20] Vita, G., Lundström, J. R. and others. (2019) The Environmental Impact of Green Consumption and Sufficiency Lifestyles Scenarios in Europe: Connecting Local Sustainability Visions to Global Consequences. *Ecological Economics.* Volume 164. ISSN 0921-8009. [Online] Available from: https://www.sciencedirect.com/science/article/pii/S0921800918308930 [Accessed on 08.04.2022]

[21] WEB–1 – 15 minutes cities, for more: https://www.15minutecity.com/blog/hello

[22] WEB–10 – Torre Reforma building, Mexico, for more: https://www.archdaily.com/792721/torre-reforma-lbr-plus-a and https://www.youtube.com/watch?v=I5g4FrdbH2M&t=1s

[23] WEB–11 – Transoceanic building in Chile, for more: https://www.archdaily.com/422189/transoceanica-building-arquitectos

[24] WEB–12 – Wooden constructions, for more: https://www.scandinaviastandard.com/

[25] WEB–2 – 3D buildings, for more: https://www.youtube.com/watch?v=2Q-l1TRRZJ8&list=RDCMUCN3aYbtQ7yCqk9DM56B0kEw&index=24

[26] WEB–3 – Brondby garden city of Copenhagen, Denmark, for more: https://www.youtube.com/watch?v=irS9_jLgV6g&t=31s

[27] WEB–4 – Clay buildings in Lithuania, for more: https://www.manonamai.lt/lt/nt-patarimai/g-46385-moliniai-namai-pliusai-bei-minusai

[28] WEB–5 – Denmark example of sustainability, for more: https://www.youtube.com/watch?v=o86Ut6kAEMQ and https://www.youtube.com/watch?v=pUbHGI-kHsU

[29] WEB–6 – Innovative Examples of Sustainable Design, https://www.architecturelab.net/innovative-examples-of-sustainable-design/

[30] WEB–7–Newbuildingmaterials,formore:https://www.youtube.com/watch?v=bsQBSVJoV04, https://www.youtube.com/watch?v=Pltz4EA5Eb0, https://www.youtube.com/watch?v=iVv_i0LRxaI.

[31] WEB–8 – Port of Copenhagen, for more: https://www.youtube.com/watch?v=fsWr0LfM_uQ

[32] WEB–9 – Robert Redford building, LA, for more: https://mparchitects.com/site/projects/robert-redford-building-nrdc.

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3. SUSTAINABLE NEW BUILDING TYPE: HOUSE AND OFFICE

3.1. Introduction

Nowadays buildings are responsible for 33% of the global energy demand (REN21 Secretariat, 2021) and 36% of greenhouse gas emissions (GHG) into the atmosphere (European Commission, 2020). Only the 15% of the energy needs required by buildings sector is powered by renewable energies (REN21 Secretariat, 2021).

The Italian situation reflects the International and European ones with about 40% of final energy demand required by residential use and only 19% of primary energy demand is satisfied by renewables (ENEA, 2021).

From 2015 Europe with the UN Agenda 2030 for sustainable development imposes to Member States the 17 goals for sustainable development (SDGs): "*to eradicate poverty, find sustainable and inclusive development solutions, ensure everyone's human rights, and generally make sure that no one is left behind by 2030*" (European Commission, 2015). Signing the European Green Deal the Member States highlights that the building sector is a key and fundamental point of this agreement to achieve energy saving and GHG reduction in the next future. Thinking about climate action, responsible consumption, sustainable cities and communities and affordable and clean energy goals.

In accordance with the main current European goals of minimizing CO_2 emissions to obtain a carbon-free economy within 2050 and of increasing energy efficiency up to 32.5% within 2030, a substantial change in building design is required.

It is now proved that all the design choices made at the initial stages of the design process considerably affected energy and environmental parameters (for instance primary energy demand, global warming potential etc.). Consequently, a sustainable multidisciplinary approach must be necessarily adopted in the design procedure to achieve nearly zero energy (nZEB) and environmentally friendly buildings: both energy and environmental performance must be considered starting from the earlier phases of the decision-making process. Building performance is surely influenced by several building typological factors (such as shape, sizing, orientation, internal distribution of functional units, window-to-wall ratio – WWR etc.) but also by technological system (for instance the choice of technological solution for the external envelope), involved in the beginning of the design process. Moreover, it is essential to carry on a study on building systems and their integration with renewable resources to produce green energy. So, it is worth noticing that the building distinguishing features become real passive strategies to be used to avoid energy-intensive buildings and to reduce GHG emissions in the context of the 2015 European Paris Agreement (European Commission, 2015).

In the following paragraph, after a brief introduction, some guidelines and design criteria will be outlined for both house (Valori, 2012) and office building [Miceli, 2016] types. It is helpful for the designers in the early stages of the design process to make the proper choice in relation to the main building typological factors, with the aim at achieving a sustainable and low-carbon building.

3.2. Residential Buildings

A quarter of Italian residential building stock was built before 1946 [ISTAT, 2018] and according to the last census performed by ENEA (Italian National Agency for new technologies, energy and sustainable economic development), 41% is classified as energy efficiency class G (ENEA, 2020) (global energy performance index for non-renewables $EP_{gl,nren}$ > 3.5 $EP_{gl,nren,rif,standard(2019/21)}$ reference building global energy performance index for non-renewable) (Italian Government, 2015). Some authors (Bianco et al., 2022) in literature highlights that with a substantial renovation (concerning both the external envelope insulation and heating systems) of the Italian residential building stock it is possible to achieve an energy saving of about 100 TWh by 2030 and 120 TWh by 2040. This scenario of a complete decarbonization of private house sector by 2050, as requested by Europe, will be only possible with the substitution of traditional fossil fuel with renewable energies to produce energy for both heating and cooling.

In recent years, especially between 2016 and 2019, an increase in sustainable residential constructions is indeed registered and 50% of the new buildings are classified as energy efficiency class A (ENEA, 2020) ($EP_{gl,nren}$ > 3.5 $EP_{gl,nren,rif,standard(2019/21)}$) (Italian Government, 2015). This is an obviously consequence of the Italian energy policy that, with the Ministerial Decree of 2015 called "Minimum Requirements Decree" (Italian Government, 2015), transposing the European directive 2010/31/UE (European Commission, 2010) and following, imposes that all private buildings must be nZEB from January 1st, 2020.

Since 1990, with the Agenda 21, when the concept of sustainable development became a key point also for architecture and building design, many experiences related to environmentally friendly residential construction have followed till the present date. In this regard, it is worth mentioning the experience of Prisma residential complex sited in Nuremberg (Germany), designed by Joachim Eble and built in 1997. This is an example of bio architecture: the building internal courtyard is characterized by East-West orientation to exploit solar radiation through the several transparent façades, the glazed roof is designed to be opened during summer season to guarantee passive cooling in nighttime and the rainfall water is storage to be reused in six different water towers, as a strategy for summer conditioning (Sympa, 2011).

The same architect participated in the design of the ecological district "Eva Lanxmeer", located in Oland, and built between 1998 and 2000. The greenhouse houses represented the key constructions in this neighborhood; they are characterized by a glazing external envelope that encloses the entire building maintaining proper internal thermal conditions for the occupants (Zonato, 2019) especially during winter season exploiting solar gains. There are many representative examples of sustainable and ecological districts and within 2030 they will be more. For instance, the Solar City district located in Linz is designed to maximize the energy saving exploiting the solar radiation or the BedZED in London should be considered the first nZEB and low-carbon district built between 2000 and 2002. In this residential and office district several active and passive strategies are used to minimize CO_2 emissions in the atmosphere such as solar and photovoltaic panels for domestic hot water and electrical energy respectively, windcatchers for passive cooling, all buildings are properly oriented in the construction site depending on the intended use and all materials have low environmental impact. Finally for the sake of completeness the Hammarby Sjöstad in Stockholm and the Masdar city, located in Emirates should be mentioned. They are both pioneer of smart and sustainable cities with the aim at nullifying the CO_2 emissions tackling climate change.

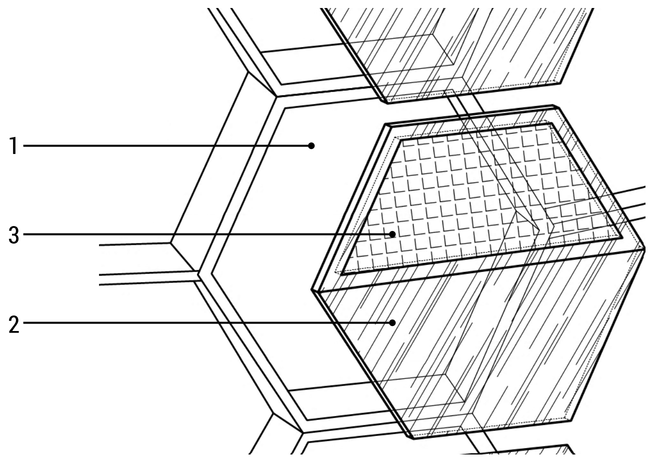


FIG. 3.1. Sketch of the Trombe walls in the southern facades of the building (Source: Valori, 2012) In the figure: 1 is the Trombe wall, 2 stands for openable double-glazing and 3 is transparent photovoltaic cell

As far as residential complex is concerned, it is worth to highlight the project called "*Uovo di struzzo con occhi di mosca*" (Ostrich egg with fly eyes) by Giuseppe Magretti (Archingegno Office) in 2010 for the city of Milan (Archingegno, 2010). The compact shape with a cyclical plan and the elliptical section (S/V – Surface/Volume ratio equal to 0.25 m^{-1}) lets to achieve the best internal comfort and well-being for the occupants for both winter and summer season. The main passive strategies are the southern external walls made of Trombe walls and small greenhouses for a total surface of 180 m^2 and a solar gain of about 5.5 kWh/m^2 (if located in Milan). Furthermore, there is a thermal water wall in the center of the building throughout its height. This passive solar system lets to storage the heat due to solar radiation and then to release it in the internal environment helping to warm up functional units. The total energy produced is equal to 5.5 kWh/m^2 (if located in Milan) (Fig. 3.1).

Another interesting research project about residential complex is done by Mario Cucinella Architects. It is called "House 100k" (Mario Cucinella Architects, 2007). The research aims at outlining a sustainable, carbon neutral and affordable residential building type of about 100 m^2. The idea is combining active and passive strategies to make the building energy independent. Energy demand should be satisfied through renewable energies: solar, geothermal and wind energy should be used to meet the electrical energy needs.

Obviously, there are also many representative examples of green and sustainable architecture built in Italy and abroad. The following ones should be mentioned because they are near past constructions looking to the future and making nature the key point of the architecture: the "One Central Park" by Jean Nouvel (Sydney 2014) and the "Torino Green", by Luciano Pia (Turin, 2012). The last one is a curious residential complex where the vertical green becomes a real part of the façades through tanks and tall trees (Galateo, 2016). They contribute to the regulation of the external climate conditions, minimizing both the façades surface temperature during summer season as sola shading system and the heat islands effect throughout the whole year. Moreover, during winter season, they protect buildings from cold wind.

3.2.1. External Layout

Firstly, it is advisable to highlight that the design of the external layout obviously depends on the geometry of the available construction site and the number of residential buildings to be constructed. Thus, since the proper external quality must be guaranteed in the project of the external environment to ensure the wellbeing of the occupants and to reduce the heat island effect. For instance, in the project of "MilanoSei" by Mario Cucinella Architects in 2018, the main purpose is a green and sustainable city district where the new design complies with the existing natural environment and infrastructure. Several green areas and trees are considered in the project of the external layout. Moreover, all the design buildings must have the opportunity to exploit the available natural resources as passive strategies such as, for instance, solar radiation or vegetation. The Gneiss Moss residential complex of about 61 houses designed by Georg W. Reinberg and built in 2000 (Salzburg) is a key example of the previously highlighted strategy. The distance between the different buildings (6 residential buildings) is calculated to all the southern façades (characterized by the presence of solar greenhouses) received the higher solar radiation to exploit for heating during winter season.

The advisable configuration for the external layout is one that guarantees the following advice for winter and summer seasons, respectively:

Winter Season

- To regulate the proper distance between buildings to exploit solar radiation and to save energy for heating.
- To avoid natural vegetation shadows or those of neighbor buildings.
- To northern orientate evergreen tall trees to avoid cold winds and to southern/ eastern/western orientate deciduous trees to exploit solar gains.
- To orientate the buildings in the construction site to use all natural sources for conditioning (for instance exploiting solar radiation trough glazing façades as passive strategy to heat internal environment) or electrical energy production.

Summer Season

- To design external vegetation as to solar shading system: to avoid overheating inside the buildings.
- To orientate the buildings in the construction site to use all natural sources for conditioning (for instance exploiting prevailing winds through windows as passive cooling to cool internal functional units).
- Especially for climate zone with very warm summer: to use external finishing materials characterized by higher reflection coefficient.

Generally, some advisable design principles for a residential complex external layout are the following ones:

- The construction site should be characterized by at least 25%. permeable flooring or green areas Also, the parking area should be included in the previous permeable areas.
- The construction site should be in an area served by basic services and infrastructure as required by many environmental protocols (such as ITACA protocol or LEED one).

3.2.2. Energy Strategies

In the following 2 subsections, both winter and summer season energy strategies and environmental ones are shown in detail for residential building type. Some examples are alscited. In general terms, for all temperate climate it is possible to individuate some strategies that aim at decreasing primary energy demand for summer and winter season, primarily exploiting the distinguishing climate characteristics of the construction site. For instance, related to some seasons features it is worth to notice as follows:

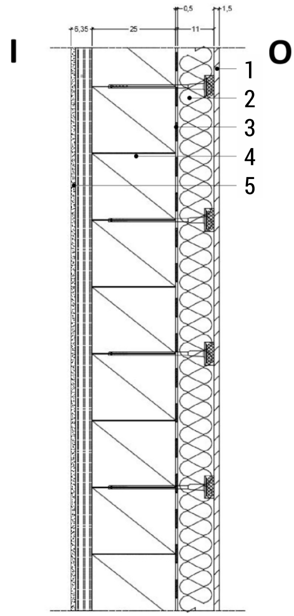
- *Temperate climate with cold winter*: the first goal is to reduce energy needs for heating because in this type of climate this contribution to the energy balance of the building is higher than the others.
- *Temperate climate with warm summer*: the first aim is decreasing the primary energy demand for cooling, paying particular attention to the overheating of the functional units during summer season.
- *Temperate climate with summer droughts*: in this case the decrease in energy demand during summer season is the main goal because this contribution is the highest one in the building energy balance. In fact, the energy need for winter season is limited.

Both winter and summer strategies must be chosen considering the highest contribution to the building energy balance, according to the climate characteristics.

3.2.2.1. Winter Season

In areas where the energy needs for heating is prevalent, to decrease energy demand, the energy strategies should be the following ones:

- Low value of the surface-volume ratio [m^{-1}] (surface means dispersing surface and volume means conditioned volume). Usually, this value is lower than 0.55 m^{-1} for a building characterized by a geometry that positively contributes to the energy performance. In this case the building will be surely characterized by a compact shape.
- Main orientation of the façades along East-West axis to exploit solar gains in cold winter days. As shown in detail in the next paragraphs, the main functional bands should be southern oriented and should hosted the primary functional units. Otherwise, the secondary ones should be northern oriented and hosted the ancillary premises that become buffer space to avoid significant heat losses.
- Regarding window-to-wall ratio (WWR): reducing the northern glazing parts to minimum required by health-hygiene standards for the specific intended use of functional units and increasing the southern WWR up to 40%-50% to catch maximum solar radiation during the day (to maximize solar gains).
- To protect the building from cold winter winds through natural (if available on site is preferred) or artificial barriers to limit dispersions by convection.
- Regarding technological solutions to adopt for the external wall the ETICS (External thermal Insulation Composite System) (Fig. 3.2) should be one of the alternatives used to minimize heat losses, to eliminate thermal bridges (also at the structure) and to reduce initial investment costs as well.



Legend
(outside-inside)
1. External finishing plaster with glass fibre net (15 mm thick)
2. EPS thermal insulation panel (110 mm thick)
3. Adhesive (5 mm thick)
4. Lightweight bricks (250 mm thick)
5. False wall made of: metal substructure and plasterboard panel (12.5 mm thick)

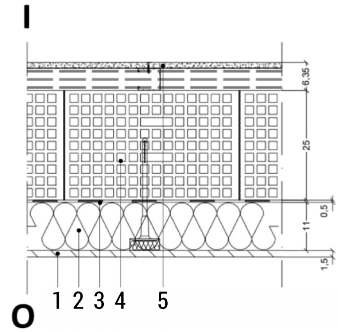
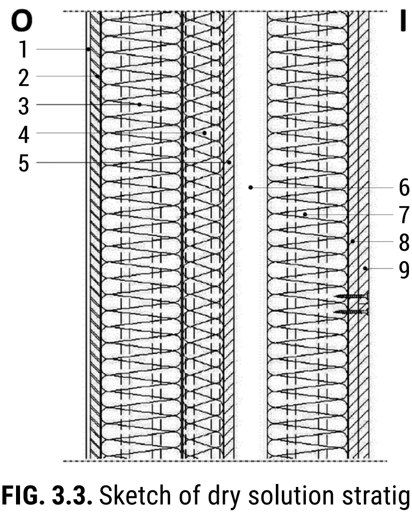


FIG. 3.2. Sketch of ETICS solution stratigraphy to be used in a sustainable residential building. The thickness of insulation is outlined considering Florence climate characterized by 1821 HDD (Source: own elaboration)

The other technological solution that could be used for a sustainable residential building is a dry one (Fig. 3.3). In this case, the advantage is surely economical, mainly linked to the time of the construction, which is shorter, if compared to the traditional technological solutions.



Legend
(outside-inside)
1. External finishing with glass fibre net (5 mm thick)
2. Cement board with glass fibre net on surfaces (12.5 mm thick)
3. Rock wool thermo-acoustic insulation panel with density equal to 70 kg/m^3 (100 mm thick)
4. Wood fibre thermo-acoustic insulation panel with density equal to 270 kg/m^3 (50 mm thick)
5. Air (41 mm thick)
6. Rock wool thermo-acoustic insulation panel with density equal to 70 kg/m^3 (100 mm thick)
7. Plasterboard panel (12.5 mm thick)
8. Plasterboard panel (12.5 mm thick) with vapour barrier made of aluminium sheet (0.025 mm thick)

FIG. 3.3. Sketch of dry solution stratigraphy to be used in a sustainable residential building. The thickness of insula-tion is outlined considering Prato climate characterized by 1668 HDD (Source: own elaboration based on Capitaneo, 2014)

However, there are several different technological solutions for the external walls that can be used and which are characterized by a continuous external insulation, ensuring decrease in heat losses. For instance, the rainscreen façade, but they are more expensive with respect the ETICS solution. As a result, these solutions are sometimes not economically convenient.

- To design in the residential complex passive strategies, properly oriented to catch the solar radiation during winter days and increase solar gains saving energy for heating. One of the possible passive strategies is the introduction of a southern solar greenhouse, as in the Gneiss Moss residential complex by Georg W. Reinberg (Saltsburg, Austria) or in the one designed by LOG ID (by Dieter Schempp) built in 1993 in Switzerland. Another different type of strategy is the Trombe Wall. This passive strategy is not recurrent in residential building; by the way there are some significant and representative examples to be highlighted such as the Solar House of Odelio, built at the end of XX century after several tentative to construct in the right way the Trombe Wall. Another example of a Trombe Wall is included in a research project of solar Decathlon 2014 by the University of Alcalà. They defined a prefabricated panel that includes a mix of clay and a PCM (phase change material). Finally, the last example is the residential complex in Marostica (Italy) designed by Cooprogetto in 1984, where there are both Trombe wall (Barra-Costantini system) and solar greenhouses.

In the following Figure 3.4 the passive strategy of the Trombe Wall used in Italy in a residential complex located in Rome, designed by Cortesini – Battisti – Tucci studio and built in 2007-2010. In this case the storage mass of the Trombe Wall is a solid mass and they are characterized by ventilation grid to exploit convective heat exchange. It is combined with a solar greenhouse to increase performance.

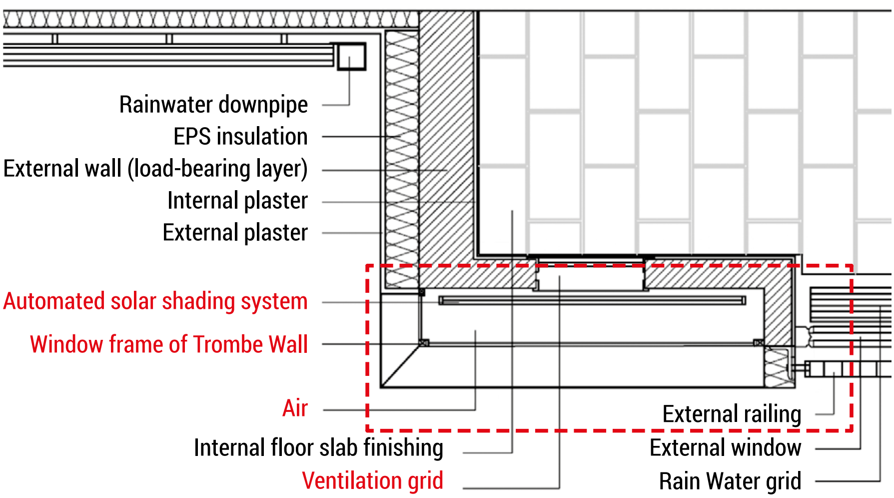


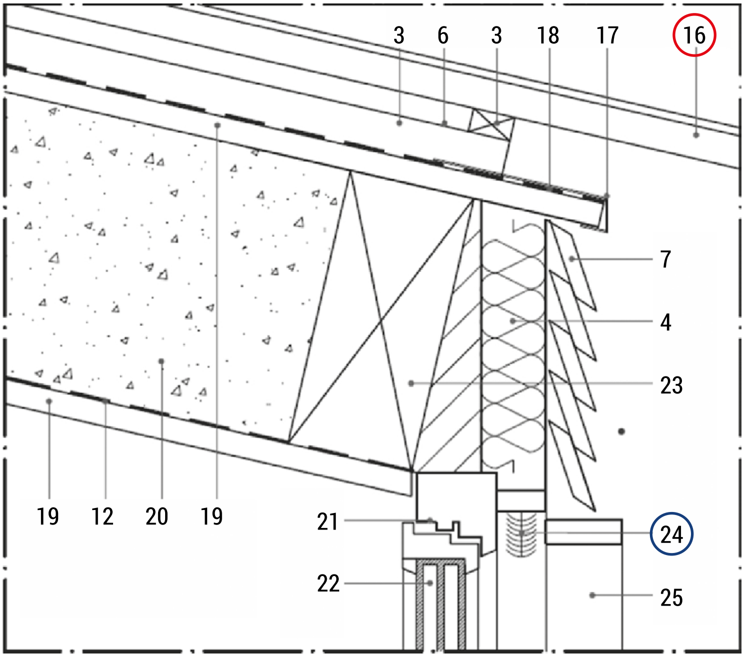
FIG. 3.4. Example of a detail of a Trombe Wall used in a residential complex located in Italy (Source: own elaboration based on Valori, 2012)

- If a ventilation system is included to guarantee the proper air change rate for this specific intended use, usually the exhaust indoor air is used to pre-heat the outside air exchange. This happens with solar greenhouse air as well. This system configuration is used in the Gneiss Moss residential complex by Georg W. Reinberg (Saltsburg, Austria) where the warm air inside the solar greenhouse is in fact used for this aim. Moreover, the exhaust air of toilets and kitchen is fed into a heat exchanger to pre-heat outdoor air for garage floor to minimize dispersions to these unheated secondary functional units.

3.2.2.2. Summer Season

In areas where the energy needs for cooling is prevalent, to decrease energy demand, the energy strategies should be the following ones:

- During summer season, to avoid summer overheating the main façades (especially southern and eastern oriented ones) should not be exposed to direct solar radiation during the warmest hours of summer days.
- Regarding the value of the WWR, it should be equal to the minimum required by health-hygiene standard to guarantee natural ventilation and lighting. This is necessary to avoid summer overheating in all the western, eastern and southern functional units. The better configuration is the one without eastern and western windows for primary functional units.
- To use solar shading systems to regulate the entry of solar radiation and so the value of the solar gains in the energy balance of the residential building. They are useful also to avoid glare in the primary functional units. In Italy they are required by legislation for South orientation. They can be fixed and so built through the geometry of the roof or directly at the windows with overhang. Otherwise, solar shading systems can be movable, with manual or automated control. These 2 different types of solar shading systems are utilized in a terraced residential complex situated Bolzano, designed by Michael Tribus and built in 2000-2001 (Fig. 3.5).
- To design natural and artificial barriers to enable fresh air enter the building to cool it during summer night and to increase the dispersion of heat storage during the day. At the same time to guarantee the proper shading of the internal functional units.
- To use in the residential complex some passive strategies to ensure proper internal air temperature during summer day and night to avoid an excessive use of cooling system and so to save both energy and money. A passive cooling during summer night is recommended. It happens when the outdoor temperature is less than the indoor one and the windows developed on opposite fronts of the building help it as well as non-excessive building width. It is possible to include some specific technological systems to ensure night cooling but at the same time people safety avoiding intrusions.

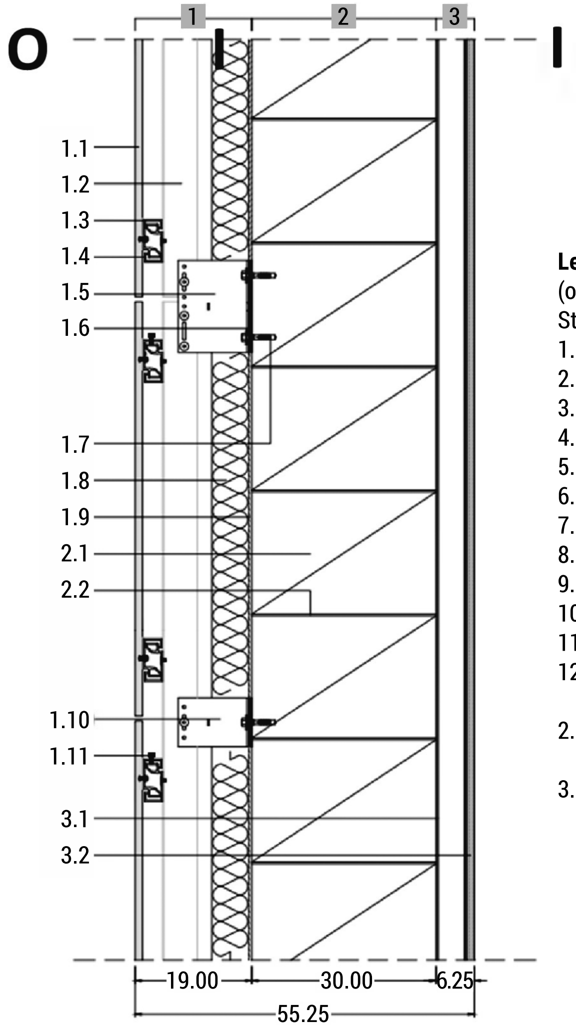


Legend

3. Wooden frame
4. Rock wool thermal insulation layer (80 mm thick)
6. Air (30 mm thick)
7. Wooden external finishing
12. Vapour barrier (0.5 mm thick)
16. Roof finishing (Fixed solar shading system)
17. Metal casing
18. Waterproof sheet (5 mm thick)
19. Wooden panel
20. Reinforced concrete slab
21. Wooden window frame
22. Double glazing
23. Wooding finishing element for roof stratigraphy
24. External blind (Movable solar shading system)
25. Wooding finishing element for external wall

FIG. 3.5. Sketch of a detail of a terraced residential complex in Bolzano with the indication of 2 different type of solar shading system: fixed one built with the finishing element of the roof top (red in figure) and movable one directly at windows (blue in figure) (Source: own elaboration based on Valori, 2012)

- Regarding the technological solution for the external wall, a stratigraphy characterized by a high surface mass [kg/m^2] is recommended to guarantee the proper time shift that for warmest summer is recommended greater than 8 hours to avoid inside overheating. A dry solution should be used but with a material for thermal insulation characterized by high density (> 70 kg/m^3). Moreover, the thickness of insulation should not be high (the minim required by legislation for minimum thermal transmittance and surely less than 16 cm) because this results in an increase in energy needs for cooling. One possible technological solution for the external wall is a rainscreen façade that allows to reduce the summer thermal load thanks to the ventilated layer (Fig. 3.6).



Legend
(outside-inside)
Stratigraphy Number 1

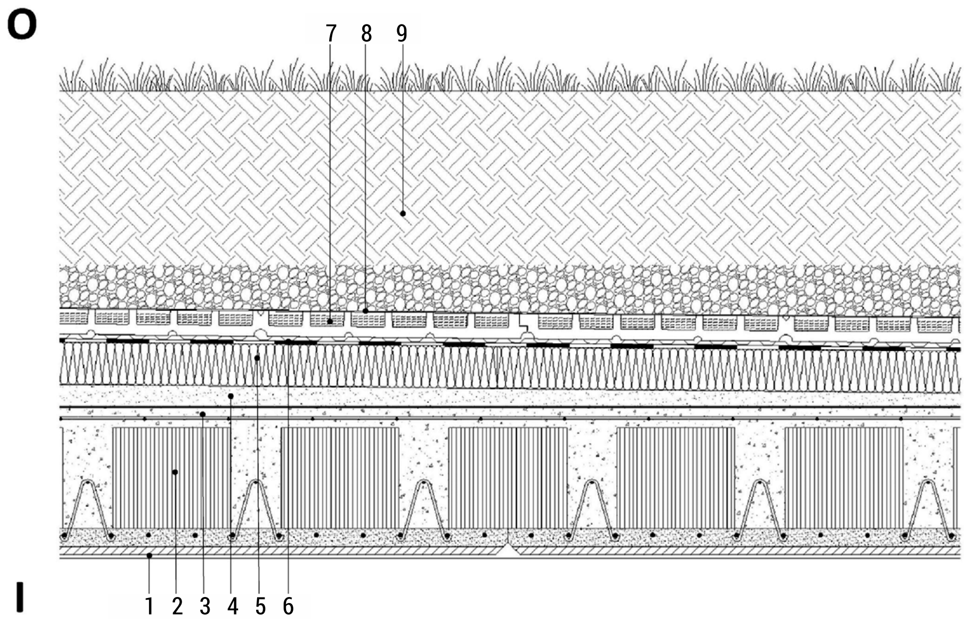
1. External finishing layer (Grès)
2. Vertical frame with T section (Aluminium)
3. Restraint clip
4. Horizontal frame
5. Fixing bracket (L section)
6. EPDM
7. Dowel
8. Thermal insulation material in rock wool
9. Adhesive
10. Fixing bracket (L section)
11. Setting crew
12. Sealing element for installation

2.1 and 2.2 Aerated concrete blocks

3.1 and 3.2 False wall with plasterboard panels and metal substructure

FIG. 3.6. Sketch of the stratigraphy of a rainscreen façade. The thickness of insulation changes with respect to the required minimum thermal transmittance with respect to the climate zone (Source: own elaboration)

- Otherwise, regarding the technological solution for the roof, the usage of green roof (Fig. 3.7) is recommended because it results in many advantages. For instance, it allows to reduce the roofing surface temperature compared to traditional finishings and consequently to improve the indoor thermal conditions and the occupants' well-being. Furthermore, it improves the microclimate conditions around the building, decreasing the heat-island effect, as well as obviously reducing CO_2 emissions.



Legend
(inside-outside)
1. Pre-mixed plaster with plastic net
2. Prefabricated floor-slab (Predalles type 240 mm + 50 mm)
3. Structural slab in reinforced concrete (50 mm thick)
4. Slope screed in lightened reinforced concrete (minimum thickness equal to 50 mm)
5. EPS thermal insulation (100 mm thick)
6. Waterproof sheet (5 mm thick)
7. Storage and Drainage element (62 mm thick)
8. Geotextile sheet
9. Soil for vegetation (450 mm thick)

FIG. 3.7. Sketch of the stratigraphy of a green. The thickness of insulation changes with respect to the required minimum thermal transmittance with respect to the climate zone (Source: own elaboration based on Capitaneo, 2014)

3.2.3. Environmental Strategies

In the context of the Paris Agreement, the environmental strategies to minimize the environmental impact for a residential complex should be the following ones:

- To use natural materials or materials with a proper percentage of recycled content, according to CAM (Minimum Environmental Criteria) to build environmental-friendly residential complex. The Global Warming Potential[1] of a construction is mainly related to the Life Cycle Assessment of materials as well and not only to the operational phase. It is better to choose materials produced near the construction site to reduce CO_2 emissions for transportation as well.
- To use passive strategies for summer and winter seasons to decrease the energy needs powered by heating and cooling systems.

- To produce energy using renewable energies to reduce the environmental impact of the operational phase. The use of active strategies is by now essential and indispensable to produce energy to satisfy building needs as well as at the same time an amount of energy to store and to fed into the grid in the context of the construction of plus energy buildings and districts and consequently smart cities. In a residential complex named "Sunny Woods" designed by Beat Kämpfen located in Zurich (Switzerland) built in 2000-2001 the solar collectors to produce service hot water are integrated in the southern façade of the building through the railings of the terraces while the photovoltaic (PV) system on-grid to powered electrical energy is installed on the roof top.

  Regarding active strategies installation and plus energy houses, it is worth to notice a German project. It is a two-story home (260 m^2) located in Leonberg (Germany), and built in 2010. The system is characterized by 15 kW_p PV system installed on the roof top, integrated with an electrical heat pump, and 7 m^2 of solar collectors. A significant amount of surplus energy is produced since the first year of operational phase (Fisch et al., 2013).

3.2.4. Building Orientation

For building orientation, the solar radiation is one of the main parameters to consider because it obviously influences the energy saving in both summer and winter season. In fact, it affects the internal distribution of functional bands, the internal layout of primary/secondary functional units, the window-to-wall ratio on the façades and the design of necessary solar shading systems for different orientation.

For this reason, the preferable orientation for a residential building is along the East-West axis, due to the possibility of maximizing the solar gains during winter season and consequently save energy for heating. At the same this configuration lets to receive less incident solar radiation on building façades during summer season, due to the greater inclination of solar rays and consequently save energy for cooling and avoiding overheating in the internal environment. By the way it is possible to achieve the same energy and environmental performance during operational phase of the residential building if it rotates maximally 20° anti-clockwise and so obtaining the main façades eastern-southern oriented.

Otherwise, the orientation of the building is obviously affected by the geometry and natural constraints of the construction site. For this reason, some considerations must be done to highlight the main possible issues:

- If the possible orientation of the main axis of the construction is along North-South direction the main issue is related to both the significant decrease in solar gains during winter season and the western orientation of the main façades for summer season. Thus, because the incidence of solar radiation on main fronts happens during the warmest hours of summer days. Moreover, another significant

issue consists in designing proper solar shading systems for eastern-western glazing parts to avoid overheating in internal functional units.
The first problem can be solved through the design of southern oriented glazing elements for instance through the construction of overhanging portions or the introduction of passive strategies such as solar greenhouses. The residential complex located in Vienna (Austria) designed by Georg W. Reinberg and built at the end of XX century is characterized by a main orientation along North-South axis. The designer to improve the energy performance of the building introduced for each single apartments a double-height solar greenhouse to exploit solar gains during winter season. The geometry of the building is designed with several variation of the height of the different houses to let the solar radiation enter in the internal spaces.

- If the possible orientation of the main axis of the construction is along Northeast/Southwest or Northwest/Southeast, the building should receive solar radiation through southwest and southeast windows during winter season. In this case the advisable orientation of main fronts to limit the possible overheating during summer season is along Northeast/Southwest axis because the solar radiation on the main fronts is at the beginning of the day.

3.2.5. Geometry of the Building

Firstly, the geometry of the building and, consequently, the shape of the floor plan, the section geometry and finally the roof one, depends not only on the available construction site but also on the characteristics of the climate and on passive strategies that the designer wants to use. Generally, for cold climates (such as Italian climate zone F, characterized by heating degree days HDD > 3000 Kd/y or E defined by 2100 < HDD < 3000 Kd/y (Italian Government, 1993)) a compact shape with a low value of the surface/volume ratio (S/V [m^{-1}]) is advisable to reduce the dispersions during winter season. Otherwise for warm-humid climate a linear shape is better to ensure cross ventilation during summer season to avoid overheating exploiting passive cooling.

In the next paragraphs, the geometry of the floor plan, section and roof of the sustainable residential building is analyzed in detail.

3.2.5.1. Floor Plan Geometry

The floor plan geometry undoubtedly influences the housing aggregation, the orientation of the functional bands and functional units, the internal layout of each single house but also natural lighting and ventilation inside the environment. It is worth to notice that there is not an optimum floor plan geometry in absolute terms but there are many possibilities to be used by designers. Then, the orientation of the primary and secondary functional units (as passive strategy) influences the energy performance and so make the building more sustainable.

The geometry of the floor plan for a sustainable residential complex could be:

- *Square*: it is usually used in climate typified by cold winter because it is characterized by high compactness (low S/V for instance < 0.50 m^{-1}) that guarantees to minimize dispersions. Usually, the stairs are placed in the center of the squared shape and to ensure proper lighting and thermal conditions, the floor plan could be rotated of about 45°. Like this there is not a completely northern oriented façade (adverse orientation) as demonstrate in Figure 3.8.

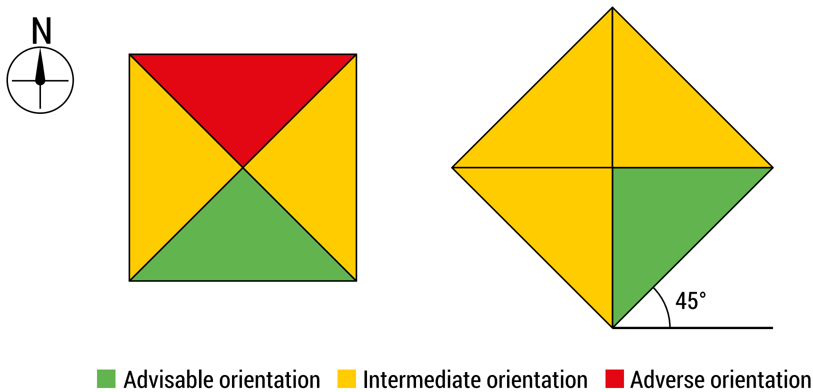


FIG. 3.8. Individuation of advisable, intermediate, and adverse orientation for a squared residential complex (Source: own elaboration based on Valori, 2012)

One Italian example of this type of configuration is a small housing complex built near Florence (climate zone D HDD = 2182 Kd/y). It is designed by Tiesse Ingegneria s.r.l., and built in 2005. It is a detached building developed onto 2 floors and accommodates 2 houses. It is oriented in the construction site rotated of 45° with respect North-South axis to guarantee a favorable orientation to the primary functional units of both houses.

- *Rectangular*: this configuration is the most recurrent one in residential building complexes. This shape is characterized by 2 symmetry axis and by one dimension greater than the other. It is generally used in several climate zones because, if properly oriented (the main fronts along East-West axis), the linear shape ensures significant solar gains during winter season and consequently energy for heating can be saved. This configuration allows to southern oriented most primary functional units and develops the secondary one northern oriented using them as buffer spaces to avoid dispersions during winter season (passive strategy).

If the East-West orientation is not possible for this kind of shape, for buildings located in the Mediterranean area, the advice is to rotate the building in such a way as to have the main façade South-East oriented. This enables to obtain solar radiation and natural lighting during the beginning of the day. Thus, minimizing the western exposure that in summer season can create overheating phenomena inside the functional units (Fig. 3.9).

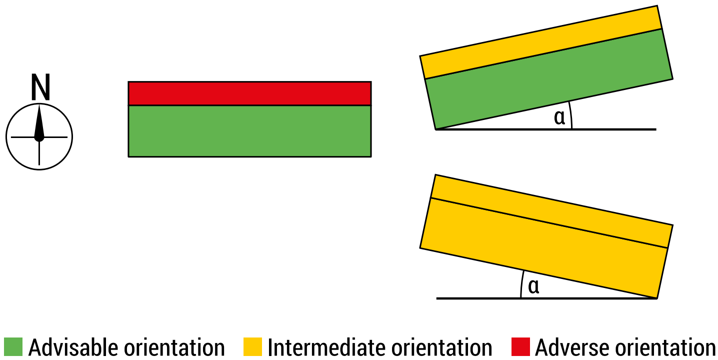


FIG. 3.9. Individuation of advisable, intermediate, and adverse orientation for a rectangular residential complex (Source: own elaboration based on Valori, 2012)

It is worth noticing that residential complexes could be designed also with *C shape, L shape* and as *courtyard building*. This type of shapes is less common in sustainable residential buildings because the C and L shapes are characterized by low compactness. If the building is East-West oriented there always will be some primary functional units not properly oriented. Courtyard buildings as well presents some critical issues especially related to the shadows of some parts of the building on others. This type of building, characterized by more articulated shape, surely have higher primary energy demand with respect to compact shape considering the same boundary conditions (such as climate zone, thermo-dynamic properties of the external envelope, air change rates for this intended use etc.).

3.2.5.2. Section Geometry

The geometry of the section of a building depends on several factors: firstly, obviously, on the internal layout and so on the distribution of functional bands and functional units, then on passive strategies used (such as fixed solar shading systems, solar greenhouses, ventilation chimneys or buffer spaces), but also on active strategies utilized that needed a specific orientation to be efficient. So, the geometry of the section as well contributes to make the residential building sustainable and influences its energy and environmental performance. Also in this case, the climate characteristics are fundamental to make the right decision about the section configuration. Some advice can be outlined to use the building shape as a passive strategy.

Cold Climate

- The stairs can become a buffer space to decrease dispersions to external environment during winter season (Fig. 3.10), but also some secondary functional units can be designed as buffer spaces to avoid heat losses such as, for instance, the garage. It occurs in the Premiere House (Treviso, 2011) where the northern garage become a buffer space for the home.

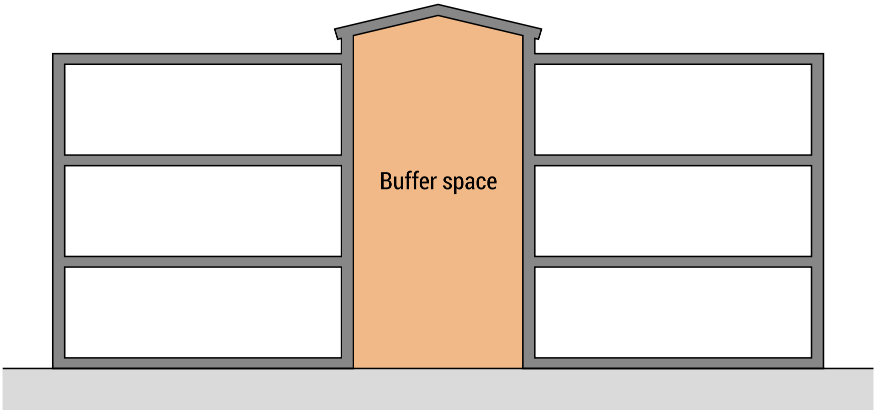


FIG. 3.10. Possible configuration of a residential complex to use the stairs as buffer space (on the left in the figure) (Source: own elaboration)

- The variation of the height of the façades with respect to the orientation is recommended. If the southern oriented front is higher than the northern one there surely are some energy advantages for cold climate during winter season: this configuration ensures an increase in solar gains for southern façade, as well as decreases heat losses for northern one. Thus, because the North front is developed onto less surface of the external envelope. The residential complex "SHE.AG1 Fastiggi House" is an example of this type of configuration with a trapezoidal cross section and, as a result, different heigh between northern and southern façade (Lusardi, 2008).

Warm Climate

- The introduction of ventilation chimneys to guarantee passive cooling during summer season is advisable. For instance, the residential complex "Giuncoli" located in Florence, is characterized by a rectangular section with 2 ventilation chimneys for each single building. This energy strategy exploits local prevailing winds to ensure passive cooling during summer night. The same strategy is used in the residential complex "Colle degli Ulivi", built in Frascati in 2016, that contributes to maintain the proper air change rate as well.
- The introduction of fixed solar shading systems, such as overhang along the façades (especially for southern oriented ones) or directly at the height of the roof plan, is advisable to regulate solar gains during summer season to save energy for cooling and prevent overheating during warm summer sunny days.

Finally, for different type of climates, the inclination of the front (usually South façade) of a building should be a strategy to improve the energy performance and, consequently, to reduce the environmental impact. For instance, in this case, the designer can have 2 possibilities depending on his goals:

- The first one is to slope the front upwards. This configuration is advisable when the main aim is exploiting solar radiation to produce energy with active strategies.

In this way, the façade receives the solar radiation even if the inclination of the solar rays is higher. At the same time, it is necessary to design right solar shading system to prevent summer overheating inside the functional units. Thus, can be reached creating the glazing parts of the façade set back from the main front. An example of this configuration of external wall characterized some residential complex in the Eva-Lanxmeer District (Netherlands, 2009).

- The second one is to slope the front downwards. This configuration is recommended when the front is characterized by the presence of a passive strategy (such as solar greenhouse). Thus, because the solar radiation can enter to the internal environment when the sun is low in the sky during winter season. Otherwise, the inclination avoids excessive solar gains during summer season. Some residential complexes in Gneiss-Moss (Saltsburg, 2000) district are an example of this previous possibility.

3.2.6. Building Functional Organization

Once defined the orientation of the building, the geometry of the construction (depending on the shape of the construction site), the energy strategies that can change the geometry of the section of the building (depending on the site analysis), it is possible to outline the internal layout and so the distribution of functional bands and functional units. In the next paragraph the internal layout of the main types of residential building are outlined, by proposing different configurations of the building type to improve energy performance according to climate characteristics.

Single-Family Building

If the residential complex is an aggregation of a single-family house (terraced house building type) and it is characterized by the right orientation (along East – West axis), the internal configuration should develop as in Figure 3.11. The functional distribution of each single-family house should be organized into 2 different functional bands with the southern one deeper than the northern one. The primary functional units (characterized by greater presence of people during the day such as living room, dining room or bedroom) (marked in green in Figure 3.11) developed in the southern oriented functional bands, while the secondary functional units (such as vertical/horizontal connections, toilets, storage) (marked in red in Figure 3.11) in the northern one. This internal distribution guarantees a better energy performance of the whole complex.

If the residential complex is situated in a cold climate, a solar greenhouse should be included along southern façade to increase solar gains during winter season. It should be characterized by a depth which is 2.50 m at least.

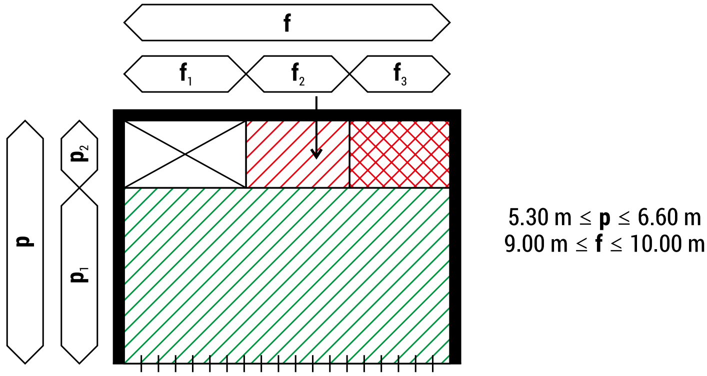


FIG. 3.11. Functional distribution of a terraced single-family house with the indication of the main dimensions of functional bands (Source: own elaboration based on Valori, 2012)

Otherwise, if the residential building is sited in a location characterized by a warm temperate climate the shape of the building should be less compact and so developed with higher width size. In this configuration, the needed solar gains for winter season are nevertheless ensured as well as natural ventilation for passive cooling is promoted. In this case an internal courtyard or a southern loggia are usually developed, to manage passive cooling (Fig. 3.12).

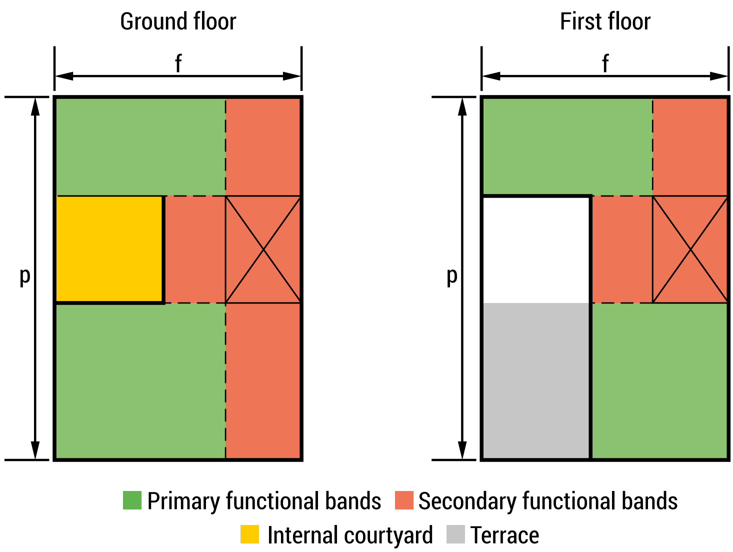


FIG. 3.12. Distribution of single-family house (possible aggregation for terraced buildings) for warm temperate climate with the integration of solar greenhouse and internal courtyard to increase energy performance of the building (Source: own elaboration based on Valori, 2012)

An example of this building type with the introduction of an internal courtyard is the residential complex designed by Solinas Verd Architectos and built in Seville (Spain, 2006-2008). Every single house is characterized by a linear shape; in this case, a solar greenhouse and an internal courtyard are included in the design to ensure proper solar gains and to avoid overheating, exploiting natural ventilation really thanks to the patio.

If the single-family residential complex is mainly northern-southern oriented, it is possible to construct some glazing elements (for instance solar greenhouse), jutting out of the building (upwards), to guarantee needed solar gains during winter season and to save energy. The already mentioned residential complex by Georg W. Reinberg in Sagedergasse is a representative example.

Multi-Family Buildings

As far as multi-family buildings (in-line and gallery building type) concerns the best geometry for the construction in this case is also the linear one, with the same internal layout developed into 2 different functional bands. The depth of the building varies in a range between 8-10 m. The difference with the single-family house is obviously the presence of the vertical connection.

As in the case of terraced buildings, a solar greenhouse can be included in the building with proper orientation (South), and it can be designed along the main southern façade (Fig. 3.13 – left side). As an alternative, if for instance the geometry of the construction site does not allow the previous configuration, the public horizontal connections (near the stairs block) can become the solar greenhouse as illustrated in Figure 3.13 (right side).

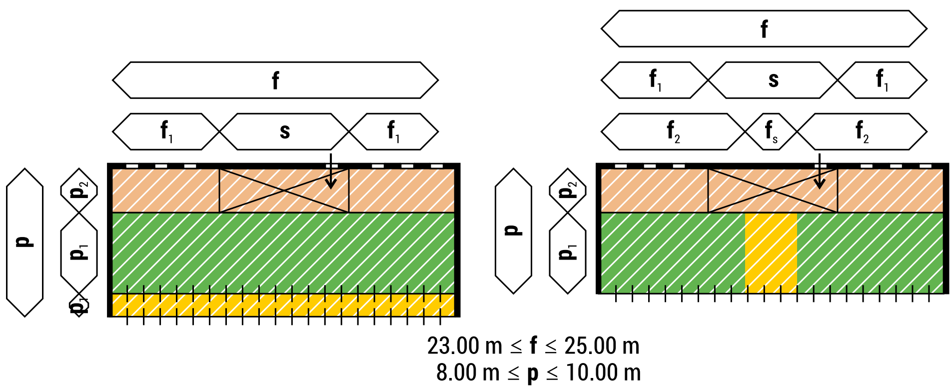


FIG. 3.13. Functional distribution of an in-line multi-family house with the indication of the main dimensions of functional bands and possible integration of a passive strategy (solar greenhouse) in 2 different ways. In the Fig. in red there is the secondary functional bands, in green the primary functional bands and in yellow the possible integration of the solar greenhouse (Source: own elaboration based on Valori, 2012)

In both cases, the stairs are developed in the northern functional bands to become a buffer space to limit dispersions for the most disadvantageous orientation. For instance, the stored heat through this passive strategy during the day could be used to preheat the external air before enters to the internal functional units.

If the multi-family residential complex is mainly northern-southern oriented, as it happens with single-family buildings, it is possible to catch maximum solar radiation constructing the building in steps (change in the section geometry of the building) or building southern projection along east and West axis (Fig. 3.14 – right side). Another possibility to improve the energy performance of a building not properly oriented is to rotate the main axis of about 30° and to include solar greenhouses along South-West façade. In this case the projections of the external wall can be used as solar shading system (Fig. 3.14 – left side). In this configuration, the East and especially West fronts are designed to catch the solar radiation during winter season and to regulate it during summer one.

Regarding the internal functional distribution, the layout configuration that ensures the best compromise between energy and environmental performance is the one that guarantees the double facing on opposite front. It happens for in-line, terraced or gallery building type. As shown in Table 3.1 the secondary functional units (such as toilets, sore room but also kitchen that is characterized by high value of internal gains) are developed northern oriented to function as buffer spaces between internal and external environment. The main functional units should be southern oriented to ensure right solar gains and proper natural lighting during the day.

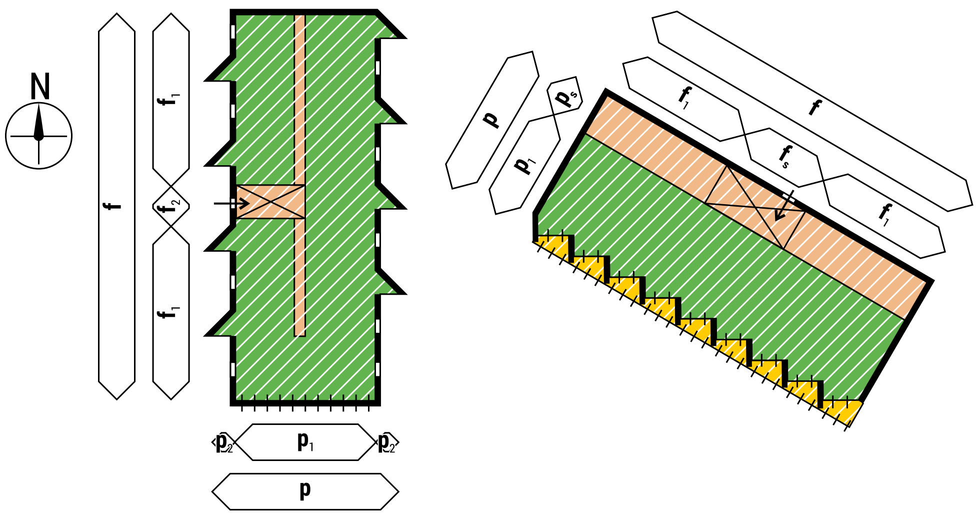


FIG. 3.14. Possible functional distribution to catch solar radiation (in 2 different ways) of an in-line multi-family house with the main axis northern-southern. In the Fig. in red there is the secondary functional bands, in green the primary functional bands and in yellow the possible integration of the solar greenhouse (Source: own elaboration based on Valori, 2012)

TABLE 3.1. Optimum functional units' orientation for residential buildings (Source: Valori, 2012)

Functional units orientation								
Functional unit	**N**	**NO**	**O**	**SO**	**S**	**SE**	**E**	**NE**
Living room			O	V	X	V		
Living/dining room			O	V	X	V		
Kitchen	X	O			O	O	O	V
Kitchenette	X	O				O	O	V
Double bedroom					X	V	V	O
Single bedroom			O	V	X	V		
Guest room					X	V	V	O
Study			O	V	X	V	O	
Bathroom	X	V	O				V	V
Utility room	X	V	O					V
Laundry	X	V						V
Garage	X	V	O					V
Horizontal connection	X	V						V
Store room	X	V						V
Stairwell	X	V	O					V
Technical rooms	X	V	O					V
Terrace			V	X	X	X	V	
Porch			V	X	X	X	V	
Greenhouse					X	V		
X optimum orientation	**V discrete orientation**		**O good orientation**				**bad orientation**	

3.2.7. Window-to-Wall Ratio

As far as window-to-wall ratio concerns, it is first worth noticing that the glazing part of the external envelope ensures both natural lighting and ventilation but also regulate the heat losses during winter season and yearly solar gains. So, they significantly influence the energy performance of the building whatever is geometry in plan or section. In the design and sizing of the glazing elements, it is fundamental to consider the orientation, but also the minimum air change rate and natural lighting required by legislation for this intended use. The advisable configurations, considering the climate characteristics, are the following ones:

- Cold climate: large size windows for South orientation. Thus, because the southern oriented windows catch direct solar radiation for the whole year and so this configuration ensures the maximum value of the solar gains to save energy during winter season. The WWR should varied between the minim value required by health-hygiene standards and 50%. A higher value of the WWR results in an increase in heat losses, due to the different of thermal transmittance between opaque and glazing external envelope. As regard summer season, the solar radiation is minimal due to the higher inclination of solar rays. For North orientation the glazing elements should be kept to a minimum and if they are present, they should be sized according to the health-hygiene standards.

- Warm climate: the dimension of windows should be limited to avoid excessive overheating of internal functional units and consequently an oversize for cooling system. So, in this case for both North and South orientation, they should be sized to guarantee minimum natural air change rate and lighting.

For both different types of climates (cold and warm), regarding southern orientation a solar shading system is needed to avoid the glare phenomenon, especially when solar rays have low inclination (winter season). Otherwise, for North orientation this issue influences on a lesser extent because the glazing elements receive only diffuse solar radiation.

The East and West glazing elements should be avoided. Thus, because they receive the maximum solar radiation in summer season during the warm daily hours and so this surely results in an overheating for the internal functional units.

Once defined the dimension of the glazing elements in the façade, considering climate characteristics and orientation, it is fundamental to consider also the geometry, the position with respect to the external envelope and the technological solutions for the glazing elements in order to regulate, not only energy performance but natural lighting as well.

- The best geometry to ensure the proper value of daylight factor is the squared one even if the rectangular one can guarantee direct lighting for a greater number of hours.
- The slope of the glazing elements should be considered. Thus, because the maximum solar radiation is achieved when the glazing surface is perpendicular with respect to the inclination of solar rays. Consequently, windows tilted upwards receive maximum solar radiation during the whole year.
- The position with respect to the external wall should improve the natural lighting inside the functional units. If the position is high on the façade a better natural lighting and the solar radiation entrance should be guaranteed for the whole width of the functional units.

Regarding the position of glazing elements in the façade it is worth to notice that for climate zones characterized by warm summer season it is necessary to guarantee passive cooling during night hours. The better configuration to achieve cross natural ventilation is when the windows are placed in opposite fronts of the same building unit.

Finally, the advice for the technological solutions for the glazing element considering the orientation are the following ones:

- South, East, and West orientation: selective glazing or solar control glazing to avoid overheating.
- North orientation: low e glazing to avoid excessive heat losses during winter season.

3.3. Office Buildings

At the beginning of XXI century the Italian offices were energy-hungry buildings with a primary energy demand of around 250 kWh/(m^2y); of which one-third is due to artificial lighting (Fabrizio et al., 2011). Nowadays, according to the ENEA report concerning energy consumption in office buildings in Italy, most of the energy demand is for conditioning (57% both heating and cooling), then 25% of energy consumption is related to equipment and 17% for artificial lighting. The current Italian energy performance index for office conditioning (according to 2019 data) is equal to 13 x 10^{-3} Tep/m^2year (ENEA, 2019).

Offices are usually the main headquarter of a company and its appearance should remind visitors of what the company represents and this impact the geometry, colors and technological solutions used for the envelope.

These are some famous representative examples:

- BMW headquarters (designed by Karl Schwanzer, renovation, Monaco di Baviera, Germany, 2006). The museum is characterized by the geometry of a petrol nozzle and the high-rise skyscraper remember 4-cylindrer engine;
- The Longaberger's Giant Basket Building (since 2019 it is a luxury hotel, Newark, Ohio 1997). Its shape is similar to a basket directly taking up the geometry of the main product of the company;
- CMA CGM Tower (designed by Zaha Hadid Architects, Marsiglia, France, 2011). It keeps in mind a ship's prow since the company is one of the major manufacturers of transport by sea (Respi, 2015).

In the last few years, a significant attention to the well-being of the workers within the office space has been paid. This had contributed, for instance, in the development of the active design where the building itself promotes users' physical activities as important part of working life and time. The active design is nowadays developing also in the construction of both energy-saver and environmental-friendly offices.

The Bullitt Center is one of the most representative examples of this type of architecture, designed by the Miller Hull Partnership, built in Seattle in 2012. The internal atrium is characterized by the presence of a stair that develops for the height of the building distinguished by a glazing external envelope. Moreover, to improve green and health transport, for bikes and locker rooms for workers are offered.

At the same time, the building is a Net Zero Energy, with PV system that power 230000 kWh/year of electrical energy, 26 geothermal probes to complete the heat pump system for heating and cooling. Furthermore, it is Net Zero Water due to the complete use of rainwater for drinking and not-drinking water. Moreover, sensors for CO_2 levels, internal air temperature and artificial lighting control are included in workstation functional units to save energy (Saghetti, 2020).

Nowadays it is necessary to consider that the pandemic period of the last 2 years had inevitably affected the traditional way of working. It has made an impact on both the organization and the internal layout distribution of the workstations. For instance, during the design process of an office building today, it is necessary to consider both working-from-home (remote working) and the office-based working. This is translated into a reduced number of fixed workstations into the offices with a rotation of employees (ex. app on mobile phone that can support the workers to reserve the office-space desk) and the increase of spaces for co-working and meetings.

In the context of both Paris Agreement (European Commission, 2015) and European Directive 2018/2002/EU (European Commission, 2018), it is fundamental and necessary to design new, smart, environmentally friendly office buildings characterized by low CO_2 emissions for construction phase as well as operational one and nearly zero energy needs. This goal can be obtained by acting on environmental and technological system of this building type as well as on active and passive energy strategies to adopt to reduce energy (both cooling and heating). Not least it is essential to produce electrical energy by renewable resources, not only to satisfy the minimum requirement of energy standards but to cover the building energy needs and to produce a higher amount of energy.

After analyzing different types of European sustainable offices, it is possible to outline some design guidelines and principles referring to two macro-category of buildings high-rise buildings and low-rise one. The first are characterized "*by a predominant horizontal development rather than in elevation. Levels are less than 10.*" (Miceli, 2016); while the second: "*have a vertical development with a small footprint. Levels are more than 10.*" (Miceli, 2016).

The design criteria for energy efficient offices are defined through several different categories: external layout, both energy and environmental design strategies, building orientation, geometry, envelope design (window-to-wall ratio related to glazing type and solar shading system), structural and technological solutions, systems, and renewables (PV system) (Miceli, 2016).

3.3.1. External Layout

Usually new office buildings are located in:

- Renovated areas for this specific intended use, close to the city center (for instance: Milan, Porta Nuova district, Italy) or in new expansion areas near the city.
- Suburbs close to the industrial facilities or in administration district (for instance: "Ropemaker" building designed by MAKE architects, London, UK, 2009).

- Residential districts where there is the intent to improve and renew an existing specific small area (for example: new headquarters of Dolce and Gabbana, in place of a 1950s residence, Milan, Italy, 2012).

Obviously, such as for houses, the offices external environment should guarantee the well-being of workers as well as decrease the building environmental impact, for instance reducing heat island effect using extended green area or guaranteeing green transport to use. By the way, there are some general design recommendations that can be followed:

- Shadows between buildings and from the surrounding natural/artificial environment should be avoided to allow the exploitation of solar radiation especially during winter season and to better design proper solar shading systems.
- Car parks located on the basement of the building should be preferred in order to both maximize green external areas and minimize the presence of the asphalt that caused the heat island effect. For instance, the Isozaki Tower in City Life, Milan, Italy, 2015 is characterized by a widespread area to include a green park, practically in the city center.
- Finishes of the external area should be characterized by materials with high reflectance coefficients to improve reflectance and especially reduce the high temperature of external sunny surfaces.

  Sometimes in order to reduce the external air temperature especially near glazing façade, external water tanks should be used. The external micro-climate should be better:
- Usage of vegetation and plants as natural barrier to protect the buildings from noise, winds, or solar radiation. Vegetation choice should vary depending on the climate zones, the scope, and the orientation. For instance, evergreen plants should be used for northern orientation to protect the façade by cold winds. While fleeting ones should be used for southern orientation to let the solar radiation enters during winter season and to shade the building façade during summer. For high rise offices this strategy is hardly applicable and usually vegetation is used only to shadow parking area. Finally, it is important the use of local plant and vegetation to reduce the water needs.
- The building should be well-connected with the city by public transports and stops should be near the offices, easily accessible for workers. Pedestrian and bike routes must be ensured and dedicated car parks for electric cars should be provided to improve green transport.
- In low-rise buildings usually the shape occupies the biggest part of the construction site, hence it is frequent that some internal functional units (for example atrium) are dedicated for common areas and shared functions. Sometimes they are directly connected with natural environment, for instance, the Federal Environment Agency building (Dessau, Germany, 2005), that has a big atrium characterized by extensive green areas and glazed roof to improve internal micro-climate and natural lighting exploitation.

- In high rise buildings the shape occupies lower surface of the area hence the external area available is more extensive. In such case, it is strategic the position of the green area with respect to the building one. In fact, it is preferable to locate the green zone in the leeward position to avoid air vortex and have a better microclimate and comfort. For instance, GSW Haus designed by Sauercbruch Hutton Architects and built in Berlin (Germany) in 1999 (Miceli, 2016).

3.3.2. Design Strategies for Energy Efficient Offices

There are many design criteria applicable to offices that can impact on the energy performance of the whole building. These design criteria can be applied to offices to achieve the proper indoor comfort conditions for the workers throughout the year as well as saving energy (for instance for heating, cooling, lighting, and mechanical ventilation) and reducing the use of the mechanical systems. All energy strategies can be grouped according to the aim they are used for (reduction of both heating and cooling energy demand) or in relation to the natural resources they are exploited (solar radiation, wind, water, and soil). The strategies that can be adopted are both passive and active ones. The former allows to improve the proper indoor comfort conditions without considering the use of mechanical systems (as passive buildings): geometry and orientation of the building, insulation and airtightness of building envelope, solar shading systems, the design of openings.

The latter involves efficient technological systems solutions that can be used to produce energy from renewables exploiting natural resources (sun, water, winds).

For instance, the solar passive strategies are defined as: "*all devices, arrangements and construction criteria aimed at heating, cooling and air-conditioning buildings by means of the free energy contribution of the sun and of the possible natural resources of the local microclimate, without the aid of mechanical systems powered by exogenous energy sources. This takes place through natural thermal flows*" (Margini et al., 2008). Such as solar greenhouse, solar chimney, or roof pond.

The solar active strategies: "*are considered to be true technological alternatives to traditional devices, in which the various constituent elements are clearly distinguishable and require some form of energy supply exogenous to the system*" (Margini et al., 2008).

Some design criteria, aimed at reducing the heating demand of the building during winter season, are presented below.

- Adopt big glazing facade or windows, especially for South orientation and cold climates to exploit the solar radiation and save energy for heating exploiting free solar gains. According to the climate characteristics this passive strategy required the best compromise between heat gains, losses and natural lighting. Additionally, at the same time, it is important to consider the possible overheating during summer season and the need of natural lighting during working hours.

  It is proved that according to the orientation of the façades, the parameters to consider for the design of the transparent envelope are window area, glazing type and solar shading systems chosen. This because all significantly affect the building energy performance.

There are many offices characterized by glazing façades. Some examples are: The Salewa Headquarters designed by Park Associati with Cino Zucchi Architects Bolzano (Italy) in 2011 or the so called "the Hub" for the Atkins office built in Bristol (UK).

- Use of a buffer space to create an intermediate zone between outside and inside, characterized by intermediate hygro-thermal conditions (for instance an atrium functional unit). It is worth to notice that the temperature difference between internal environmental and buffer space is less than the one with the external environment. This permits to reduce heat dispersions (if closed) during winter months and to ensure passive cooling (if transparent parts can be opened) during summer period.

  For instance, the Federal Environmental Agency built in Dessau (Germany) and in the 3M Headquarters built in Pilotello (Italy). In both these buildings the internal atrium (used as buffer space) hosted plants and green areas, contributing to improve the microclimate during summer season, as well as avoiding overheating (cooling and ventilating).

At this point, a brief digression about atrium is necessary. It is worth noticing that the design of an atrium (as passive strategy) required to consider many parameters to improve the overall energy performance of the office building (Bazzocchi, 2013).

Firstly, it depends on the type of office building (low rise type or high rise one).

For low-rise offices, the design of an atrium is a recurrent design strategy that significantly affects the overall energy performance. Generally, it impacts the entire height of the building, and it permits the maximization of windows on both external and internal facades. It can be covered by a glazing roof (or a roof partly glazing and partly with PV panel integrated) where portion of it can be opened. In such case the greenhouse effect and the chimney effect are exploited to save energy for heating and cooling respectively.

Otherwise for high-rise offices the atrium would be developed only for few levels (ex.2-4 storey) and in such case it affects the overall energy performance to a lesser extent.

For design the atrium in low-rise buildings, to obtain both energy and environmental performance, it is fundamental to consider:

- The position relating to the geometry of the floor plan (EASE, 2015):
  - Attached: glazed and developed along one of the external walls of the building.
  - Linear: characterized by elongated shape between 2 building blocks.
  - Integrated: glazed and with one external façade.
  - Core: glazed and located in the center of the building.
- The geometry and the dimensions since they affect natural lighting.
- The presence of the roof (open or close) because it influences the S/V ratio [m^{-1}]. The S/V ration means the ratio between the dispersing surfaces and conditioning volume.

- The geometry of the roof (ex. flat roof versus shed one) since impacts on good both natural ventilation and daylighting (advantages to achieve).
- The automation of the roof (for instance the presence of several sensors to automatically open the transparent part of the roof).

For the design of the atrium in high-rise buildings:

- Usually, it is located at the entrance where the hall/reception functional units are conceived. The atrium would impact vertically more levels to improve micro-climate, exploiting natural air ventilation due to chimney effect (it should be connected helicoidally with other levels). Such as the atria in Mary Axe designed by Foster and Partners in UK.
- The dimensions of the atrium can privilege the predominance of the chimney effect or the greenhouse effect. In fact, if the dimensions are contained, air velocity is improved, and the chimney effect is predominant.

To conclude, it is advisable to highlight that the design of the atrium should be combined with the window-to-wall ratio design. For instance, in the Commerzbank (designed by Foster and Partners) the atrium combined to glazing façade (usually double skin façade) and green area is used in different level of the building to ensure right microclimate conditions.

Some design criteria aimed at reducing the cooling demand of the building during summer season are shown below.

- Usage of solar shading system to regulate solar radiation and natural lighting inside the environment, avoiding overheating and preventing glare in workstations, especially for offices with high value of WWR. The regulation of the solar radiation can be achieved also with the geometry of the building façade such as Vodafone Headquarters (designed by Barbosa & Guimarães Arquitetos, Oporto, Portugal, 2009).
- Adopt passive cooling strategies exploiting natural ventilation to ventilate and cool the internal environment to prevent overheating and excessive use of mechanical systems.

  The passive cooling strategies can be classified as: microclimate cooling, geothermal cooling, evaporative cooling and radiative one. In the offices the most recurrent one is the microclimate cooling: comfort ventilation, free cooling, or structural cooling. These passive strategies are strictly related to the windows design (obviously based on the intended use of the buildings), the prevailing winds direction (to improve cross ventilation), the structural solutions adopted and the internal partitions design.

  Specifically, there are many ways to guarantee passive cooling in offices:

  - Solar chimneys such as the one of 115 m in the Hydro Place designed by Kuwambra Payne McKenna Blumberg architects in Manitoba (CA) in 2009. This building receives the LEED Platinum environmental-energy certification with energy needs lower than 85 kWh/yr.

– Water tubs to guarantee evaporative cooling such as in the atrium of the International Federal Agency. In this case the air is cooled by evaporating water and the strategy better performed in climate characterized by relative humidity lower than 30%.
– Indirect free cooling exploiting the soil to cool air or water before enters the building functional areas. This strategy is still used in the building of the International Federal Agency.

It is worth noticing that for guaranteeing proper air change rate in buildings with this intended use it is important obviously to install mechanical ventilation systems. The mixed-mode systems are usually needed for ventilation and conditioning and so combining passive cooling and colling systems. In this case to save energy and control real internal conditions in terms of both concentration of pollutants and internal thermal-hygrometric conditions to activate ventilation, an automated monitoring is necessary (such as BACS – Building and Automation Control System).

Design Strategies to Reduce Emissions of Greenhouse Gas

Such as in residential building the main strategy to reduce the emissions is producing energy exploiting renewables. The integration of PV system in office buildings is recurrent and there are 4 possible configurations:

- Overcladding (cool roof or façade): the PV system creates the external layer of the roof/façade. This is the case of Buhler Electricitè Office, Kurmann & Cretton SA, Monthey (Switzerland), 2008-2011.
- Enclosure (warm roof or façade): the PV system are installed on usual glazing system. For instance, the Autobrennero A22 Office, Studio Associato Giovannazzi, Trento (Italy) 2009.
- Shading devices: the PV system are arranged on the solar shading system choose for the building. An example of this PV system installation is the FEAT Headquaters, Claudio Lo Riso, Lugano (Switzerland), 1997.
- Glazing roof: in this case the PV system is installed on the glazing roof of the building. A representative case of this design choice is Vovartis Campus Gehry Building, Gehry & Partners Ltd, Basel (Switzerland), 2008.

Other strategies, as for residential buildings, are:

- The usage of materials according to CAM (Minimum Environmental Criteria). Building components must be made of natural materials or those ones that include a precise percentage of recycled materials.
- The management of natural and artificial lighting is fundamental to save energy. Specifically, automated control system to control daylighting intensity and brightness of the workplace are highly recommended.

Building Orientation

Solar radiation is the main driver for the proper orientation of the building more than the prevailing winds direction. This is proved by the assumption that winds are more difficult to control. However, it is possible to adopt natural or artificial barrier to deviate and mitigate wind actions; as example rotating the building with the main axis perpendicular to the prevailing winds direction (if it is applicable, for instance if the shape of the construction site allows it).

With respect to solar radiation the best orientation for an office building is with main axis on East-West direction. Thus, to exploit solar gains and to better control the solar radiation inside the building to prevent overheating or glare issues. In detail:

- For low-rise offices: if the floor plan is a rectangle, it should develop along East-West axis, as explained before. This orientation can be changed of a small angle equal to +/– 15°. This slight rotation does not influence the energy performance of the building. If the floor plan is a square, the rotation of 45° with respect to North-South axis is recommended to avoid disadvantageous exposition for workstations. In this case, a specific study on shading devices is needed.
- For high-rise offices: in this case the prevailing winds mostly affect the orientation and the position of the building. This occurs for 2 different reasons: the horizontal forces on the load-bearing structure and the exploitation of natural ventilation for cooling. The recommended shape for the floor plan is the circular one.

Geometry of the Building: Floor Plan Layout and Functional Distribution

For offices, 3 main recurring types of configurations can be represented (Fig. 3.15):

- High-rise type with compact shape of the floor plan (A). This is a 12-storey building with a polar symmetry of the floor plan. The floor plan is characterized by a squared shape with about 24 m side. Services (ex. toilets, vertical connections, etc.) are developed in the center of the square and a horizontal connection links all office working areas.
- High-rise type with linear shape of the floor plan (B). This is a 12-storey building characterized by a linear shape with main dimensions 12 m x 48 m. Services are grouped in the center of the building and a horizontal connection link the different office working area developing on both sides.
- Low-rise type with internal open courtyard (C). This is a 4-storey building with main dimensions of the floor plan equal to 36 m x 60 m. The open central courtyard is characterized by linear shape (12 m x 36 m). Services are grouped in eastern and western front to leave the offices arranged in the most advantageous orientations (Miceli, 2013).

In the following Table 3.2 the geometry characterization of the different office building type is shown for completeness. Regarding to the dimensioning of the floor plan (A, B, C), a surface of 15.5 m^2 for each single worker are considered. The number of workers is equal to 446. In Table 3.2 the first 6 lines are related to the parameters distinguishing the floor plan of the building, while the remaining the characteristics of the whole building.

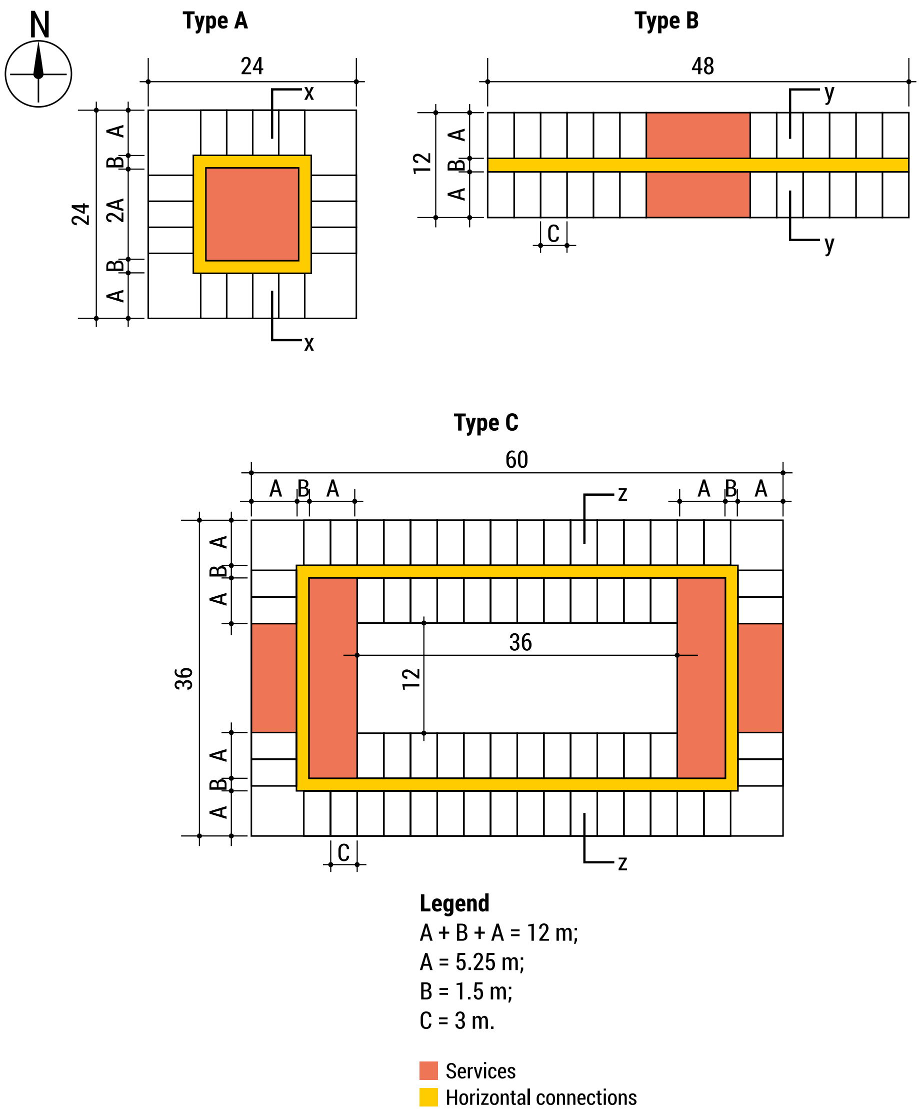


FIG. 3.15. Some possible geometries (A, B, C) for a sustainable office building with the indications of the main dimensions and services and horizontal connection functional bands (Source: own elaboration based on Miceli, 2016)

The functional macro-zones of an office building are the following ones:

- Working area as cellular space, open space, combination of both (primary functional area). It can be considered the primary functional area.
- Horizontal and vertical connections as stairs, elevators and corridors.
- Area for services. For instance: reception, meeting rooms, library, break and relax area, toilets, storage, etc. It can be considered the secondary functional area.

TABLE 3.2. Geometry characterization of the floor plan of the different type of outlined office buildings with the indication of aspect ratio, main dimensions of the floor plan (a, b), sizes of the courtyard (c, d), gross area of the floor plan (A_{FP}), number of levels (N_L), total height of the building (H_{tot}), total gross area of the building (A_T), volume of the building (V), number of workers (N_w), A/V ratio (Source: Miceli, 2016)

Type	A	B	C
Aspect ratio	a:b = 1	a:b = 4	a:b = 1.6 c:d = 3
a [m]	24	48	60
b [m]	24	12	36
c [m]	–	–	36
d [m]	–	–	12
A_{fp} [m^2]	576	576	1728
N_L	12	12	4
H_{tot}	48	48	16
A_T [m^2]	6912	6912	6912
V [m^3]	27648	27648	27648
N_w	446	446	446
A/V ratio [m^{-1}]	0.21	0.25	0.29

The following Table 3.3 shows some representative dimensions, related to each function, recommended for a sustainable office building. This size ensures workers well-being during working time. Sizes are deduced from environmental system analysis of several sustainable office buildings and some reference in literature (Arredi, 2004) by averaging.

TABLE 3.3. Square meters for person for the main functional zones and macro-zones of sustainable office buildings (Source: Miceli, 2016). It is worth to notice that the Italian manuals suggest from 5 m^2 – to 10 m^2 for person. Italian regulations minimum is 5 m^2 per person; single office minimum 9 m^2 per person. In the tables offices macro-zone includes area for the access to the workstation, area for special services and vertical and horizontal connections; services macro-zone includes all the secondary functional units that support the office

Space requirements for office work	Space adopted [m^2/pers]	Macro-zones [m^2/pers]
Work station area	7.5	OFFICES: 10.8
Area for access to the work station: internal circulation	8.3	
Are for special services: meeting rooms, showing rooms etc...	10.8	
Vertical and horizontal connections	12.4	SERVICES: 4.8
Area for services that support office zones: archive, break area, toilets, etc...	15.5	

Structure

Vertical load-bearing structure

The most recurring structural solution for a low-rise sustainable office building in Italy, is the reinforced concrete load-bearing structure. While for the high-rise one is the mixed one (combining steel and reinforced concrete).

The choice of materials mainly depends on the construction local tradition, but also on availability of local materials. It is preferable to use them to reduce both economic and environmental costs as well as to verify the impact of the entire production cycle LCA (Life Cycle Assessment).

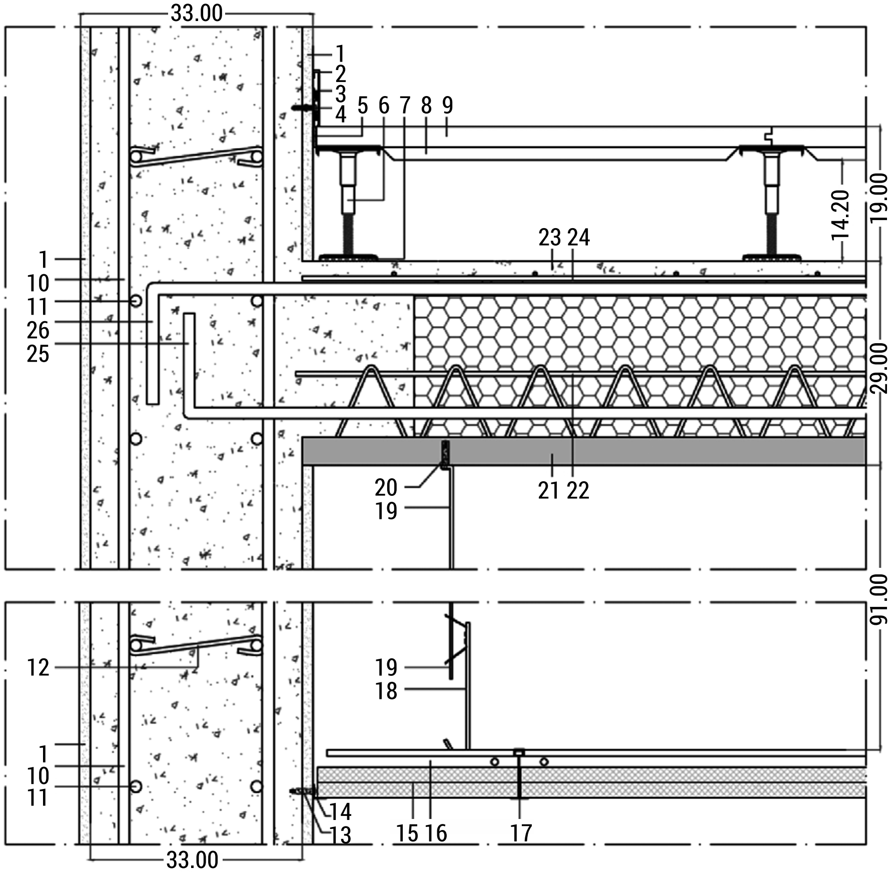
Horizontal load-bearing structure

The solution with reinforced concrete slabs is the most recommended. It should be combined with floating floor to allow electrical systems installation and improve the flexibility of internal spaces.

The solution of reinforced concrete slab without false ceiling and systems exposed could be preferable because it is economically convenient, and the floor slab would perform better as thermal mass. In fact, it ensures to store heat during winter season (solar radiation exploitation) and to cool the building during summer one (natural ventilation exploitation).

Despite in such case it is important to provide acoustic strategies to improve acoustic comfort (ex. punctual acoustic panels on the workstation).

In Figure 3.16 an alternative to the reinforced concrete horizontal slab is illustrated. The detail shows a *predalle* slab type completed with floating floor and false ceiling, both for the installation of systems. Sometimes, in the false ceiling, the radiant panels for both heating and cooling are installed.



Legend

1. Internal plaster
2. Aluminium baseboard
3. Baseboard bracket
4. Baseboard dowel
5. Elastic joint
6. Floating floor substructure
7. Acoustic insulation
8. Floating floor horizontal substructure
9. Floating floor panel
10. Vertical Reinforcement
11. Horizontal Reinforcement
12. Pins
13. Dowel for fixing L-shape false-ceiling board profile
14. L-shape false-ceiling board profile
15. False ceiling plasterboard panel
16. False ceiling main substructure, T-shape
17. False ceiling secondary substructure, L-shape
18. False ceiling Suspension hook
19. False ceiling Pendant
20. Dowel
21. Predalles floor slab
22. Predalles floor slab
23. Concrete slab for floor slab with internal reinforcement (24)

25.-26. Linking reinforcement

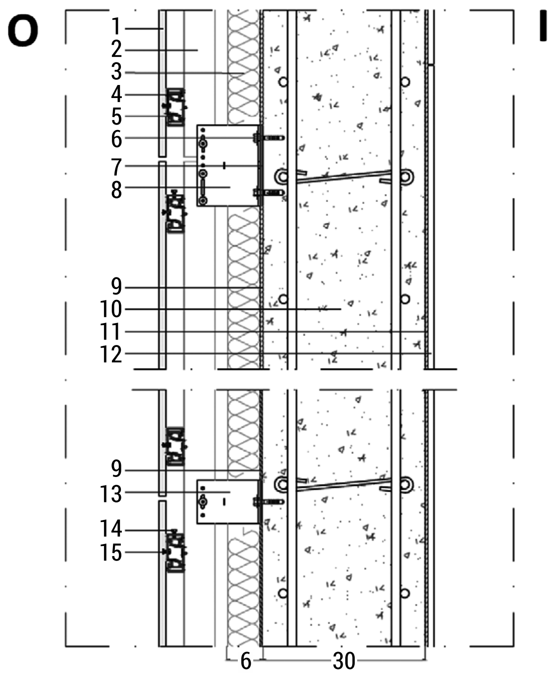
FIG. 3.16. Possible floor slab detail with predalles type solution completed with floating floor and false ceiling (Source: own elaboration)

Technological Solutions for the Building Envelope

External wall

The most recurring solutions for the external envelope are:

- Lightweight bricks for load-bearing layer with gypsum plaster as internal finishing, an external EPS insulation layer (thickness depends on climate zone and systems used for heating and cooling), rainscreen façade with aluminum substructure and several types of external finishing that are available on markets (aluminum panels, ceramics tiles etc.…). Sometimes they become ventilated façades as well. Figure 3.17.
- Glazing external wall (usually regardless orientation), using double skin façade or simple curtain wall. In this scenario, a specific attention to the type of glazing according to the climate and the orientation should be provided.



Legend
(outside-inside)

1. Cladding panel
2. Aluminium vertical sub-structure
3. Thermal insulation
4. Aluminium horizontal sub-structure
5. Clip
6. Dowel
7. EPDM thermal break
8. L-shape bracket
9. Adhesive
10. Reinforced concrete structure
11. Adhesive for external cladding
12. Internal finishing
13. C-shape bracket

FIG. 3.17. Possible technological solution with rainscreen façade and lightweight external finishing applied on a reinforce concrete load-bearing structure (Unipol Tower, Italy) (Source: own elaboration)

Airtightness of the envelope must be guaranteed to ensure proper internal thermal conditions.

For both cases PV panel should be integrated in the façade. For the first solution, PV panels disposed on the parapet should be preferable. It can be also sloped to improve the electricity production.

For the second solution, PV panels can be integrated into the transparent façade also creating a solar radiation protection.

As regard the thickness of insulation some considerations are needed.

The optimum thickness of insulation material depends on the answer to the question if it is economically convenient increasing the thickness of the insulation on the envelope or heating and cooling trough systems.

This answer is impacted through several parameters: climate conditions (heating dree-days – HDD and cooling degree-days CDD); composition of the external wall (ex. insulation type and its thermal properties); type of systems; type of energy source; costs of both material and the energy source.

In the following Table 3.4 the optimum thickness of insulation (looking at costs) is shown with respect to possible range of HDD (in this case according to current Italian standard) and 2 different types of system:

- System 1: condensing gas boiler (efficiency equal to 0.9) for both heating and service hot water and air conditioning system (seasonal performance factor equal to 2) for cooling and fan coils as terminals. The sources are gas and electricity.
- System 2: reversible heat pump (Heat Pump and Compression Chiller) for heating (COP = 3), cooling (COP = 2) and service hot water fan coils as terminals. The sources are both electricity and renewables.

TABLE 3.4. Optimum thickness of insulation for the envelope of an office building considering EPS insulation material with common thermal properties (λ=0.032 W/mK) considering 2 different type of system. In the table $T_{i,opt}$ means the thickness of insulation [cm] and $U_{i,opt}$ stands for thermal transmittance [W/m^{2}K] (Source: Miceli, 2016)

Heating Degree Days	System 1		System 2	
[kd/y]	$T_{1,opt}$ [cm]	$U_{1,opt}$ [W/m^{2}K]	$T_{2,opt}$ [cm]	$U_{2,opt}$ [W/m^{2}K]
600 < HHD < 900	7	0.26	6	0.29
900 < HHD < 1400	8	0.24	7	0.26
1400 < HHD < 2100	10	0.21	8	0.24
2100 < HHD < 3000	12	0.19	10	0.21

Roof

Roof could be opaque to permit preferably the installation of PV systems, or it can be a green roof. In the last case the roof stratigraphy become a passive strategy to improve the thermal indoor comfort.

If the office building has an atrium, the roof can be made by glazing openable elements (skylights) to permit natural ventilation and night cooling.

Glazing

Here below three examples of glazing adopted especially in Southern countries.

- Glass type 1: 6 mm Pyrolitic Clear Glass + 16 mm Argon + 44.2 laminated glass with PVB interlayer; properties: LSG=1.12, SHGC=0.63, VT=0.71, U=1.7 W/(m^2K).
- Glass type 2: 6 mm Spectral Selective Glass + 16 mm Argon + 44.2 laminated glass with PVB interlayer; properties: LSG=1.63, SHGC=0.41, VT=0.67, U=1.37 W/(m^2K).
- Glass type 3: 6 mm Low-e Spectral Selective Glass + 16 mm Argon + 44.2 laminated glass with PVB interlayer; properties: LSG=2.04, SHGC=0.24, VT=0.49, U=1.01 W/(m^2K).

Where: LGS stands for Light to Solar Gains ratio, SHGC means Solar Heat Gain Coefficient, VT is Visible Transmittance and U stands for thermal transmittance.

Window-to-Wall Ratio

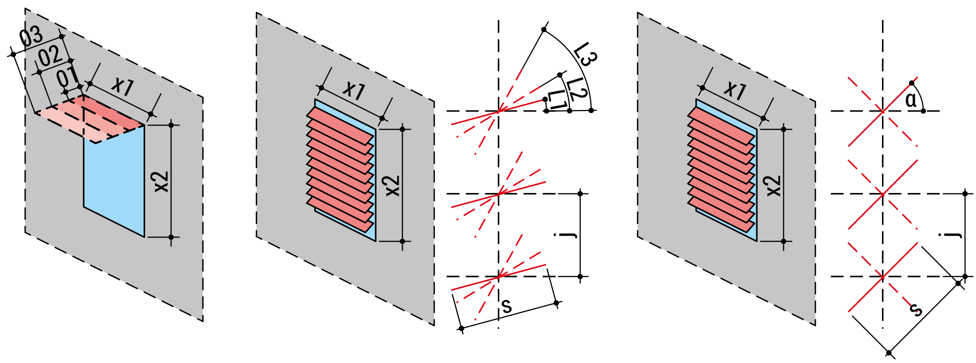
The design of the WWR parameter is fundamental (especially for those buildings characterised by curtain wall for most facades, regardless orientation), for the following reasons:

- It affects ad regulates the natural lighting within the offices functional units and can permit the optimization of the artificial lighting that is one of the main energy consumption.
- It permits the control of the solar radiation. For instance, WWR with higher values permit the reduction of the heating demand, while WWR with lower values reduce the overheating and the cooling demand.

In order to give proper recommendations about the adoption of WWR and to calculate how this solution impact on the energy demand of the building; different parameters are considered: climate conditions, different types of glasses (as detailed in the previous paragraph), the typology of solar shading devices (overhang or horizontal louvres for South orientation and vertical blinds for East/West orientations with high or low reflectance) (Fig. 3.18), the type of system (system 1 and system 2 as explained before) and the final energy demand.

It is worth to notice that for North orientation shading devices are not recommended.

Overhang	Horizontal louvres	Blinds (vertical for East/West orientation)



01 = 0.50 m;
02 = 1.00 m;
03 = 1.5 m;
x1 and x2 vary according to WWR
	L1 = 15°;
	L2 = 30°;
	L3 = 60° (fixed during year);
	s = 0.30 m;
	l = 0.15 m;
	x1 and x2 vary according to WWR
		0° < α < 180° during the year;
		s = 0.30 m;
		l = 0.15 m;
		x1 and x2 vary according to WWR
		M/H = Medium/High reflectance

FIG. 3.18. Different type of solar shading systems and related characteristics considered to recommend the advisable WWR for designing sustainable office buildings (Source: own elaboration based on Miceli, 2016)

The advisable solutions for WWR are detailed in the following Figure 3.19 considering 3 different cities belonging to different Italian climate zones:

- Milan (2100 < HHD < 3000 Kd/y).
- Florence (1400 < HHD < 2100 Kd/y).
- Palermo (600 < HHD < 900 Kd/y).

In the tables the colours green/yellow/red idientify the STRONGLY, LESS and NOT recommendeable actions. The different colours are outlined on the base of the difference (D) between the final energy demand of the considered solution and the one of the best configuration:

- STRONGLY: D < 5 kWh/(m^2year) – (+).
- LESS: 5 kWh/m^2year < D < 10 kWh/(m^2year) – (-).
- NOT: > 10 kWh/(m^2year) – (0).

Milan

System 1

South
Overhang

WWR	O1	O2	O3
20%	+	+	–
30%	+	+	+
40%	+	+	+
50%	–	+	+
60%	0	–	+
70%	0	–	–
80%	0	0	0
90%	0	0	0
100%	0	0	0

South
Horizontal Louvres

WWR	L1	L2	L3
20%	–	0	0
30%	–	0	0
40%	–	0	0
50%	+	–	–
60%	+	+	+
70%	+	–	–
80%	–	–	–
90%	0	0	0
100%	0	0	0

East
Vertical blinds

WWR	MVB	HVB
20%	–	+
30%	–	+
40%	–	+
50%	–	+
60%	0	+
70%	0	–
80%	0	0
90%	0	0
100%	0	0

West
Vertical blinds

WWR	MVB	HVB
20%	–	+
30%	–	+
40%	–	+
50%	0	+
60%	0	–
70%	0	0
80%	0	0
90%	0	0
100%	0	0

System 2

WWR	O1	O2	O3
20%	–	–	–
30%	–	+	–
40%	+	+	+
50%	–	+	+
60%	0	–	+
70%	0	0	–
80%	0	0	–
90%	0	0	0
100%	0	0	0

WWR	L1	L2	L3
20%	0	0	0
30%	0	0	0
40%	–	0	0
50%	+	–	–
60%	+	+	+
70%	+	+	+
80%	–	–	–
90%	0	0	0
100%	0	0	0

WWR	MVB	HVB
20%	0	–
30%	–	+
40%	–	+
50%	–	+
60%	–	+
70%	–	+
80%	0	–
90%	0	–
100%	0	0

WWR	MVB	HVB
20%	0	–
30%	0	+
40%	–	+
50%	–	+
60%	–	–
70%	–	0
80%	0	–
90%	0	–
100%	0	0

Florence

System 1

South
Overhang

WWR	O1	O2	O3
20%	+	–	–
30%	+	+	–
40%	+	+	+
50%	–	+	+
60%	0	+	+
70%	0	–	–
80%	0	0	–
90%	0	0	0
100%	0	0	0

South
Horizontal Louvres

WWR	L1	L2	L3
20%	0	0	0
30%	0	0	0
40%	–	0	0
50%	+	–	–
60%	+	+	+
70%	+	+	+
80%	–	–	–
90%	0	0	0
100%	0	0	0

East
Vertical blinds

WWR	MVB	HVB
20%	–	–
30%	–	+
40%	–	+
50%	–	+
60%	–	+
70%	0	–
80%	0	–
90%	0	–
100%	0	0

West
Vertical blinds

WWR	MVB	HVB
20%	0	–
30%	–	+
40%	–	+
50%	0	+
60%	0	+
70%	0	–
80%	0	–
90%	0	0
100%	0	0

System 2

WWR	O1	O2	O3
20%	–	–	–
30%	–	+	+
40%	+	+	+
50%	–	+	+
60%	0	–	+
70%	0	0	–
80%	0	0	0
90%	0	0	0
100%	0	0	0

WWR	L1	L2	L3
20%	0	0	0
30%	0	0	0
40%	–	0	0
50%	+	–	–
60%	+	+	+
70%	+	+	+
80%	–	–	–
90%	0	0	0
100%	0	0	0

WWR	MVB	HVB
20%	0	–
30%	–	+
40%	–	+
50%	–	+
60%	–	+
70%	–	+
80%	0	–
90%	0	–
100%	0	–

WWR	MVB	HVB
20%	0	–
30%	0	+
40%	–	+
50%	–	+
60%	–	+
70%	–	+
80%	0	–
90%	0	–
100%	0	0

Palermo

System 1

	South Overhang			South Horizontal Louvres			East Vertical blinds		West Vertical blinds	
WWR	01	02	03	L1	L2	L3	MVB	HVB	MVB	HVB
20%	+	+	+	–	–	0	0	–	0	0
30%	–	+	+	+	–	0	0	+	0	–
40%	0	+	+	+	–	–	0	+	0	+
50%	0	–	+	+	+	+	0	+	0	+
60%	0	0	–	+	+	+	0	+	0	+
70%	0	0	0	0	–	–	0	–	0	–
80%	0	0	0	0	0	0	0	–	0	–
90%	0	0	0	0	0	0	0	0	0	0
100%	0	0	0	0	0	0	0	0	0	0

System 2

	South Overhang			South Horizontal Louvres			East Vertical blinds		West Vertical blinds	
WWR	01	02	03	L1	L2	L3	MVB	HVB	MVB	HVB
20%	+	+	+	–	–	0	0	–	0	0
30%	–	+	+	+	–	0	0	+	0	–
40%	0	+	+	+	–	–	0	+	0	+
50%	0	–	+	+	+	+	0	+	0	+
60%	0	0	–	+	+	+	0	+	0	+
70%	0	0	0	0	–	–	0	–	0	–
80%	0	0	0	0	0	0	0	–	0	–
90%	0	0	0	0	0	0	0	0	0	–
100%	0	0	0	0	0	0	0	0	0	0

FIG. 3.19. Advisable WWR ratio for Milan, Florence e Palermo considering different types of glass, system, and shading devices (Source: own elaboration based on Miceli, 2016)

Systems and Renewables

For sustainable office buildings two configurations of systems are summarized: the first one (System 1) is a traditional solution, the second one (system 2) the most efficient:

- *System 1*: condensing gas boiler (efficiency equal to 0.9) for both heating and service hot water and air conditioning system (seasonal performance factor equal to 2) for cooling and fan coils as terminals. The sources are gas and electricity respectively.
- *System 2*: reversible heat pump (Heat Pump and Compression Chiller) for heating (COP=3), cooling (COP=2) and service hot water fan coils as terminals. The sources are both electricity and renewables.

Both configurations should be integrated with a monitoring system to manage and save energy for both heating and cooling. Therefore "System 2" is the most common and more recent system configuration and it permit the reduction of CO_2 since the exploitation of renewables.

As regard active strategies, PV panels are the most recommended to partly cover the electricity demand. According to different geometries (type A, B, C) it is possible to dispose PV system in several different configurations:

- On the roof (flat or sloped).
- On southern façade (ex. vertical position, entire sloped façade, sloped only the parapet, applied on solar shading systems).

It is worth to notice that to maximize electrical energy production:

- For high-rise office buildings (A rectangular or B square floor plan): PV panels should be disposed in a roof (both flat and sloped) and mainly positioned in the Southern façade that should be sloped.
- For low-rise office buildings: with internal courtyard (C) the best energy performance of the building is achieved with PV systems installed on the sloped roof and on southern façade that should be sloped.

With respect to lighting system the use of high-performance lamps (light power density equal to 8 W/m^2) is recommended as well as automatic daylight harvesting control and occupancy sensors.

Footnotes

[1] "Global Warming Potential (GWP) is defined as the cumulative radiative forcing, both direct and indirect effects, over a specific time horizon resulting from the emission of a unit mass of gas related to some reference gas (CO_2)." (Source: Iyyanki V. Muralikrishna,Valli Manickam (2017) Chapter Fourteen – Air Pollution Control Technologies, *Environmental Management*, pp. 337-397)

References

[1] Agenzia Nazionale Efficienza Energetica (ENEA). (2019) Report *Benckmark di onsumo enegetico degli edifici per uffici in Italia*. Available from https://www.enea.it/it/Stampa/File/Rapporto_BenchmarkConsumiUffici_EneaAssoimmobiliare_2019.pdf [Accessed on 25.01.2022].

[2] Agenzia Nazionale Efficienza Energetica (ENEA). (2020) Report *Rapporto annuale 2020. Certificazione Energetica degli edifici*. Available from https://www.pubblicazioni.enea.it/le-pubblicazioni-enea/edizioni-enea/anno-2020/rapporto-annuale-sulla-certificazione-energetica-degli-edifici-2020.html [Accessed on 24.01.2022].

[3] Agenzia Nazionale Efficienza Energetica (ENEA). (2021) Report *RAEE2021 Rapporto Annuale Efficienza Energetica*. Available from https://www.efficienzaenergetica.enea.it/pubblicazioni/raee-rapporto-annuale-sull-efficienza-energetica/rapporto-annuale-sull-efficienza-energetica-2022.html [Accessed on 26.01.2022].

[4] Arredi, M.P. (2004) Ediliza per uffici. Progettare metodi tecniche norme realizzazioni. UTET, Torino. ISBN: 978-8802061504.

[5] Bazzocchi, F., Di Naso, V., Miceli, S. (2013) Toward NZEB Office Buildings. *Conference Proceedings of 39th World Congress on Housing Science*, 2, 135-141, September 2013, Milano.

[6] Bianco, V., Marmori, C. (2022) Modelling the development of energy efficiency measures for the residential sector. The case of Italy. *Sustainable Energy technologies and Assessents*, 49, 101777.

[7] Capitaneo, L. (2014) Bachelor's Thesis Un progetto di social housing nel Comune di Prato, Tesi per il Corso di Laurea in Scienze dell'Ingegneria Edile, Scuola di Ingegneria. Supervisor: Prof. Vincenzo Di Naso.

[8] EASE. (2015) EASE Guidebook. Sunspaces and Atria, Eduation for Architects in Solar Energy, Section 2.2.

[9] European Commission. (2010) European Directive (EU) 2010/31 of 18 June 2010 of the European parliament and of the Council of 19 May 2010 on the energy performance of buildings.

[10] European Commission. (2018) European Directive (EU) 2018/2002 of 21 December 2018 of the European parliament and of the Council of 11 December 2018 on amending Directive 2012/27/EU on energy efficiency.

[11] Fabrizio, E., Guglielmino, D., Monetti, V. (2011) Italian benchmark building models: The Office Building. *Conference Proceedings of 12th Conference of international Building performance Simulation Association*, 14-16 November 2011, Sydney.

[12] Fisch, M.N., Wilken T., Stähr C. (2013) EnergyPLUS Buildings and districts as renewable energy sources. Dr. M. Norbert Fisch, Leonenberg. ISBN 978-3-00-041246-2

[13] Galateo, S. (2016) Lucano Pia 25 Green. I grandi temi dell'architettura. I condomini, 29, 58-63.

[14] Italian Government. (1993) Regolamento Recante Norme per la Progettazione, L'installazione, L'esercizio e la Manutenzione Degli Impianti Termici Degli Edifici ai fini del Contenimento dei Consumi di Energia, in Attuazione dell'art. 4, Comma 4, della L. 9 Gennaio 1991, n. 10 (2) (3).

[15] Italian Government. (2015) Ministerial Decree of 26 Giugno 2015 Applicazione Delle Metodologie di Calcolo Delle Prestazioni Energetiche e Definizione Delle Prescrizioni e dei Requisiti Minimi Degli Edifici.

[16] Istituto Nazionale di Statistica (ISTAT). (2018) Report Censimento ISTAT 2018 Sugli Edifici Residenziali e Non. 18 Costruzioni. [Online] Available from https://www.istat.it/it/files/2015/12/C18.pdf [Accessed on 24.01.2022].

[17] Lusardi, A. (2008) Angelo Mingozzi Il quartiere residenziale sostenibile di Villa fastiggi (PS). Costruire in laterizio, 125, 40-45.

[18] Magrini, A. Ena, D. (2008) Tecnologie solari attive e passive. EPC Libri, Roma. ISBN: 9788881844210

[19] Miceli, S. (2013) Architectural design for nZEB office buildings. *Conference proceedings* of Forum of Young Researchers in Sustainable buildings. Low-tech and high-tech solutions for buildings, 25-26 June 2013, Prague.

[20] Miceli, S. (2016) The methodology to identify design criteria for energy efficient office buildings and a case study. Conference proceedings of World Sustainable Energy Days, February 2016, Wels.

[21] Miceli, S. (2016) PhD Thesis Investigation of deisgn criteria for energy efficient office buildins in Italy, Tesi di Dottorato in International Doctorate in Civil and Environmental Engineering, Dipartimento di Ingegneria Civile e ambientale, Università di Firenze e Department of Architecture, Civil Engineering and Environmental Sciences, University of Braunschweig. Superviors: Proff. Frida Bazzocchi, M. Norbert Fisch, Vincenzo Di Naso.

[22] Respi, R. (2015) Zaha Hadid Architects CMA CGM Tower. *I grandi temi dell'architettura. Headquarters*, 18, 58.

[23] Secretariat REN21. (2021) Report *Renewables 2021 Global Status Report*. [Online] Available from https://www.ren21.net/gsr-2021/ [Accessed on 26.01.2022].

[24] Valori, A. (2012) PhD Thesis Metodi e tecniche di progetto per edifici residenziali sostenibili, Tesi di Dottorato in Ingegneria Civile e Ambientale, Ciclo XXIV, Curriculum: Edilizia e Territorio, Facoltà di Ingegneria. Supervisors: Proff. Franco Nuti, Frida Bazzochi, Giuseppe Grazzini.

[25] WEB–1: European Commission. (2020) *A Renovation Wave*. [Online] Available from: https://eur-lex.europa.eu/resource.html?uri=cellar:0638aa1d-0f02-11eb-bc07-01aa75ed71a1.0003.02/DOC_1&format=PDF [Accessed on 20.01.2022].

[26] WEB–2: European Commission. (2015) *Paris Agreement*. [Online] Available from: https://ec.europa.eu/clima/eu-action/international-action-climatechange/climate-negotiations/paris-agreement_en [Accessed on 20.01.2022].

[27] WEB–3: European Commission. (2015) *Sustainable Development Goals*. [Online] Available from: https://ec europa eu/international partnerships/sustainable development goals_en [Accessed on 26.01.2022].

[28] WEB–4: Luciana Sympa. (2011) *Joachim Eble, maestro della bioarchitettura*. [Online] Available from: https://ec.europa.eu/clima/eu-action/international-action-climatechange/climate-negotiations/paris-agreement_en [Accessed on 25.01.2022].

[29] WEB–5: Archingegno. (2010) *Uovo di struzzo con occhi di mosca*. [Online] Available from: http://www.archingegnobio.it/ [Accessed on 25.01.2022].

[30] WEB–6: Mario Cucinella Architects. (2007) *Casa 100k* [Online] Available from: https://www.mcarchitects.it/project/casa-100k [Accessed on 26.01.2022].

[31] WEB–7: Erika Seghetti. (2020) *Bullit center: una lezione di greenbuilding* [Online] Available from: https://www.green.it/bullitt-center-greenbuilding/ [Accessed on 18.02.2022].

[32] Zonato, R. (2019) Master Thesis Analisi multiscala del quartiere ecologico "EVA LANXMEER" dal principio al materiale nella costruzione di un valore. Politecnico di Torino, Dipartimento di Architettura e Design. Supervisor: Prof. Andrea Bocco.

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4. EUROPEAN LOW ENERGY BUILDING

4.1. Low Energy Building and its Meaning in 2022

The concept of low energy buildings is changing continuously with frequent changes to regulations, requirements and law acts to comply with. Actual energy consumption factors are significantly lower that it could be predicted several years ago, especially in case of primary energy facts that take into account renewable energy sources. Anyway, due to external conditions like local climate parameters or availability of renewable energy sources (RES), national concepts of low energy buildings or nZEBs differ.

Consequently, every few years, new national regulations regarding heat transfer coefficients of external barriers like roofs, windows or walls are changed and the values are reduced. In countries located in northern and eastern Europe, like Poland, Lithuania or Latvia, it is crucial to ensure low heat losses in winter, because of significantly low external temperatures, hence high difference between indoor and outdoor temperature. According to guide (Passivhaus Institut, Passive House Component Guidelines) Latvia and Lithuania are defined as cold, while Poland cold/cool temperate. Current requirements for the maximum U values (heat transfer coefficients) for new buildings are shown in Table 4.1.

TABLE 4.1. U values in Poland, Lithuania and Latvia (Source: own elaboration based on Announcement of the Minister of Investment and Development of 8 April 2019; Muranoa et al., 2017; WEB–1; WEB–2)

	Country		
Type of barrier [W/m^{2}K]	Poland	Lithuania	Latvia
External wall [W/m^{2}K]	0.20	0.12k	0.18k’
Roof [W/m^{2}K]	0.15	0.10k	0.15k’
Window [W/m^{2}K]	0.90	1.00k	1.30k’

* k = 20/(θi − θe),– temperature correction factor, where θi = indoor air temperature in degrees Celsius, θe = outdoor air temperature or design temperature of adjacent space in degrees Celsius. Temperature of unheated spaces is determined separately. If indoor air temperature θi = 20°C and outdoor air θe = 0°C, then k = 1

** k’ = 19//(θi − θe), depending on climate zones, k’ for residential buildings is from 0.95 (Liepāja) to 1.09 (Alūksne)

In countries located in southern Europe, like Spain or Italy, the limit is significantly higher (Table 4.2). According to guide (Passivhaus Institut, Passive House Component Guidelines) Italy is cool temperate/warm temperature/warm depending on its part, while Spain as warm temperature/warm.

TABLE 4.2. U values in Spain and Italy (Source: own elaboration based on Borrallo-Jiménez et al., 2022; Bac et al., 2022; Ministerio de Fomento, 2019; Berardi et al., 2018; Muranoa et al., 2017)

	Country	
Type of barrier [W/m^{2}K]	Spain	Italy
External wall [W/m^{2}K]	0.56	0.26-0.43
Roof [W/m^{2}K]	0.44	0.25-0.35
Window [W/m^{2}K]	2.30	1.40-3.00

National requirements differ significantly, not only between themselves but also in comparison with other local and regional regulations. On the one hand in some cases, for example in Poland, U limits are clear and constant for the whole country, while in other cases they depend on a country zone. Moreover, as shown by Borrallo-Jimenez et al. (Borrallo-Jiménez et al., 2022), the regulations of the Spanish Technical Building Code (Ministry of Public Works and Transport, Royal Decree, 2019) consider several climate classifications, adjusting their requirements to the climatic zone of the new building, whereas the Passive House (PH) rules (Muranoa et al., 2017) for warm climates take into account two climate classifications for Spain. Moreover, requirements related to the usage of RESs and primary energy factors come and go. EPDB 2010 recast (European Parliament, Council of the European Union, 2010) promotes the usage of RES, as well as cost-optimal technologies that guarantee a healthy and comfortable environment.

In case of nZEBs, the limiting and optimizing values of U values are more complicated, than for PHs or low energy buildings, as they cannot be easily established. It is important to improve the energy performance of buildings not only by reduction of heat transfer coefficients of external barriers. Thus, it is crucial to combine low energy HVAC, DHW and lighting systems and smart technologies with renewable energy sources (D'Agostino et al., 2021).

Similar approach to achieving the of nZEBs level was presented by Firlag and Piasecki (Firlag & Piasecki, 2018). Fabrizio (Fabrizio, 2020) noted that the design of a ZEB required a holistic approach and its target could be reached with the best combination of envelope, systems and energy sources, under technical and financial constraints that change in space and time.

In Poland, Bac (Bac, 2022) studied the level of awareness of Polish architects regarding the possibilities of improving the energy efficiency of buildings, the use of energy performance, and the achievement of the nZEB standard. Martinez-de-Alegria et al. (Martinez-de-Alegria et al., 2021) analyzed a set of certified PH buildings and found that they met requirements for nearly zero-energy buildings under the Spanish certification system.

D'Agostino et al. (D'Agostino et al., 2021) reported examples of nZEBs best practices from many countries like Poland, France, Germany, Bulgaria, Croa-tia, Austria etc. They set the lowest value of external wall U coefficient at the level of 0.08 W/(m^{2}K), while the highest U = 0.4 W/(m^{2}K) was found in Croa-tia. In case of windows, the values were between 0.27 (Estonia) and 1.76 W/(m^{2}K) (France). The heat transfer coefficient for roofs differed from 0.07 (Poland) to 0.26 W/(m^{2}K) (Bulgaria).

4.2. Examples of low Energy Buildings Located in Several EU Countries

4.2.1. Description of the Building With Low Energy Consumption

The building of Laboratory of Energy Efficient Architecture and Renewable Energy (LEEARE) was chosen as a model facility that is characterized by low energy consumption. It was established in August 2015 and is located at the Faculty of Architecture of the Bialystok University of Technology (BUT). The author of the idea and the conceptual design was D.Arch. Adam Turecki, and the design was prepared by architect Andrzej Rydzewski. LEEARE was made as part of a multi-stage project financed 80% by the European Union and 20% by BUT. The title of this project was "Study of the effectiveness of active and passive methods to improve the energy efficiency infrastructure located at BUT and supported by renewable energy sources". More information on this subject was presented in publication (Żukowski, 2017). This laboratory building was designed to be used as a typical single-family building (Fig. 4.1). It has a basement and two overground storeys. Net conditioned building area, denoted in further calculations as A_{net}, is 177.47 m^2.

FIG. 4.1. Laboratory of Energy Efficient Architecture and Renewable Energy – south facade (Source: photo by M. Żukowski)

The facility contains many modern solutions and technologies that use renewable energy sources. These are thermal solar collectors (TSC) for domestic hot water (DHW) heating, photovoltaic (PV) panels and wind turbines. The source of energy is a ground-water heat pump. A ventilated Double Skin Facade (DSF) is a passive element used to increase the heat gain from solar radiation. Building partitions are characterized by very high thermal insulation. Their characteristics are presented in Table 4.3.

TABLE 4.3. U values [W/m^2 K] of selected partitions (Source: own elaboration)

Type of partition	U value [W/m^2 K]
External wall	0.113
Wall below grade	0.175
Ground floor	0.136
Roof	0.080
External window	0.780
Internal window	1.512

4.2.2. Model of the Building and HVAC Systems

In order to determine the energy performance of the building studied in this chapter, its model was developed. The DesignBuilder software was used for modelling the body of the laboratory building as well as heating and ventilation systems. Figure 4.2 shows the layout of the test object. A render view without the basement but with two solar thermal collectors and a photovoltaic array is shown in Figure 4.3. The shading of the building is set for April 15 at 11 am.

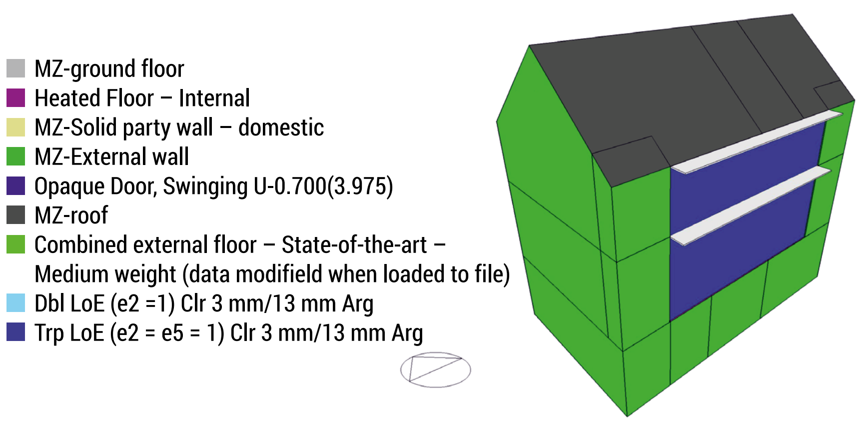

FIG. 4.2. Model of the building body including the type of partitions (Source: own elaboration)

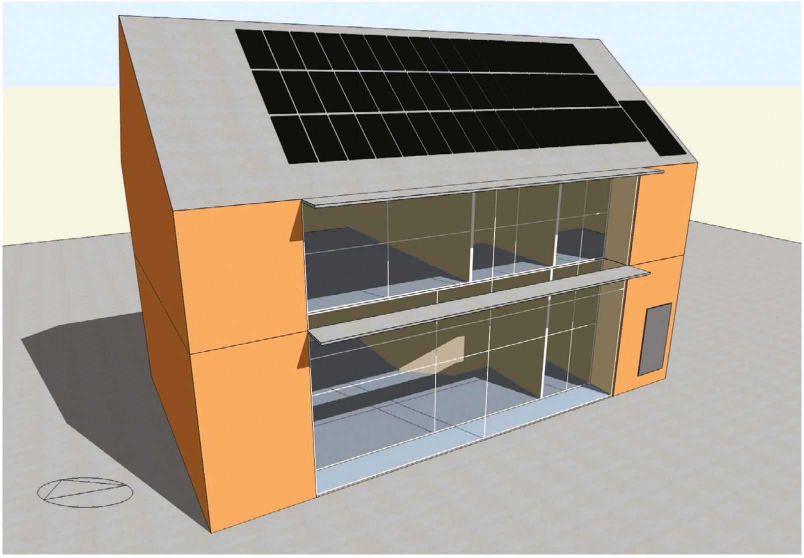

FIG. 4.3. View of the laboratory building with solar collectors on the roof and one on the facade (Source: own elaboration)

The energy source is a glycol-water heat pump with a ground heat exchanger, which consists of 4 vertical probes 100 m deep (Fig. 4.4). The conditioned spaces are heated by means of underfloor heating. The building is equipped with a mechanical ventilation with a heat recovery unit from the exhaust air. The air from the toilets is exhausted directly to the outside. The production of domestic hot water (DHW) is supported by two solar collectors with a total area of 3.97 m^2 (Fig. 4.5). One is on the roof and the other on the south facade. The heat is stored in a water tank with a capacity of 750 liters. The demand for DHW is estimated at 99.79 m^3. The photovoltaic system consists of 48 PV modules BP585 with dimensions of 1209 mm by 537 mm and a maximum power of 85 W.

In order to demonstrate the influence of climatic parameters on the building characteristics, the following five locations in Europe were selected:

- Bialystok (Poland),
- Kaunas (Lithuania),
- Helsinki (Finland),
- Bologna (Italy),
- Cordoba (Spain).

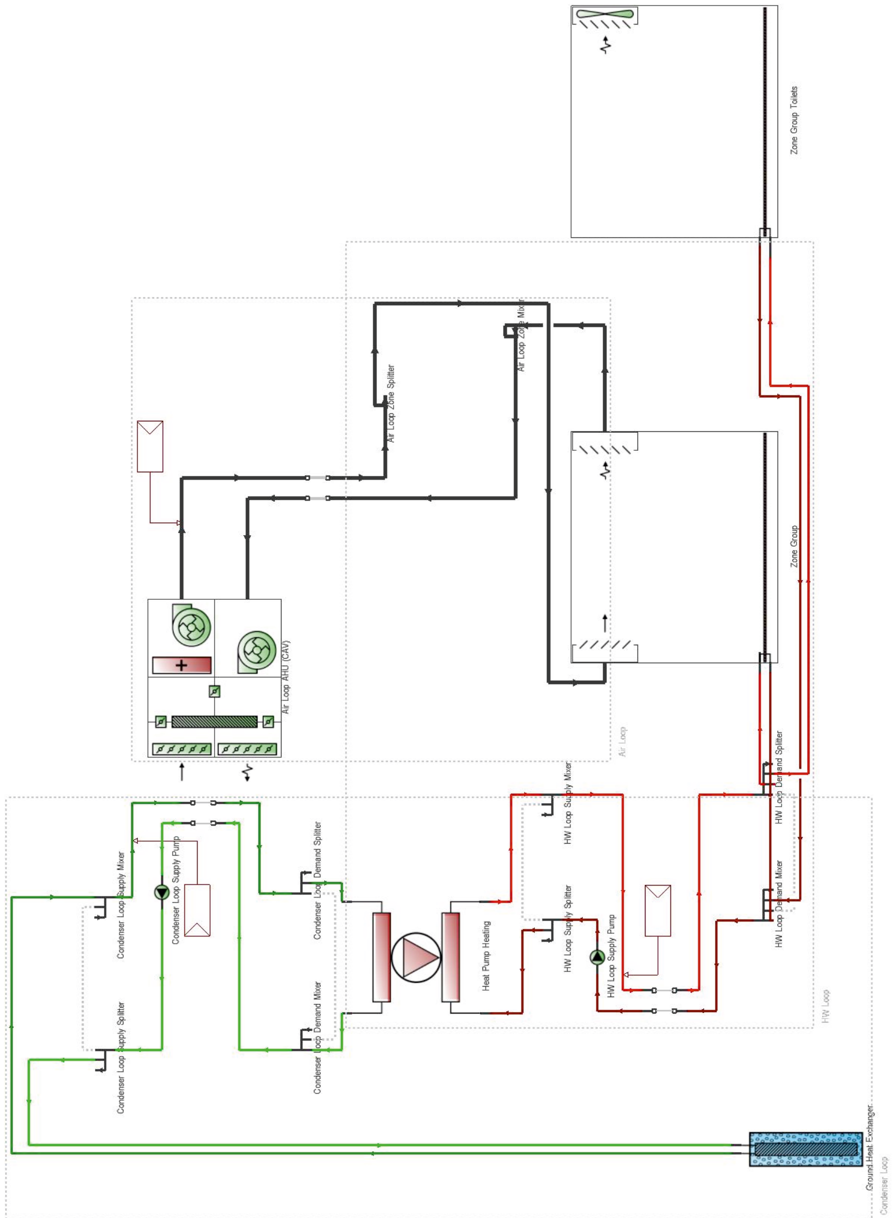

FIG. 4.4. Scheme of the heating and ventilation system (Source: own elaboration)

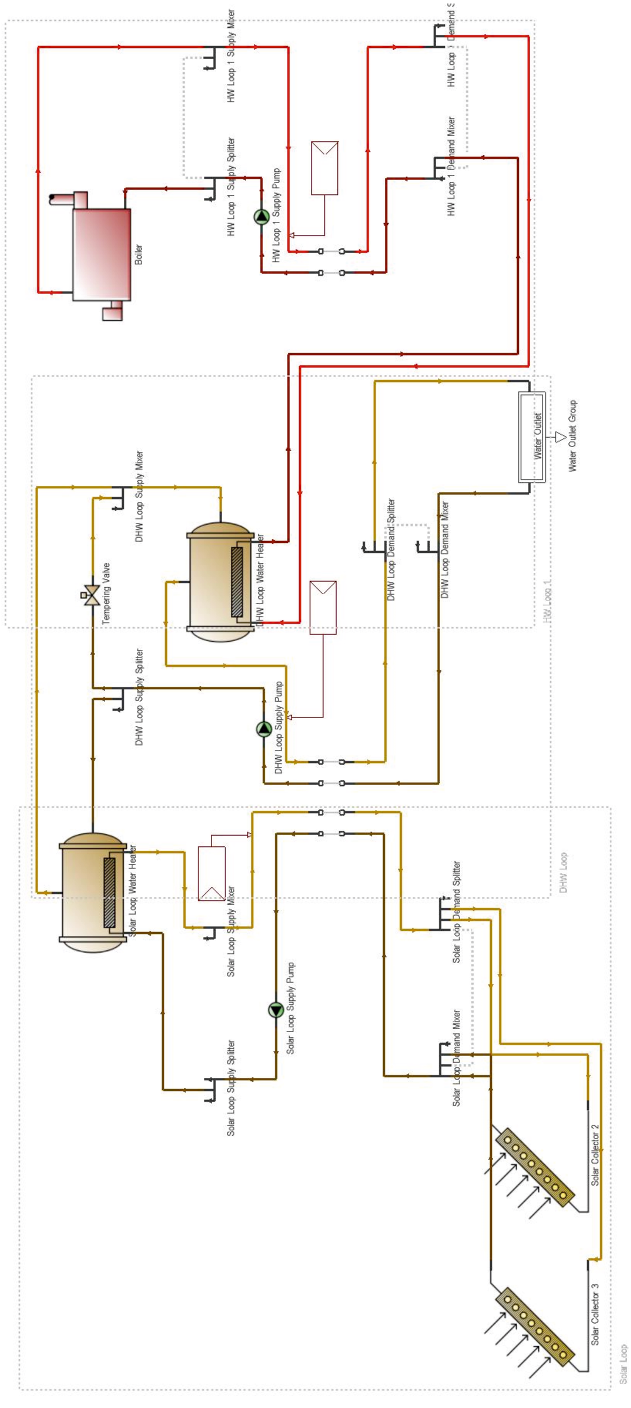

FIG. 4.5. Scheme of the solar domestic hot water system (Source: own elaboration)

Many climatic parameters influence the energy consumption of a building. Average monthly value of solar radiation intensity (Fig. 4.6, Fig. 4.7) and dry bulb temperature (Fig. 4.8) were selected for comparison. The highest intensity of direct solar radiation is in Cordoba. It is over four times higher than in Bialystok and almost two and a half times higher than in Bologna. In the case of diffuse radiation, it is the lowest in Cordoba in summer and the highest in winter. In other locations, the distribution of this radiation fraction is almost similar. Cordoba has by far the highest outside air temperature, especially in winter. The temperature in Bologna is slightly lower, while Bialystok, Kaunas, and Helsinki have a similar but significantly lower outside air temperature.

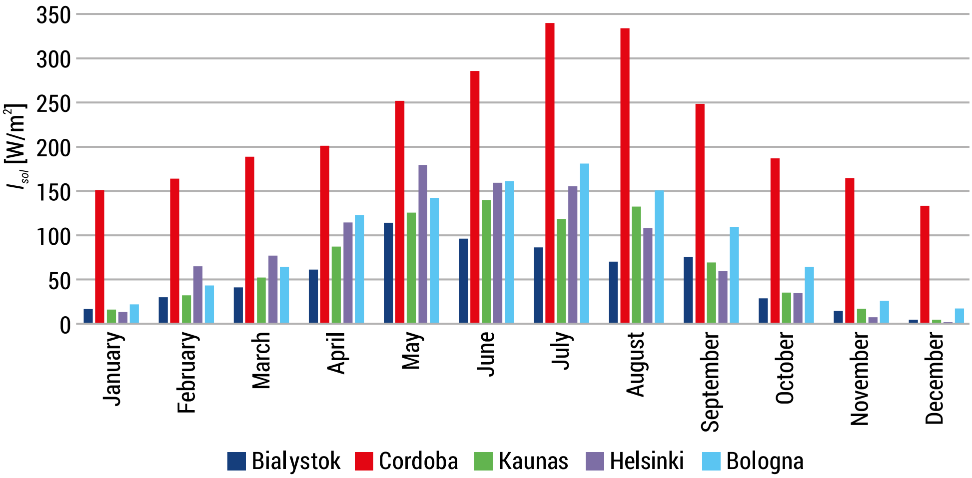

FIG. 4.6. Average monthly direct solar radiation rate per area [W/m^2] (Source: own elaboration)

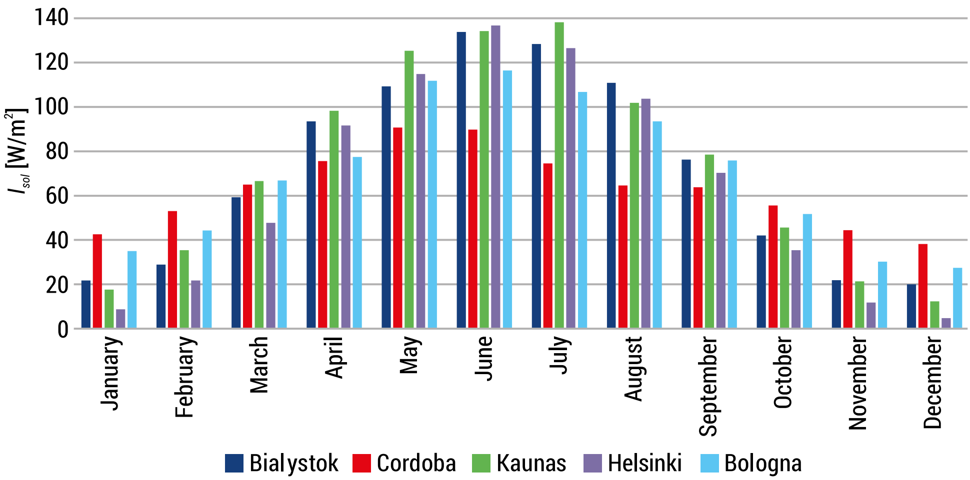

FIG. 4.7. Average monthly diffuse solar radiation rate per area [W/m^2] (Source: own elaboration)

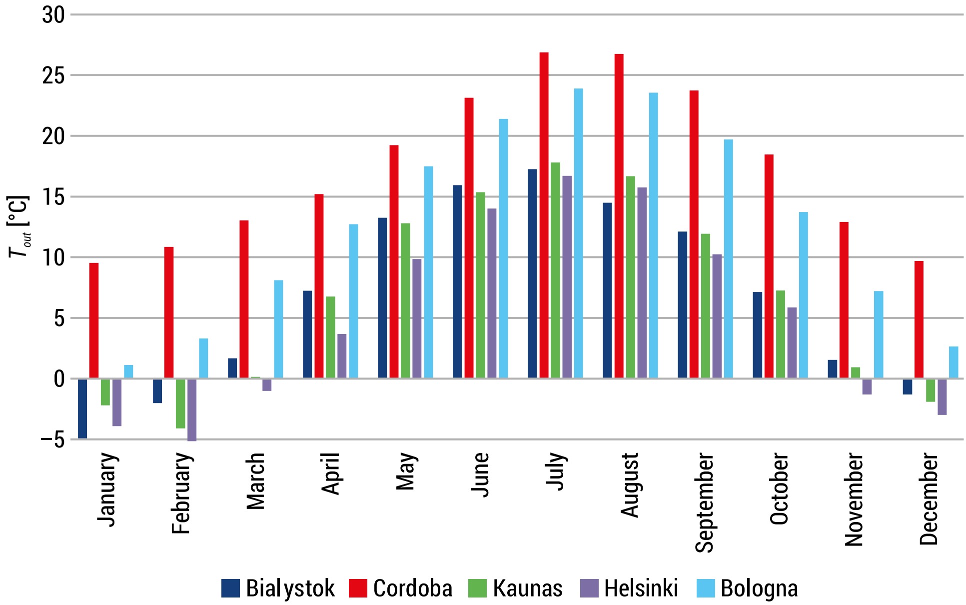

FIG. 4.8. Average monthly outdoor air dry-bulb temperature [°C] (Source: own elaboration)

4.2.3. Results of Simulations

Multivariate calculations were made over a period of one year for a typical meteorological year. First, the amount of energy needed to heat the building was determined. The simulation results for five locations are presented in Table 4.4. The E_F symbol denotes the final energy consumed by the building. It includes energy for heating, ventilation, DHW production and lighting. Total domestic primary energy demand, which is harvested directly from natural resources, has been marked as E_P. The Primary Energy Factor (*PEF*) was used to determine the E_P value and is defined as:

$$PEF = \frac{E_P}{E_F} \tag{4.1}$$

The value of coefficient *PEF* was assumed to be 2.5 for grid supplied electricity.

TABLE 4.4. Results of calculations of yearly energy demand (Source: own elaboration)

	Bialystok	Kaunas	Helsinki	Bologna	Cordoba
E_F [kWh]	7383.4	7249.0	7885.9	5803.4	4780.1
E_P [kWh]	18458.5	18122.4	19714.9	14508.4	11950.4

Obviously, the lowest energy consumption is in Cordoba. This is due to the highest values of the average temperature of the outside air and the intensity of solar radiation. Energy demand is around 20% higher in Bologna. However, in other locations, primary energy consumption is over 50% higher than in Cordoba.

Table 4.4 shows the R_{EF} and R_{EP} coefficients determining the energy consumption related to m^2 of space with controlled temperature:

$$E_{PF} = \frac{E_F}{A_{net}} \tag{4.2}$$

$$E_{PP} = \frac{E_P}{A_{net}} \tag{4.3}$$

The building's energy class was assessed on the basis of the Building Energy Rating (*BER*) value and is included in the last row of Table 4.5. The following primary energy consumption levels in kWh/m^2 were assumed for the building's energy category:

- $E_P < 25$ kWh/(m^2 year) – A1
- $E_P > 25$ kWh/(m^2 year) – A2
- $E_P > 50$ kWh/(m^2 year) – A3
- $E_P > 75$ kWh/(m^2 year) – B1
- $E_P > 100$ kWh/(m^2 year) – B2
- $E_P > 125$ kWh/(m^2 year) – B3
- $E_P > 150$ kWh/(m^2 year) – C1
- $E_P > 175$ kWh/(m^2 year) – C2
- $E_P > 200$ kWh/(m^2 year) – C3

TABLE 4.5. Yearly energy consumption per unit of conditioned area (Source: own elaboration)

	Bialystok	**Kaunas**	**Helsinki**	**Bologna**	**Cordoba**
E_{PF} [kWh/m^2]	41.60	40.85	44.44	32.70	26.93
E_{PP} [kWh/m^2]	104.01	102.12	111.09	81.75	67.34
Building Energy Rating (*BER*)	B2	B2	B2	B1	A3

The first three locations, i.e. Bialystok, Kaunas and Helsinki, have B2 in terms of energy consumption and a house with such characteristics cannot be classified as energy-efficient. The situation is slightly better in Bologna, and this type of building located in Cordoba already has a demand for non-renewable energy slightly below the upper limit of the energy-saving building.

The above results do not take into account the other energy sources using conversion of solar radiation technology. The next Table (4.6) compares the amount of energy produced by thermal solar collectors and photovoltaic cells.

TABLE 4.6. Yearly energy converted by solar collectors and photovoltaic cells (Source: own elaboration)

	Bialystok	**Kaunas**	**Helsinki**	**Bologna**	**Cordoba**
Thermal solar collectors [kWh]	1186.4	1318.9	1459.3	1466.8	2468.4
Photovoltaic cells [kWh]	3199.7	3680.3	3820.7	4084.4	6635.1

Based on the analysis of the results in Table 4.6, it can be seen that renewable energy systems are most efficient when they are located in Cordoba. The amount of energy obtained as a result of solar radiation conversion is almost double that of other locations.

Having considered renewable energy sources, a clear improvement in the level of primary energy consumption can be noticed (Table 4.7). This time, the buildings in Bialystok, Kaunas and Helsinki have BER at A2 level. The same building located in Bologna should be classified as passive, or actually almost zero-energy.

TABLE 4.7. Yearly energy consumption including renewable energy sources (Source: own elaboration)

	Bialystok	**Kaunas**	**Helsinki**	**Bologna**	**Cordoba**
E_{EF} [kWh]	2997.3	2249.8	2606.0	252.2	−4323.4
E_{EP} [kWh]	7493.3	5624.4	6514.9	630.5	< 0
R_{EP} [kWh/m^2]	42.22	31.69	36.71	3.55	< 0
Building Energy Rating (*BER*)	A2	A2	A2	A1	A1

This type of analysis should end with identifying those elements that have the greatest impact on the building's energy consumption. For this purpose, an exemplary percentage energy balance was prepared for a building located in Bialystok. As can be easily seen from the graph shown in Fig. 4.9, the biggest components of this balance are: energy consumption generated by electrical equipment, indoor lighting, and fans. Thus, in order to further reduce the level of energy consumption of this facility, it would be necessary to use computer and office equipment with a lower energy demand and to use more energy-efficient lighting that automatically controls its operation. A big source of savings can also be the replacement of the air handling unit with a more energy-efficient one or only the replacement of the fans and the use of control of their operation based on the concentration of carbon dioxide.

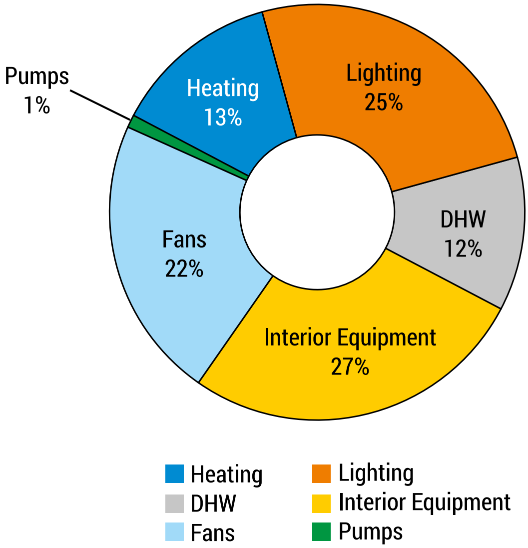

FIG. 4.9. Balance of final energy consumption (Source: own elaboration)

4.2.4. Summary of the Analysis and Conclusions

According to the regulations in force in the European Union, currently built houses must have a low demand for non-renewable energy. This chapter covers the analysis of a building with low energy consumption. The object of research was a laboratory building located at the Faculty of Architecture of Bialystok University of Technology. Its external partitions are characterized by a very high thermal resistance. Besides, a double skin facade was also designed to maximize heat gain from solar radiation. Various renewable energy systems were used in this building, such as: ground heat pump with vertical probes, thermal solar collectors and photovoltaic cells. The use of these types of technologies allowed for a significant reduction in the demand for primary energy compared to standard design solutions used in construction.

Currently, it is considered an energy-efficient house that consumes less than 70 kWh/(m^{2}year), low-energy from 15 to 30 kWh/(m^{2}year), passive from 0 to 15 kWh/(m^{2}year), and zero-energy that is the object does not consume primary energy. Based on the analysis, it should be concluded that the laboratory building meets the criteria of an energy-efficient house for three locations: Bialystok, Kaunas and Helsinki. It could be called passive in case we locate this building in Bologna. This house would produce more energy than it consumes, if built in the Cordoba area.

In the building, that is the object of this analysis, no air cooling devices are installed and only passive methods are used. Of course, in the summer this worsens the thermal comfort in towns such as Bologna and, above all, Cordoba. The use of air conditioning devices would significantly increase the demand for non-renewable energy. However, it should be noted that the excess energy produced by the photovoltaic system in Cordoba can be used to power air conditioning units during the summer. Thus, further energy analysis should take into account HVAC systems specif-ic for local needs.

Acknowledgments

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References

[1] Announcement of the Minister of Investment and Development of 8 April 2019 on the publication of the uniform text of the Regulation of the Minister of Infrastructure on technical conditions to be met by buildings and their location. (2019) [Online] Available from: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20190001065/O/D20191065.pdf.

[2] Bac, A. (2019) Research into the Possibility of Achieving the NZEB Standard in Poland by 2021 – Architect's Perspective. *Sustainability in Energy and Buildings*, 163, 665-675.

[3] Berardi, U., Tronchin, L., Manfren, M., Nastasi, B. (2018) On the Effects of Variation of Thermal Conductivity in Buildings in the Italian Construction Sector. *Energies 2018*, 11(4), 872 [Online] Availble from: https://doi.org/10.3390/en11040872.

[4] Borrallo-Jiménez, M., Lopez De Asiain, M., Esquivias, P.M., Delgado-Trujillo, D. (2022) Compa-rative study between the Passive House Standard in warm climates and Nearly Zero Energy Buildings under Spanish Technical Building Code in a dwelling design in Seville. *Energy&Buildings*, 254, 111570.

[5] D'Agostino, D., Tzeiranaki, S.T., Zangheri, P., Bertoldi, P. (2021) Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe. *Energy Strategy Reviews*, 36, 100680.

[6] Fabrizio, E. (2020) Zero Energy Buildings: A Reached Target or a Starting Point? *Appl. Sci. 2020*, [Online] Available from: 10(2), 512; https://doi.org/10.3390/app10020512.

[7] Firlag, Sz., Piasecki, M. (2018) NZEB Renovation Definition in a Heating Dominated Climate: Case Study of Poland. *Appl. Sci. 2018*, 8(9), 1605, [Online] Available from: https://doi.org/10.3390/app8091605.

[8] European Parliament, Council of the European Union. (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).

[9] Martinez-de-Alegria, I., Rio, R-M., Zarrabeitia, E., Álvareza, I. (2021) Heating demand as an energy performance indicator: A case study of buildings built under the passive house standard in Spain. *Energy Policy*, 159, 112604.

[10] Ministerio de Fomento (Ministry of Public Works and Transport). (2019) CTE-DB-HE Energy Saving (Documento Básico HE Ahorro de Energía), in: Código Técnico de La Edificacion, [Online] Available from: p. 50. http://www.arquitectura-tecnica.com/hit/Hit2016-2/DBHE.pdf [Accessed on 27.11.2021].

[11] Ministry of Public Works and Transport. (2019) Royal Decree 732/2019, 20th December, that modifies the Technical Building Code, [Online] Available from: https://www.boe. es/boe/dias/2019/12/27/pdfs/BOE-A-2019-18528.pdf.

[12] Murano, G., Ballarinia, I., Dirutiglianoa, D., Primoa, E., Corrado, V. (2017) The significant imbalance of nZEB energy need for heating and cooling in Italian climatic zones. *Energy Procedia* 126, 258–265.

[13] Passivhaus Institut, Passive House Component Guidelines, (n.d.). [Online] Available from: https://passiv.de/maps/component_guidelines/ (accessed 12 January 2021)

[14] WEB–1: Robertas, E., Baranauskas, T., (2018) Implementation of the EPBD in Lithuania [Online] Available from: https://epbd-ca.eu/ca-outcomes/outcomes-2015-2018/book-2018/countries/lithuania [Accessed on 27.11.2021].

[15] WEB–2: Edgars Garkājis, Rūta Mājeniece (2016) Implementation of the EPBD in Latvia [Online] Available from: https://epbd-ca.eu/ca-outcomes/outcomes-2015-2018/book-2018/countries/latvia [Accessed on 28.11.2021].

[16] Żukowski, M. (2017) HVAC systems supported by renewable energy sources – case studies carried out at Bialystok University of Technology, *Advances in Renewable Energy Research*, 33–44. [Online] Available from: https://doi.org/10.1201/9781315148670.

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5. RAINSCREEN SYSTEM

5.1. Introduction

In the context of envelope systems, the attention must be paid to buildings' energy and environmental issues; defining solutions that allow energy savings (Alagna, 2007), increase internal comfort conditions (Bazzocchi, 2002), easy to build, suitable for several context as well as durable. Compared to traditional models, these are systems that made the external envelope increasingly developed in a set of complex techniques, integrating architectural, structural, energy and systems features. Thus, the vertical closure becomes one of the most important technological elements in the design, to provide the best well-being conditions for the occupants in relation to functional peculiarities and its context. This happens because the vertical closure is the real filter between inside and outside, becoming the interface between systems that absorbs and releases heat, cools, changes air in the rooms and regulates natural lighting entry, etc.

On this regard, the main current interests are increasingly focused on the overall performance of the building, especially in reference to energy savings, including by means of automation processes, developing standardisation and prefabrication techniques of buildings construction and improving traditional products performance through new and environmentally friendly uses.

If we deal with only with the external wall component, despite the great variability of existing solutions, the different technologies that can be typologically classified refer to only two main approaches.

The first one is related to the testing and implementation of materials and related techniques belonging to tradition or an evolution of it, such as stone, ceramic, bricks but also composite, used with innovative methods. Otherwise, the second one is related to the use of metal and glass materials, particularly evolved and highly technological. However, there is a strong link in both contexts between the technical-constructive characteristics and those related to the energy operation of the envelope.

The naturally ventilated rainscreen façades technology belongs to the first category. They are widely used because of the benefits that they offer, not least the morphological flexibility, the variety of materials and cladding formats allowed. "*The rainscreen façade is a vertical closure that activates a rising air movement inside using radiant heat from the outside*" (Raffaellini, 1994; Baglioni & Gottfried, 1995).

This technology can be considered as an evolution of the more traditional external insulation and its applications are several nowadays (Lucchini, 1999). Despite being the "simplest" of the so-called "advanced screen" technologies, they are the result of a complex design, particularly related to the thermo-dynamic behaviour of the façade.

There are many studies about the influence on buildings energy and environmental performance of using a ventilated façade. Gagliano et al. (Gagliano et al., 2020) demonstrate that the use of this technology lets saving energy from 20% to 55%, comparing it with a conventional unventilated façade in 2 representatives days of summer and winter seasons. Otherwise, some authors investigate the role and the influence of the type of the external cladding on the thermal behaviour of the ventilated façade and the energy performance of the building (Stazi et al., 2020; Fantucci et al., 2020). Other studies are concerned with the installation of a PV system on a forced ventilated façade and its integration with a heat pump to assess the benefits for a nZEB (Nearly Zero Energy Buildings) construction (García-Gáfaro, 2022). In this case, the decrease in heating consumption is about 21% for a residential building located in Spain.

5.2. Cladding Materials

External cladding is one of the most important formal components of the envelope, in relation to their materiality, colour but also format and size. Nowadays most façade claddings are developments of ancient materials, often combined with other very modern ones, that made their installation easier and improve their performance.

In the construction of complex façades (such as ventilated façades) these materials are used in an innovative way, even if they are derived from traditions such as natural materials. Since the technologies of the systems are contemporary, and generally mechanically dry installed. Moreover, the application methods are modern as well as the reduced thicknesses used. Furthermore, the design intentions of the author of the architectural work, who used traditional cladding materials on advanced screen façade or ventilated ones, often contrast with the non-load-bearing light façade. The latter is recognisable in the organisation of the fronts, size of openings, pattern of voids and solids on façade, creating formal effects hardly belong to historical constructive tradition (Gregorini, 1996).

There are many different cladding materials and the most used in complex facades are:

- natural stones and ceramics, typical of tradition, always used in wet-installation as construction materials for external facades and currently used in dry-installation solutions;
- bricks, which, certainly derive from the evolution of traditional construction techniques in their use with mixed wet/dry installation, and assume a more contemporary use in dry installation;
- large-format glazing, their use derives from the modern history of architecture;
- fibre cement, belonging to the most recent tradition of prefabrication;
- metal laminates, some are more common, others more recent and innovative;

- plastics, less commonly utilised but sometimes used as cladding for lightweight panels;
- composites, generally made up of inert materials and resins, provide a variety of aesthetic effects and are characterised by performances that natural materials could not have.

The main characteristics of some types of cladding are outlined below.

Stone Claddings
These natural materials have always been used in construction because of their considerable aesthetic value. They derive form the most classic building tradition (Blanco, 1993; Blanco, 1992).

Ornamental rocks can be grouped into 4 different categories, here classified according to commonly used commercial qualifications:

- "Marble": it is a crystalline, compact, polishable rock, mainly made up of minerals with a Mohs hardness of 3 to 4. This category includes so-called marbles, i.e., recrystallised metamorphic limestones; calcifers and cipollines, limestones, dolomites and polishable calcareous breccias; alabasters; serpentinites; ophicalcites.
- "Granite": it is a compact, polishable phanero-crystalline rock, predominantly composed of material of Mohs hardness 6 to 7, such as quartz, feldspars and feldspathoids. The granites proper (phanero-crystalline acid intrusive magmatic rocks consisting of quartz, sodic-potassium feldspars and micas); other intrusive magmatic rocks (diorites, granodiorites, syenites, gabbros, etc.); the corresponding effusive magmatic rocks with porphyritic structure; some rocks of similar composition such as gneiss and serizi, all belong to this category.
- "Travertine": it is a sedimentary limestone rock of chemical deposit with a vacuolar structural characteristic, almost always polishable.
- "Stone": this term refers to a category of rocks with a wide variety of mineralogical compositions. Normally they cannot be polished and can be divided into two basic groups: soft and/or not very compact rocks (calcarenites, sandstones with calcareous cement, etc.), and hard and/or compact rocks (micascist quartzites, lastroid gneisses, slates, etc. or volcanic rocks such as basalts, trachytes, leucitites, etc.). Nowadays, one of the main problems with these materials is determining their performance. This issue occurs particularly when they are applied with low thickness by mechanical fixing systems.

Considerable attention must be paid to the design of the system, from the substructure to the fixing systems, and to the joints, which must allow relative displacements between stone components. Absorption of elastic movements both between the substrate and cladding and the different slabs is generally resolved by the joints. In fact, they are the distancing of the perimeters of the different cladding slabs, with the aim of allowing free slabs displacements.

The closed joint installation scheme becomes an unaffordable solution because of the tendency to increasingly reduce the slabs thickness and the greater elasticity of the building structures. This type of technique is only recommended for claddings of limited size. In the case of a closed joint façade, the unavoidable settlements, elastic failures and differential thermal deformations between the cladding materials and the structure can result in slabs collapse and overloading the anchoring brackets and the cladding fixings. Moreover, this solution requires the joints to be left open at the floor slab. On the other hand, regarding the installation of medium-sized slabs, open joints ensure structural adjustments and displacements generated by thermal variations without contact between any of the adjacent elements.

To guarantee proper design, another very important feature to consider is the coordination and planning of construction tolerances.

Although high-tech façades are industrial products, they are inevitably linked to in-situ structures. Therefore, they require construction tolerances, especially in relation to the points of contact with the building load-bearing structure (Boeri, 1996).

Several UNI (Italian National Agency of Unification) standards define the classification of these materials, the methods to carry out the product acceptance or the control of the stone products characteristics, the rules to follow for proper technical information. Furthermore, the most important physical-mechanical characteristics for stone products identification and choice and the testing methods.

Ceramic Claddings

All products obtained by firing clays are included under the generic name of "ceramics", in relation to the raw material purity, the relationship with appropriate additives, as well as the firing degree.

Historically, ceramics have been used as facade cladding with dry installation when formats of a significant size were made. Today it is precisely the large formats allowed and related contained weight, that made this product competitive, in relation to formal quality, performance and cost.

Ceramic materials can be divided into several types:

- porous paste products (earthenware, majolica, pottery), which can be painted, englobed or glazed;
- products with a compact paste, such as stoneware (ordinary or natural and fine or compound) and porcelain (hard and soft).

Finally, among the ceramic products that are difficult to classify, there is clinker. In its production clays are used and added with colouring oxides, fluxes and chamotte.

In the clinker production process, the rather high firing temperature (1200–1300°C) enables the achievement of "clinkerisation", i.e., the vitrification of the mass. This property makes clinker one of the most resistant ceramic materials to aggressive agents.

Fine or composite porcelain stoneware is widely used in rainscreen facades. These differ from ordinary porcelain stoneware by clay greater purity and decrease in iron oxides. Latter materials allow to obtain products with predetermined colours, even in paste form.

As far as ceramic materials requirements are concerned, they have very good mechanical resistance to compression and limited reliability to tensile strength. Ceramic materials have a marked degree of fragility. It increases as the firing temperature rises. In fact, ceramic elements of considerable size and small thickness are more easily subject to brittle fracture.

When using ceramic elements larger than 25 x 25 cm, special attention must be paid to the installation conditions. Particularly, the deformability of the tile support must be checked, i.e., thermal expansion and elastic deformation.

Imbibition property and permeability (dependent on porosity) are almost irrelevant in products with a compact paste, such as stoneware and porcelain, where the porosity must be less than 4%. Frostiness is inversely related to the degree of firing of the material and its waterproofness and compactness. However, it is always advisable to test for frost resistance the samples of ceramic materials used outdoors. The durability of ceramics is high in the case of dense body products, whereas in the case of porous body products, it is determined by frost and aging resistance. Regarding fire resistance, ceramic materials are generally more resistant than other materials, such as stone.

It is worth noticing that currently production of ceramic coverings offers on the market products with various treatments, including self-cleaning products (with a titanium dioxide coating) that give the material photocatalytic, super-hydrophilic and anti-bacterial properties. Other treatments can be mentioned, although generally not intended for façade applications, are silver-based, and give the material high anti-bacterial and anti-microbial properties.

The ceramic slabs can be fixed using either visible or not-visible fixing systems. With visible fixings, the slabs are supported by fixing clips of different types depending on the requirements to meet.

Clips must be fixed to allow for joints that permit possible expansion. The clips may be painted in colours like those of the ceramic slabs. In this case, they can be only slightly visible. Otherwise, if the design intention to leave them visible, they are not painted or coloured in a tint contrasting with that of the ceramic slabs. The vertical joint between the slabs generally varies from 4 to 8 mm, while the horizontal joint is approximately 8÷10 mm. Additionally, when the system is installed, applying a single-component silicone or polyurethane sealant to the slab-profile interface is advisable. Thus for 2 reasons:

- eliminating possible vibration of the slabs with wind;
- if breaking occurs, allowing slabs to be held until they are replaced.

To avoid slabs vibrations when exposed to wind action, an alternative solution is to insert a neoprene gasket in the aluminium profile of the substructure.

Ceramic tiles can also be fixed to the substructure by hidden fixings. In systems with concealed fixing made of dowels on the back of the slab and connected with clips, the substructure can have both vertical and horizontal profiles. The distance between vertical ones does not depend on the module of the tiles, but on wind loads and building height. As regard the horizontal ones, the ceramic slabs are bound on them, and they will be at least 2 per slab. When the slabs are fastened using stainless steel dowels, thanks to their truncated-cone shape, they can be accommodated in the back of the slabs. Between the slab and the dowel there is a thin layer of neoprene. The drilling of the slabs is carried out in the factory. It is done using special tools that also create the undercut for the dowel as well. Once expanded, the dowel guarantees considerable resistance to tearing.

The cladding slabs are, then, fastened with shaped aluminium clips, normally 4 for each slab (2 load bearing and 2 containing). In this case it is worth noticing that the load-bearing clips are characterised by micrometric adjustment screw related to the fastening system to the transom.

For slabs thicker than 10.5 mm, an alternative not-visible fastening system, was made of mullions placed at each vertical joint. Mechanical stainless-steel support and restraint hooks are fixed to vertical profiles. Hooks are included into recesses made along the horizontal sides of the slabs.

To guarantee greater safety for the systems, it is advisable to glue a fibreglass mesh on the back of the tiles. It is generally a square mesh (4 x 4 or 5 x 5 mm), with an elastic adhesive (two-component polyurethane) that prevents fragments from falling off, in case of accidental tile breakage. This operation must necessarily be carried out on the portions of the façade located in the area where people pass by.

Brick Claddings

Brick is a traditional material that is currently subject of both product and process innovation. Additionally to traditional bricks production includes external cladding bricks with predominantly dry construction as well. Such as required for rainscreen facades. There is also a mixed "dry-wet" system. It enables to create external walls with a traditional design, but with technologies typical of drywall systems. The production also includes components for complex façades, such as variously shaped sunshades, slats, staves, squares, etc.

There are several products specifically dedicated to the complex facades' construction, including: plates, panels, and tiles.

The terracotta plate is characterised by rectangular shape, and it is for instance 50 mm thick with through holes for lightening. The elements are obtained by drawing. The tiles can have shaped sides or continuous grooves (kerf) in both upper and lower sides. Slots are necessary to include load-bearing elements and two continuous sloping kerfs on the back. The latter are used in special cases where the plate is horizontal, such as in lintels or windowsills.

For façade installation, joints are generally approximately 6 mm wide both horizontally and vertically, with protection to prevent rainwater penetration.

Terracotta panels are obtained by a process of clay drawing too. They are flat elements, generally 25 mm thick with rounded or shaped edges. To give the panel greater rigidity, they are characterised by a flaring at both lower and upper side. More stiffness is required when sides present holes needed to fasten to the substructure. This is a hidden and diffused type, as it is along the entire groove.

The substructure can be made of stainless steel or aluminium. When the substructure system includes mullions and transoms on the façade:

- the horizontal joints are created directly by positioning the support beam of the cladding element. Due to its special shape, it permits the required distance;
- the vertical ones are created simply by positioning the panels correctly on the transom, by sliding them.

The brick tiles developed from the typical horizontal elements used, for example, in the construction of floors. They are obtained by drawing from clay as well.

Longitudinally the voids through the elements have a lightening function and constitute an air chamber to the advantage of thermal resistance.

The special shape of both upper and lower edges allows mechanical fixings. When the substructure includes brackets (supported by mullions) to support and hold the cladding, they are usually made of stainless steel. Each bracket retains 2 both upper and lower sides and it is placed (on axis) at the intersection between horizontal and vertical joints resulting from the joining of the tiles. Generally, a small rubber element is applied at the steel-brick interface to ensure uniform transmission of stresses from the brick to the steel, avoiding stress peaks on the brick that has a brittle mechanical behaviour (Acocella, 2018).

Lightweight Multi-Layer Aluminium Panel Claddings

Multilayer, lightweight aluminium panels are often used in façade cladding, particularly in high-end manufacturing and tertiary construction.

Aluminium is characterised by its lightness, hardness, and good plasticity. Otherwise, it has a low mechanical resistance. This is improved by producing alloys with copper, zinc, silicon, magnesium, etc., that are characterised by a high resistance to atmospheric agents and particularly to corrosion.

There is a wide range of products. Considering as an example the best-known products, they consist of two aluminium sheets, including a mineral core.

The panels are manufactured in the factory using processes that allow cutting them to size.

The outer sheets are 0.5 mm thick while the inner ones are usually 2 to 5 mm thick, but can also be thicker. The panels do not undergo any surface corrugation or delamination and are particularly rigid and resistant to pressure and impact. If the size of the panels exceeds one square metre, especially in thinner thicknesses, it is advisable to apply to the back a stiffening element, such as a rigid insulation panel.

An important characteristic of this product is the possibility of being shaped, and therefore also folded on site. This allows a very wide range of applications, unrelated to large-scale mass production, making it particularly suitable for the usual façade cladding panels as well as for pillar cladding, roofing parapet one and corner elements.

The panel finishes are of various types: natural aluminium, pre-painted coil-coating, with natural and coloured anodising, PVC coating. The external side is pre-painted. There is also a very wide range of paint colours, both from the colour brochure and to order; they can also be metallised (Braicovich, 1998; Gottfried, 2003).

5.3. Façade System

There are now several types of high-tech technology façades, including naturally ventilated ones. They are one of the best systems for external building insulation.

The ventilated wall is rainscreen façade technology where all layers (including insulation one) are located outside the building load-bearing structure.

Thanks to the chimney effect created in the ventilation layer, during summer season the façade reduces the thermal flow entering the building and so decreases overheating inside the building. Otherwise, thanks to the external insulation, during winter season it keeps the internal surface temperature high. Additionally, the ventilation on the insulation external side eliminates possible condensation (Fig. 5.1) (Ciampi et al., 1998; Ibanez-Puy et al., 2017; Lin et al., 2022).

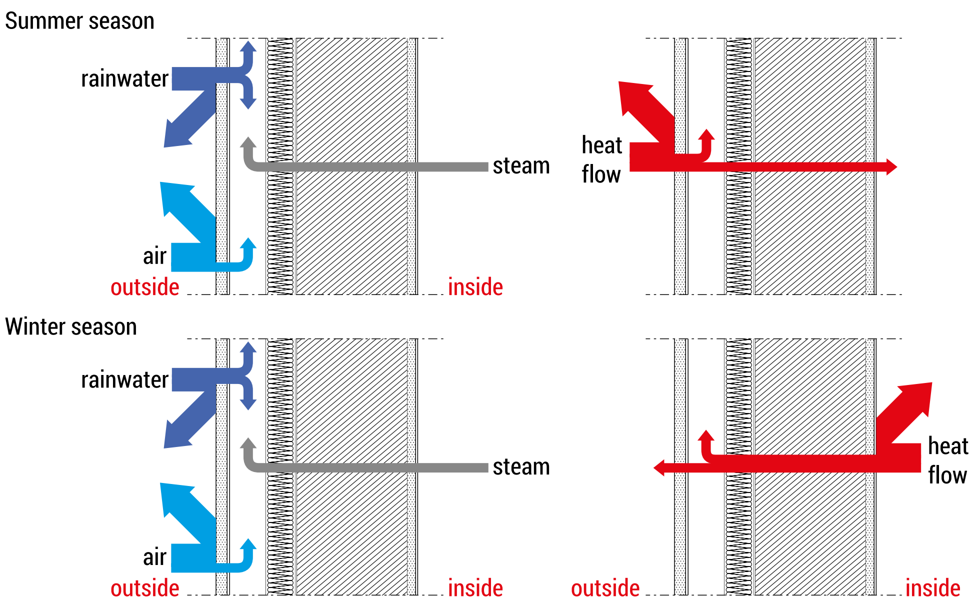

FIG. 5.1. Functioning diagram of a rainscreen façade in summer and winter season (Source: own elaboration)

From the load bearing layer, the ventilated façade stratigraphy is made of (inside-outside): an insulation system, with thermal insulation directly applied on the external wall (i.e., its external side), an open-air cavity and, finally, the outer face, i.e., the covering layer. In the air layer an air rising movement is triggered (chimney effect) permitted by appropriately positioned openings protected by grids.

The possibility of natural ventilation must be ensured through the correct sizing of the ventilation openings. These are generally located at both the lower and upper ends of the external cladding, and at suitable heights to ensure the chimney effect.

The ventilated wall is a non-load-bearing wall, and the cladding have its own supporting structure, called substructure. It is supported and constrained to the main structure of the building and the load-bearing layer of the wall.

The substructure is made of several components. These elements are fixed to the load-bearing wall layer and support the cladding. The covering will be offset by at least 17÷18 cm from the external side of the structure.

The ventilated wall is made up of the following layers (Ciampi, 2007). They are outlined in succession starting from the structural side to the outside.

Load-Bearing Layer

The load-bearing layer must carry the loads of the ventilated wall system. This occurs when it is not directly connected to the building load-bearing structure. Today, thanks to the great variety of available components on the market, the ventilated wall system can be installed on any type of support, using appropriate elements. The system required that the supporting structure must be characterised by flatness, verticality, and horizontality. The ventilated façade system should be applied to buildings with a certain geometric regularity, characterised by a ratio between full and empty spaces to allow "ventilation chambers" correctly functioning.

The load bearing layer can be either a structural element, a wall or both. It must necessarily be statically verified since it represents the load-bearing element for the whole system.

The load bearing layer can be:

- non-continuous if the building structure is a reinforced concrete or steel frame. Therefore, it will have non-load-bearing external vertical walls;
- continuous if the building structure is a load-bearing masonry, variously built (traditional brick masonry, small elements, and blocks), or with reinforced concrete diaphragm.

In the first case, the anchorage of the mechanical devices supporting the substructure is directly on the framed load-bearing structure, and the so-called system retrofit fixings can be anchored on the walls. However, in the second case, the positions of the substructure supporting fixings will not be determined by the structural frames' modularity.

Regularization Layer

A levelling layer may be applied on the outside of the load bearing layer. Generally, if the resistant layer is a masonry, it consists of a cement mortar plaster (2 cm thick) to make the surface regular and coplanar to apply then the insulation material.

The regularization layer is used in both the case of non-continuous load-bearing support (walls), or continuous one except in the case of reinforced concrete diaphragm. Before positioning the insulation layer, it is important to check the condition of the substrate surface and to assess any possible geometric irregularities to correctly apply it.

Insulation Layer

This is the insulating layer, placed uniformly, either close to the load-bearing layer or of regularisation one (when present). This application is the "coat" of the building, with the aim at improving the thermal insulation and minimising possible thermal bridges.

It must be chosen appropriately because it must necessarily be:

- with low thermal transmittance value;
- hydrophobic;
- fire resistant so it avoids flame propagation during possible fire event;
- non-perishable and non-alterable;
- self-supporting and with sufficient mechanical resistance.

Although there are several products available on market, generally mineral or vegetable fibres as well as cellular plastic rigid insulating panels are used in rainscreen systems to meet performance requirements. They are suitably sized according to the overall energy performance of the wall and applied directly on it.

They are installed using mechanical elements consisting of fasteners (usually plastic with top as a disc) and adhesives, or both.

Insulation materials can be:

- inorganic or mineral origin (e.g., mineral fibre insulation, glass foam, perlite sheets and slabs, vermiculite);
- organic origin, derived by synthetic raw materials (e.g., polystyrene rigid foam, expanded polystyrene particle foam, extruded polystyrene rigid foam, polyurethane rigid foam, formaldehyde-based foam, phenolic resin-based rigid foam) or by natural ones (e.g., cotton, linen, hemp, wood fibre, coconut fibre, cork, sheep wool, reed, cellulose fibre).

Ventilation Layer

In naturally ventilated facades, the ventilation layer consists of an air chamber connected to the outside environment. It is located between the insulation layer and the cladding of the wall and functions like a natural convection chimney. The ventilation is external-external type, i.e., it is not connected with either the interior rooms or the building's system.

The fundamental role of the cavity is to enhance the thermal comfort and more generally to achieve well-being conditions inside the building (Gagliano et al., 2022). The air convective motion activated allows: the evacuation of water vapour coming from inside, allows the elimination of the negative effects caused by any water penetration and the control of interstitial condensation. The latter permit to reduce the possibility of condensation phenomena that could lead to the deterioration of the materials.

During summer, ventilation contributes to a significant decrease in heat flux into the building. While in winter season, it has a positive effect on condensation and frost formation, but it does not ensure any thermal benefits in terms of controlling energy losses. There would be advantages if the ventilation chamber could be closed because this would increase the overall thermal insulation of the wall.

This opportunity would become feasible by providing a manual or automatic control system for opening/closing the ventilation openings. Even in this case the ventilation cavity would not be airtight since in almost all cases the joint between the cladding elements is open. If the air cavity would be closed surely some of system benefits would be lost.

The operation of the ventilation chamber is closely related to the environmental boundary conditions, the building morphology, and the wall composition. To activate a real chimney effect, the air gap must have an adequate section (at least 6 cm) without any obstacles inside (for instance the substructure components can cause turbulence phenomena).

For effective ventilation the air cavity must have a constant thickness between the air inlet and outlet openings, maintaining a regular and continuous configuration. During the design of the system, all possible causes that could influence the smoothcirculation of air have to be considered. For instance, elements (generally horizontal) interrupting the verticality of the air layer must be avoided because they could trigger local turbulence effects and interfere with the main upward air movement.

The sub-division of the ventilation chamber is often unavoidable. On this regard, the proper functioning of all the different parts must be verified. In the design phase all the various ways in which ventilation happens in the façade are necessarily evaluated. Unlikely it is uniform, varying according to the building morphology and size of the, the façade technology chosen and the specific orientation and exposure of the building. All those parameters will affect the operation of the ventilation chimneys.

Ventilation openings are usually located at both the bottom and the top of the air ventilation layer. They are protected by gratings to limit the entry of insects and other small animals, and by flashings to avoid rainwater entry. The openings must be necessarily positioned whenever the ventilation chamber is interrupted, for instance by the presence of windows.

The design of the shape, size and positioning of the ventilation openings in the façade is also important. This because they make a key contribution to the correct functioning of the ventilation "chimneys". Generally, the size of the ventilation openings must be at least 70÷80 % of the ventilation chamber section. The type of protection system for the openings is another aspect to consider. It must not obstruct or divert the flow of air in an uncontrolled way (Fig. 5.2).

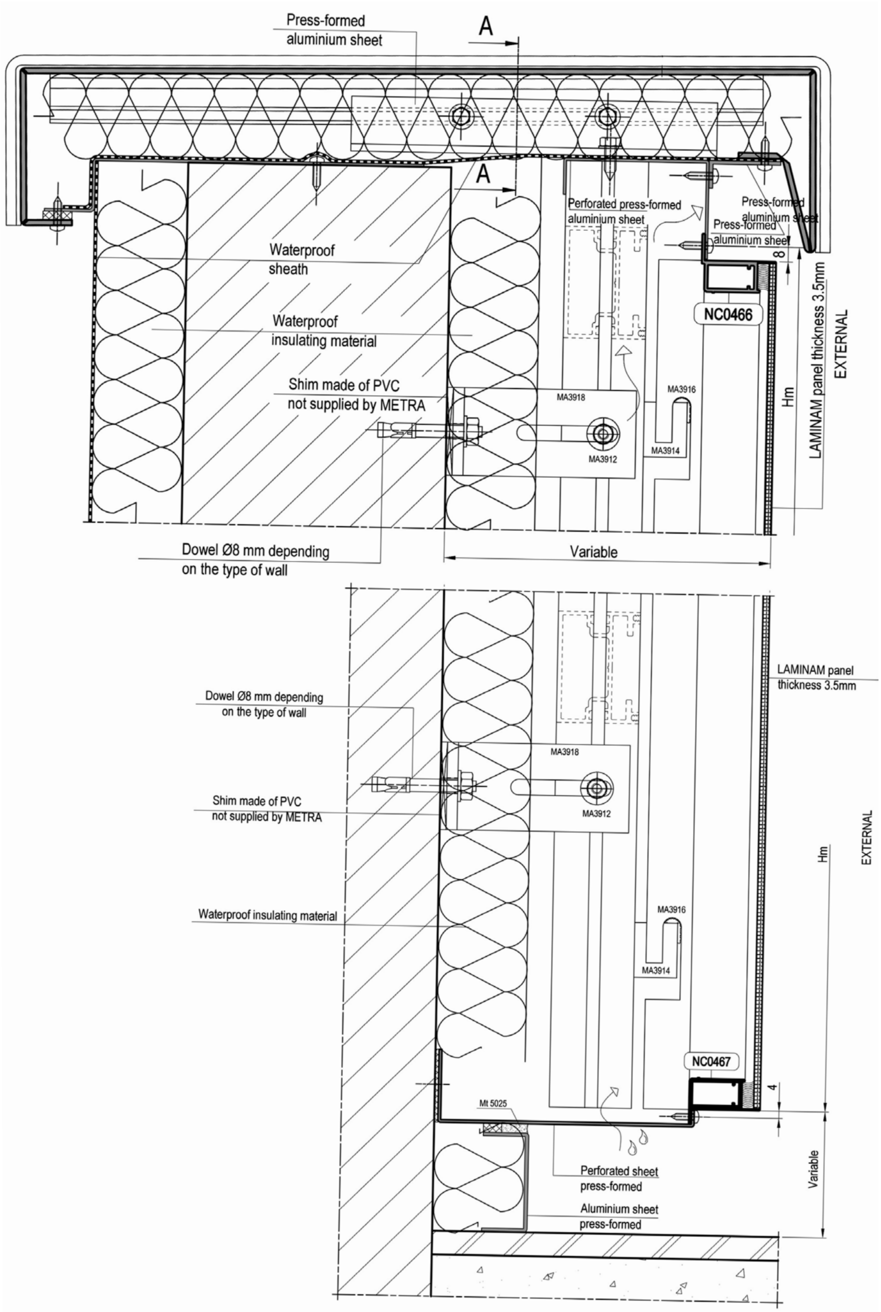

FIG. 5.2. Example of a vertical section of a rainscreen façade showing ventilation openings at both the top and bottom (Source: The technical material in question is the property of METRA Spa)

Substructure System

Substructures are very important. They are anchored to the building load-bearing structure and enable the anchoring of the cladding fixing systems. Metal components must be used to support and fix the ventilated facades. These elements are anchored to the building external structure, and they are the façade supporting structures involving dry fitting for the individual components.

The substructures enable the cladding elements to be supported or retained through fixing devices such as pins, plates, inserts, etc. They are accommodated in special holes, grooves, or slots in the cladding.

The design of this system depends on the load conditions, the thermal actions, the differential displacements of the structures, but mainly on the properties of the cladding, the format of the elements as well as the aesthetic-formal features to obtained.

A substructure could mean a simple component (such as a bracket), but it is generally made up of a set of components (such as a mesh made up of welded and/or bolted vertical and horizontal profiles). The assembly of these elements constitutes the support for the external cladding as well as suitably distancing it from the insulating layer to create the ventilation chamber.

Nowadays the materials used for both the substructures and the cladding fastening systems are metals, in particular stainless steel, galvanised steel, and aluminium. The design and assembly of the substructure must always consider the principles of statics to guarantee safety and correct deformation under the action of both horizontal (wind and earthquake) and vertical loads (weight of the structure and of the cladding).

The quantity and size of the support elements will be determined in each individual case based on the specific stresses. Supporting components are usually fixed with dowels to the load bearing layer and equipped with vertical and horizontal adjustment.

Basically, the choice of system will depend on the type of cladding element to use on the façade and more specifically on the choice of the type of fixing of the cladding element to the substructure (Fig. 5.4).

To clarify the relationships between the elements, the diagram in Figure 5.3 is used.

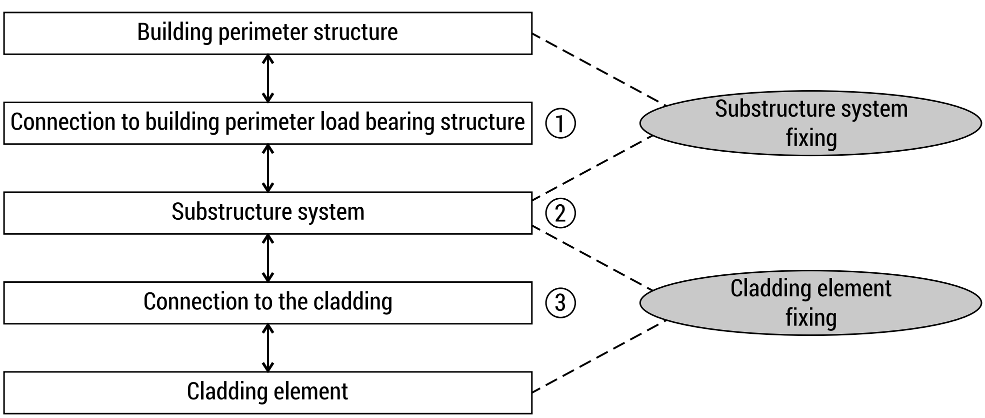

FIG. 5.3. Connections between different layers (Source: own elaboration)

Methods for classifying substructures may be various and the used one attributes a fundamental role to the cladding fixing type. The multiple characteristics of anchors allow the proper application of the same fixing to several different materials and types.

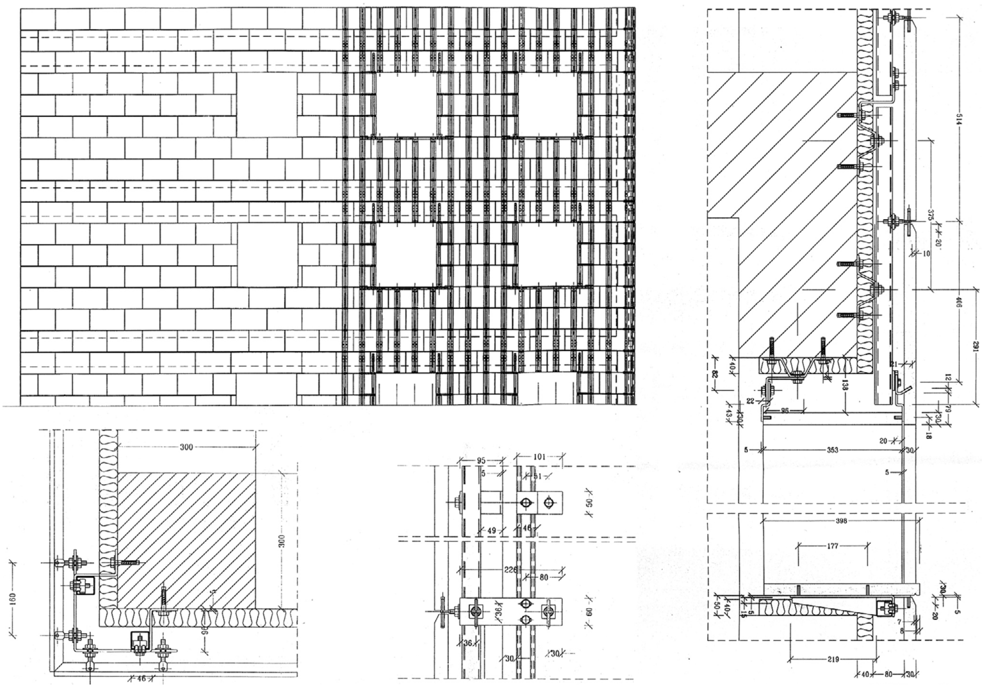

FIG. 5.4. Example of a rainscreen façade with a mullion substructure and cladding fixing with pegs (Source: own elaboration based on Senesi & Maronaro)

The following Table 5.1 shows for each materials macro-categories the possible type of fixing system.

TABLE 5.1. Possible cladding fixings (Source: own elaboration)

Material type	Possible type of cladding fixing	
	Point fixing system	Distributed system
Stone	Pegs in holes, brackets in grooves on edges.	Continuous profile within grooves on edges.
	Dowels on the back.	
Ceramics and composite	Pegs in holes, brackets in grooves on edges.	Continuous profile within grooves on edges.
	Edge clips.	
	Dowels on back.	
	Brackets within grooves on back.	

Material type	Possible type of cladding fixing	
	Point fixing system	Distributed system
Brick	Dowels on back Pegs/Brackets on edges.	Continuous profile within grooves on edges.
	Dowels on back.	Support brackets.
Metal alloys	Point fixing through Grips offered by the coating.	Grips offered by the cladding.
Lightweight panles	Dowels on back.	
	Grips offered by the coating.	

Connections to the Cladding

Cladding fasteners (mainly mechanical connections but also chemical-mechanical one) can be divided into two groups.

The most used type is point fixing systems. In this case, the fastening is carried out by a sufficient minimum number of anchorages of the cladding, so the system is isostatic (also called "safe life"). When using these systems, measures must be taken to limit damage in the event of a collapse of the cladding. The materials used today for these couplings are stainless steel (AISI 304 and 316), or treated with anti-corrosive procedures, and aluminium alloy.

The second type is the diffuse fixing systems, built by anchorage components that constrain the cladding in a diffuse manner, obtaining a hyperstatic type system (also called "fail safe"). In case of failure of a cladding element this connection system limits its total collapse.

Connections' type can be distinguished between hidden cladding fastening systems, (i.e., those with components that are not visible when the façade is completed) and exposed ones (the cladding fastening component is visible or partially visible). *Visible fastening systems* are exclusively of the point fixing type. If there are 4 fasteners per cladding slab, two have the function of carrying it and the others must retain it in relation to the depression caused by the wind.

Concealed fastening systems can be either point systems or diffused ones; the former generally include special dowels accommodate in non-passing holes made on the slabs back; the latter, generally used for stone materials, include continuous plate accommodate in a continuous groove on the slab edge.

Point fixing systems include components that constrain the covering as follows.

- *Pegs inserted into holes in the cladding slab edge*: depending on requirements, these holes and the resulting pegs can be applied both on the horizontal edges (top and bottom) of the slabs and on the vertical ones (Fig. 5.5). Pegs (made of AISI 304 stainless steel) are installed on holes made on the slab edges. This type of delicate connection requires great precision both when drilling the holes on the cladding edges and during installation. Before inserting the pegs, an elastic tube made of nylon, or another plastic material, is accommodated in the holes to prevent direct contact between peg and cladding. The holes on the bottom should be filled with mastic to prevent either any stagnation of rainwater that could stain or deteriorate the material as well as create dangerous situations of frost that could cause the cladding to break.

- *Brackets inserted into grooves on the cladding edges*: the brackets are inserted into suitable size grooves on the horizontal edges of the cladding by milling, to produce carvings, also known as "kerfs". This type of processing allows greater flexibility during construction. In some cases, the kerfs are also combined with pegs, resulting in a mixed fixing on the same slab.

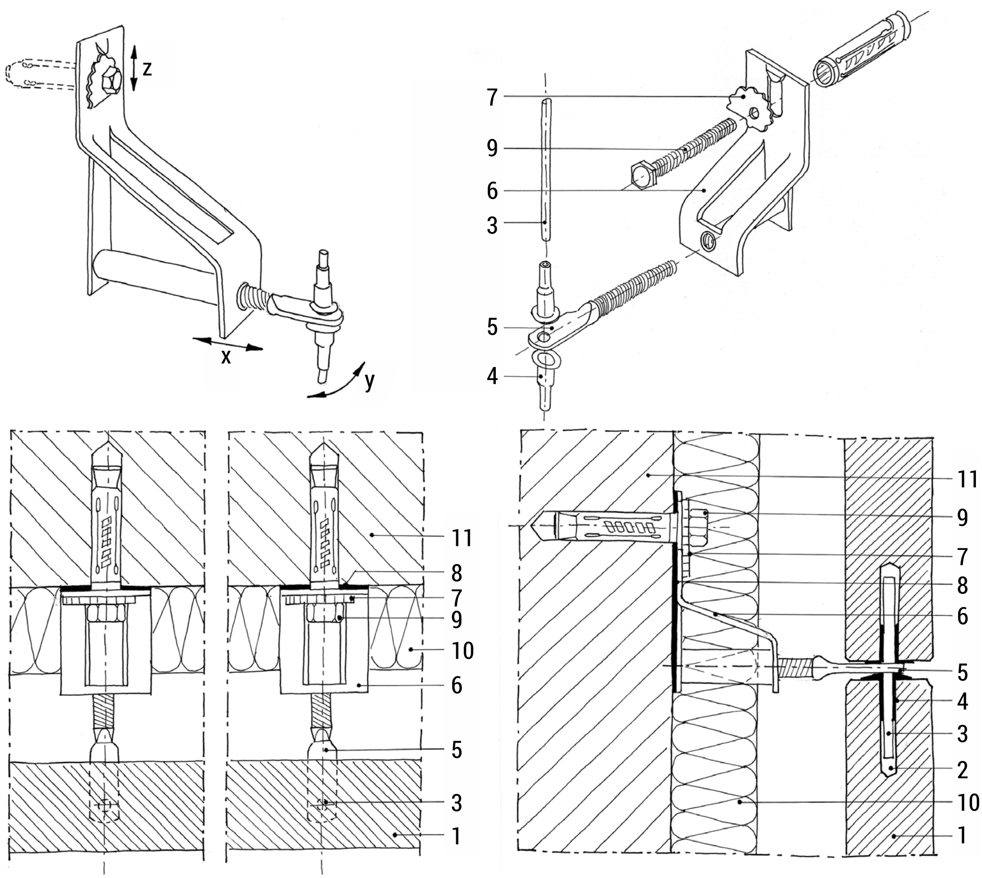

FIG. 5.5. Point fixing system with pegs in holes in the cladding edge. Caption: 1. Cladding; 2. Peg accommodation; 3. Peg; 4. Nylon tube; 5. Adjustment screw; 6. Fixing bracket; 7. Adjustment washer; 8. Bracket thermal break; 9. Expansion anchor; 10. Insulation panel; 11. Load bearing layer (Source: own elaboration)

- *Clips or brackets in grooves or recesses on the cladding slab back*: this fixing is carried out by shaped stainless-steel clips or brackets that fit into suitable size and oriented grooves (slots) milled into the back of the cladding. The substructure is usually made of extruded aluminium (Fig. 5.6).

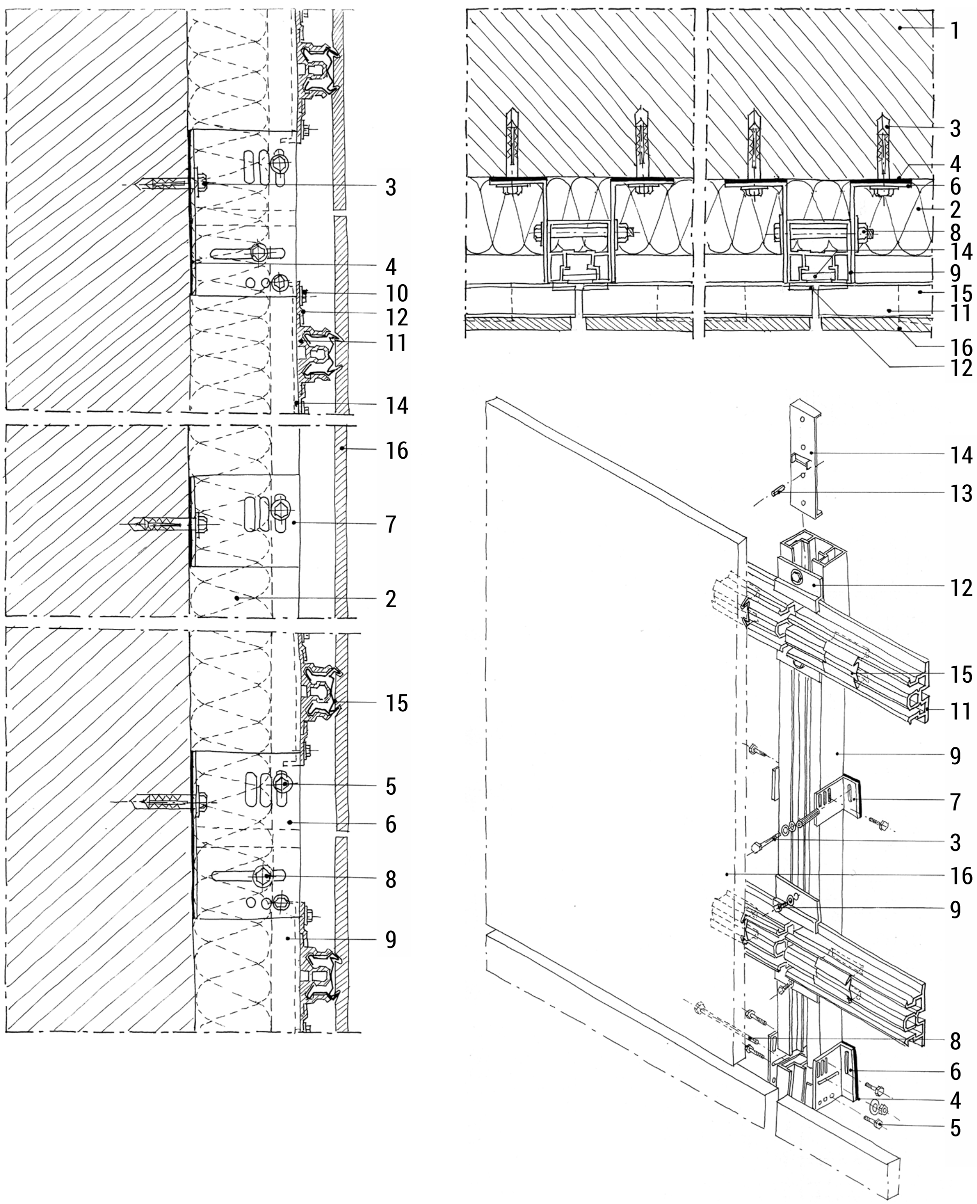

FIG. 5.6. Point fixing system with brackets in grooves on the back of the cladding, with mullions and transoms. Caption: 1. Load bearing layer; 2. Insulation panel; 3. Expansion anchor; 4. Bracket thermal break; 5. Self-tapping screws; 6. Main fixing bracket; 7. Secondary fixing bracket; 8. Bracket clamping screw; 9. Aluminium mullion; 10. Screw for fixing the little bracket to the slider node; 11. Aluminium transom; 12. Little bracket; 13. Set screw; 14. Slider node; 15 Snap-on fixing clips; 16. Cladding (Source: own elaboration)

- *Dowels on slab back:* this type of fixing consists of dry fitting metal inserts, generally involves of concealed threaded pins or bushings, on the back of the slab in fixed positions, connected to the substructure. This system may include self-locking threaded male/female bushes in austenitic stainless steel on the back of the slabs (they could be thinner). This mechanical locking system is not visible and has a certain variety of products (even without protrusions on the back of the slab).
- *Clips on the edge*: this type of fixing is achieved by steel or aluminium clips which support the cladding on the lower side and hold it on the upper one. This type of fixing is visible because part of the clip is also visible on the cladding outer face. This type of fixing does not require any machining of the cladding slabs.
- *Shaped brackets on the cladding edges*: this hidden fixing is carried out by shaped plates. They fit to the cladding element profile and support or retain it punctually. The edge of the cladding (generally made of brick) is shaped during the production phase to hide the fixing system as well as to perfectly fit the brackets.
- *Grips provided by the cladding*: thanks to the shape, in this case the cladding elements create grooves for their own attachment to the substructure and are hung on it. This is only possible for certain materials (aluminium) or components (lightweight boards) where the production process allows to shape them in such a manner that they can be fixed to the substructure in this way.
- *Point through-hole fastening*: This type of fastening connects the cladding to the substructure by self-tapping screws or rivets, passing directly through the cladding element edges. They are used with aluminium substructures and for lightweight claddings such as metal alloy panels. In the case of heavy cladding, steel dowels are used with a steel substructure (Fig. 5.7, Fig. 5.8).

The following types belong to the distributed fixing systems.

- *Continuous profile within grooves on edges*: the groove (kerf), that accommodates the profile, is obtained by milling or forming over the entire width of the horizontal slab edges. In this case the cladding element must be thick enough to allow fixing without the sides becoming fragile.
- *Support brackets*: made of steel, they are usually associated with ventilated façade with a heavy external finishing made of brick.
- *Grips provided by the cladding*: in this case the cladding is fixed by fastening the suitably shaped horizontal edges of the cladding panels. This is a typical system of metal alloy cladding.

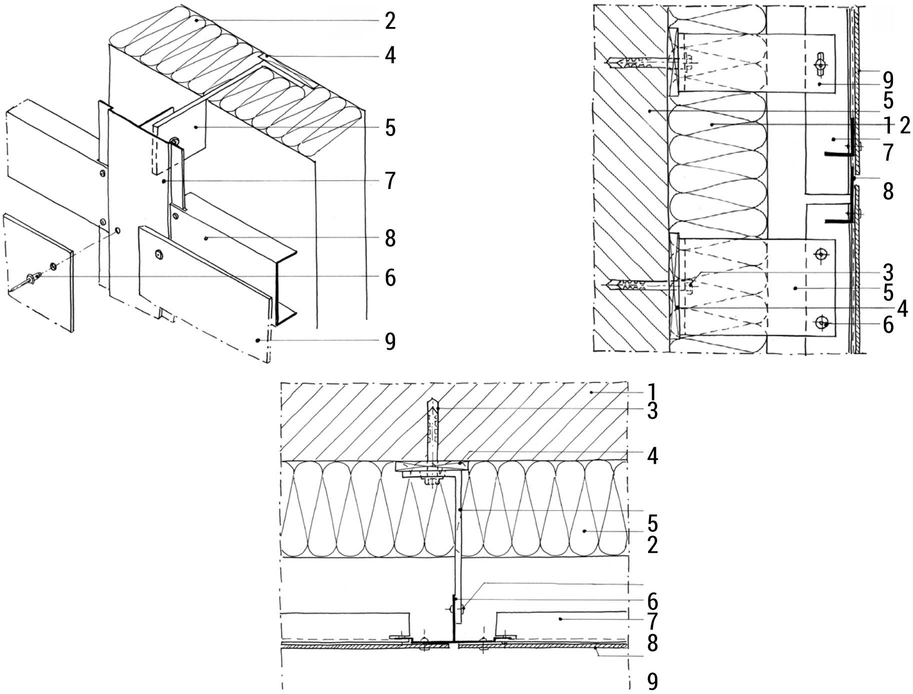

FIG. 5.7. Point fixing system through the cladding, with mullions and transoms. Key: 1. Load bearing layer; 2. Insulation panel; 3. Expansion anchor; 4. Bracket thermal break; 5. Fixing bracket; 6. Rivet; 7. T-shaped aluminium mullion; 8. U-shaped aluminium transom; 9. Cladding (Source: own elaboration)

FIG. 5.8. Point fixing system through the cladding, with mullions. Backhaus Mahl, Albstadt-Tailfingen – Germany (Source: © Courtesy of Alucobond, © Elisabeth Leblanc)

Supporting Structure

Through a profiles mesh, the structural frames supporting the cladding fasteners allow the transfer of all the stresses (inherent and induced) to the load bearing layer by proper fastenings. The mesh may consist of metal profiles (stainless steel, aluminium, or less recommended galvanised carbon steel) arranged to identify a main and a secondary frame. In general, the vertical development prevails (mullions), since all the connections to the load-bearing structures of the building can easily be made. Particularly in the case of framed structures because it is easy to fix them to the slabs' side beams. Often, a secondary system is connected to the main frame, made with metal profiles warped in the opposite direction (transoms). In other cases, the wall is built exclusively with stringers or brackets, directly anchored to the necessarily continuous load-bearing structure.

System components are also used to correct any out-of-plumbness: usually shims are applied between the substructure and the fixing system to the main structure and/or between the substructure and the fixing system of the cladding. Generally, the elements are connected to each other oval-shaped slots to allow installation tolerances and differential displacements. It is worth to notice that the most used mullion and transom sub-structures may sometimes have the disadvantage of avoiding (through transom) the air ascensional movement in the ventilation layer. Consequently, a carefully evaluation of the operation of the ventilated cavity is required. Obviously, if there are real functional deficits and the same system must be kept, the use of fixing devices to distance transoms is needed to increase the cross-section of the ventilation cavity.

It should also be noted that since the substructure system is almost entirely made of metal, it must be connected to an earthing system.

The substructures may be

- *mullions (or transoms)*: in this system, the façade modules have straight vertical joints, while the horizontal ones may be staggered.
  On the other hand, in the case of transoms the horizontal joints are straight, while the vertical joints may be staggered.
- *mullions and transoms (or transoms and mullions)*: this system allows the widest possible modularity of the cladding. It may have straight vertical joints, straight horizontal joints, staggered joints, or continuous joints; this is because the cladding panels geometry is independent by the vertical sub-frame.
- *with brackets directly fixed to the main continuous structural support*: in this case the position of the brackets obviously will be decisively connected to the geometry of the modular mesh of the facade cladding.

Finally, the substructures must be constrained to the building by a suitable fastening system:

- *mechanical anchors*, made of galvanised or stainless steel: these have excellent resistance to sliding and maintain their sealing capacity almost unchanged, even in partial initial slipping event. There is a wide range of dowels on the market, suitable for all load requirements and all types of load bearing layer.

- *chemical anchors*, external or internal mixing type and particularly suitable for use on non-compact fixing bases.
- *profiles embedded in the casting during the construction of the load bearing structure*, made of normal and stainless steel, heat-rolled or cold-formed, with pressed or welded anchors. They are usually C-shaped, allowing the insertion of the bolts needed to fix the other ventilated façade elements. They are supplied by the manufacturers with a foam filler to prevent concrete enters during casting.
- *Bolted joints in the case of structural steel frames*: these must be suitably designed to cope the tensile and especially shear stresses caused by the loads resulting from the substructure and the external cladding.

Joints System

The joint is the space between the perimeter of each cladding element with the aim at allowing free movement due to differential displacement. Additionally, to a precise functional connotation, this element determines and characterises the façade aesthetics, highlighting its modularity. The rarely solution of the closed joint requires a gap of about 2÷3 mm between the cladding elements. In these cases, it is advisable to leave the corresponding joints with the slab open of about 15÷20 mm. Open joints allow greater displacement of the cladding elements, and generally of 6÷7 mm. This system, which is the most widely used, allows to accommodate medium-large slabs without any contact between them during settlements and movements caused by thermal expansion.

References

[1] Acocella, A. (2018) Involucri in cotto. Sistemi innovative per il rivestimento in architettura, Firenze, Sannini Impruneta.

[2] Alagna, A. (2007) Tecnologie per le forme dell'architettura contemporanea. I sistemi di chiusura: qualità ed efficienza energetica, Firenze, Alinea. ISBN: 978-88-6055-137-5.

[3] Baglioni, A., Gottfried, A. (1995) Manuale di progettazione edilizia. Vol. 4, Milano, Hoepli.

[4] Bazzocchi, F. (a cura di) (2002) Facciate ventilate. Architettura, prestazioni e tecnologia. Firenze, Alinea.

[5] Blanco, G. (1992) Pavimenti e rivestimenti lapidei, Roma, Ed. NIS.

[6] Blanco, G. (1993) Le pietre ornamentali in architettura, Roma, Ed. NIS.

[7] Boeri, A. (1996) Pietre naturali nelle costruzioni: requisiti, criteri progettuali, applicazioni e prestazioni, Milano, HOEPLI.

[8] Braicovich, E. (1998) L'architetto e l'alluminio. *Nuova finestra*.

[9] Ciampi, M., Tuoni, G. (1998) Sul comportamento delle pareti ventilate in re-gime periodico. *La Termotecnica*, 11.

[10] Fantucci, S., Serra, V., Carbonaro, C. (2020) An experimental sensitivity analysis on the summer thermal performance of an Opaque Ventilated Façade. *Energy and Buildings*, 225, 110354.

[11] Gagliano, A., Aneli, S. (2020) Analysis of the energy performance of an Opaque Ventilated Façade under winter and summer weather conditions. *Solar Energy*, 205, 531-544.

[12] García-Gáfaro, C., Escudero-Revilla, C., Flores-Abascal, I., Erkoreka-Gonzales, A. (2022) A photovoltaic forced ventilated façade (PV-FVF) as heat source for a heat pump: Assessing its energetical profit in nZEB buildings. *Energy and Buildings*, 261, 111979.

[13] Gottfried, A. (2003) I rivestimenti, Milano, HOEPLI. ISBN: 9788820331498.

[14] Ibanez-Puy, M., Vidaurre-Arbizu, M., S. Fernandez, J.A., M. Gomez, C. (2017) Opaque ventilated faacdes: thermal and energy performance review. *Renewable and Sustainable Energy Reviews*, 79, 180-191.

[15] Lin, Z., Song, Y., Chu, Y. (2022) An experimental study of the summer and winter thermal performance of an opaque ventilated façade in cold zone of China. *Building and Environment*, 218, 109108.

[16] Lucchini, A. (1999) Pareti ventilate, Bologna, SAIE.

[17] Raffaellini, G. (1994) Manuale di progettazione edilizia. Vol. 2, Milano, Hoepli.

[18] Stazi, S., Ulpiani, G., Pergolini, M., Di Perna, C. (2020) The role of wall layers properties on the thermal performance of ventilated façades: Experimental investigation of narrow-cavity design. *Energy and Buildings*, 209, 109622.

[19] WEB–1: Ciampi, A. (2007) Facciate ventilate in cotto. [Online] Available from: https://www.arketipomagazine.it/facciate-ventilate-in-cotto/ [Accessed on 21.03.2022].

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6. GLASS FAÇADE

6.1. Introduction

Modern and especially contemporary architecture clearly shows a search for external wall dematerialisation.

This led to research in the field of technologies for glass envelopes characterised by making the wall immaterial, with the aim to pursuit what is defined as the paradigm of lightness.

The used technological systems are glass and metal façades belonging to the envelope systems defined as curtain walls.

The EN 13830:2015 "Curtain wall – Product standard" defines curtain wall as: *"part of the building envelope made of a framework usually consisting of horizontal and vertical profiles, connected together and anchored to the supporting structure of the building, and containing fixed and/or openable infills. which provides all the required functions of an internal or external wall or part thereof, but does not contribute to the load bearing for stability of the structure of the building. curtain walling is designed as a self-*-supporting *construction which transmits dead-loads, imposed loads, environmental load (wind, snow, etc.) and seismic load to the main building structure".*

The previous definition highlights some elements that are essential for understanding the concept of curtain wall:

- it is always possible to identify a framework that is the structure of the façade;
- the structure of the façade is like a structural grid;
- the façade does not cooperate with the building structure; therefore it turns out to be exclusively self-supporting and carried by the building;
- the curtain wall must meet all the requirements for external closures.

It is worth to notice that the standard specifies the main technical characteristics of curtain walls and includes an overview of performance requirements and test criteria necessary to comply with the essential requirements of the Construction Products Directive, thus providing appropriate principles for defining technical product specifications.

The normative definition of its field of application would suggest that the specified requirements could be met by a considerable number of technologies currently produced. Otherwise currently interpretation exclusively refers to curtain walls considered as kits with both mechanical fixing and bonded glazing. The latter are the only systems that can be defined as a curtain wall according to the standard.

However, if we leave the scope of the harmonised standard, these façades declined in a considerable variety of technological solutions, united using metal to make the substructure and glass panels to constitute the vertical closure.

The initial considerations highlight the tendency of the most advanced technologies, which sometimes does not coincide with the best performing ones, to minimise the size of the substructure. In fact, it is worth to notice that compositional research has not so far been supported by an equally detailed study concerning the performance of glass envelopes. Sometimes a "conscious" use related to energy issues is lacking.

The chapter only deals with technologies related to glass and metal curtain walls as external walls.

However, careful use of these systems requires integration with other technical elements to achieve an appropriate level of envelope performance, such as solar shading systems.

However, it is clear that considering all elements, the glazed infil[1] has a key role, since both thermal and acoustic insulation are almost totally entrusted to it. It is worth to notice that an integration of an opaque into the façade is possible. The latter are usually used to improve the overall performance of the envelope. The way in which these portions are treated is also fundamental to the stylish definition of the façade.

6.2. Classification

Glass and metal curtain walls always have an auxiliary structure where the various wall components are integrated, from the transparent elements (either fixed or openable) to any opaque ones.

This type of façade is classified according to both the geometric relationship between the substructure and the infill panels (glazed or opaque) and how the infill panels are fixed to the substructure.

Two typologies are generally identified:

a) *stick system façades*, in which the substructure is in the same plane as the infill panels;
b) *point fixed glass façade*, where the substructure is on a different plane with respect to the glazing.

Further distinctions within the two typologies are closely related to the specific technologies and construction methods. The performance of the technical solutions belonging to the two typologies is very different, so the choice in their use must be weighted according to the type of the expected performance level.

The stick system façades can also be classified according to the way in which the glazing is fixed to the substructure:

a) *traditional façades*, where the infill panels are fixed to the mullions and transoms by mechanical fixings;
b) bonded glazing or SSG (structural sealant glazing), where glazing is guaranteed by sealant bonding;

but also, in relation to the different levels of prefabrication of the façade:

a) *site-assembled façades*, which are the most traditional and widespread, where the assembly of the various industrialised components takes place on site;
b) *unitised curtain wall*, where portions of the façade are made in the production plant and only then are the parts assembled on site.

The classification of *point fixed glass façade* is much more complex and the understanding of these systems requires knowledge and understanding of specific technologies.

The solutions are distinguished by:

a) the point fixing systems;
b) substructures for vertical loads;
c) substructures for horizontal loads (wind bracing);
d) possible connection systems between fixings and substructures.

6.3. The Technology

Glass and metal curtain walls must meet all the requirements of an external wall[2]. The achievement of adequate performance levels suitable for civil use as well as the use of a fragile material such as glass as a cladding make curtain walls one of the most complex technological systems used in construction.

The main difficulties are related to achieving sufficient air and water tightness as all dry construction systems. In particular, the joints, the anchorage systems to the building structure and the drainage systems (when available) are the most affected elements.

Furthermore, in this specific case there are difficulties in obtaining satisfactory levels of both acoustic and thermal insulation.

The two curtain wall typologies use very different technologies. Therefore, *stick system façades* and *point fixed glass façade* will be separately analysed. In both cases all the elements made up the system will be identified and analysed.

6.3.1. Stick System Façades

The stick system façades consist of (Fig. 6.1):

a) vertical structural elements called *mullions*, which perform the main structural function;
b) connecting elements between the mullions to ensure their structural continuity, defined *spigots*;

c) horizontal structural elements named *transoms*;
d) the system for anchoring the façade to the main building structure usually consisting of *fixing brackets*;
e) the façade closure system consisting of glazed or opaque infill panels;
f) elements interfacing the substructure to the glazing consisting of *glazing gaskets*.

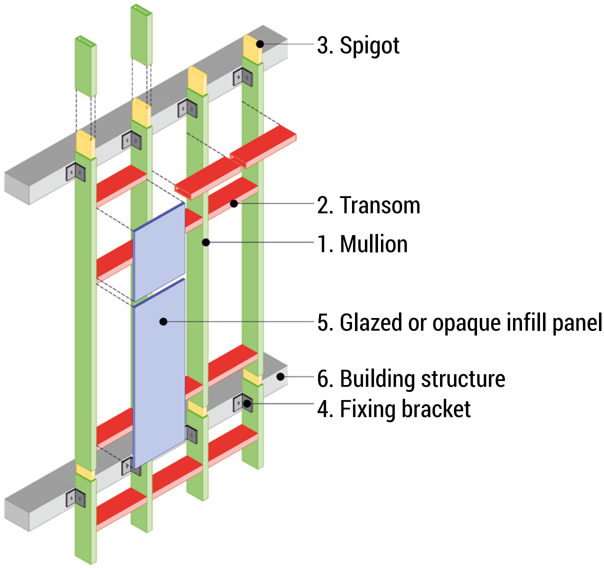


FIG. 6.1. Example scheme of the façade system as exemplified in EN 13119:2016 (Source: own elaboration)

The structure that guarantees the self-supporting of a curtain wall is a system of mullions and transoms, generally made of aluminium[3], linked and anchored to the main building structure. Mullions are the elements characterised by main structural function. The transoms, the glazing and the opaque infill panels transmitted loads to mullions that transfer them to the load-bearing edge beams or directly to the floor to which they are anchored.

Mullions are designed considering a static scheme of a simply supported beam, with a length equal to the ceiling height.

The elements for anchoring the mullions are called fixing brackets. In addition to their purely structural function, these elements absorb the constructional tolerances of the load-bearing structure, particularly if it is made of reinforced concrete. Possible adjustments are of about 15-20 mm in 3 space directions. This guarantees the installation of windows and doors, which require millimetric precision, despite the certain presence of inaccuracies of a few centimetres, typical of reinforced concrete technology.

Adjustments are usually achieved by combining slotted holes and C-shaped serrated channel profile of steel with hammerhead screws.

Since it is not obviously possible to use mullions of the same length as the entire height of the building, the system is made up of individual pieces of the same span. Each element is anchored directly to the fixing bracket at one end only. The other is connected by a spigot to the adjacent upright, which is fixed to the building structure by a fixing bracket. The spigot consists of a box-like element that is inserted into the two mullions to be connected. It is fixed on one side and left free on the other, to obtain a sliding telescopic connection, thanks to the presence of a joint of about 20 mm between one mullion and the other. The aim is to avoid tension inside the mullions due to the expansion caused by thermal variations.

The substructure is generally made of aluminium, so it is essential to reduce heat loss between internal and external environment. For that, there are insulating elements inside the profiles that break the continuity of the profile in the direction of heat flow. These profiles are called *thermal break profiles*. The most used system consists of glass-fibre coated polyamide bars which guarantee the structural continuity of the profile section, when linked to the aluminium parts. The geometry of the bars is strictly dependent on system type.

Glazed or opaque infill panels are directly connected to the substructure. It generally provides support around the entire perimeter of the panel (Fig. 6.2).

FIG. 6.2. Example of stick system façades with mechanical fixing. Expansion of El.En. S.p.A. factory, Calenzano (FI) – Italy. Designer: Vincenzo Di Naso (Source: photos by V. Di Naso)

As already mentioned, the most significant distinction within the analysed type relates to the method of fixing the infill panels. The traditional façades (about 70% of the production) adopt a slab retention system which exploits the presence of a *pressure plate* (where the glazing gaskets are inserted). It restrains the slab by contrast. The pressure plate is fixed by screws tightened inside the mullion (Fig. 6.3).

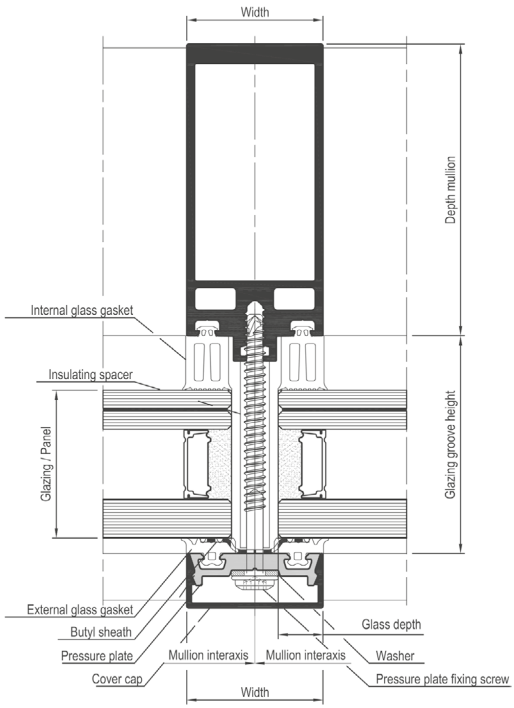
Both the pressure plate and the screws are protected by a *cover cap* that contributes to its durability as well as aesthetically characterised the façade. It limits galvanic bridges between the steel screws and the aluminium pressure plate.

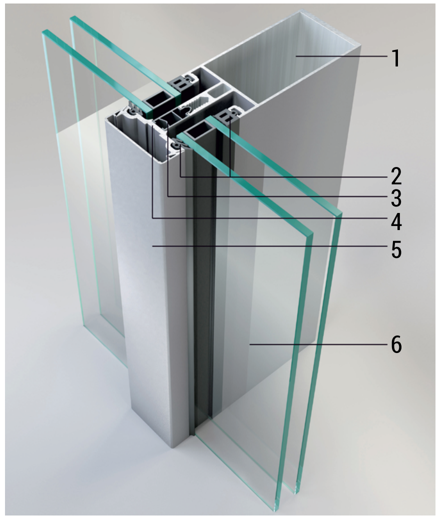
In the case of traditional facades, the used cross-section of both mullions and transoms is morphologically identical.

On the other hand, bonded glazing façade use silicone sealants to bond the infill panels. Sealants are synthetic polymers where silicon atoms are bound to oxygen to form macromolecules (Fig. 6.4).

These compounds are characterised by:

a) a chemical structure that allows an interface between organic and inorganic materials;
b) a remarkable stability between the silicon and oxygen molecules enables to maintain their mechanical and physical properties under extreme conditions of exposure to several environments.





1 – Mullion
2 – EPDM gaskets for glazing
3 – Spacer
4 – Pressor
5 – Cover
6 – Insulating glass with air space

FIG. 6.3. Cross-section of the mullion and three-dimensional view of a stick system façades with mechanical fixing (Source: The technical material in question is the property of METRA Spa)

The advantages that this solution provides are:

a) a slight improvement in thermal insulation performance compared to a traditional system;
b) the possibility of achieving a certain level of prefabrication;
c) to ensure the continuity of the glass on the external surface of the façade, not interrupted by the presence of the mullions/transoms, the main reason for using this system.

The issue of secure panel fixing in this façade type is absolutely importance. The most delicate phase in the manufacturing process is obviously the bonding of the glazing to the aluminium profiles. Since precise environmental conditions are required to ensure optimal bonding, which cannot be achieved on the construction site, this work must be carried out in the factory. To do this, the sheet is glued to an aluminium frame at the factory, and then mechanically connected to the mullion and transom substructure on site.

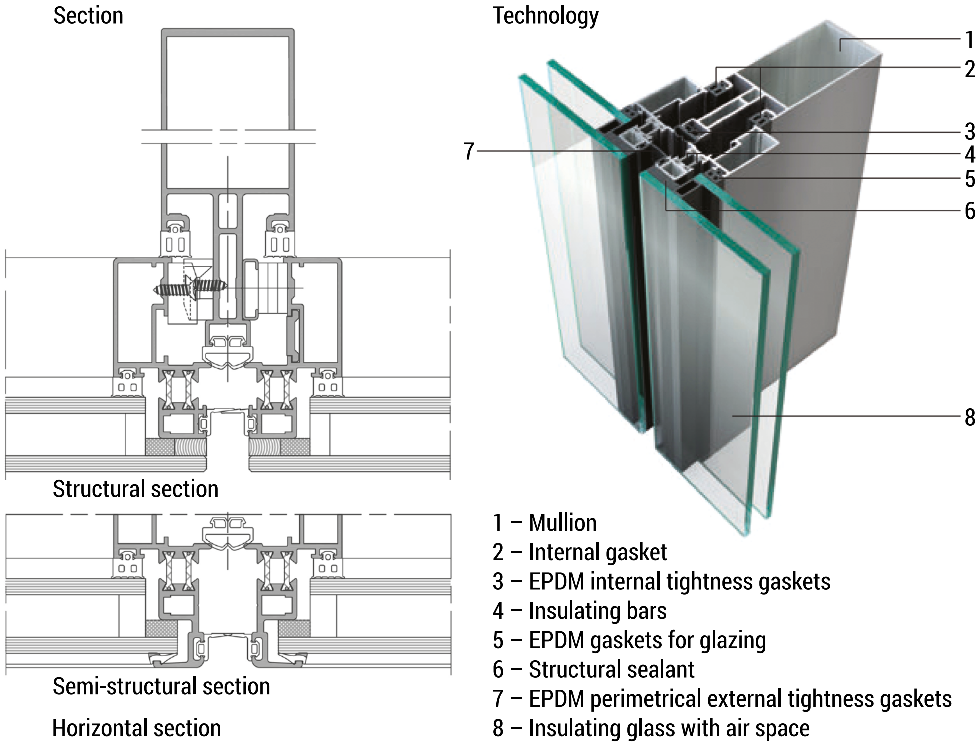


FIG. 6.4. Cross-section of the mullion and three-dimensional view of a stick system façades with bonded fixing (Source: The technical material in question is the property of METRA Spa)

This system has the advantage that the aluminium frame can be a movable frame for the openings, so that the openable portions of the façade are not detectable when closed.

Otherwise, in the case of traditional façades the openings are clearly marked because of the presence of the profiles that make up the mobile frame, clearly distinguishable within the grid of mullions and transoms.

The proper design of the elements that interface the two materials as well as a careful study to ensure water and air tightness ensure the best performance and functioning of the façade.

The first issue is related to the second one and the seals play a key role.

However, the airtightness and watertightness performance of a curtain wall is the result of the overall behaviour of several components:

a) the elastic deformations of the frame elements, which must be contained in such a way that the function of the joints is not impaired;
b) vertical and horizontal dilatation joints at the connection of the transoms to the mullions and between one mullion and the next one;

c) joints at corner solutions or connections to adjacent construction, or where there is a slope change (interface solution between façade and roof or sloping façade);
d) glass sealants and glazing gaskets.

Regarding glass gaskets, two aspects must be considered:
a) deformation of the frame elements may compromise the watertightness of the façade;
b) rainwater is accumulated near the joints.

When designing a façade system, it is assumed that it is impossible to eliminate all water infiltration. It is therefore important to prevent such infiltrations from reaching the interior.

This technique is based on the hypothesis that the water can pass through the first defence line made of external glazing gaskets and then intercepted and expelled by a second one made of a complex of drips and channels created into the profiles of both mullions and transoms. Those are capable of conducting the rainwater and condensation towards drainage and expulsion slots (*drainage holes*). This also explains the need to use a corrosion-resistant material such as aluminium for the substructure.

The third possibility consists of eliminating, or at least reducing, the intensity of the forces that "conduct" water into the façade joints. This design and construction method is normally named *pressure equalisation*.

The glazing gaskets[4] play a very important role, as they must support the differentiated movement of the insulated glass unit with respect to the metal frame as well as ensuring watertightness, airtightness, thermal insulation, and soundproofing.

Within the two types previously described it is possible to have two different design approaches with reference to the possible façade prefabrication. The most frequently used solution is to assemble the façade entirely on site, considering the level of prefabrication that can be implemented based on the used façade: traditional or bonded glazing. This for both greater guarantees of performance and for lower costs for use on ordinary building construction sites (Fig. 6.5).

FIG. 6.5. Example of site-assembled traditional stick system façades. Commodora Wheels building in Ghedi (BS)– Italy. Designer: Studio Associato di Ingegneria Civile Ingg. Vecchi (Source: © courtesy of METRA Spa)

6.3.2. Unitised Curtain Wall

In some applications it is preferable to use *unitised curtain wall* using pre-assembled modules. The latter require only few operations outside the workshop to complete, i.e., those necessary to position and anchor the modules on site.

The module generally consists of a façade module as high as the storey and as wide as one or more vertical modules of the system (Fig. 6.6).

The ensemble may consist of a single-skin or double-skin façade module that will be later addressed.

The technological features that characterise it are in any case identical.

The birth of the cellular system is the result of the vertical development of the buildings, which makes it problematic, if not impossible, to set up external scaffolding, which is necessary for the implementation of “traditional” technologies.

With the possibility of having a pre-assembled module, workers are only on the floor where the module is located and on the upper one. The installation is carried out with the façade element lifted by a lifting machine located on the floors above the assembly floor.

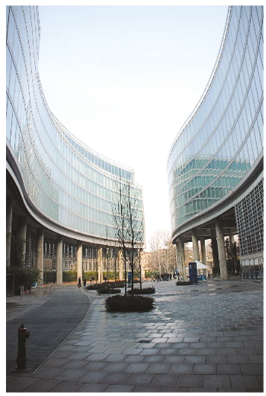


FIG. 6.6. Example of unitised curtain wall. Region Lombardy Headquarters in Milano – Italy. Designer: Pei Cobb Freed & Partners (Source: © courtesy of METRA Spa)

Additionally, considerable advantages can be achieved in terms of construction time, because only a small number of operations are required on site to install the cell. This is typical of prefabricated systems.

Regarding the façade system technologies, the unitised curtain walls do not differ from the solutions previously shown.

Their peculiarities are linked to the problems distinguished large envelope elements and particularly those relating to the tightness of the joints between the elements and their correct positioning on site.

This involves in peculiar solutions both in correspondence with the transoms and the mullions perimeter to the prefabricated module (always present) and in the anchoring system to the main building structure.

The problem of creating a self-supporting element, which also has a water and airtightness system already in place, led to the design of elements without glass components on the edge.

Additionally, if the unitised curtain wall uses stick system façade technology, mullions and transoms must always be provided at the perimeter, named as 'half mullion' and 'half transom'.

This necessarily means that there is always a doubling of these elements at the joints. These components are placed next to the corresponding elements of the adjacent prefabricated module and the joint solution generally foresees the presence of three or four water barriers. The latter can be made up of gaskets that work by pressure (generally only for the mullions) or gaskets (usually used for the transoms) that sometimes are adjusted within a "male-female" gap between nearby profiles.

Finer solutions present the second solution for both mullions and transoms. The fact that the prefabricated module is an element of a simple façade or a double skin does not substantially change things.

Therefore, there are two unitised curtain wall configurations depending on the interface logic of the perimeter profiles of the façade modules (Figs. 6.7 – 6.10):

- Unit type "European", characterised by the same profile on the right and left and profiles connected by several gaskets;
- Unit type "American", where the profiles have a different workmanship and the cells are joined by a mechanical connection, thus creating profiles that will require fewer gaskets.

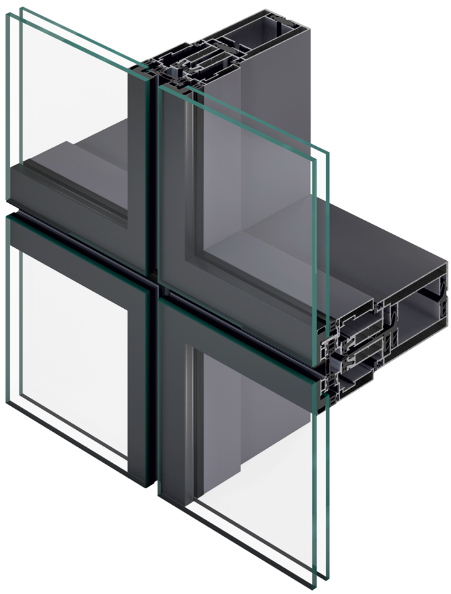


FIG. 6.7. Three-dimensional view of a unitised curtain wall system façades with bonded fixing (Source: The technical material in question is the property of METRA Spa)

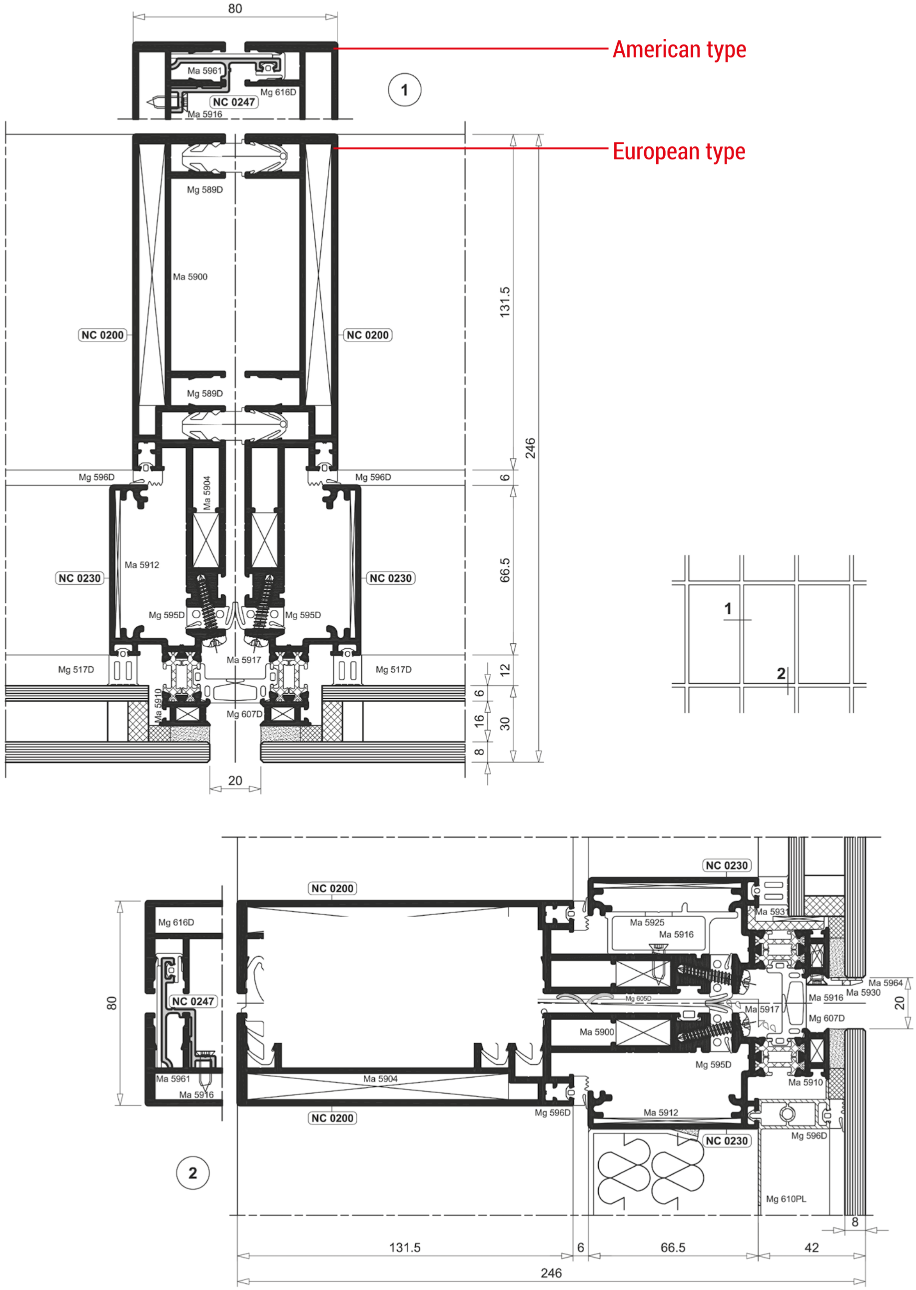


FIG. 6.8. Cross-section of the mullion (on the left) and of the transom (on the right) of a unitised curtain wall system façades with bonded fixing. Note in the cross section the solution for the opaque infill panel (Source: The technical material in question is the property of METRA Spa)

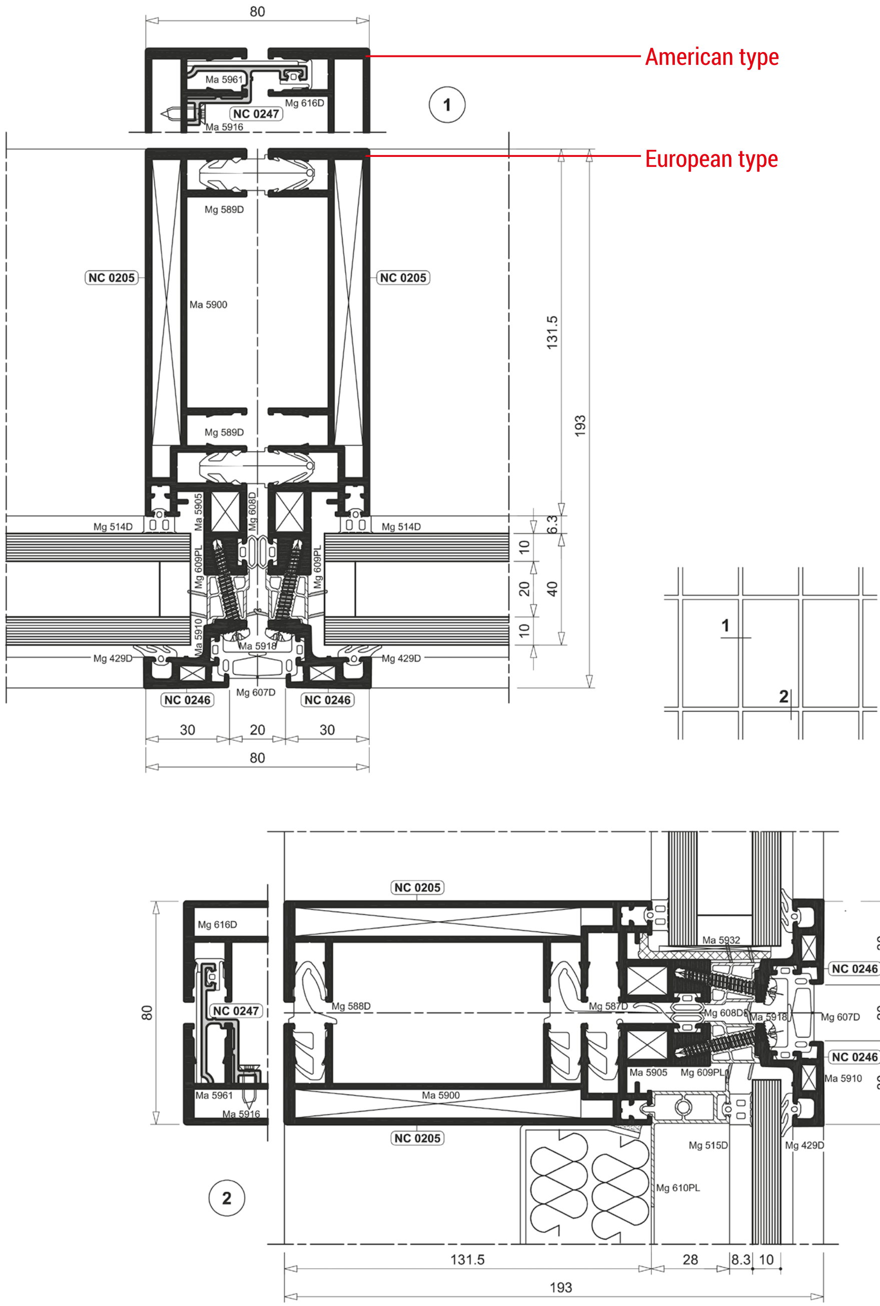


FIG. 6.9. Cross-section of the mullion (on the left) and of the transom (on the right) of a unitised curtain wall system façades with mechanical fixing. It is worth to notice the solution for the opaque infill panel in the cross section (Source: The technical material in question is the property of METRA Spa)

FIG. 6.10. View of the facade under construction (top left), a fixing bracket detail (top right), detail of the upper "half transom" of a module of a unitised curtain wall module (bottom left) and assembly phase of a unitised curtain wall module (bottom right). New Palace of Justice in Florence – Italy. Designer: Arch. Leonardo Ricci (Source: photos by V. Di Naso)

6.3.3. Point-Fixed Glass Façade

The technology of *point-fixed glass façade* is much more recent than that of the stick system façades. In this case the load-bearing structure of the façade has been considerably dematerialised. So, it can be limited to a bracing system made up exclusively of connecting rods and cables or even glass. In any case, the façade structure is placed on a different plane with respect to the glazing and the glass pane is not held in a continuous manner but only in certain points.

Starting from a certain number of significant realisations, it is possible to identify the components that characterise this façade system, to be orientated in the design choice that involves their application (Di Naso, 2007).

It is necessary to highlight that the stylish definition of the façade corresponds to the identification of the structural solution, since in this type of façade all the elements made up the system contribute to its stability. The classification of the system components can be articulated through the identification of the structural elements and their function.

A suspended glazing unit is characterised by the following elements:

a) the point fixing systems,
b) the substructure systems for vertical loads,

c) the substructure systems for horizontal loads (bracing solutions),
d) possible connection systems between fixings and substructures.

When choosing the type of components during the design process (previously listed), it is necessary to proceed hierarchically. This because some technological elements are not compatible with each other.

As far as the fixing systems are concerned, there are solutions with or without perforation of the pane (through-fixing and clamp fixing).

Whatever the system, the priority is to reduce the bending stresses generated by external actions or to transfer them outside the plane of the glazing to the secondary structure. So, the pane is stressed predominantly axially, which is much more compatible with the mechanical characteristics of tempered glass.

In the case of *through-fixing*, the glass pane is drilled to allow the insertion of the intended support accessory (bolt through fixing). It is possible to have different solutions regarding both the way the glass pane is drilled, and the type of constraint provided by the fixing.

As far as the type of hole is concerned, the glass panes can be drilled in different ways, even if these only imply a different aesthetic-formal result, i.e., *straight drilling*, in which the straight hole allows the fixing accessory to pass through the glass pane, thus remaining partly outside it, or *countersunk drilling*, in which the countersunk hole allows the fixing accessory to remain inside the plane of the pane. As far as the depth of the hole is concerned, in the case of insulated glass unit, i.e. composed of two or more glass panes, it is possible to drill only one pane or both (Fig. 6.11).

Constraints are also distinguished by the different types of fixing technique. Generally, a distinction is made between *rotule* and *semi-rigid fixing*.

The *rotule*[5] or *articulated bolt* is a fixing type that allows relative rotation between the glazing and the fastener and is therefore similar to a spherical hinge (Fig. 6.12, Fig. 6.13).

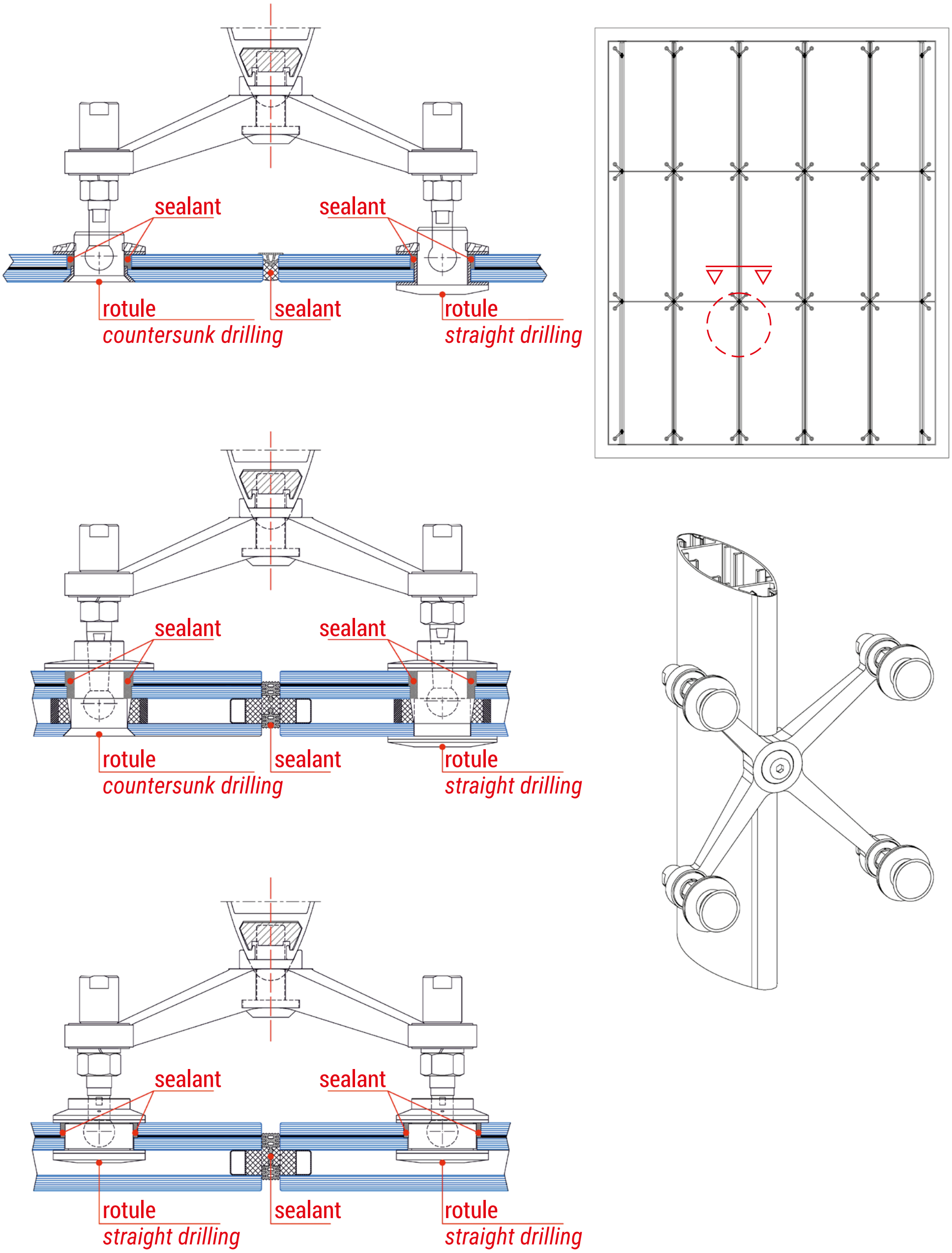


FIG. 6.11. Examples of rotule fixings with both countersunk and straight drilling. Above is the single pane solution, in the middle is the insulated glass unit solution with a hole in both panes, and below is the insulated glass unit solution with a hole in the inner pane only (Source: The technical material in question is the property of Faraone Srl, the reworking is by the authors)

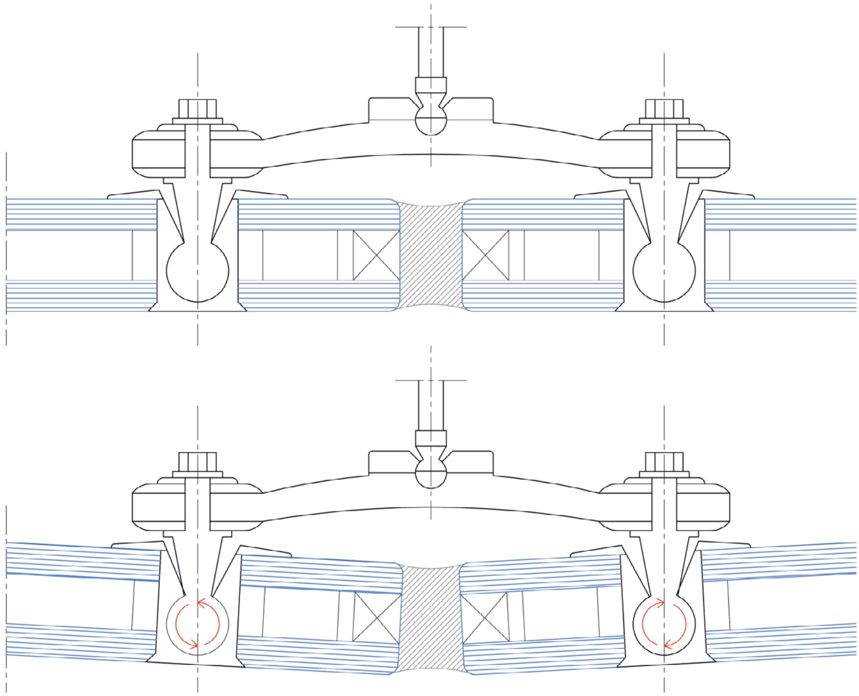


FIG. 6.12. Example of system behaviour for horizontal loads in the case of the articulated bolt (Source: own elaboration)

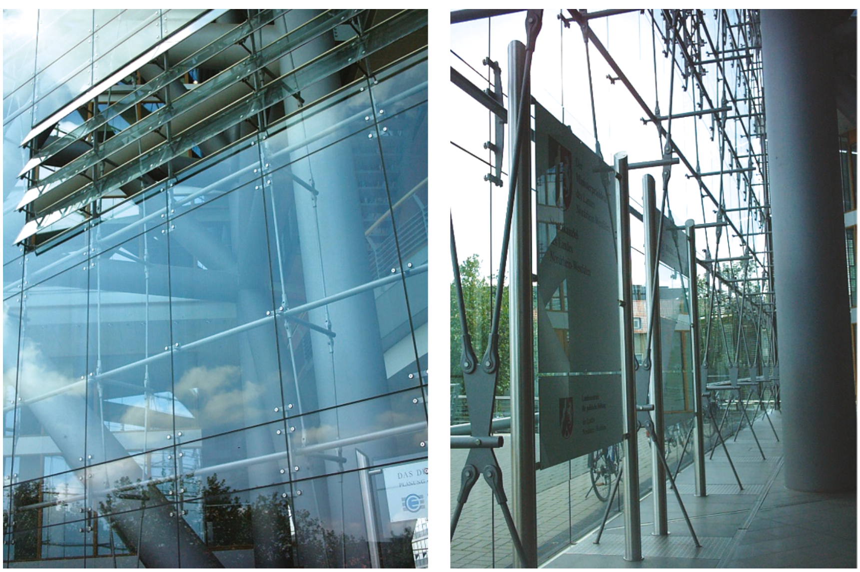


FIG. 6.13. Example of point-fixed glass façade with through-fixing. Stadttor, Düsseldorf – Germany. Designer: Petzinka Pink und Partner (Source: photos by V. Di Naso)

On the other hand, *Semi-rigid fixings*[6] consist of a non-articulated screw, non-rigidly connected to the substructure through the interposition of components made of flexible material (neoprene, silicone, etc.) between the elements.

Instead in the case of *clamps*, this is done by a clamp attached to the edge of the gla-zing. So, the system does not involve drilling. The solutions vary according to the position of the fixing, perimeter, or corner, which determines both different constraints for the slab and a different aesthetic characterisation of the façade. The perimeter clamp is achieved by two-way clamp gripping two glass panes, upper and lower one (Fig. 6.15). Each pane is usually "held" through four clamps: two on the upper edge and two on the lower edge. Clamps are accommodated in the horizontal development of the pane. It is worth to notice that this type of clamping is the easiest way to obtain a staggered arrangement of the glass panes. The angle clamp consists of so-called "cloverleaf" clamps placed where four panes meet (Fig. 6.14).

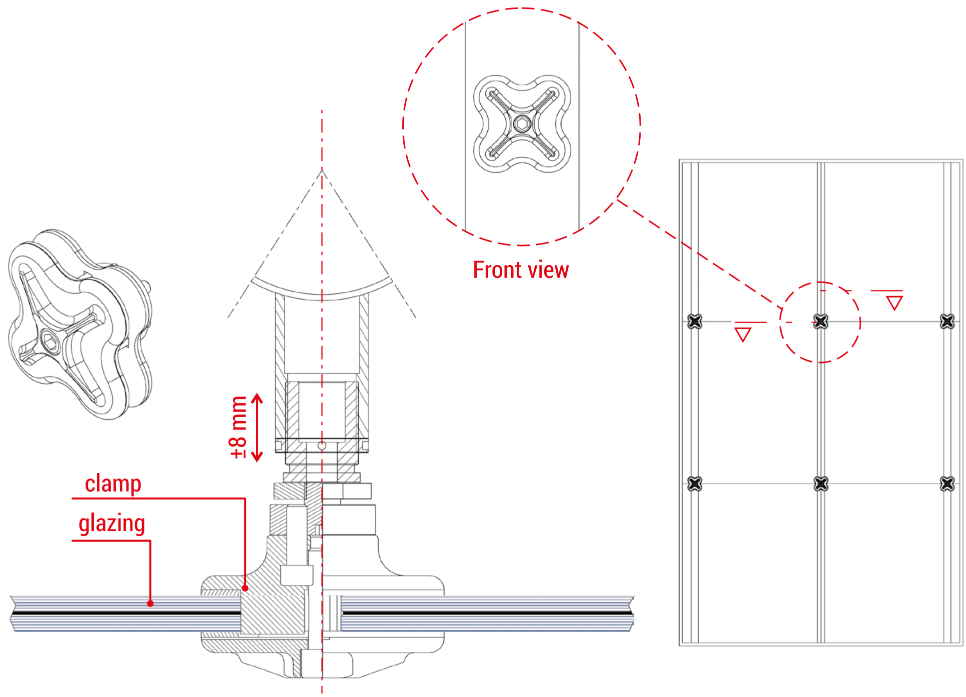


FIG. 6.14. Examples of clamp fixings of the cloverleaf type (Source: The technical material in question is the property of Faraone Srl, the reworking is by the authors)

Façade system elements resistant to vertical loads can be identified. A façade component does not always fulfil only this function. Sometimes, the same element contributes to ensuring the stability of the façade system in relation to horizontal loads.

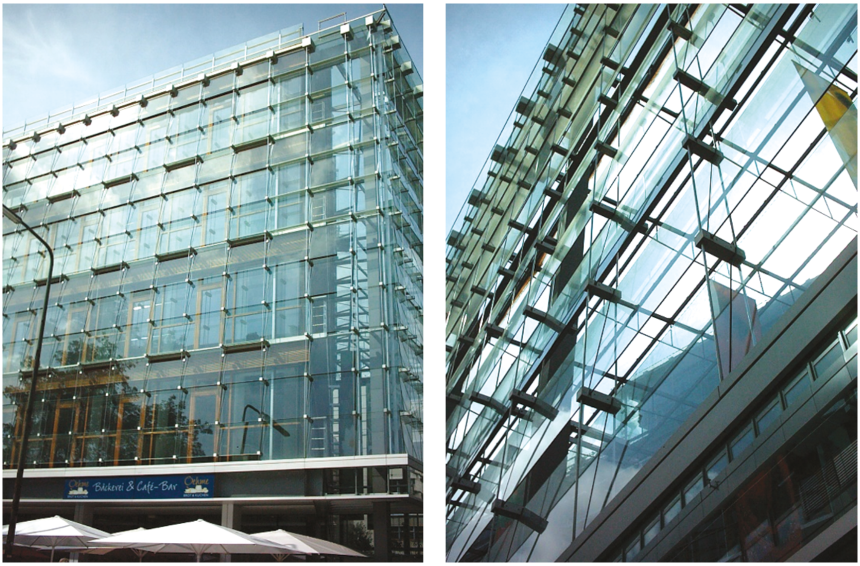


FIG. 6.15. Example of point-fixed glass façade with clamp. Office building H19, Düsseldorf – Germany. Designer: Petzinka Pink und Partner (Source: photos by V. Di Naso)

It should also be emphasised that the type of substructure adopted is closely linked to the type of fixing.

The following cases can occur:

a) *No dedicated substructure*: this is the case where the glass panes of the façade themselves perform a structural function, i.e., inside the façade the upper panes carry the lower ones, as „curtain system". These systems are called suspended glazing as opposed to all others (known as free-standing glazing). This type can only be combined with through-fixing.

b) *Vertical cables*: this is one of the substructure choices which guarantees the lowest formal impact; the vertical loads are totally supported by generally steel cables that transmit these loads to the main load bearing structures of the building. All types of fixing can be used to hold the glazing. In the case of through fixings, components mediate the relationship between the fixing element and the cable (stars, plates, etc.). While in the case of clamps, a direct connection between cable and clamp fixing element is possible. The vertical cable solution is the preferred one using clamps because it minimizes the façade system components as well as the substructure impact on the glazing. Some considerations needed concern with the two different types of clamps. Each vertical series of clamps is generally supported by a separate cable. Perimeter clamps are arranged in intermediate positions in relation to the width of the glass pane. In this case two suspension cables for each vertical series of panes will be clearly visible on the front. Otherwise, in the case of corner clamps since they are placed on the slabs' corners, the cables will pass at the vertical joints. they are practically invisible from the outside.

c) Mullions: this solution is the most classic and simplest one. In this case a mullion is used to support the vertical loads due to the glazing weight. Mullion is obviously placed on a different plane with respect to the slabs. The mullions will be anchored to the load-bearing structure of the building and can be made of very different materials such as wood, metal or glass itself. However, it is worth to highlight that this technical solution is suitable for façades of reduced vertical development. In this case the design does not aim for maximum dematerialisation and transparency of the envelope, except for the solution with glass mullions. All fixing systems can be used in these applications, even if they are usually combined with through-fixing systems.
d) *Partial suspended mullions*: this solution is a hybrid between the previous cable and mullion solutions. It involves the use of small uprights, generally slightly higher than the height of a façade pane, together with steel cables. In this case the mullions are suspended from steel cables and provide anchorage for the pane fixings. In detail the mullions pick up the vertical loads of a limited number of slabs and transfer them to the cables. The latter ensure loads passage to the main building structure. Since the mullions are subjected to a rather low static load, it is possible to define materials and shapes with a certain freedom. This allows for different choices aimed at aesthetic characterisation of the façade. All fixing systems can be used.

Components (different from glazing) to ensure resistance to horizontal loads acting orthogonally to the façade surface can always be found among glazing system. These elements are not always exclusively dedicated to this purpose.

The following cases can be found:

a) *Mullions:* if a façade is built with vertical mullions, these can also provide bracing. It is evident that to engage the mullions with bending stresses will require the use of much larger sections than would be sufficient for a simple axial action, thus reducing the effect of great transparency which should be characteristic of this type of façade.
b) *Cables*: the use of cables let pursuing several ways linked to the choice of structures for supporting vertical loads.

   There are mainly two ways of using cables, namely through single pretensioned cable structures and through double pretensioned cable structures.

   In the case of single pretensioned cables: it is possible to use a single row of cables, or two rows of cables placed in a surface parallel to that of the facade, subjected to pretensioning.

   These are the two more frequent solutions:

   - The first one involves a single row of cables vertically arranged. In the case of vertical structures with partial mullions or cables it may coincide with the suspension cable itself. In the latter case, the structure is called a 'single cable'.
   - The second one involves both horizontal and vertical cables.

Obviously, applying the first solution a considerable minimisation of the substructure is achieved. The use of the single pretensioned cable can also be combined with a mullion structure. In these applications, the cable is placed on a plane orthogonal to the façade one and in correspondence with the mullion, to form a bracing structure consisting of the mullion/cable system.

In the case of pretensioned double cables, two-dimensional structures are required when the size of the façade is important (Fig. 6.16). This type of substructure involves the use of cable systems connected to each other and to the fixings by connecting rods to form flat structures with a parabolic cable pattern. These structures obviously are arranged on planes perpendicular to that of the façade, generally horizontal and/or vertical.

FIG. 6.16. Example of suspended glazing. Note the vertical bracing in the photo. Stadttor, Düsseldorf – Germany. Designer: Petzinka Pink und Partner (Source: photos by V. Di Naso)

In many applications the use of certain other technical components that mediate the relationship between the substructure and the fixings, such as the star-shaped supports used for through-fixing, can be identified.

For this type of element additionally to industrialised production, components are generally made by the industry for specific applications, especially to achieve a specific architectural characterisation of the façade. These elements, which are usually linked to specific applications, are difficult to classify (Fig. 6.17).

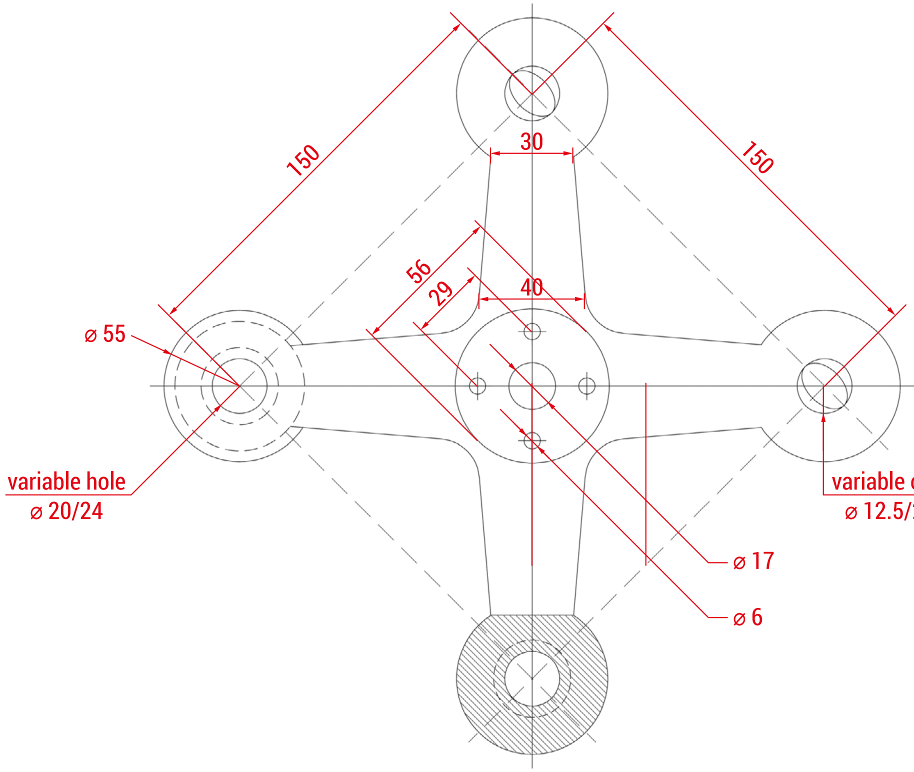


FIG. 6.17. Example of a "star" as a mediating element between the substructure and the fixing of the glazing. FIAT footbridge, Turin – Italy. Designer: Adriano Vanara (Source: own elaboration)

6.3.4. Double Skin Façade

To introduce this section referred to double skin façades, a classification of complex glazed façade systems should be made.

Four basic elements can be identified (Fig. 6.18):

1. tempered or laminated glass,
2. insulating glazing,
3. wind-resistant shading system (usually shed),
4. non-wind resistant shading system (curtain).

The combination of these four elements identifies five types of façades (Fig. 6.18):

1. single skin façade with external screen,
2. single skin façade with integrated screen,
3. single skin façade with internal screen,
4. double-skin façade with a forced-ventilated cavity,
5. double skin façade with a naturally ventilated cavity.

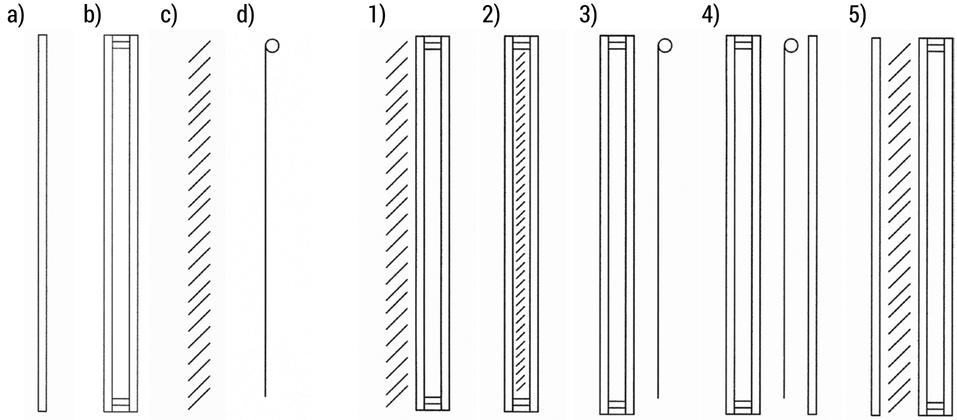


FIG. 6.18. Basic elements of the classification of complex glazed façade systems (left): a) float or laminated glass; b) insulating glazing; c) wind-resistant shading system (usually shed); d) non-wind-resistant shading system (curtain). Classification of complex glazed façade systems (right): 1) single-skin façade with an external screen; 2) single-skin façade with an integrated screen; 3) single-skin façade with an internal screen; 4) double-skin façade with a forced ventilated cavity; 5) double-skin façade with a naturally ventilated cavity (Source: own elaboration)

The single skin façade with external screen uses an insulating glass unit with an external wind resistant shading system.

Among the three single skin façade solutions, this is undoubtedly the one that provides the best results in terms of environmental comfort.

Indeed, the share of solar radiation that is absorbed by the shading system can be dispersed outdoor.

The choice of such a system involves aspects of architectural language to a considerable extent.

The single skin façade with integrated screen is the most recent one.

This involves the use of an insulating glass unit and a shading system integrated into the glazing, i.e., closed within the cavity.

Although this system is undoubtedly the one that makes the glazing “cleaner”, it presents significant problems of glazing surface temperatures.

The single skin façade with internal screen uses an insulating glazing with an internal shading system. As this is protected from external agents, it must not have any static resources. Usually, curtains are used. This solution is the most classic of those described here and it is characterised by several issues.

By placing the shading system inside, it will transfer to the room all the absorbed heat and part of reflected one. This because if a low-e glass is used it will not leak the radiation in the infrared.

The double-skin façade with a forced-ventilated cavity consists of an external insulating glass unit, an internal toughened or laminated glass pane a shading system placed between. The latter does not need to have wind resistance, as it is protected by the outer glazing.

A double-skin façade with a naturally ventilated cavity consists of an external toughened or laminated glass pane, an internal insulating glass unit and a wind-resistant shading system place in between, as the cavity in this case is open to the outside.

Double facades are composed of two wall structures and an air cavity in between.

One wall constitutes the actual diaphragm with the outside and so it is the actual façade; while the other one (called the second wall) can be facing either the rooms inside the building or the outside environment to create the air cavity.

The insulation external skin can be either internal or external depending on the functioning of the whole façade system.

Practically, the system has a ventilated "double glazing" with shading and aims at reflecting as much solar radiation as possible.

Usually, the solar shading systems are optimally located inside the cavity to guarantee the best performance.

In some systems the adopted technology is unitised curtain wall system façade, with frames to support the two portions of the wall, spaced out from the cavity and with internal shading devices. In other systems the construction is carried out by two separate façades, an internal façade and an external one, both with their own substructure.

Normally, the choice of one or the other solution depends on the size of the ventilation chamber: usually, up to a cavity of about 50 cm the cellular façade solution can be used; however, with larger cavity this is more complex, and it may be necessary to install the two walls separately.

The external wall of the façade has openings that allow the entry and exit of external air, and in some typologies the ventilation is connected with the systems or directly with the internal environment (through vents).

Devices for opening and closing the ventilation vents are needed to control inlet/outlet flows, especially since in winter season the naturally ventilated double skin façade only well performs if the cavity is closed, inhibiting ventilation.

There are several classification modes, but basically in our opinion double-skinned faces have three basic types of operation (Di Naso, 2002):

- closed-system,
- forced ventilation,
- natural ventilation.

Closed-system facades, also known as pressure-compensated facades, are double-skin systems with only small openings on the outside to regulate the vapour pressure and avoid condensation in the cavity.

These façades, suitable for climatic zones characterised by low summer temperature, have the disadvantage of an excessive increase in cavity temperature, especially in summer. To avoid it as much as possible the insulating glass is placed inside.

This technology guarantees:

- good performance in terms of acoustic protection (e.g., when the building is located in a high traffic area);

- excellent thermal performance in winter;
- good protection of solar shading.

Forced-ventilated façades have variable cavity sizes, and they are connected to the conditioning systems, that air-condition the building all year round.
In these systems there is always the opportunity to open the inner skin to access the cavity for maintenance, while the outer wall is thermally insulated and is a real barrier with the outside.

This technology provides the following advantages:
- limiting the consumption of energy for rooms cooling, as the hot air inside the cavity, due to the absorption of solar radiation by the shading, which is then released into the cavity, is directly extracted from the cavity;
- redistributing energy within the unexposed areas of the building, using solar energy according to the orientation of the building during the day;
- locating workstations adjacent to the façade, that never reaches excessively high temperatures;
- ensuring good acoustic insulation.

Often the automation process involves the whole building to manage:
- opening/closing of ventilation vents (external side);
- optimised orientation of solar shading systems;
- opening/closing of air intake vents (internal side);
- opening/closing of air inlet vents to indoor environments;
- activation of systems;
- opening/closing of internal windows and doors towards the cavity.

The air intake vents from interior can have different shapes in relation to the various possible locations, including openings under the internal doors and windows, such as in the Deutsche Bank Towers in Frankfurt by Mario Bellini Architects, or in correspondence with the lighting systems, such as in the Lloyd's Headquarters in London by Rogers Stirk Harbour + Partners.

There are many ways to extract or introduce air into the cavity, even if the most common is to position vents in the thickness of the floor slab.

In many cases there is also the opportunity for users to open or close the internal skin completely to personally exploit and manage the thermal possibilities offered by the heat of the air in the cavity.

Naturally ventilated façades have the insulating skin in contact with the interior environment, and the second skin with the exterior one, as is the case with all ventilated façades. The advantages offered by this system are:
- overall improvement of the thermal performance of the building if the system is applied as part of an integrated design process of architecture, structure, systems;
- elimination of heat inside the cavity in summer season;

- possibility of opening internal windows and doors in the intermediate seasons, thus exploiting the mild air temperature in the cavity;
- limited maintenance of solar protection systems inside the cavity;
- good thermal insulation provided by the façade during winter, if closed or without ventilation;
- good noise protection for low-rise buildings.

They are especially used in the cases where the building is not able to make the most of natural ventilation of the rooms due to its position, orientation, morphology, etc. However, it is always necessary for the building to be equipped with an adequate system, although not connected to the façade, to guarantee total satisfaction of the thermal performance in all possible conditions and to tackle extreme temperatures.

Certainly, although it is not essential, the performance of the system can be improved if the vents in the cavity can be closes and opened as well as the air flow can be regulated depending on external conditions.

This typology is characterised by four main systems according to both the mode of ventilation within the cavity and partitions division (Fig. 6.19) (Oesterle et al. 2001):

- box windows,
- corridor façade,
- multistorey surface,
- shaft-box façade.

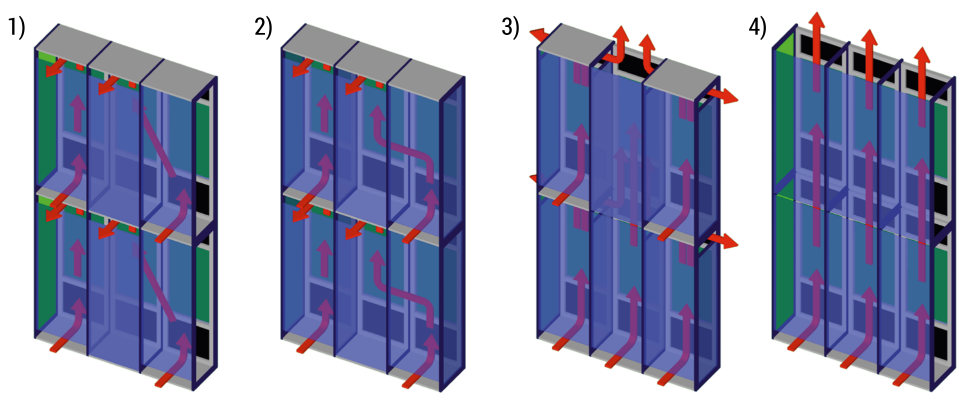


FIG. 6.19. Sketches of the main types of natural ventilation systems depending on the mode of ventilation within the cavity: 1) corridor windows façade; 2) box windows façade; 3) shaft-box façade; 4) multistorey façade (Source: own elaboration)

The box windows are the most common types (e.g. Commerzbank in Frankfurt by Foster + Partners, where the system does not cover the entire façade). It has a more reduced compartmentalisation and a limited distance between the inlet and outlet vents, allowing greater control over its operation and performance, especially in terms of:

- limited increase in temperature in the cavity;

- noise protection in relation to the urban environment and between different floors;
- control of the spread of fire and smoke in a fire event;
- good ventilation of the interior spaces.

The corridor system (one storey height) also guarantees the performance of the cellular system, but some care is required in its design. For instance, the ventilation openings must be carefully positioned so they do not overlap or interfere with the air entering and leaving the ventilation cavity.

In the case of the multistorey type, the cavity is extended over several floors or even the entire height of the façade: in this case the chimney effect can also be exploited, by opening the window and door frames inwards, to extract stale air from internal rooms. However, special attention must be paid to the design of the system to control possible turbulence generated by the technological components in the cavity, as well as to the size of the cavity section to guarantee the chimney effect.

In the shaft-box type, also known as the chimney type, the compartmentation starts vertically, over several floors, and the air is directed into real ventilation chimneys. These chimneys, generally of limited width, usually require an autonomous structure inserted into the thickness of the facade, as they must not have transversal elements that hinder the "draught" to function correctly. An application of the system can be found in the Photonic Centre in Berlin by Sauerburchhutton work office.

The design considerations needed in naturally ventilated double skin façade systems are similar to those of the building-rainscreen facade system both from a physical-technical and structural point of view. These are mainly:

- type of partitioning;
- size of the cavity;
- position of the solar shading system;
- position and morphology of the air inlets and outlets;
- technology of the solution at the windows;
- possibility of cleaning and maintenance.

Starting from the three types of double skin facades previously described, it is possible to identify a number of categories and subcategories of operation.

The parameters adopted for this analysis are:

- opening/closing of the inner skin;
- opening/closing of the outer skin;
- relationship between the cavity and the plant system;
- height of the cavity.

For each sub-category it will be possible to establish winter and summer operation, the use of shading and the possibility of adopting a mixed system during the intermediate seasons.

Category A

Category A includes systems that keep the inner skin sealed in both winter and summer seasons (Fig. 6.20).

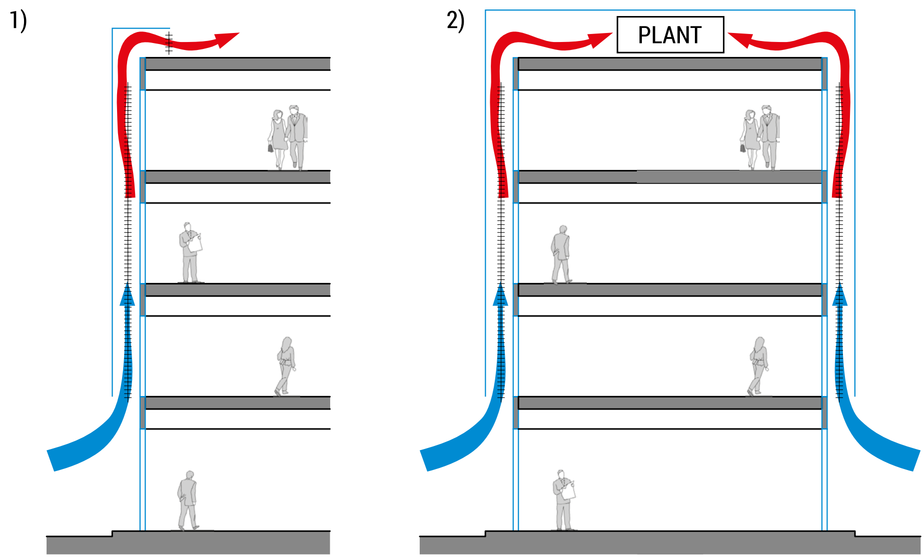


FIG. 6.20. Diagrams of operating categories and subcategories: 1) Category A, subcategory 1; 2) Category A, subcategory 2 (Source: own elaboration)

Category A, subcategory 1

Systems in subcategory 1 are distinguished by the possibility of natural ventilation of the cavity and the lack of interaction between the systems and the façade.

Operation during winter season

During winter season, the façade operates as a thermal buffer.

The cavity is closed (inside and outside) keeping the two skins sealed. The vents at the top and bottom of the cavity are therefore closed.

In this way, an insulating layer of warm air daily accumulates by convection along the entire cavity.

The warm air lowers the overall heat transfer value of the façade by decreasing the temperature gradient ($T_0 – T_i$) between the building and the outside environment. This significantly reduces heat loss by conduction.

Operation during summer season

During summer season, the "chimney effect" inside the cavity is exploited.

The vents at the top and at the base are open.

The air entering at the base of the chimney warms up, either by the heat given off by the external skin and by the solar radiation that enters the cavity. Then by convection rises to the top of the chimney.

The ventilation produced by the heated air reduces heat transmission to the inner skin.

The presence of an external glass skin also reduces solar radiation directed at the internal skin by at least 80%. In this application, the cavity can extend the full height of the building. Since the inner skin is sealed, there is no risk of exhausted air coming from inside the rooms on the lower floors could contaminate those on the upper floors.

However, this type of cavity partitioning is not recommended in hot climates. The accumulation of hot air on the upper floors could cause overheating.

In this case it is advisable to partition the cavity for each floor.

In moderate and cold climates, the inner skin is usually made of insulating glazing.

The shading system
The solar shading system can be placed either inside or outside the cavity.

Category A, subcategory 2
Systems in subcategory 2 are distinguished by the possibility of ventilating the cavity with the intervention of the conditioning system.

Operation during winter season
During winter season, the façade operates as a thermal buffer; as far as the passive operation of the chimney is concerned, the system functions in the same way as in subcategory 1. Additionally, the conditions inside the cavity can be modified by mechanical heating or cooling.

Operation during summer season
Again, during summer season the "chimney effect" is used, which is created inside the cavity.

The vents at the base are open and the façade operates as the previous sub-category.

However, in this case the air also produces a thermal buffer, acting by cooling the temperature.

The buffer zone is usually extended over several levels, often the entire height of the building.

Again, the presence of an external glass skin reduces direct solar radiation reaching the innermost skin.

The shading system
The solar shading system can be placed either inside or outside the cavity.

Category B
Category B includes systems where both the outer and inner skin can be opened (Fig. 6.21).

Category B, subcategory 1

Systems in subcategory 1 are distinguished by the possibility of naturally ventilating the cavity. The cavity is subdivided into pairs of floors or single floors.

Generally, the inner skin consists of insulating glass unit.

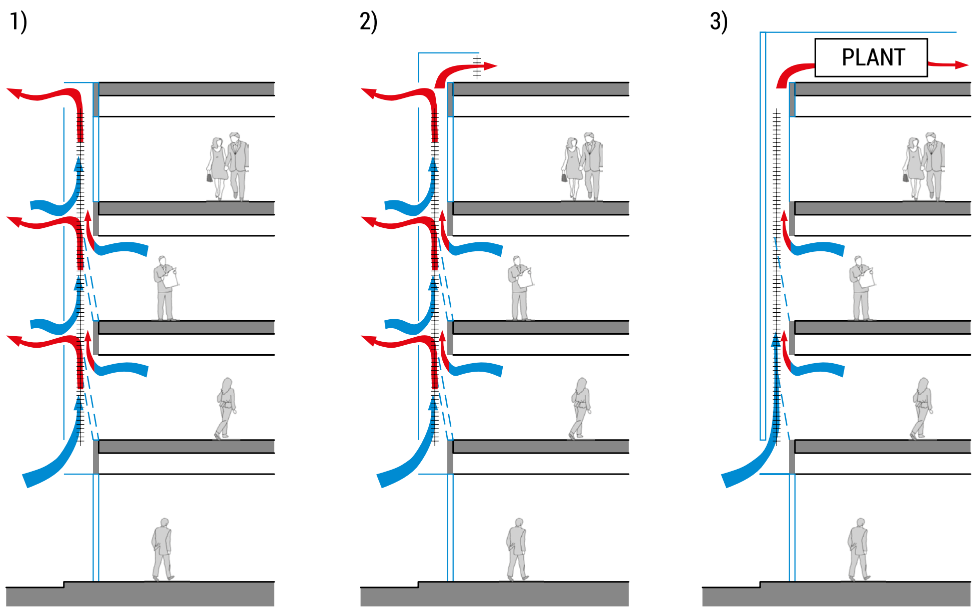


FIG. 6.21. Diagrams of operating categories and subcategories: 1) Category B, subcategory 1; 2) Category B, subcategory 2; 3) Category C (Source: own elaboration)

Combined system

The system can be used to passively ventilate the building.

The effectiveness of the application depends on the floor depth of the building (maximum 14-16m depth depending on the size of the external openings) and the peak heat loads, both heating and cooling, which are obviously related to the type of climate zone where the building is located.

In the case that the previously cited parameters could compromise the effectiveness of the natural ventilation, a combined system with a mechanical heating and cooling system can be used especially during critical periods of the year.

Operation during winter season

During winter season, the inner skin of the façade is closed.

Stale air, mechanically extracted, is brought into the cavity where it is passively or mechanically removed through ventilation in the chimney.

The façade performs as a thermal buffer, thus reducing heat loss.

Additionally, dispersion due to interior ventilation is eliminated by keeping the inner skin closed.

Operation during summer season

During summer season, the "chimney effect is also exploited. Two cases can be distinguished:

- Outside temperature below 15-16 °C. Only the outer skin is opened to ventilate the cavity and eliminate the energy absorbed by the shading system and the other elements of the façade;
- Outside temperature above 15-16 °C. The inner skin is also opened. Passive ventilation of the building is guaranteed, and exhausted air was naturally removed.

When outside temperature is high the thermal inertia of the building needed to be involved. The night cooling occurs during night hours of summer season. This strategy uses the flow and the air currents that are created inside the building due to the thermal gradient present between the internal and external environment (Grosso, 2008) and/or different pressures acting on the building envelope, this in synergy with the exploitation of inertial masses in the environments that partly absorbed heat from incoming air. The night air is used: it has a lower temperature than the internal air of the building to remove heat from the rooms, due to natural ventilation using vents at the base of the building and at the top (chimney effect).

The shading system

In this type of system, the shading system is usually placed in the cavity, although it can also be placed outside.

Category B, subcategory 2

Subcategory 2 systems are distinguished by the possibility of naturally ventilating the cavity by vents on the outer skin.

The chimney is continuous over the whole height of the building. Generally, the inner skin consists of insulating glass unit.

Combined system

The same considerations as for sub-category 1 apply.

Operation during winter season

During winter season, the inner skin of the façade is closed.

Exhausted air, mechanically extracted, is brought into the cavity where it is passively or mechanically removed through ventilation in the chimney.

The façade operates as a thermal buffer, thus reducing heat loss. Additionally, dispersion due to interior ventilation is eliminated by keeping the inner skin closed.

Operation during summer season

During summer season, the "chimney effect" is exploited, but the entire height of the building is involved.

The operation is entirely like subcategory 1.

The shading system
The shading system is usually placed in the cavity, although it can also be placed outside.

Category C
Category C includes systems with an openable inner skin and where the conditions within the cavity are controlled by the system (Fig. 6.21).

Operation during winter season
During winter season, the air flow rate into the cavity is reduced to create a thermal buffer, thus reducing heat loss.

During moderate weather conditions, comfort conditions can be achieved by adjusting the mechanical air intake and extraction.

Operation during summer season
During summer season, particularly during hot periods, a considerable number of air changes can be carried out inside the cavity.

In this way, a thermal buffer is created between the outside and the inside by removing the heated exhaust air.

The shading system
In this case, the solar shading system can be placed either inside or outside the cavity.

Category D
Category D includes systems where the cavity is sealed (Fig. 6.22).

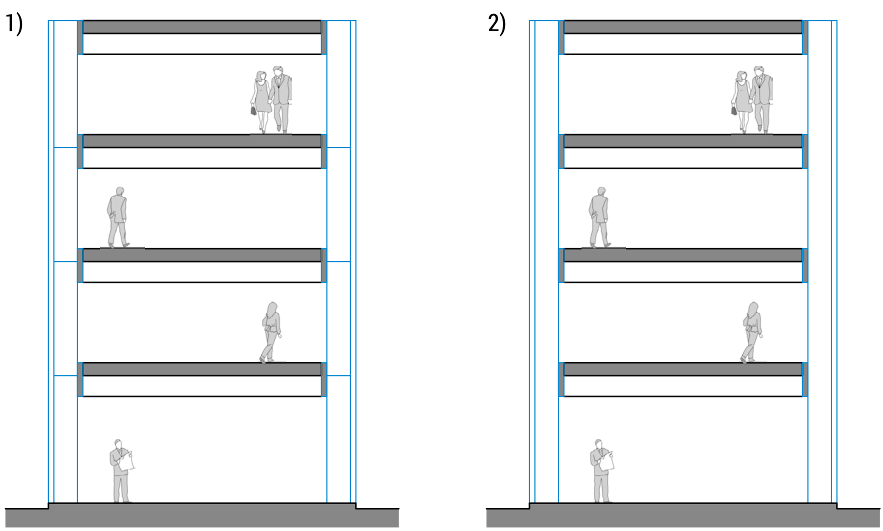


FIG. 6.22. Diagrams of operating categories and subcategories: 1) Category D, subcategory 1; 2) Category D, subcategory 2 (Source: own elaboration)

Category D, subcategory 1
The systems in subcategory 1 are characterised by the conditioning of the cavity and the compartmentalisation of the cavity, floor by floor.

Operation during winter season
The double skin, being a sealed system, prevents infiltration from the inside to the outside and vice versa.

The system operates as a thermal buffer between inside and outside.

Operation during summer season
Operation during summer season is like winter one.

In addition, the presence of an outer glass skin reduces the solar radiation directed at the inner skin.

The presence of an air conditioning system is obviously necessary, as simple mechanical ventilation would not be sufficient to compensate for the peak heat loads for heating during the hottest periods.

Shading system
The solar shading system can be placed either inside or outside the cavity.

However, an external shading system solution can be particularly efficient in preventing the absorbed solar energy from being transmitted into the building. This is especially true if the cavity is not ventilated.

Category D, subcategory 2
Subcategory 2 systems are characterised by the conditioning of the cavity and the extension of the cavity to the entire height of the building.

Operation during winter and summer season
The operation is quite similar to subcategory 1.

The only difference is due to the variation of the conditions inside the cavity on the different floors (inside the rooms).

This is due to the stratification of air at increasing temperature from bottom to top, due to the chimney effect.

Shading system
As for subcategory 1.

Category E
Category E includes systems with high sound absorption, i.e., where the usage of a double skin façade is mainly due to acoustic comfort requirements. Such systems are usually characterised by a massive external surface (Fig. 6.23).

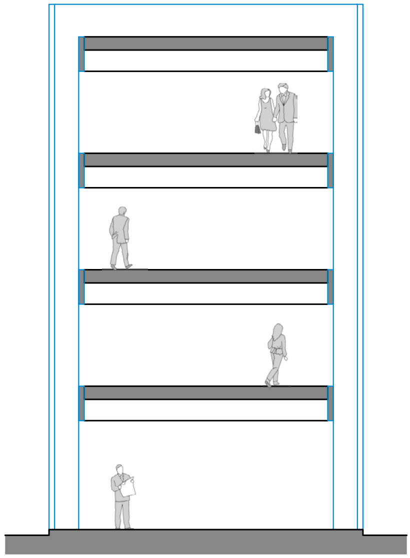


FIG. 6.23. Operating category diagram: Category E (Source: own elaboration)

The 4 most interesting cases are showed (Fig. 6.24, Fig. 6.25, Fig. 6.26 and Fig. 6.27).

It is worth pointing out that the exemplifying typologies previously presented only reveal a typical behaviour of the double skin system, but they are strictly related to the location of the building the typology and morphology of the building. The latter affects the distribution of the pressure coefficients on the relative external surface (Klaus, 1995).

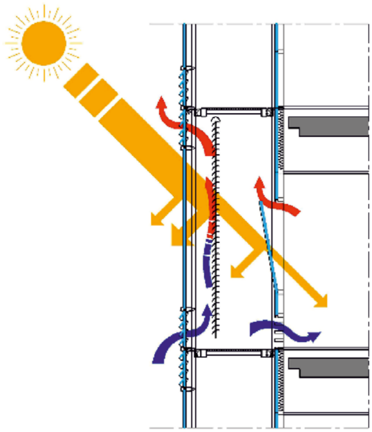
The reduction in heating/cooling demand is related to the orientation of the building and its shape as well as the ratio of surface area to volume, while other aspects to be considered are the size and position of window surfaces.

The study of these parameters and their relationships must be integrated with the choice of wall system technology maybe resulting from:

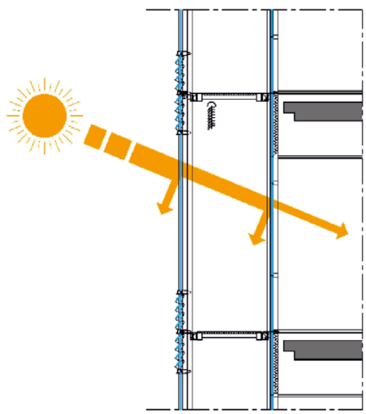
- type of compartmentation;
- the type of materials used and their performance;
- the size of the cavity;
- position of the solar shading system;
- position and morphology of the air inlet and outlet vents;
- morphology and technology of the solution at the windows and doors;
- relationship with the plant system.

Undoubtedly, in all the cases described, the overall improvement in the thermal performance of the building can only be achieved if the system is applied as part of an integrated design process of the various architectural, structural and plant components. In this process the presence of experts in very specialised disciplines such as climatology and building aerodynamics is also fundamental.

Summer



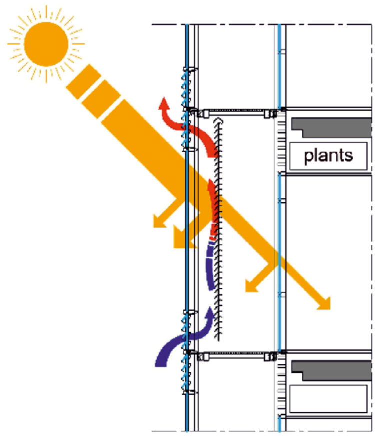
Winter



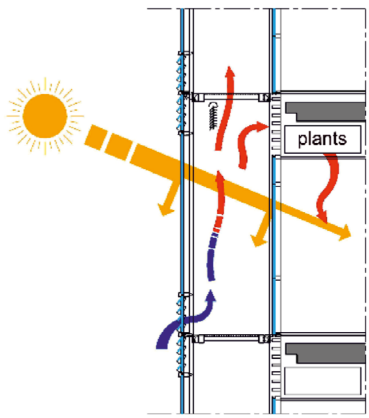
Summer:	Mid-season:	Winter:
• natural ventilation of the cavity and interior spaces • natural night cooling of the masses • control of radiation through the shading system	• natural ventilation of the interior	• closed cavity acting as a thermal buffer

FIG. 6.24. Functional diagrams of the most interesting double skins. Case 1: Double skin façade, natural ventilation of rooms during summer and mid-seasons. *Insulating façade in contact with the inside and second skin to the outside* (Source: own elaboration)

Summer



Winter



Summer:	Mid-season:	Winter:
• natural cavity ventilation • closed interior skin • forced ventilation of rooms • control of radiation by shading system	• summer operation	• closed inner leather • cavity for pre-heating of the air to be treated

FIG. 6.25. Functional diagrams of the most interesting double skins. Case 2: Double skin façade, natural ventilation of the cavity and air preheating during the winter season. Insulating façade in contact with the interior and second skin to the exterior (Source: own elaboration)

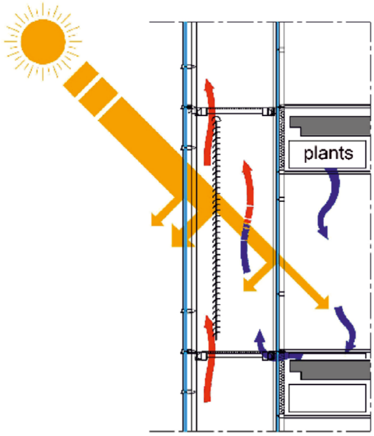
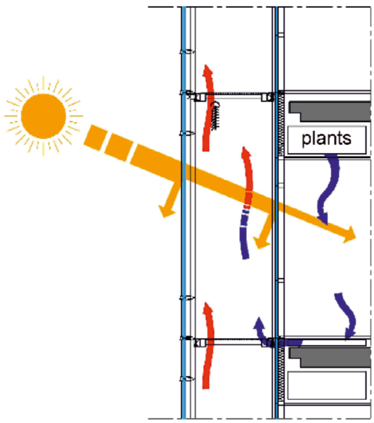
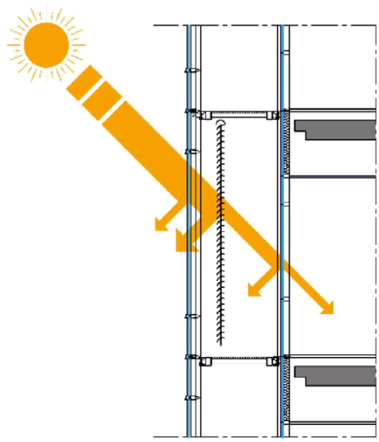
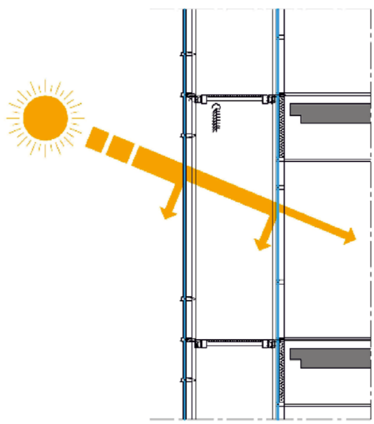
<table>
<tr><th colspan="3">Summer</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><th colspan="3">Winter</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td>Summer:
• closed outher skin
• facade acting as a thermal buffer
• forced ventilation of rooms
• forced ventilation of the landscape with air from the inside
• control of radiation through shading system</td><td>Mid-season:
• summer operation</td><td>Winter:
• summer operation</td></tr>
</table>

Fig. 6.26. Functional diagrams of the most interesting double skins. Case 3: Double skin façade, forced ventilation of the cavity with air from the inside. Insulating façade in contact with the interior and second skin to the exterior (Source: own elaboration)

Summer



Winter



Summer:	Mid-season:	Winter:
• forced ventilation of rooms • closed internal and external skin • facade acting as a thermal buffer • control of radiation through the shading system	• summer operation	• summer operation

Fig. 6.27. Functional diagrams of the most interesting double skins. Case 4: Double skin façade, closed non-ventilated cavity (suitable for cold climate zones). Insulating façade in contact with the interior and second skin to the exterior (Source: own elaboration)

Footnotes

1 Commonly used glass is called sodium-calcium glass, mostly composed of SiO_2 (silica) and calcium carbonate and sodium carbonate.

The single sodium-calcic glass pane is called *float* glass. This derives from the process of producing the panes. These are obtained by pouring glass at high temperature, therefore very fluid, on a bed of molten tin (T = 1000°C). Since there is no chemical interaction between tin and glass, and since the latter is lighter than the former, the glass "stretches" over the tin to form a pane with good flatness characteristics.

This production process leads to the formation of micro-cracks or cracks on the surface due to the different cooling rates of the two surfaces of the glass pane. While the surface in contact with the air begins to cool immediately, the surface in contact with the tin remains at a temperature of 1000°C until the sheet is extracted. In addition, this face captures a small amount of tin sufficient to be able to identify a "tin side" with less transparency and non-reflection characteristics.

The mechanical behaviour of the glass sheets will be characterised, to a large extent, by two phenomena:
- fragile fracture;
- static fatigue.

Reducing the effect of micro-cracks can allow the mechanical strength to increase and limit the dispersion of strength values. Two types of treatment can be carried out for this purpose:
- thermal hardening;
- chemical hardening.

The principle is to introduce residual stresses on the panes and specifically a state of compression on the surface of the glass. This is equivalent to providing prestress and means that, in very empirical terms, the mechanical strength of the glass is the original plus that of the prestress.

The first technique, which is the most widely used, consists of heating the part to a temperature sufficient to obtain complete relaxation of the internal stresses and then suddenly cooling it. The principle underlying this process is the same as that of the most common hardening processes, i.e. during cooling the external surface of the material hardens faster than the internal surface, thus determining a parabolic stress trend. The thickness involved in the treatment is of the order of 2÷3 mm.

The second, which is less commonly used in construction, uses KNO_3 salt baths to introduce K^+ cations into the glass by diffusion.

However, since safety is an essential factor in glass applications in the building industry, tempering treatment is not sufficient to guarantee it, and it is necessary to ensure that the pane even if shattered, remains in place until it is replaced. To guarantee safety laminated glass is used, consisting of two float sheets with a PVB (Polyvinyl Butyral) film in between, with a thickness of 0.38 mm or more, which is highly elastic and retains glass fragments in the event of breakage. There is also the possibility of using special PVBs to significantly increase the acoustic insulation of the glazing. Generally, the presence of this component is highlighted with the letter "A" in the coding of the glass lamination. In a a stick system façades system, however, more complex glazing called double glazing or insulating glass units are usually used. These consist of:
- two panes of glass
- metal interlayer, usually aluminium or plastic material;
- a butyl bead on the interlayer, which must be uniform and unbroken, as this is the first barrier to water and air in the glazing;
- mastic, usually neutral silicone, forming the second barrier, which is superimposed on the butyl cord;
- metal oxide film.

A cavity is thus left between the two panes of glass, which can contain air or noble gases (Krypton, Argon, SF_6) to provide the system with thermal resistance that the glass would not otherwise have. However, the thermal performance of a glazing is not only a function of the cavity in it. In fact, in many systems there is an internal pane of glass capable of absorbing radiation in the infrared range and this ensures that heat loss is limited in winter. During the summer, however, it is necessary for the glazing to have both a good insulating capacity and a shield against solar radiation, in order to limit the heat provided by solar radiation. For this purpose, a film of metal oxides, known as a *coating*, is applied to the surface of the outermost glass facing the cavity (so as to preserve it from the action of atmospheric agents), which allows part of the solar radiation to be reflected.

2 The Italian standard UNI 7959 "Vertical perimeter walls – Analysis and requirements" aims at "[...] *an analysis of the requirements of vertical perimeter walls in relation to the conditions of use and constitutes a reference for the design, production, construction and use of external wall elements.*".

3 Generally, the material used is aluminium. The choice of this metal is fundamentally linked to the following reasons:
– its ductility, which makes it possible to obtain profiles with very complex shapes;
– its low weight;
– resistance to corrosion.

4 The material most commonly used for this purpose is E.P.D.M. (Ethylene Propylene Diene Monomer), which has excellent mechanical properties, high resistance to permanent deformation, thermal insensitivity, adequate chemical inertia towards aggressive acid agents, good water proofing and an excellent working temperature range (-20/+130 °C); on the other hand, it is characterised by very low flame resistance and poor resistance to hydrocarbon solvents and mineral oils. The colour is exclusively black.

5 The rotule was designed in 1981 by P. Rice, M. Francis and I. Richtie, founders of the RFR studio, in the project for the bioclimatic greenhouses of the Parc de la Villette inside the Cité des Sciences et de l'Industrie in Paris. The glazing of the Villette in Paris is designed in such a way that the glass panes that compose it, as well as being a closure element, also perform the function of supporting the vertical loads weighing on the façade. Only the horizontal loads are transferred to a secondary steel structure on a different plane to the glass panes, and the connection between the panes and the substructure is made by points using a system of connecting rods and anchoring elements. The element that makes this possible is the point fixing system passing through the pane, known as the articulated bolt or rotule.

This consists of a spherical head joint, inserted into the milled hole drilled at each corner of the slab and coplanar to it, with the possibility of freely rotating at an angle of about 10° to its axis. This makes it possible to transfer the bending effects, generated by external forces, out of the plane of the glazing to the secondary structure. The experiment had already been preceded by a conceptually similar solution in architect Norman Foster's Willis Faber & Dumas building in Ipswich, England. In the glazing of this building, the glass already fulfils a structural function, but does not reach the level of technological sophistication of the Villette.

6 Semi-rigid fixing is historically the first point fixing system for glass panes. Pilkington had been searching since the 1950's for a technology that would allow the elimination of the frame from glass facades, pursuing the path of point fixing of the sheets. The result of this research led in 1982 to the creation of a pointwise joint between the structure and the glass module, located in the glass plane, the Planar 902 system, a solution which did not, however, allow applications such as those of Villette in Paris. In fact, Pilkington's system, due to a certain rigidity of the fastening, induced peak flexural stresses in the panes under load around the fastening.

References

[1] Di Naso, V. (2007) Tecnologia della trasparenza: progetto e tecnica delle vetrate appese, in the proceedings of "L'involucro edilizio – Una progettazione complessa" Università Politecnica delle Marche, 22-24 November 2007, Ancona, ALINEA Editrice, Firenze, ISBN: 9788860552235.

[2] Di Naso, V. (2002) Le facciate a ventilazione naturale in vetro a doppia pelle, in Facciate ventilate. Architettura prestazioni e tecnologia (Edited by Bazzocchi F.), Firenze, Alinea Editrice, Firenze. ISBN: 8881256282.

[3] Grosso, M. (2008) Il raffrescamento passivo degli edifici in zone a clima temperato: principi e archetipi bioclimatici, criteri progettuali, metodi di calcolo, esempi progettuali. Maggioli Editore Santarcangelo di Romagna. ISBN: 9788838739637.

[4] Klaus, D. (1995) The Technology of Ecological Building – Basic principles and measures, examples and ideas, Birkhauser, Berlin. ISBN: 0817654615.

[5] Oesterle, E., Lieb, R., Lutz, M., Heusler, W. (2001) Double-Skin Facades: integrated planning, Prestel, Munich. ISBN: 3791325043.

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7. GREEN FAÇADE

7.1. Introduction

Vegetation has always been used as a functional element of human spaces, for instance it can protect against wind, shade solar radiation, it can improve the microclimate in built environments and define collective and private spaces. However, in recent decades the progressive decrease in green areas and the intensive exploitation of land for food production have significantly compromised the water retention capacity of the land.

This dramatically affects urban areas in case of heavy rains and extreme weather conditions as well as led to a significant decrease in the filtering capacity of plants to remove pollutant dust and produce oxygen. Additionally, the current need of more liveable urban spaces as along with ever-decreasing availability of space for building led to an increase in the demand for existing urban spaces renovation and redevelopment. In these areas the introduction of green spaces plays a key role.

In this context the application of green roofs and walls in buildings becomes fundamental. It assumes an important role in the phenomenon now called Going Green. The benefits of integrating greenery into the building envelope affect several issues: environmental, economic, and social, generally reducing greenhouse gases and pollutants, improving air quality and comfort conditions inside and outside the building, and helping to maintain biodiversity.

The use of green in construction can allow:

- urban heat island effect mitigation: in a temperate climate a 10% increase in green infrastructure could lead to a reduction urban matrix temperature of up to 2.5°C (Cameron et al., 2014);
- improvement in health and well-being conditions: several studies have shown that the use of green areas, or their continuous visions, can bring benefits to health and quality of life;
- air quality improvement: the process of photosynthesis consumes CO_2 and releases O_2; moreover, certain types of plants reduce the presence of particles in the air that are harmful to human health (such as carbon dioxide, carbon monoxide, nitrogen dioxide and fine dust);
- urban decoration: vegetation walls improve aesthetics and create a feeling of closeness to nature in densely urbanised areas;

- ecological value increase: greenery provides water, food and protection for birds and butterflies, safeguarding their survival;
- stormwater resilience improvement: green buildings provide greater control over stormwater, filtering impurities before they enter the groundwater.

Thanks also to the growing attention towards environmental issues, technical green systems are gaining considerable interest and green walls are also becoming more widespread. Green walls are not new to architectural practice, because archetypes of green walls are historically found in basic construction in geographical regions with both cold and Mediterranean climates, but this technology has recently considerably evolved.

In Italy there is a dedicated technical standard (UNI 11235:2015, "Instructions for the design, implementation, control and maintenance of green roofs") for the consolidated techniques for green roofs. Otherwise for green walls there are no standards and the solutions proposed by manufacturers are varied and numerous. It is worth to notice that green wall systems are generally more complex than those for green roofs, both because the vegetation is placed on a vertical surface and because of the relationship between the facade systems and other wall components, such as openings.

It is worth to specify that green vertical systems do not guarantee the required performance for a vertical closure and therefore these must be provided by dedicated layers included in the back-standing load-bearing wall.

Plants are the most important component as well as the most delicate and responsible for the formal success of the green wall systems (Corrado, 2010). They guarantee the functionality of the whole system made of a series of technical elements such as substructures, plants and various components. At the beginning of the project, it is therefore essential to collaborate closely with experienced professionals, as the choice and management of a green wall system implies knowledge that is usually far from architectural practice.

The following aspects should be considered when choosing the essences:
- seasonal vegetative cycle;
- direct solar radiation needs;
- maximum size achievable;
- growth speed;
- leaf density and thickness.

The specific benefits of green wall application can be summarised as follows (Bellomo, 2005; Ariaudo, Fracastoro, 2007; Tatano, 2008; Köeler, 2008; Corgnati et al. 2009; Santi, 2010; Campiotti et al., 2013).

- *Energy saving*. Vertical greenery works as a true insulating surface for external walls. During summer season, overheated façades result in rising rooms internal temperature and consequently increases in energy consumption needed for conditioning systems. This consumption is reduced if the external wall is shaded by a layer of vegetation which considerably decreases the heat flow and, thus, limits the transfer of thermal energy. So, the first mechanism that contributes to summer energy savings is the shading function. Additionally, the green façade allows the presence of an air cavity between the green finishing and the load-bearing wall. During winter season the leaves reflect and absorb the infrared radiation emitted by the building, leading to a reduction in the radiative heat loss of the building. For this reason, green systems bring benefits in terms of energy savings both in Mediterranean and colder climate areas. A significant reduction in wind speed in the air layer close to the outer surface of the wall load-bearing layer is achievable. This improves thermal resistance, thanks to the attenuated effect of air movements on the façades and a reduction in convective heat losses.

- *Building protection*. The building envelope is protected by the vegetation, especially against temperature fluctuations. The latter cause the building materials to expand and contract, compromising the lifespan of the materials.
- *Acoustic insulation*. In contexts strongly affected by city traffic and the related noise, the use of vegetated walls can reduce this problem thanks to the screening effect of the vegetation.
- *Increased estate value*. Various studies have shown that buildings with vertical greenery, especially located in highly urbanised contexts, increase the value of the building by giving quality to the landscape.

In contemporary times, the most important figure in the industrialised development of green wall systems is Patrick Blanc, a French researcher who patented the Mur Vegetal system (Blanc, 2008).

Before him, green wall applications followed an artisanal approach. He proposed an innovative system exploiting the ability of roots to grow without necessarily requiring cultivation soil (technique of hydroponic cultivation). Architects such as Jean Nouvel and Renzo Piano had an important role in the dissemination of Blanc's solution, realising the potential of green walls in architecture and promoting internationally their use. This achievement contributed to the development of subsequent industrialised vertical green solutions and to the spread of the application of greenery on buildings vertical walls.

More and more designers are choosing to adopt these types of enclosures because of their formal qualities, functional characteristics and eco-sustainability. Thanks to the current demand for vertical green solutions, an important activity of industrialisation of solutions, subsystems and components has been started. Today many green façade systems are proposed by the industrial market and include a wide range of greening types.

Any vertical greening installation is composed of 3 sub-systems which, starting from the outside of the enclosure and moving inwards, are:

1. greening system;
2. mediation subsystem with the building;
3. building wall used to accommodate the greening.

There is no univocal classification of green wall solutions in literature (Spagnolli, 1995; Bellomo, 2005; Poli T. 2006; Lambertini, 2007; Bit,2012; Jim, 2015; Santi, 2016) but the first fundamental possible distinction is between:

- vertical gardens;
- vertical green systems.

Vertical gardens are real high gardens, characterised by the presence of vegetal species planted in pots, placed directly in the covering system, or installed on terraces or balconies for the entire height of the building.

As far as vertical green systems are concerned, two further typological categories, differing for the relative executive and planting peculiarities can be identified:

- vegetated claddings (or green façade);
- vertical vegetated closures (or living walls).

The term "vegetated claddings" refers to those façades characterised by climbing plant species, rooted in the ground or in pots, using the walls of the building as a support for their development (called direct); an evolution of this system is the use of grids or support systems where plant can grow, possibly spaced from the wall behind (called indirect).

On the other hands, "vertical vegetated enclosures" consist of modular elements (in general panels) which are mounted on the opaque external wall by a supporting sub-structure. These panels contain the substrate for planting the vegetation. Both the substrate and the plants are then brought up to the full height of the façade. The species used are not climbers, but generally evergreens, and require a suitable irrigation system.

Finally, living walls represent a sub-typology of vegetated vertical closures. Although they are characterised by most of the characteristics of the belonging category, they have specific features which give them an autonomous technological declination. They are made with a textile substrate, without the use of soil. This substrate usually consists of a double layer of synthetic felt. The plants are here placed manually, and the characteristics of hydroponic cultivation are exploited. The latter is based on the use of a nutritive solution to provide for the needs of the plants. In this system, no type of modular vegetation structure is used.

A scheme for the classification of green façade systems follows. It is based on their constructional characteristics (Fig. 7.1).

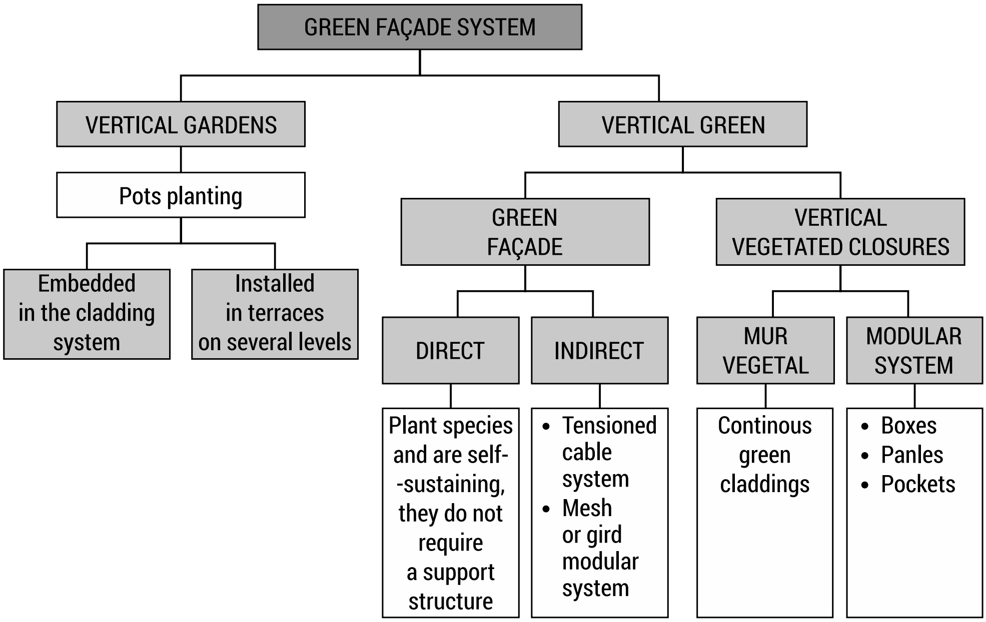


FIG. 7.1. Classification of vegetated façade systems according to their construction characteristic (Source: own elaboration)

7.2. Green Façade

Within the panorama of industrialised products available on the market, it can be said that green façades are the best known and most historicised systems for greening walls. Vegetable cladding has been part of building practice for centuries. Initially, it was made with climbing species directly attached to wall surfaces. Then, it evolved over time through the introduction of a system of mediation between plants and the wall. Thus, because direct interaction could cause problems to building surfaces (e.g., localised disintegration caused by the epigeal organs of plants, the presence of humidity, dirt, etc.). In green facades the plants used are usually climbing plants. Anyway, most plants grow vertically, in search of sunlight as an energy source. Climbing species belong to a wide range of botanical families and can be described as plants "*halfway between a grass, a bush and a tall tree, differing from the latter in the habit of their stems, which are slender and particularly flexible, and therefore require a rigid support to sustain them*" (Bellomo, 2005). Thanks to their physical characteristics and vegetal ramifications, they can climb vertically in different ways. Some of them are self-supporting, as they have aerial or sucker roots, while others, with a tendency to intertwine, require special support elements: these include fickle plants (plants that cling with the aid of tendrils and intertwining species).

The green covering is a relatively simple system. In the indirect types, it consists of a series of substructures and other components that are functional for planting and biological proliferation, additionally to the actual vegetation. These elements constitute the support for the planting of the vegetation and can be substructures with nets, grids or cables, to manage the vegetal ramifications, pots and flower boxes, etc. and a possible irrigation system. When creating a green covering, it is necessary to choose how to install the plants depending on the project requirements. There are basically two options: plants to be placed in the ground or in pots. The second option can include pots located on the ground or, more frequently, above ground, integrated into the technological systems even if planting vegetation directly in the ground is always advisable, in certain conditions potting is necessary such as the following cases:

- when it is not possible to use natural terrain at ground level (condition typical of urban contexts);
- in the case of large walls to be covered, where several green stripes needed to be vertically arranged;
- in cases where the cladding is to be created using plants with a drooping habit, which can only be planted in raised pots.

When planting in pots, it is important to guarantee the proper composition of substrate elements within the pots and a correct balance between draining and water-retaining elements. Generally, the involved layers are:

- vegetation substrate for plant's roots. The substrate is usually made of soil-based materials depending on the species chosen and the requirements (e.g. loam, peat, humus, etc.);
- filter layer, it prevents fine particles of the substrate from descending into the underlying drainage layer and accommodates the anchoring of the root systems. Generally, geotextile materials with adequate tensile, shear and punching resistance, as well as water permeability, are used for this layer;
- drainage layer, which ensures the drainage of water passing through it, since stagnant water can cause root asphyxia. Moreover, the draining layer must inferiorly accumulate reserve water to supply the root systems when needed. The materials used are usually loose materials with high water retention and drainage capacity (such as volcanic lapilli, pumice, expanded clay, etc.);
- possible supplementary layers for specific needs, such as additional water storage mats, sheaths, root barrier layers, etc.

Once the species for greening the façade has been chosen, it is necessary to understand how the plant system must be installed. Thanks to their aerial or suction branches, some plant species can cling and grow vertically depending on their characteristics. While all other types of climbers require a supporting subsystem. However, it is worth to notice that it is always advisable to provide a support system (even in the case of self-supporting species) as aerial roots or suction cups can cause walls damage over time.

Generally, plant growth support system is always needed, adequately designed and sized according to the characteristics of the chosen plant. Each species will require a different support depending on fixing system and growth. The supports can be:

- simple (e.g., nets or tensioned cables fixed to the walls by dowels, rigid metal or wooden gratings, etc.);
- relatively complex (e.g., double layers of nets, projecting shelves containing planters, etc.);
- very complex (such as real spatial structures), depending on the design and planting requirements.

However, these features can be generalised thanks to the common characteristics of plants and their way of growth.

As fickle plants expand vertically, they require vertical linear structures, usually vertically tensioned wire ropes. During the initial phases of plant growth, fickle species can also be diverted along horizontal lines by subsystems such as ties or other, if necessary. For fickle plants of moderate growth, the optimal distance between the vertical supports is 20-40 cm. While for those with vigorous growth, the supports could also be spaced up to a maximum of 80 cm.

Self-supporting plants with tendrils or intertwining plants require supports that combine vertical and horizontal directions. Such supports can be obtained either by tensioned cables or by mesh or grid structures. A combination of rigid horizontal and vertical linear supports made of different materials (wire mesh or polymer matrix structures, electro-welded mesh, etc) can be obtained. The mesh size of the nets can be between 10 and 60 cm, depending on the growth characteristics of the species used.

Theoretically plants with epigeal organs do not require support. But it is always advisable to adopt a support structure that distances them from the wall. Aerial and sucker roots have a very dense spacing between their root organs, and usually tend to spread easily on continuous surfaces. So, the supports for the growth of these plants must allow as much surface continuity as possible. For this reason, close-meshed nets with a pitch of between 2 and 10 cm are often used.

Care must be paid to ensure a suitable distance between the planting material and the building surface. All types of support should be installed a few centimetres away from the rear wall, as they will need to provide a suitable space for plants growth, as well as ensuring that branches and plant organs do not interfere with the wall surface. It is possible to state that each different species would require a different distance from the wall, but some standard dimensions can be adopted (Table 7.1).

TABLE 7.1. Indicative minimum distances to adopt between the plant system and the vertical wall (Source: own elaboration)

Plants type	Distance from vertical wall
Plant species with low or medium growth vigor (e.g. Clemantis, Lonicera)	80 ÷ 150 mm
Vigorous or very vigorous species (e.g. Wisteria, Phalloppia, Celastrus)	150 ÷ 200 mm

In some specific locations of the building (at the ground connection, at the top, in the corner portions and at the interfaces with windows and doors), it will be necessary to adopt some precautions. In general, at the ground connection, if the stem of the plants is accessible, it must be protected with metal elements. At the top it is needed to cover the space between the wall and the plant cladding, especially if the wall may be affected by rainwater leaching. In the corners the continuity of the growth of the plants must be guaranteed. In correspondence with the openings acting with periodic pruning or designing slots that allow the distancing of the plants are the alternatives (Fig. 7.2).

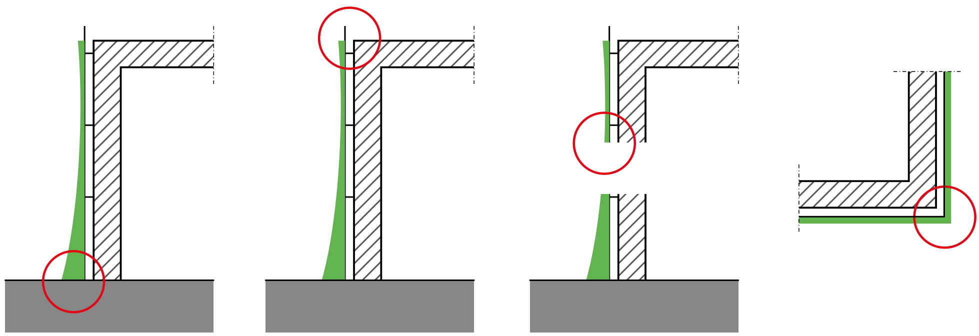


FIG. 7.2. Diagram of the characteristic nodes concerning the connection between the vegetal covering and the building (Source: own elaboration)

The support system must be made from materials that do not damage the vegetation. Unappropriated design choices concerning with support structures sometimes affects plant development. For instance, some species that suffer from high temperatures may not tolerate dark coloured supports. In other cases, some species tend to reject metal structures preferring other materials such as wood or polymers. The support must provide adequate support for the plant system according to the peculiarities of proliferation, different from species to species. For example, an excessive spacing of the support elements may not allow the plant to adequately develop. The substructure of the cladding should also not deform under the weight of the plant and accidental loads. Durability is also an important parameter for cladding support systems: they must guarantee a suitable service life, as well as the maintenance of the dimensional and strength characteristics throughout the entire life cycle. The most used material for the substructures is steel, due to its strength and versatility. Wood and polymers can also be used: they represent an interesting alternative as they combine strength, lightness and versatility of use. For pot plants, the size and shape of the containers will be the most important aspects, as well as the composition of the substrates, drainage, and irrigation system. Environmental factors must also be considered. Only certain species adapt very well to any exposure. A wrong selection of plants, depending on the sun exposure or the climatic and micro-climatic characteristics of the environment, could affect the performance of the plant system.

Types of Vegetated Claddings

The systems involving the presence of support elements for vegetation (indirect systems) will be outlined. In these cases, it is essential to know how the plants cling to the supports (Table 7.2), to guarantee an appropriate choice of the configuration of the substructure and to ensure a continuous distribution of the vegetation on the wall.

The weight of the creepers is another important element to determine when choosing the support structure. It essentially depends on the consistency of woody component and leaf mass. Each species develops with its own volume and density, and the maximum weight of the woody part of a climber depends on the height of the plant and the maximum size of the stems.

TABLE 7.2. Possible configurations of support structures depending on how plant species are anchored to the support (Source: own elaboration)

Ways of anchoring climbers	Types of plant essences	Horizontal distance between elements	Vertical distance between elements	Configuration of supports	Maximum growth height
VOLUBLE	Lonicera, Aristolochia, Actinidia, Akebia, Humulus, Wisteria, Falloppia, Celastrus	H= 200-800 mm	V= 500 ÷ 2000 mm	Vertical ropes Vertical ropes with horizontal supports Inclined ropes	20 m
VITICCI	Rosa, Jasminum, Rubus		V= 500 ÷ 2000 mm	Horizontal ropes Vertical ropes with horizontal supports	6 m

Ways of anchoring climbers	Types of plant essences	Horizontal distance between elements	Vertical distance between elements	Configuration of supports	Maximum growth height
INTERWEAVING	Ampelopsis, Clementis vitalva, Vitis vinifera, Passiflora	H= 200 ÷ 800 mm	V= 500 ÷ 2000 mm	Vertical ropes with horizontal supports	15 m

The following Table 7.3 summarises the main commercially available technical alternatives of substructure elements for plant claddings.

TABLE 7.3. Table summarising the classification of indirect vegetated claddings systems (Source: own elaboration)

CLASSIFICATION OF SUBSTRUCTURES OF INDIRECT VEGETATED CLADDINGS SYSTEMS					
	SUPPORTING ELEMENTS FOR PLANT SPECIES	*SUBSTRUCTURE MATERIAL*	*FIXING ELEMENT TO LOAD-BEARING LAYER*	*FIXING ELEMENT MATERIAL*	*FIXING TO LOAD-BEARING STRUCTURE*
TENSOR CABLES SYSTEMS	Vertical tensor cables (bi-directional option)	Galvanised and stainless steel	Spacers	Stainless steel	Mechanical/ chemical dowels
	Modular interweaving with vertical tensor cables	Galvanised and stainless steel	Spacers	Stainless steel	Mechanical/ chemical dowels
	Bi-directional tensor cables with metal mesh	Galvanised and stainless steel	Spacers	Stainless steel	Mechanical/ chemical dowels
MODULAR SYSTEMS GRID OR MESH	Bi-directional grid with rigid box	Galvanised steel	Optional brackets and mullions	Galvanised steel	Mechanical/ chemical dowels
	Bidirectional spatial grid	Galvanised steel	Optional brackets and mullions	Galvanised steel	Mechanical/ chemical dowels
	Electro welded mesh with geo-composite module	Galvanised steel	Brackets and mullions	Galvanised steel	Mechanical/ chemical dowels
	Electro welded mesh with rigid box	Galvanised steel	Brackets and mullions	Galvanised steel	Mechanical/ chemical dowels

Some commercially available systems are described below.

Tensor cables systems with bi-directional option

The system presents a lightweight solution adaptable to project needs. All components are made of AISI 316 and AISI 316L stainless steel.

The key element is a system of vertical ropes mechanically fixed at several points to steel spacers bound to the load-bearing layer. The stainless-steel braided cables are 6 wires with diameter ⌀4 mm. Mechanical dowels allow the spacers anchoring to the load-bearing layer. The length of the cables is freely chosen. There are three possible configurations, distinguished by the tensor system at the bottom end and the resulting tension that can be applied to the cable. Depending on the design requirements the system can include horizontal stainless steel stiffening bars with circular cross-section ⌀4 mm, fixed to the cables and spacers by mechanically fixed steel or polyethylene clamps. The high corrosion resistance of the materials guarantees durability and low maintenance (Fig. 7.3).

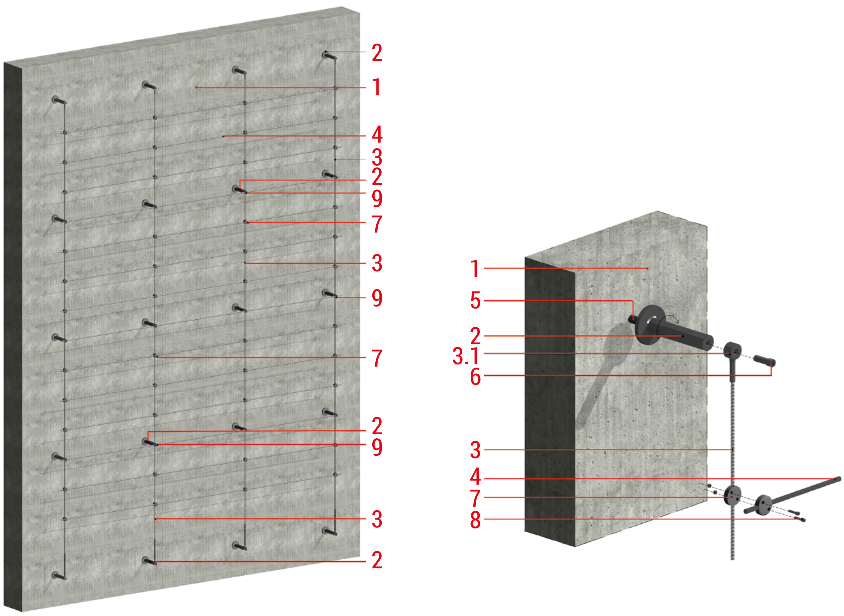


FIG. 7.3. Axonometry and detail. Legend: 1. Load bearing layer; 2. AISI 316 stainless steel spacer; 3. AISI 316 braided steel vertical support rope; 3.1. AISI 316 stainless steel ring for fixing to end spacers; 3.2. Circular profile (⌀4 mm) for horizontal stiffening in AISI316 steel (optional); 5. Mechanical anchor for fixing spacers to the load-bearing layer; 6. Crossed polyethylene or stainless-steel clamp for anchoring the stiffeners; 8. Bolt and nut system for fixing polyethylene clamps; 9. Crossed AISI316 steel clamp for fixing with central spacers; 10. Bolt for fixing steel clamp (Source: own elaboration)

Modular interweaving with vertical tensor cables system

All system components are made of AISI 316 and AISI 316L stainless steel. The basic element is vertical braided steel ropes combined with steel angle profiles horizontally arranged. The fixing system consists of steel spacers anchored to the wall load-bearing layer by screwing in previously inserted mechanical dowels. The system of ropes is available in three possible variants, differentiated according to the tensor present at the bottom end. Ropes are fixed to the two extreme angle profiles, the upper one by a steel "nail", the lower one by bolts. The latter also allow the definition of the state of tension pre-defined during the design. By adding horizontal bars, connected to the ropes by clamps, it is possible to create grids of different sizes according to the needs and loads deriving from the plant species installed, as well as the requirements of the plant. This system is particularly suitable for medium and large-sized vegetated claddings. The high corrosion resistance of the materials guarantees durability and low maintenance (Fig. 7.4).

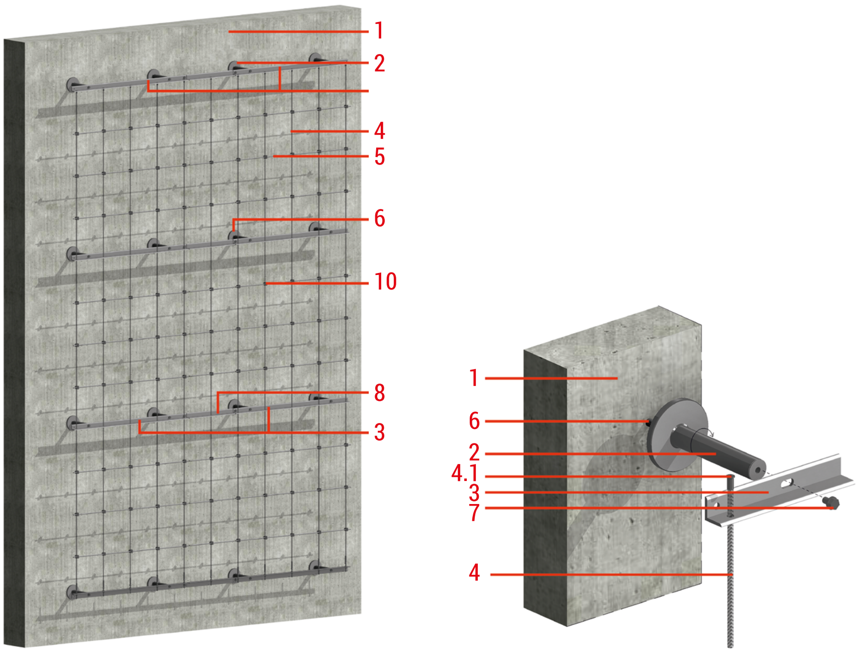


FIG. 7.4. Axonometry and detail. Legend: 1. Load bearing layer; 2. AISI 316 stainless steel spacer; 3. AISI 316 steel angle profile, L section 30x30 mm (4 mm thick and variable length); 4. AISI316 braided steel vertical support rope, circular section ⌀4 mm; 4.1. AISI316 steel nail for upper fixing; 4.2. Circular profile (⌀4 mm) for horizontal stiffening in AISI316 steel; 6. Mechanical dowel for fixing spacers to the load bearing layer; 7. Hexagonal screw for fastening the horizontal profile to the spacers; 8. Horizontal connection element between two gratings, AISI316 steel profile with L-section 30x30mm (thickness 4 mm and length 340 mm); 9. Screw and nut system for fastening the connection element; 10. Cross clamp in AISI316 steel or polyethylene for fixing horizontal stiffeners (Source: own elaboration)

Bi-directional tensor cables with metal mesh

All system components are made of AISI 316 and AISI 316L stainless steel. The mesh, with its spacers and connections, is a modular system adaptable according to the needs of the project. The module consists of steel spacers, fixed to the resistant layer by mechanical dowels. Forks, characterised by variable geometry depending on the number of supported ropes, are attached to the outer spacers by hexagonal head screws. These provide anchorage for the perimeter rope systems supporting the metal mesh. Through mechanically fastened clamps, the inner spacers work as an auxiliary support for the ropes. The cable diameter and mesh size are particularly suitable for climbing plants. The system can be used for medium to large-scale plantings. The high corrosion resistance of the materials guarantees durability and limited maintenance interventions (Fig. 7.5).

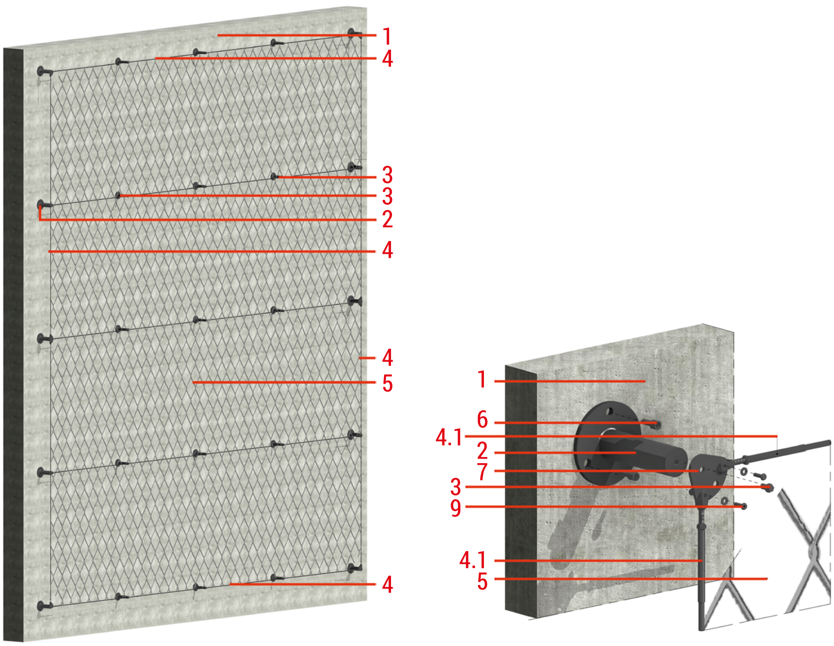


FIG. 7.5. Axonometry and detail. Legend: 1. Load bearing layer; 2. AISI 316 stainless steel lateral spacer; 3. AISI 316 stainless steel central spacer; 4. AISI 316 braided steel support cable, circular section ⌀4 mm; 4.1. AISI 316 braided steel cable; 4.2. AISI 316 stainless steel threaded sensor; 5. AISI 316 stainless steel braided metal mesh; 6. Screw for fastening spacers; 7. AISI 316 stainless steel fork (5 mm thick); 8. Hexagonal head screw for fastening the fork to the spacer; 9. Screw for fastening the support cable to the fork; 10. Single or crossed clamp in AISI 316 stainless steel; 11. Mechanical dowel for fixing central spacers (Source: own elaboration)

Modular system with Bi-directional grid with rigid box

The base module consists of supporting panels made up of a stainless-steel grid framed by metal profiles anchored at the ends to a system of brackets by hexagonal head screws. The two upper anchoring brackets also act as supports for a drilled stainless-steel box where the creepers rooted in pots are planted. The four perimeter support brackets are anchored to the load-bearing wall by mechanical dowels, inserted in suitable slots in the metal profiles. This connection also allows the management of vertical tolerances. Each gridded panel has a size of 90x150 cm. This system is anchored to the façade by a steel frame. The latter provides access for maintenance between the wall and the metal boxes. The system also includes the installation of an irrigation system, related to the drainage one (growing substrate), to install at different levels if necessary (Fig. 7.6).

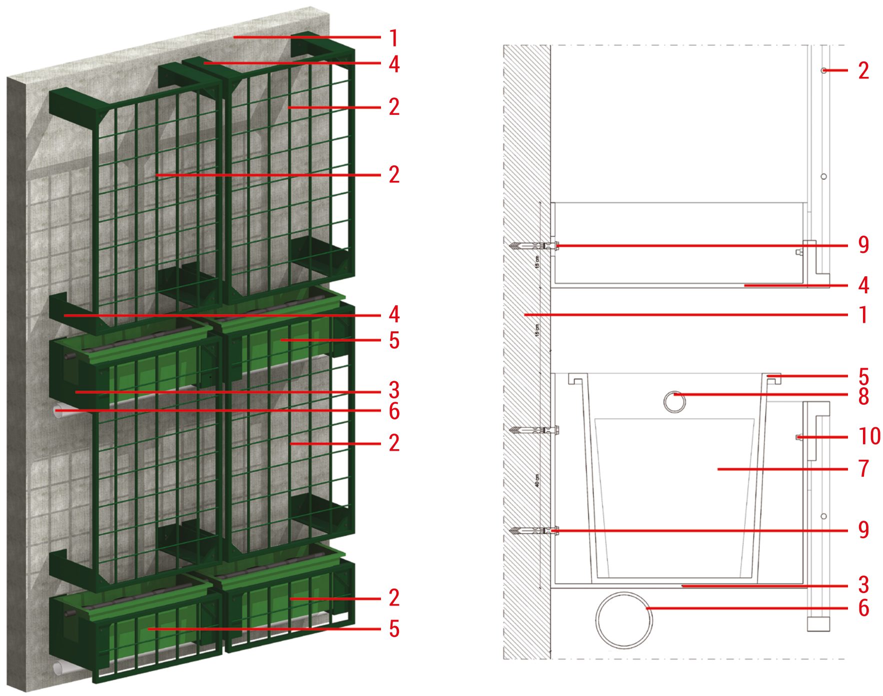


FIG. 7.6. Axonometry and vertical section. Legend: 1. Load bearing layer; 2. Coloured galvanised steel bi-directional grating; 3. Coloured galvanised steel fixing bracket for arranging containers; 4. Coloured galvanised steel fixing bracket; 5. Box; 6. Drainage system: polyethylene profile, circular cross-section ⌀100 mm; 7. Containment vessel made of polyethylene (⌀max 280 mm) with cultivation substrate (soil); 8. Irrigation system: drip line, circular profile ⌀30 mm made of polyethylene; 9. Mechanical anchor for anchoring the brackets to the resistant layer; 10. Hexagonal head screw for fixing the grid (Source: own elaboration)

Modular system with bidirectional spatial grid

It is a system of welded wire mesh panels, used to support the development of climbing plants. The modular panel consists of a 65 mm thick volumetric galvanised steel grid made up of 3 mm diameter rods. The latter are anchored to the substructure by angle-profile brackets, made of coloured galvanised steel, 45x60 mm in section and 4 mm thick, and by support brackets made of shaped coloured galvanised steel profiles, 15x80 mm in section and 4 mm thick. The substructure is built recurring to coloured galvanised steel central T-mullions and lateral L-shaped ones. These mullions are anchored to the load-baring layer by mechanical dowels (Fig. 7.7).

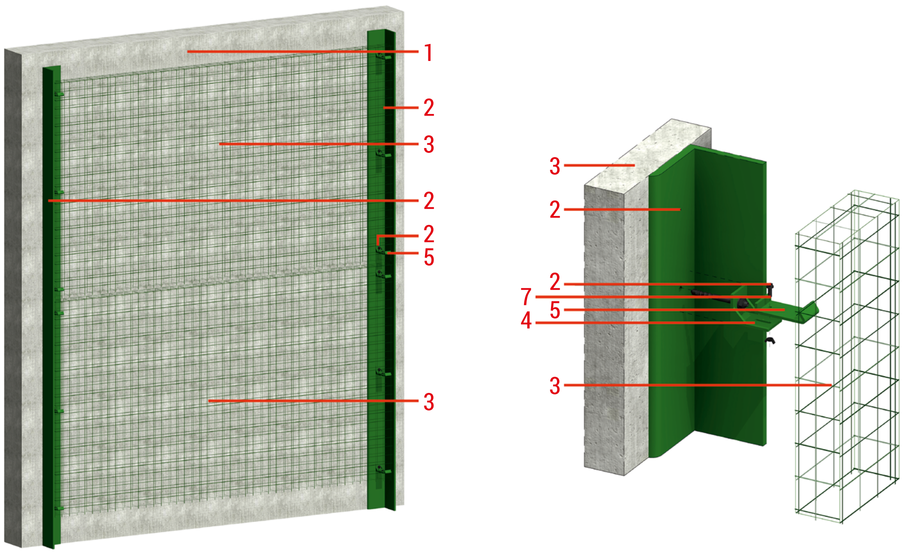


FIG. 7.7. Axonometry and vertical section. Legend: 1. Load bearing layer; 2. Coloured galvanised steel central upright, T-profile, 120 x 240 mm section; 3. Coloured galvanised steel side mullion, L-profile, 120 x 120 mm section; 4. Modular panel: 65 mm thick galvanised steel grating made of ⌀3 mm bars; 5. Anchoring bracket, wing profile with coloured galvanised steel stiffeners, section 45 x 60 mm, thickness 4 mm; 6. Green screen panel support bracket, shaped profile in coloured galvanised steel, section 15 x 80 mm, thickness 4 mm; 7. Screw with nuts for slotted connection of the brackets; 8. Mechanical dowel for anchoring the mullions to the load-bearing layer (Source: own elaboration)

Modular system with Electro welded mesh with geo-composite module

It is a modular system for greenery on façade with climbing plants. It consists of an aluminium box containing the cultivation substrate and electro-welded mesh to provide height support for the climbing plants. The system is supported by galvanised steel brackets and mullions that bears the base module. They are fixed to the wall load-bearing layer using dowels. The system is completed by transoms in galvanised steel corner profiles. Metal hooks are here attached to guarantee support for the electro-welded mesh inserted inside the box. The system also includes an automated, centralised irrigation system for the supply of water and nutrients (Fig. 7.8).

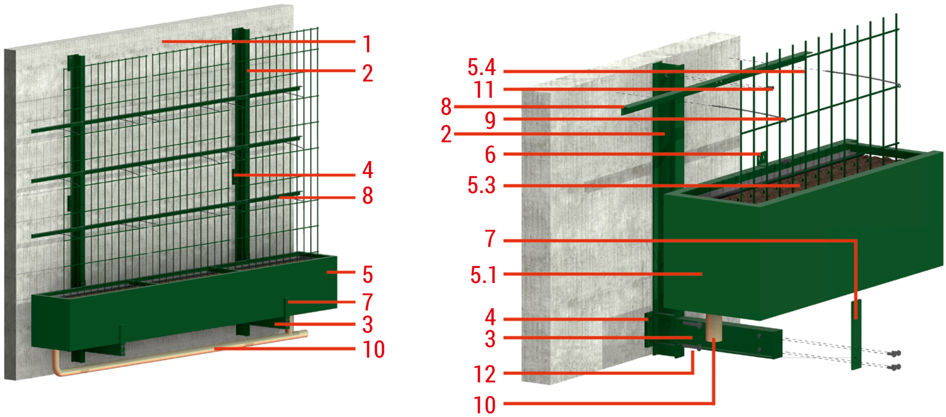


FIG. 7.8. Axonometry and vertical section. Legend: 1. Load bearing layer; 2. Satin-finish galvanised steel upright, IPE120 profile with stiffeners; 3. Satin-finish galvanised steel bracket, IPE120 profile with rectangular plate welded at the head; 4. Plate for anchoring the upright, section 150 x 150 mm, thickness 15 mm; 5. Plant placement form; 5.1 Satin-finished aluminium tank, section 50 x 50 cm; 5.2. Aluminium profile for stiffening the module; 5.3. Cultivation substrate, soil; 5.4. Electro-welded satin galvanised steel mesh, ⌀8/80 mm, 220 cm high; 5.5. Drip-feed irrigation system; 6. Galvanised steel profile for fixing the tank; 7. Galvanised steel profile for fixing the pool, section 300 x 64 mm, thickness 10 mm; 8. Corner profile for fixing electro-welded mesh, section 40 x 40 mm, thickness 5 mm; 9. Flexible aluminium arm for fixing the mesh; 10. Drainage system, circular PVC profile ⌀70 mm; 11. Anchor bolt to the mullion (Source: own elaboration)

Modular system with electro welded mesh with rigid box

It is a modular system designed to create vertical climbing plants. The load-bearing structure is made up of steel C-shaped mullions for anchoring the system. These C-section mullions are fixed to the resistant layer by mechanical dowels. There is also a system of brackets, consisting of a fixing plate (8 mm thick) and a profile with the same C-section, 30 cm long, welded together. The mullions and brackets are mutually bounded by hammer-head screws. Above the supporting brackets there are two corner profiles, necessary for the fixing of the multi-layered element for the insertion of the plants. This element composed, starting from the outer side, by a geotextile containment mat made of coconut fibre and a geocomposite layer longitudinally sewn to obtain cultivation chambers containing a pre-fixed quantity of inert mixture. The latter layer supports an electro-welded and hot galvanised mesh (circular section ⌀5 mm), specially shaped to confine a polyurethane mat containing the cultivation layer for climbing species. The pre-designed modular panel with climbing plants is installed on site and secured to the two perforated corner profiles with stainless steel clamps (Fig. 7.9).

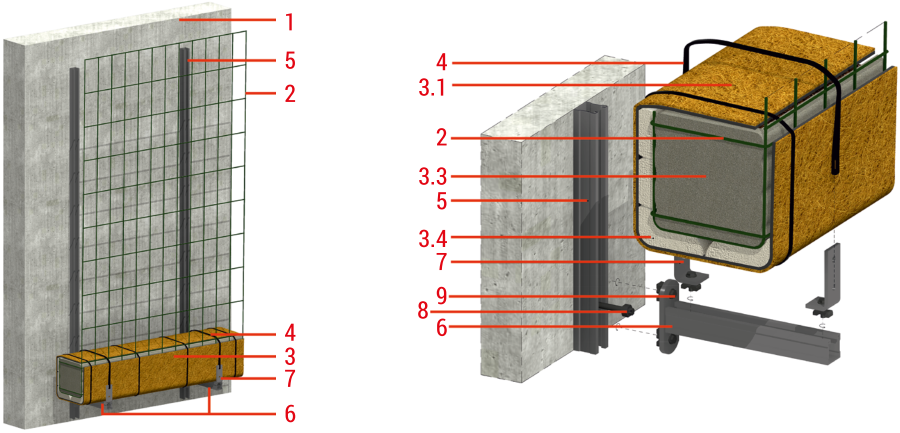


FIG. 7.9. Axonometry and detail. Legend: 1. Resistant layer; 2. Galvanised steel electro-welded mesh, circular section ⌀5 mm; 3. Module; 3.1 Polyethylene cladding panel and coconut fibre geotextile (12 mm thick); 3.2. Cultivation sub-layer; 3.3. Polyurethane containment mat (25 mm thick); 3.4. Geocomposite fabric bag with inert mixture; 4. Stainless steel strap for fixing the module; 5. S250GD steel mullion, C-section profile 9.5x41.3x41.3 mm (2 mm thick); 6. S250GD steel bracket, fixing plate (8 mm thick) welded to a C-section profile 9.5x41.3x41.3 mm (2 mm thick); 7. S250GD steel angle profile, cross-section 105x41 mm (6 mm thick); 8. Dowel for fixing the mullion to the load bearing layer; 9. Hammerhead screw (Source: own elaboration)

7.3. Living Walls

Considering all the different possible types available, living walls present fairly complex technologies which allow the green component and the technological systems to be complementary.

These systems are always dry-assembled and have some invariant or primary elements secondary ones.

The primary elements or layers of a living wall are:

- vegetation layer,
- cultivation layer,
- element of protection from the action of the roots,
- water-tight element,
- supporting and mediating technologies between the green system and the remaining part of the building closure,
- supporting elements,
- irrigation system.

The secondary elements or layers are:

- barrier layer or vapour screen,
- thermal insulation layer,

- vapour pressure diffusion and/or equalisation layer,
- separation and/or flow layer, for the absorption of differential expansion between materials of different origin.

Focusing on the plant layer, the general requirement is to maintain an optimal vegetative state for as long as possible. In relation to the climatic context, the success of the greening layer depends on the synergy between the design and implementation strategies related to the substrate, the plant component and all the related subsystems of irrigation, plant nutrition and drainage of the cultivation layers. As regards planting methods, it is worth to specify that the plants can be arranged on the wall in two different ways: through the direct introduction of young plants on the substrate surface, or through the placing of suitably preformed panels or pre-cultivated portions of the substrate. Depending on these methods, the formal and functional characteristics of the living walls will also vary, especially during the first period of installation. In the first case it will be necessary to wait some time before the wall has adequate formal and functional characteristics, while in the second case the wall will be completely vegetated immediately.

The cultivation layer may be organic (e.g., appropriately designed and mixed substrates with an earthy matrix) or inorganic (e.g., felts, mineral substances, fibres of various kinds, etc.). The material characteristics and thickness must be foreseen and sized according to the plants arranged. Depending on the size and weight of the plants, specific substrates will be required, or substrates with certain characteristics of resistance and water retention. This is because the water and nutritional needs of the plants will vary depending on the size and type of vegetation.

The root inhibitor element is required to provide adequate resistance to the action of the plant's root systems, to prevent it from penetrating into the layers behind it and impair the functionality of the closure. Root protections are classified as mechanical or chemical barrier, depending on the mode of protective action. In the first case, the material that forms the barrier cannot be attacked by the root organs, while in the second option special additives are introduced reacting to the stresses exerted by the roots. There are two methods for creating the root inhibitor apparatus, depending on whether it consists of a separate element or is integrated with other existing layers, which is the most common practice.

The main requirement for the sealing element is being waterproof. Some specificities must be considered in the design phase of the sealing element:

- the sealing element is normally protected from thermal actions produced by solar radiation;
- in some cases it may be subject to root action. This action will take the form of mechanical, chemical and bio-logical stress;
- when placed in direct contact with growing media, it will be subjected to biological and chemical agents due to the substances that make up the substrate itself and/or the compounds that may be supplied to the plants by fertilisation.

The materials adopted for waterproofing green enclosures can be bituminous, polyolefin, PVC, or even breathable membranes, when allowed by the greening technology chosen.

The substructure supporting the greening system is the mediating interface between the waterproofing layer and the enclosure behind it. It must support all the various components that make up the greening system and it is desirable that it ensures a ventilation gap behind the green package, to both guarantee the evaporation of any condensation and minimise the possibility of plant roots reaching the enclosure. The main attention must be paid to the correct structural dimensioning, carried out considering as a permanent load all the volume masses in a condition of water saturation. The substructure must be made of durable and resistant material (such as stainless steel, aluminium, fibre-reinforced polymer materials, etc.).

The irrigation system must provide an adequate quantity of water to the plant species, according to the different specific needs, the installation method, the climatic region and the microclimate of the area. This system consists of an integrated sub-system, composed of technological apparatus such as pumps, pipes, etc. Given the geometric and technological configuration of the vertical vegetated enclosures, it will always be necessary to integrate an automated irrigation system. This is because these green areas can reach a considerable height and use thin cultivation substrates, with a low water storage capacity, and because it is difficult to carry out this operation manually. It follows that the irrigation system is a constituent element of systems in which vertical vegetated enclosures are adopted. The type of irrigation system, the methods and the relative frequency of watering cycles will depend directly on the plant species used and the technology adopted in the substrates, which may include conventional or hydroponic cultivation. The latter cultivation method has become commonplace in vegetated closure systems since Patrick Blanc's patent, as it ensures overcoming many of the constructive and agronomic criticalities associated with bringing natural soil into the wall.

Also, in the case of green vegetated enclosures, particular connections between the green apparatus and other architectural elements must be studied in detail. These are: connection to the ground; at the top; nodes in correspondence of windows and doors and building projections; corner junction between green facades.

Generally, at the ground connection there is a gutter to receive and collect the water percolating from the wall, or an underground drainage system made of inert materials. At the top, there is usually a metal flashing, as in the case of green façades. At the window and door frames there is often a water collection element above the window and doorframes, as well as vertical slats and sills which also act as boundary elements. At the building corners there may be metal angles or panels may be placed ensuring overlapping of one façade onto the other.

Vertical vegetated enclosures can be divided into modular systems and vegetated walls. The first type, characterised by a high level of industrialisation and rationalisation of assembly, is made up of modules containing the substrate, i.e. the layer on which the plants grow, made up of slabs of expanded material or earth, and sometimes includes pre-planting. The second type, such as Patrick Blanc's "Le Mur Végétal" system, is made with a textile substrate, without the use of soil. This layer generally consists of a double layer of synthetic felt in which the plants are placed manually by the operator who inserts them into special pockets between the two fabrics, exploiting the characteristics of hydroponic cultivation. Both systems are integrated with irrigation or fertigation systems to guarantee plant nutrition in an automatic and programmable manner.

Table 7.4 shows, by way of example, some of the essences that can be used in vertical vegetated enclosures as well as some of their characteristics.

TABLE 7.4. Table with the characteristics of some plant species that can be used for living walls (Source: own elaboration)

TYPES OF ESSENCES	DESCRIPTION	PLANT ESSENCES	HEIGHT DEVELOPMENT [cm]	TOTAL WEIGHT [kg/m^2]
HERBACEOUS GROUND COVER	Plants do not develop woody branches; small plants produce compact vegetation	Marsilea crenata, Episcia, Fittonia, Pilea, Sedum spectabile, Vinca	5 ÷ 20	15 ÷ 25
MUSCINALE	Plants with small both stems and leaves, lacking vascular tissues; primitive plant organisms growing in damp places, on soil, rocks and tree bark	Aploide, Dawsonia superba, Sphagnum, Vesicularia	10 ÷ 30	10 ÷ 25
FERN	Plants with fronds. Most varieties have a globular, almost stemless development	Asplenium, Anthurium, Salvinia natans	60 ÷ 120	10 ÷ 20
EPIPHYTES	Plants that do not take root in the soil but settle on the trunks or branches of other plants, using them as support without damaging them or drawing nourishment from them.	Drynaria, Medinilla, Rhipsalis, Clusia	10 ÷ 30	2 ÷ 8
SMALL ARBUSTIVE	Woody perennial bushy species, whose branches separate from the central stem or whose trunk is not present.	Abelia, Berberis, Kerria, Begonia, Buxus Sempervirens, Spirea, Liguraria, Bergenia	60 ÷ 150	20 ÷ 40

Table 7.5 classifies the modular systems of living walls, while the Mur Vegetal have no specific subtypes.

TABLE 7.5. Classification table for modular living wall systems (Source: own elaboration)

CLASSIFICATION OF MODULAR LIVING WALLS SYSTEMS					
	CLADDING SYSTEM	*CLADDING FIXING*	*SUBSTRUCTURE TYPES*	*SUBSTRUCTURE MATERIAL*	*FIXING TO LOAD-BEARING LAYER*
MODULAR PANELS SYSTEM	Recycled polyethylene panel with rockwool growing layer	Supported by the cladding	Mullions and transoms system	Stainless steel	Mechanical/ chemical dowels
	Multilayer panel with rockwool growing substrate	Threaded screws anchored on structural panel	Mullions and brackets system	Galvanised steel	Mechanical/ chemical dowels
SYSTEM WITH BOXES	Shaped box in recycled polypropylene for culture pots	Supported by the cladding	Mullions and transoms system	Stainless steel	Mechanical/ chemical dowels
	Expanded polypropylene boxes containing growing substrate	By gravity through aluminium clip and curved rod	Mullions and brackets system	Alluminium	Mechanical/ chemical dowels
POCKETS SYSTEMS	Rigid EPP boxes with recessed culture pockets	Clips on top edge	Tramsoms system	Alluminium	Threaded screws
	Multilayer geocomposite panel with notched pockets	Box profile on shaped plates fixed with screws	Mullions system	Galvanised steel	Mechanical/ chemical dowels

Some systems available on market are described below.

Modular panels system

It is a pre-designed modular system, including automatic irrigation. It consists of panels made of an aluminium support plate and a recycled polyethylene cladding, perforated to create pocket with rockwool growing substrate for plant roots. The support structure, in front of a hydrophobic polyethylene panel, consists of C-section mullions and transoms made of plates, welded together. The panels are housed in an aluminium frame with hooks on the rear side that allow fixing by gravity to the metal transoms. Cold-folded aluminium sheets are arranged on the sides and at the top. They conceal the irrigation system and delimitate the whole system (Fig. 7.10).

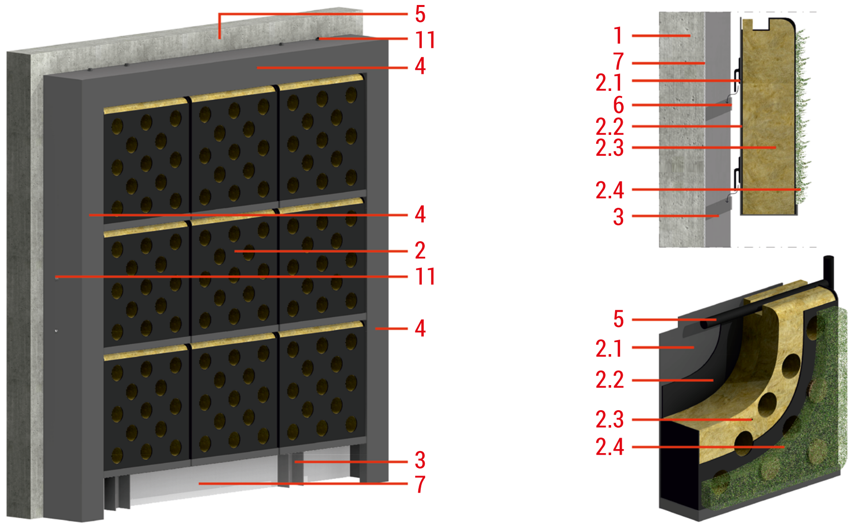


FIG. 7.10. Axonometry, section and detail of the panel. Legend: 1. Load-bearing layer; 2. Panel; 2.1 Aluminium backing sheet, 4mm thick; 2.2. Recycled polyethylene cladding layer, 4mm thick; 2.3. Perforated rock wool growing substrate, 75 mm thick; 2.4. Plants; 3. Mullion, C-section profile 38 x 51 mm, 2 mm thick; 4. Cold-bent aluminium sheet, 2 mm thick; 5. Drip lines irrigation system, circular profile ⌀16 mm; 6. Tramsoms, flat profile 20 x 2 mm; 7. Hydrophobic polyethylene panel, 2 mm thick; 8. Corner profile for sheet metal fastening, L-section profile 70 x 50 mm, 2 mm thick; 9. Mechanical anchor for fixing to the load-bearing layer; 10. Hexagonal screw for anchoring the angle profile; 11. Hexagonal screw for fixing the sheet metal (Source: own elaboration)

System with boxes

It is a pre-designed modular system consisting of shaped boxes made of recycled polyethylene where two to five polyethylene pots (maximum diameter 125 mm) with soil as a growing substrate are arranged. The system is supported by a galvanised steel structure made up of C-profile uprights and transoms (plates). They are fixed to each other and mechanically fastened to the wall load-bearing layer by dowels. A 2 mm thick hydrophobic polyethylene panel is arranged between these two elements. The boxes are hung from the transoms by hooks positioned on the back. The system includes an automated irrigation system with drip lines placed every five horizontal alignments. The containers are shaped to always guarantee a water reserve at the bottom (Fig. 7.11).

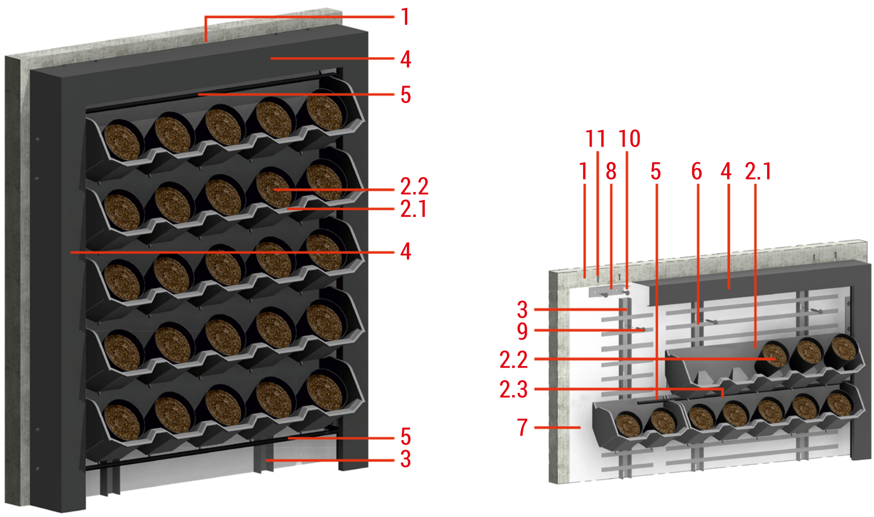


FIG. 7.11. Axonometry and detail of the panel fixing. Legend: 1. Load-bearing layer; 2. Box; 2. Shaped polyethylene container; 2.2. Pot (⌀ max 125mm) with growing medium (soil); 2.3. Water drainage channel; 2.4. Plants; 2.5. Water reservoir; 3. Mullion, C-section profile 38 x 51 mm, 2 mm thick; 4. Cold-bent aluminium sheet, 2 mm thick; 5. Drip lines irrigation system, circular profile ⌀16 mm; 6. Transom, flat profile 20 x 2 mm; 7. Hydrophobic polyethylene panel, 2 mm thick; 8. Corner profile for sheet metal fastening, L-section profile 70 x 50 mm, 2 mm thick; 9. Mechanical anchor for fixing to the resistant layer; 10. Hexagonal screw for anchoring the angle profile; 11. Hexagonal screw for fixing the sheet metal (Source: own elaboration)

Modular multilayer panel system

It consists of a multi-layer module anchored to a back-to-back panel. The support structure is generally made up of galvanised steel t or L-shaped mullions fixed by brackets and mechanical dowels to the resistant layer. Cement agglomerate panels (12 mm thick) are fixed to these elements by self-threading screws. There is an external hydrophobic panel to ensure that the irrigated area remains in front of the support panel. The panel is fixed by galvanised C-section steel transoms which provide support for the base module and the starting point for the irrigation system. The module is a multi-layered element consisting of a recycled polypropylene box containing the rockwool growing substrate. The module is horizontally spaced by the extruded polyethylene geocomposite drainage layer. The standard panels are L60 x H45 cm approximately 22 cm thick and weigh 15 kg (water saturated) (Fig. 7.12).

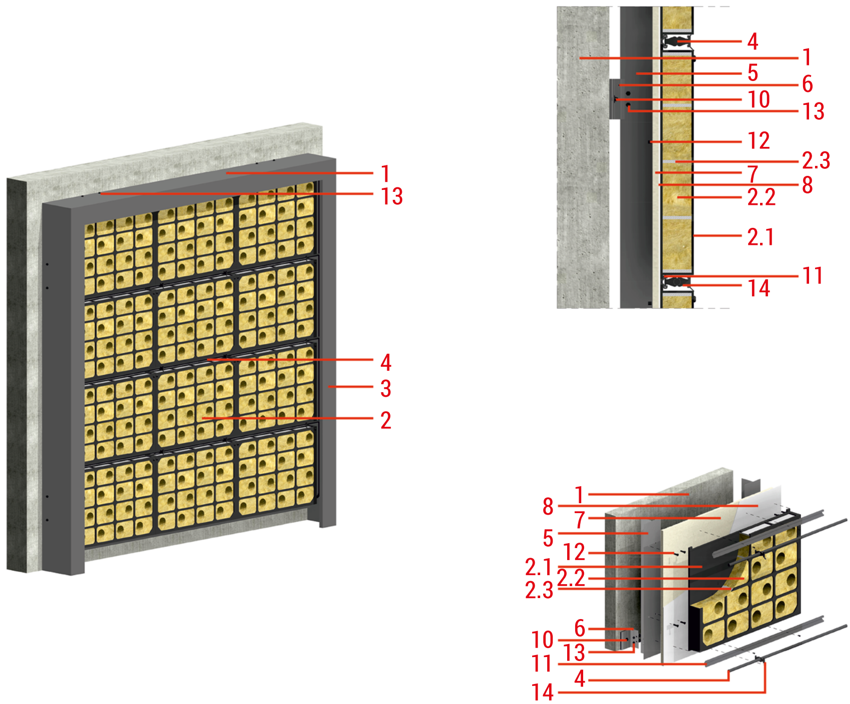
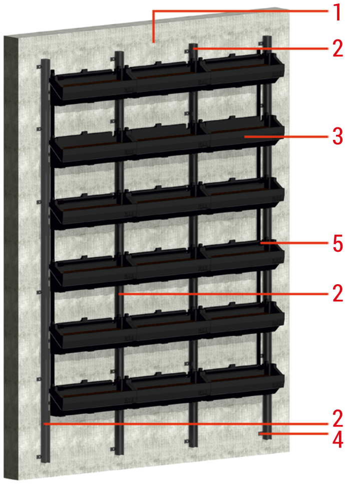


FIG. 7.12. Axonometry, section and detail of the panel fixing. Legend: 1. Load-bearing layer; 2. Panel; 2.1 Recycled polypropylene containment box, 4 mm thick; 2.2. Rockwool growing substrate, 55 mm thick; 2.3. Geocomposite drainage layer made of extruded polyethylene; 2.4. Plants; 3. Cold-formed aluminium sheet, 2 mm thick; 4. Driplines irrigation system, circular profile ⌀13 mm; 5. Galvanised steel mullion, T (or L) section profile 60 x 100 (50) mm, 2 mm thick; 6. Mullion fixing bracket, galvanised steel profile; 7. Cement particle board; 8. Hydrophobic polyethylene panel, 2 mm thick; 9. Corner profile for sheet metal fastening, L-section profile 70 x 50 mm, 2 mm thick; 10. Mechanical anchor for anchoring to the resistant layer; 11. Galvanised steel support beam, C-section profile 12 x 26 mm, 2 mm thick; 12. Hexagonal head screw; 14. Clamp for anchoring the thermal profile of the irrigation system; 15. Hexagonal head screw for anchoring the corner profile (Source: own elaboration)

Boxes system

It is a modular system made up of modular expanded polypropylene (EPP) boxes measuring L60 x W17 x H19 cm containing the growing substrate (soil). Boxes are individually attached to the support structure by adjustable aluminium clips and galvanised steel rods ⌀5 mm. The substructure consists of aluminium mullions with a 48 x 37 mm shaped section that are fixed to the resistant layer by aluminium anchoring brackets and mechanical dowels positioned at various heights. The system includes an irrigation system with drip lines arranged at each level (Fig. 7.13).



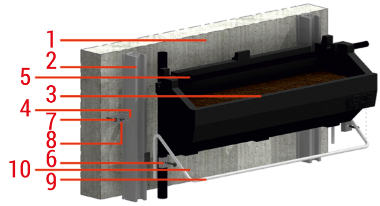


FIG. 7.13. Axonometry and detail of the base module. Legend: 1. Load-bearing layer; 2. Aluminium mullion EN AW 6060-T6, shaped section 48 x 37 mm; 3. EPP modular basin, standard dimensions 60 x 17 x 19 cm (LxWxH); 4. Single anchor bracket in aluminium EN AW 6060-T6; 5. Screws for fixing the mullion; 6. Adjustable aluminium clip with M6 dowel for fixing the modular pool; 7. Mechanical dowel for anchoring to the load-bearing layer; 8. Screws for fixing the mullion; 9. Galvanised steel rod ⌀5 mm for supporting the modular pool; 10. Screws for fixing support bar (Source: own elaboration)

Boxes with culture pockets system

It is a modular system with interchangeable plant boxes characterised by a size of L40 x H40 cm and slots where the plants are arranged. Each row of boxes is placed on a shaped aluminium profile that is both a gutter for water reservoir and support for the boxes. The module consists of a box container with nine EPP pockets, a microfibre panel for irrigating the plants, a stiff polypropylene panel and the growing substrate. The system is fixed by polypropylene clamps and perimetrically enclosed by a folded aluminium profile. The total weight of the module, including the plants, is 35÷40 kg/m^2 (Fig. 7.14).

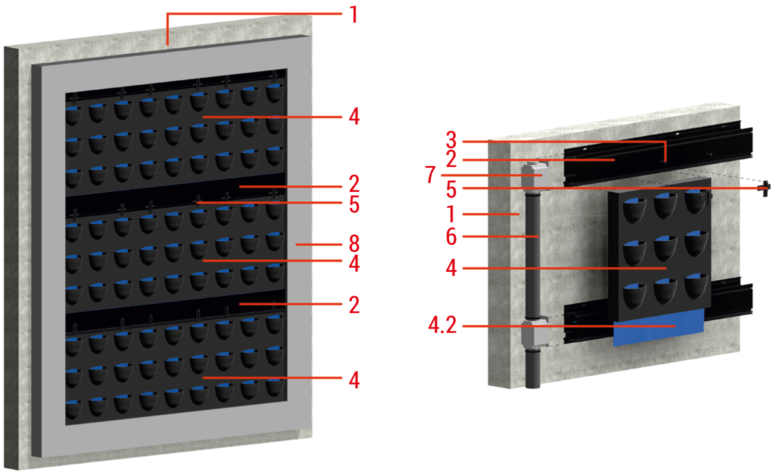
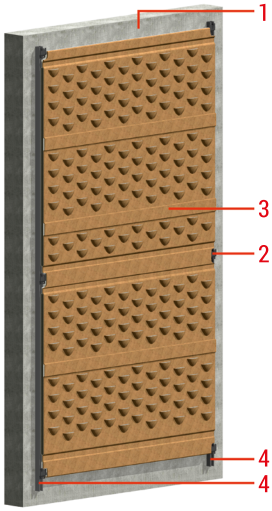


FIG. 7.14. Axonometry and detail of the base module. Legend: 1. Load-bearing layer; 2. Shaped aluminium profile, Al6063 T5: support and water reserve for upper panel; 3. Mechanical anchor for fixing to the resistant layer; 4. Module; 5. Polypropylene clamp for module fixing; 6. Circular profile for irrigation system; 7. Box with pump for irrigation water delivery; 8. Folded aluminium profile for perimeter delimitation (Source: own elaboration)

Pockets system

It is a modular system with mullions made of galvanised steel C-profiles with grooves, fixed by mechanical or chemical dowels to the wall load-bearing layer. Shaped galvanised steel S-section plates for supporting the panel are fixed to mullions with hammerhead bolts. Panel is fixed by gravity by transversal bars inserted in special slots. These support bars have box sections with a rectangular cross-section. They are inserted into slots in the geocomposite panel at the top, at intervals of 190 cm. The fastening is punctual and visible, completed with a second hammerhead bolt inserted at the top once the profile has been arranged on the anchor plate. The panel consists of two bidirectional geocomposite layers and a polyurethane substrate, joined together by discrete quilting with polyester thread. Slots are made in the module to accommodate the fixing bars for supporting the system and the seam is regularly interrupted to allow the transverse insertion of drip profiles for irrigation (Fig. 7.15).



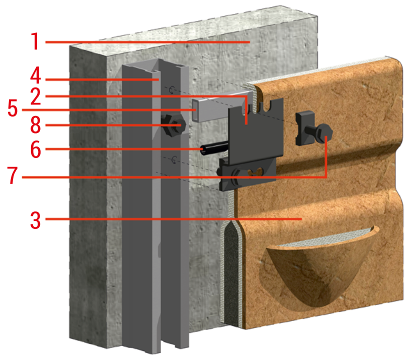


FIG. 7.15. Axonometry and detail of the fastening node. Legend: 1. Load bearing layer; 2. Stainless steel fixing plate; 3. Panel; 4. Mullion; 5. Stainless steel fixing bar, box profile 20 x 9.5 mm (2 mm thick); 6. Driplines (irrigation system); 7. Hammer-head screw for fixing the plate to the mullion; 8. Mullion fixing dowel (Source: own elaboration)

Mur Vegetal

In this system plants grow on panels covered with four layers of felt, using hydroponics techniques. These panels are supported by a modular aluminium frame made up of box profiles measuring 60 x 30 mm, 4 mm thick, spaced from the wall to ensure adequate ventilation. The system is equipped with an automatic control system for the fertigation and lighting cycles. The aluminium substructure holds the plant panels. The substructure is supported by aluminium brackets and anchored to the wall by mechanical dowels. Each panel consists of an aluminium frame and a FOREX sheet covered with 3-4 layers of felt, suitably engraved to create the planting pockets.

According to the hydroponics method, in Each pocket there is a plant (Fig. 7.16).

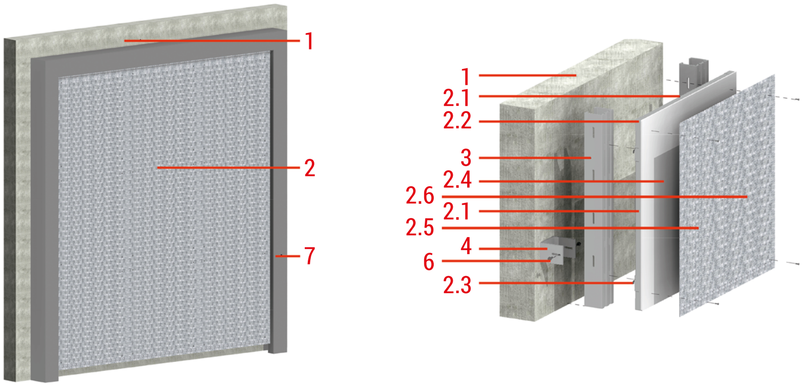


FIG. 7.16. Axonometry and detail of the basic module. Legend: 1. Load bearing layer; 2. Modular panel; 2.1 Bi-directional aluminium frame, box profiles 60 x 30 mm, 4 mm thick; 2.2. Corner joint; 2.3. Plate with gravity anchorage hook; 2.4. PVC stiffening panel; 2.5. Four layers of felt for water drainage, root growth and plant containment; 2.6. Plants; 3. Aluminium mullion, C-section 125 x 100 mm, 8 mm thick; 4. Aluminium anchoring bracket; 5. Mechanical anchor for anchoring to the load bearing layer; 6. Screws for fixing upright to bracket system; 7. Aluminium profile for perimeter containment (Source: own elaboration)

References

[1] Ariaudo, F., Fracastoro, G.V. (2007) Il verde parietale come elemento di controllo dei carichi termici, *Il Progetto Sostenibile*,1.

[2] Bellomo, A. (2005) Pareti verdi – linee guida alla progettazione, Sistemi Editoriali.

[3] Bit, E. (2012) Il nuovo verde verticale: tecnologie, progetti, linee guida, Wolters Kluwer, Italia.

[4] Blanc, P. (2008) The Vertical Garden. From nature to the city, W. W. Norton, New York, London.

[5] Cameron R.W.F, Taylor J.E., Emmett M.R. (2014) What's "cool" in the world of green facades? How plant choice influences the cooling properties of green walls, *Building and Environment*, 73.

[6] Campiotti, C.A., Di Bonito, R., Giagnacovo, G., Colletta, R., Scoccianti, M., Viola, C. (2013) Eco-Greenroof & Vertical Grenery system, Eco-Sistemi Vegetali per l'Efficienza Energetica e il Risparmio di Energia negli Edifici Urbani, ENEA.

[7] Corgnati, S.P., Ariaudo, F., Fracastoro, G.V., Raimondo, D. (2009) Verde verticale, abbattimento dei carichi termici estivi e valutazione dei risparmi energetici derivanti, *NEMETON*, 1.

[8] Corrado, M. (2010) Il verde verticale, Esselibri S.P.A, Napoli.

[9] Jim, C.Y. (2015) Greenwall classification and critical design-management assessments, *Ecological Engineering*.

[10] Köeler, M. (2008) Green façades – a view back and some visions, *Urban, Ecosystems*,11.

[11] Lambertini, A., Ciampi M. (2007) Giardini in verticale, Verbavolant, Roma.

[12] Poli, T. (2006) Pelle verde, *Modulo*, 319.

[13] Poli, T. (2006), Verde in powinno byc [13] Poli T. (2006) Verde in quota, *Modulo*, 324.

[14] Santi G. (2010) Green living walls, I sistemi di inverdimento verticale integrati all'involucro edilizio: schermatura solare, termoregolazione e produzione di ossigeno, *Il soleatre-centoses-santagradi* – sezione dell'International Solar Energy Society, 2.

[15] Santi G. (2016) Il Prato e l'Architettura, architettura e tecnica del verde verticale per le costruzioni, CLD Libri, Pisa.

[16] Spagnolli P. (1995) Le tipologie di verde pensile, *Acer*, 5.

[17] Tatano V. (2008) Verde. Naturalizzare in verticale, Maggioli, Rimini.

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8. ENERGY EFFICIENT BUILDING MATERIALS

8.1. Introduction

In today's world, energy efficiency is the most sought characteristic. Enhancing energy efficiency and hence moving towards sustainability is considered the primary requirement. Buildings are the places where we spend most of our time and thus they consume more than one-third of the energy consumption. This forces the stakeholders to think about the new ways to strike a dynamic balance between comfortable human dwelling, efficient resource management, and protecting our environment (Verma et al., 2022). Reducing energy consumption in buildings is essential in order to alleviate deteriorating impacts on the environment. Improving the energy efficiency of buildings is becoming a priority by converting buildings from energy consumers to energy-neutral or even energy-positive entities, which produce more energy from renewable sources than they consume. To improve the building performance, building efficiency requires the integration of superior architecture and engineering designs, energy-efficient building materials, quality construction practices, and intelligent operation of the structures (Li et al., 2021).

Increasing the energy efficiency of buildings is not a new issue. This is a challenge not only in Lithuania, but also in many other European coun-tries, as evidenced by the actions and initiatives of the European Union. Since the climate of Lithuania is transitional between midlatitude maritime and continental, the issue of thermal insulation of buildings is important from an economic and ecological point of view. The construction industry is increasingly integrating natural and ecological organic thermal insulation materials such as: wood wool, insulation cork board, cellulose fibres, hemp, sheep's wool, flax, straw bales and etc. But in this chapter we will discuss about traditional, state-of-the-art and possible materials and solu-tions on the Lithuanian market such as: Structural Insulated Panels (SIPs), Insulating Concrete Forms (ICFs) and Vacuum Insulation Panels (VIPs).

8.2. Structural Insulated Panels (SIPs)

Structural insulated panels (SIPs) have been applied in building structures as curtain walls since the early 1960s, where the panels typically deliver sufficient composite action to satisfy structural specifications (Amran et al., 2020).

Energy loss from the external wall of the building accounted for a large proportion of energy consumption. Improving the thermal performance of the building envelope is an effective way to promote building energy conservation. Structural insulated panels (Fig. 8.1) are used for various applications, such as with an exterior wall, roof, floor, or foundation system. SIPs have excellent thermal performance, and can significantly reduce energy consumption during the operation of the building. In addition, SIPs have significant advantages, such as high strength-to-weight ratio and ease of construction, and have been increasingly used in residential and office buildings (Du et al., 2021).

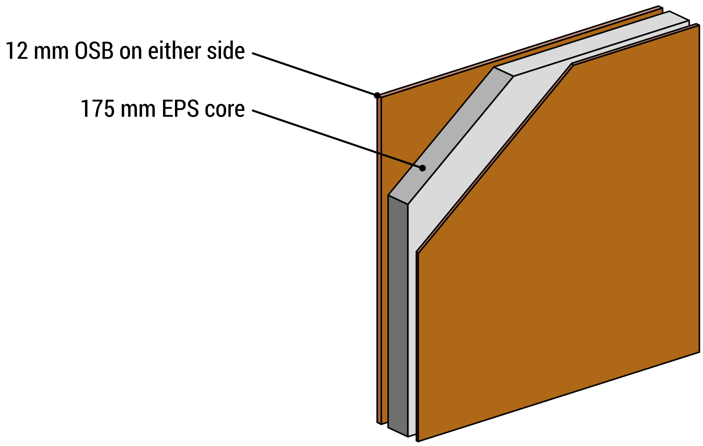

FIG. 8.1. SIP with typical material thicknesses. Note: OSB – oriented strand board, EPS – expanded polystyrene (Source: Dhaif & Stephan, 2021)

Structural insulated panels are most commonly used as an alternative to typical lumber framing in residential construction, though some variations are used in light commercial construction. The advantages of building with SIPs, versus typical timber framing, include reduced construction time, reduced labor requirement, and most of all the increased thermal efficiency of the overall structure. The reduction in construction time and labor required are tied together and are a direct result of the prefabricated components and the integration of structure and insulation (Purasinghe et al., 2018). SIPs are manufactured and pre-cut at a factory according to plans submitted by a builder and can include features such as window openings, headers, and posts to the panels (Harris et al., 2019). SIP is an engineering construction material because it provides several favorable features, such as being lightweight, high strength, environmentally friendly, and having excellent thermal and acoustic performance. However, SIP has some disadvantages, such as the release of gas (classified as a carcinogen) from the surface layer of formaldehyde-based adhesive binder, the inability of expanded polystyrene (EPS) as a core layer to break down in the environment after destruction, and low fire resistance (Thongcharoen et al., 2021).

8.2.1. SIPs Components, Technical Data and Details

Facing materials used in SIPs can be oriented strand board (OSB), plywood, metal, cementitious, magnesium, plastic, or other structural panel products. Core materials used in SIP construction include expanded polystyrene (EPS) (Fig. 8.2), extruded polystyrene (XPS), polyurethane (PUR), and polyisocyanurate (PIR). These components are used in commercial and residential construction projects worldwide (Bai et al., 2017). SIP is a sandwich panel that is utilized as a structural member such as a wall, roof, and floor for concrete structures. SIP varies in different thicknesses of two layers of rigid material like skin and a thicker layer as the core. It can be made of various materials based on its application (Panjehpour et al., 2013). By incorporating the EPS system, the structural stability of the system improves, it also has a high thermal resistance. This foam contains 3 to 6 million independent closed cells per cubic meter of volume and more than 98% air. Analyzing the different components of SIP, it is necessary to mention the importance of gypsum plasterboards which thanks to their water tightness, rigidity, and thermal insulation properties reduces the transfer of heat through their porous structure, forming a thermal barrier (Murillo et al., 2021).

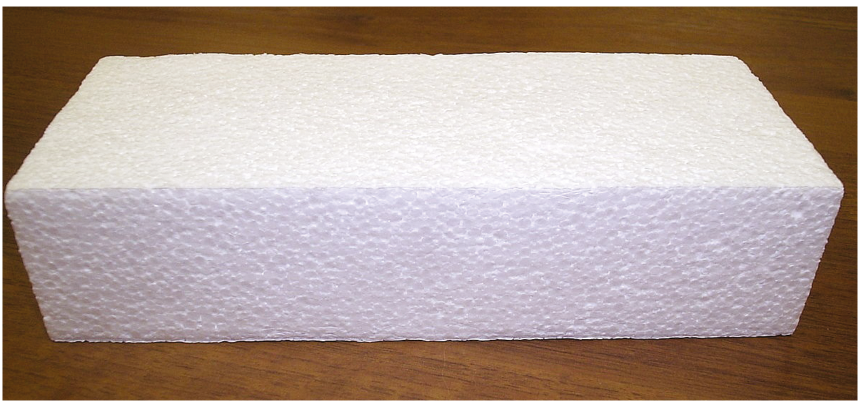

FIG. 8.2. Expanded polystyrene (EPS) (Source: WEB–1)

OSB is formed by layering strands of wood in specific orientations and gluing and compressing them. These panels are manufactured off-site in standardised sizes and are used mainly for external walls and roofs (Fig. 8.3). The R-value of SIPs ranges between 2.7 $(m^2{\cdot}K)/W$ ($U = 0.37$ $W/(m^2{\cdot}K)$) and 6 $(m^2{\cdot}K)/W$ ($U = 0.167$ $W/(m^2{\cdot}K)$), depending on the panel thickness. In the USA, SIP-built houses save 12–14% in energy use, compared to stud-framed houses (Dhaif & Stephan, 2021). SIPs have approximately 42% higher R-value compared to a typical timber-framed wall (Harris et al., 2019).

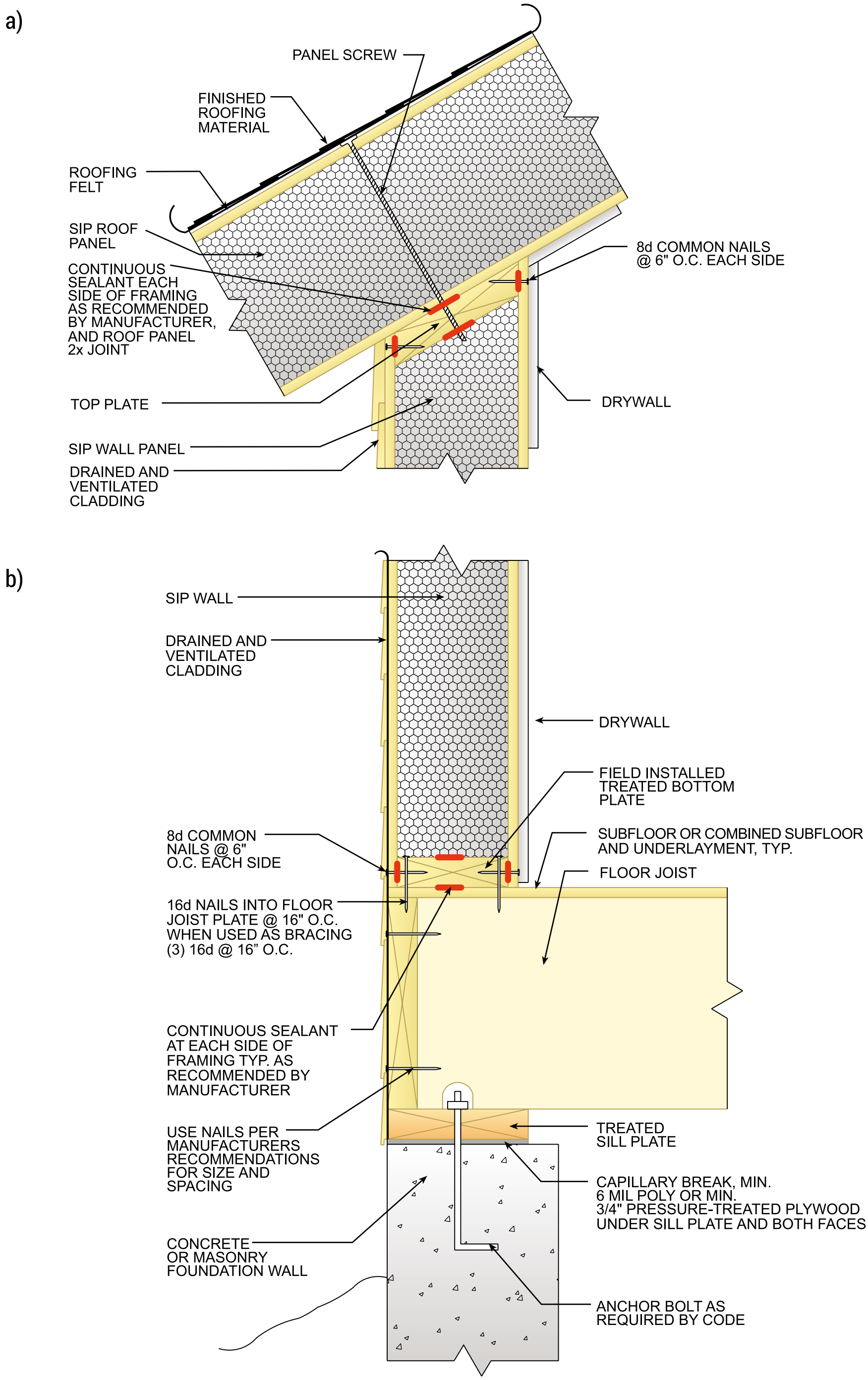

FIG. 8.3. Structural insulated panels: a) roof-to-wall panel connections, b) foundation connections (Source: WEB–3)

Walls are manufactured as either small individual panels, typically 1.2×2.4 m (OSB sheet sized panels), or as larger panels made from multiple or single large-format sheets of OSB. Panels with a length or height up to 6 m can be manufactured to provide double height spaces or large panels for increased speed of erection. Panels are joined using either solid timber within the ends of the panels or SIP-based insulated splines, depending on the manufacturer's specific system and/or structural requirements. The splines are fixed into the ends of the panels using either nail, screw, or bolt fixings and sealed. SIPs can form both pitched and flat roof structures and can be finished with any form of normal roof covering (WEB–2). SIP can reduce the construction time by 45%, and the electric set time by 89%, whereas its investment cost is 68% higher than the conventionally framed house building. Compared with brick and concrete structure houses, SIP houses can result in energy demand savings of about 60% (Geng et al., 2021).

The SIP panels are made from the highest quality materials: oriented strand boards at least 12 mm thick and polyurethane glue is used for gluing the panels. Table 8.1 shows the dimensions of the SIP panels, considering that two 12 mm thick OSB boards are used from the edges.

TABLE 8.1. Dimensions of SIP panels (Source: WEB–4)

Dimensions [mm]	
Width	1250
Height	2500, 2800, 3000
Thickness	124, 174, 224, 274, 324, 374

8.3. Insulating Concrete Forms (ICFs)

Insulating concrete forms (ICF) walls most commonly consist of concrete between polystyrene foam, although other form materials such as polyurethane, recycled wood, and cement mixtures exist as well.

ICF is a building material that is increasingly being used in construction. An ICF wall section consists of expanded polystyrene (EPS) forms and poured concrete with polymer ties connecting the EPS forms, depicted (Fig. 8.4). One difference between ICF and traditional construction is that after the concrete has cured, the polystyrene forms remain in place. Additional reinforcement, such as rebar, can be added according to the structural design using internal strapping made of polypropylene (Rajagopalan et al., 2010).

Insulating concrete forms result in cast-in-place concrete walls that are sandwiched between two layers of insulation material. Common applications for this method of construction are low-rise buildings, with property uses ranging from residential to commercial to industrial. Traditional finishes are applied to interior and exterior faces, so the buildings look similar to typical construction, although the walls are usually thicker (WEB–5).

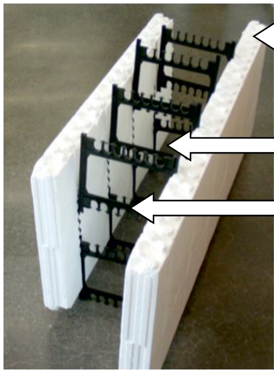

FIG. 8.4. Insulating concrete form (Source: Rajagopalan et al., 2010)

The blocks are used to form the interior and exterior walls of the structure, sometimes coined “Lego”. The ICF units are stacked in the shape of the wall, reinforcing steel is added into the formed cavity, and then concrete is placed into the form. The result is a reinforced concrete wall with a layer of insulation on each side. The combination of reinforced concrete and insulation provides an ideal load-bearing wall, thermal envelope, fire barrier, and sound barrier. ICF wall systems have been used for bearing-wall buildings ranging from single-story to high-rise buildings more than 20 stories tall and everything in between. In addition to ICF walls, there are also ICF floor and roof systems (WEB–6).

According to the JSC Šilputa (JSC Šilputa, 2021a) ICF block products are cut with a special knife or saw. Products must be protected from prolonged exposure to the sun, atmospheric precipitation, and mechanical damage. ICF blocks must fit together and with each other so that there are no cracks. If cracks occur, they must be filled with sealing materials (e.g. low-expansion polyurethane foam). ICF blocks must be mounted so that they do not intersect at four corners.

8.3.1. Types of Systems

There are a variety of different block and panel systems, using typically either expanded polystyrene insulation (EPS) or extruded polystyrene (XPS). Within three general types, ICF systems are further categorized by the concrete core shape they produce – flat, interrupted grid, uninterrupted grid or post-and-beam (VanderWerf & White, 1998). Flat systems are similar to conventional poured walls, with a continuous thickness of concrete throughout the entire wall. On the other hand, grid systems have a waffle pattern where the concrete is thicker at some points. The post and beam systems have horizontal and vertical elements of concrete that are completely encapsulated in foam insulation (WEB–7).

The blocks that make up the insulating formwork are manufactured in a variety of shapes and component types, creating limitless design opportunities. Any type of foundation, flooring, partition, stair, or roofing system is compatible with ICF construction.

8.3.2. Energy Efficiency with Insulated Concrete Forms

The thermal resistance (R) value of the EPS panels can be as high as 5.3 $(m^2 \cdot K)/W$ which makes ICF a perfect insulated wall for buildings. Meanwhile, the concrete inside the ICF can be used as thermal storage (Ekrami et al., 2015). The higher R-value of ICF provides greater insulation to the building by keeping the controlled temperature for longer periods. The thermal insulation behavior of ICF reduces power demand and makes the building more energy-efficient. Thus, the ICF system helps in sustainable building construction by affording high thermal insulation with improved structural strength (Solomon & Hemalatha, 2020).

ICFs' main appeal is the potential energy savings that directly come from minimizing the amount of energy required to cool and heat the buildings. Those savings can add up to 20% or more. The typical R-value for any building made with the use of ICFs is about 20 $(m^2 \cdot K)/W$. Hence, during its service life, a single building can save vast amounts of CO_2 compared to others. Actually, ICF construction has two main advantages when it comes to the energy performance of the building. Primarily, it seals and covers well enough to prevent air leakage. Second, it has two even layers of insulation, one from the inside and one from the outside. Take note that there are no thermal bridges. Hence, the tight building envelope gradually reduces heat loss (WEB–8).

Thermal bridges are part of the limit of the heated volume of a building where the uniform thermal resistance changes due to the complete or partial unevenness of the structure. The unevenness is due to the difference in material, thickness, density, surface, position, and/or heat transfer coefficient from the adjacent homogeneous structure.

The walls of the ICF blocks from JSC Šilputa (Table 8.2) are assembled dry, without glue and mixtures, the blocks are connected to each other with ridges (similar to "Lego" blocks), additionally reinforced and the inside is filled with concrete. A solid monolithic construction without thermal bridges (Fig. 8.5) is obtained fairly quickly and easily. The walls are concreted at a height of 3 m, which in practice means that concrete must be poured after a single floor. The concrete compressive strength class must be specified by the constructor. The walls must be supported before pouring the concrete. Pillars are built on the inside of the walls every 1.4 m. The buildings to be used for the construction of the ICF NEO Thermo blocks are designed in accordance with the Eurocode LST EN 1992-1-1 "Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings" (JSC Šilputa, 2021a).

TABLE 8.2. Declared properties of ICF Thermo blocks (Source: JSC Šilputa, 2021b)

Name	Unit	Value
Thermal conductivity	W/(m·K)	0.030
Height	mm	300
Width	mm	250-500
Length	mm	1000
Compressive strength	kPa	200
Reaction to fire		E

Specialists of JSC Šilputa have calculated that the thermal resistance of a monolithic 0.5 m thick ICF NEO block wall is R = 11.33 $(m^2·K)/W$.

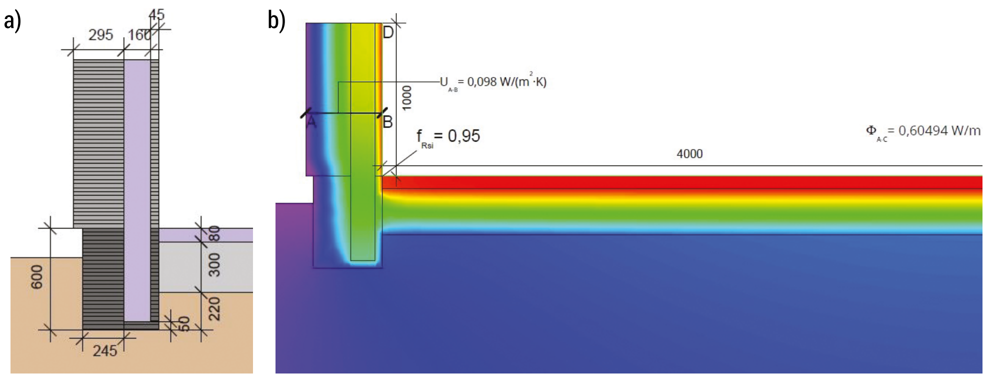

FIG. 8.5. Plinth foundation made from Thermo blocks EPS 200 NEO 295 mm. a) plinth scheme, b) temperature field in the structure (Ψ = 0.13928 W/(m·K)), (Source: JSC Šilputa, 2018)

Where:

– reinforced fine-grained concrete 1% steel ($λ_{ds}$=2.300 W/(m·K))

– EPS 200 N $λ_D$ = 0.030 W/(m·K) + soaking $Δλ_w$ = 0.002 W/(m·K) + reinforcement Δλ = 0.002 W/(m·K) ($λ_{ds}$=0.034 W/(m·K))

– EPS 200 N $λ_D$ = 0.030 W/(m·K) + soaking $Δλ_w$ = 0.010 W/(m·K) + reinforcement Δλ = 0.003 W/(m·K) ($λ_{ds}$=0.043 W/(m·K))

– EPS 200 N $λ_D$ = 0.030 W/(m·K) + soaking $Δλ_w$ = 0.006 W/(m·K) ($λ_{ds}$=0.036 W/(m·K))

– sand and gravel ($λ_{ds}$=2.000 W/(m·K))

$λ_{ds}$ – the design thermal conductivity of the layer, W/(m·K)

$λ_D$ – the declared value of the thermal conductivity coefficient of a thermal insulation construction product, W/(m·K)

$Δλ_w$ – correction of the thermal conductivity coefficient due to additional soaking of the thermal insulation construction product in the enclosure, W/(m·K)

U – heat transfer coefficient, $W/(m^2·K)$

f_{Rsi} – internal surface temperature coefficient,

Φ – heat flow, W

Ψ – linear thermal bridge transmittance parameter, W/(m·K)

This chapter fills the gap and compares the ICF wall system and the cavity wall system from an LCA (Life-cycle Assessment) perspective in terms of energy performance. The reference building is a semi-detached house with single-family occupancy located in Edinburgh and Bristol, in the United Kingdom, with 100 m^2 of living area and a service life of 50 years. Figure 8.6 presents the schematic drawings of two exterior wall systems for this case.

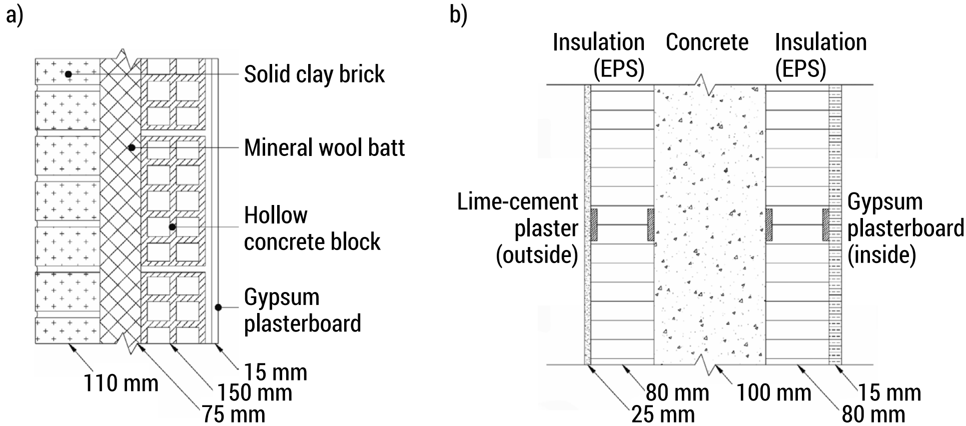

FIG. 8.6. Exterior wall with section details a) – cavity wall system; b) – ICF wall system (Source: Broun et al., 2014)

The alternative exterior wall systems used for this building are ICF and cavity walls. The functional unit was considered as 1 m^2 of each exterior wall system. It can be concluded that ICF walls are a better option than cavity walls. For colder climates, ICF walls perform better with respect to insulation, and hence, greater savings in energy are realized. In this case for the ICF wall system U-value = 0.21 $W/(m^2{\cdot}K)$ and for the cavity wall system 0.34 $W/(m^2{\cdot}K)$ (Broun et al., 2014).

8.3.3. Details of Insulated Concrete Forms Construction

ICF NEO Thermo blocks manufactured by JSC Šilputa consist of two polystyrene foam (EPS 200 NEO) walls, which are connected to each other by two metal frames (Fig. 8.7 and Figure 8.10) and are filled with reinforced concrete in the empty cavity. The graphite contained in the polystyrene foam adds better thermal insulation, bending, compression and water absorption properties to the block. The metal frame in the block provides strength and allows the casting of solid monolithic buildings.

Gray polystyrene foam, the thermal insulation properties of which are improved by the addition of graphite to the raw material of the polystyrene foam. Small particles of graphite reflect or absorb infrared rays, thus significantly reducing heat loss.

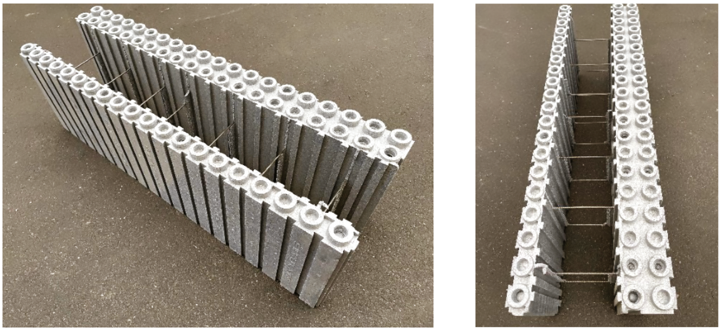

FIG. 8.7. ICF NEO Thermo blocks (Source: photos by JSC Šilputa)

The compressive strength of the ICF NEO wall blocks is 200 kPa or, more simply, 1 m^2 withstands a load of 20 tons, wall blocks can be used for basement walls and filled with a layer of soil, and the walls of the house can be finished after a year – blocks resistant to UV rays.

ICF Thermo blocks are used in exterior basement walls, grate, external plastered walls, walls with clinker tiles, and partitions.

The outer corner piece is mounted by supporting the two blocks on each other and forming a 90° angle between them (Fig. 8.8). A straight saw is used to cut ICF NEO Thermo blocks. Blocks can be cut both vertically and horizontally. Block joints are made in the middle of the wall. In block A, on which block B rests, a 45 mm thick piece of polystyrene foam is cut at the concrete cavity, without damaging the frame in the block. The walls are installed from the corners and openings (Fig. 8.9), corner blocks are used to form the corners, and closing blocks are used for the openings. If shortening is required, the blocks are easily cut.

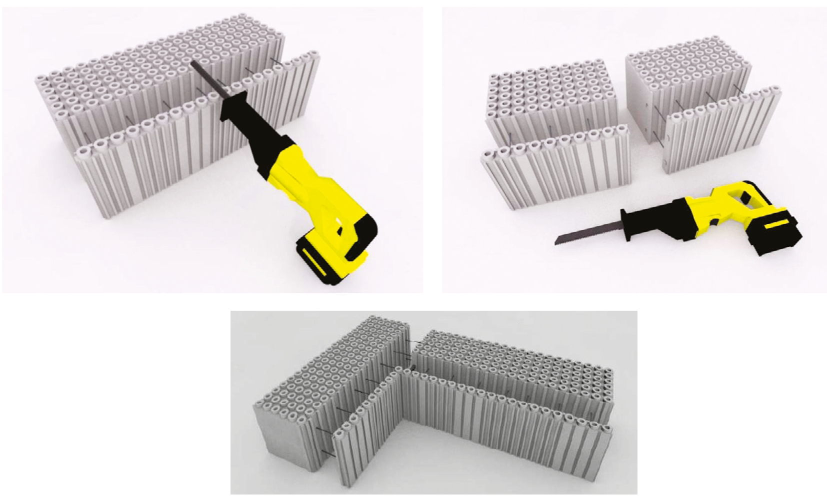

FIG. 8.8. Blocks cutting and installation of block corner pieces (Source: JSC Šilputa, 2021a)

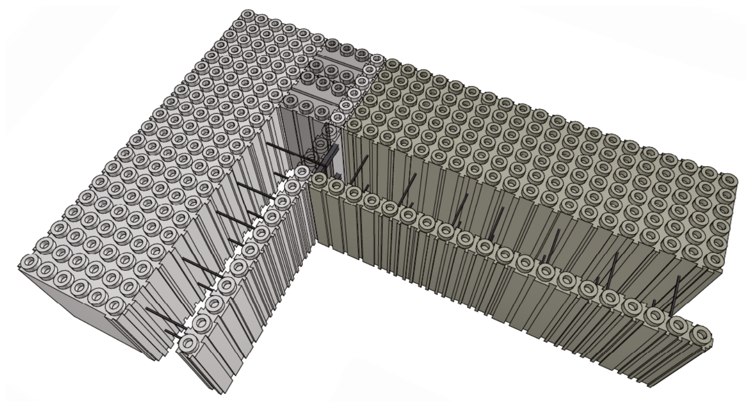

FIG. 8.9. Spatial scheme of the outer corner connection (Source: JSC Šilputa, 2021a)

Depending on the type of blocks (Table 8.3), the outer layer of insulation and concrete differs.

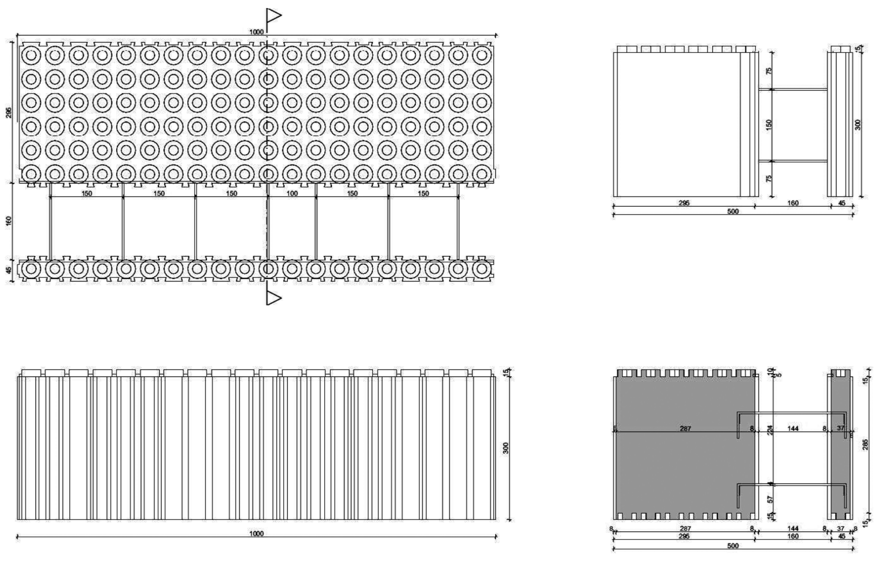

FIG. 8.10. ICF Thermo block EPS 200 NEO (200 kPa) (Source: JSC Šilputa, 2021c)

TABLE 8.3. Thermo block types (Source: JSC Šilputa, 2021a)

Block type	Inner insulation layer [m]	Outer insulation layer [m]	Concrete layer [m]
ICF 45×160×45	0.045	0.045	0.160
ICF 45×160×95	0.045	0.095	0.160
ICF 45×160×145	0.045	0.145	0.160
ICF 45×160×195	0.045	0.195	0.160

Block type	Inner insulation layer [m]	Outer insulation layer [m]	Concrete layer [m]
ICF 45×160×245	0.045	0.245	0.160
ICF 45×160×295	0.045	0.295	0.160
ICF 45×210×45	0.045	0.045	0.210
ICF 45×210×95	0.045	0.095	0.210
ICF 45×210×145	0.045	0.145	0.210
ICF 45×210×195	0.045	0.195	0.210
ICF 45×210×245	0.045	0.245	0.210

8.4. Vacuum Insulation Panels (VIPs)

Demand for energy-efficient buildings has grown drastically in recent years and this trend will continue in the future.

Vacuum insulation panels (VIP) are regarded as one of the most upcoming high-performance thermal insulation solutions. Thermal conductivity for a VIP can be as low as 0.002–0.004 W/(m·K) depending on the core material. VIPs have been utilized with success for applications such as freezers and thermal packaging, and during the last decade, they have also been used for building applications in increasing numbers, where one of the main driving forces is the increased focus on e.g. passive houses, zero energy buildings and zero-emission buildings (Kalnæs & Jelle, 2014). Energy used for heating, ventilation, and air conditioning in commercial and residential buildings contributes to a significant portion of the total energy consumed in many countries. Energy-efficient vacuum insulation panels present thin but highly effective insulation solutions, to reduce thermal losses for both new and renovated buildings (Boafo et al., 2014). Effective thermal performance of a building envelope is crucial to reducing total energy consumption in buildings. In the past decades, different insulating materials and techniques have been proposed to improve building energy efficiency. Among various insulating materials vacuum insulation panels, due to their extremely low thermal conductivity, become one of the emerging materials, striving for replacing conventional insulation materials (Li & Lin, 2021). Vacuum insulation panels are a space-saving (Fig. 8.11) alternative to conventional thermal insulation, thanks to their five to eight times higher thermal resistivity. As gas permeation through the envelope barrier may drastically reduce the insulation efficiency, aging effects and service life expectations are crucial aspects of those high-performance insulation units (Brunner & Simmler, 2008).

However, the fact that VIPs cannot be cut on-site, they can be easily damaged during their handling, installation, and use, and have an envelope that can cause thermal bridging in the junction between panels or when combined with other materials, has hindered their penetration in the construction market (Uriarte et al., 2019).

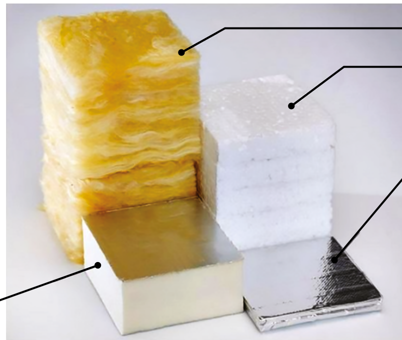

FIG. 8.11. Comparison in thickness between materials (Source: WEB–9)

8.4.1. VIP Technical Data

KEVOTHERMAL vacuum insulation panels have a particularly low thermal conductivity, which means a much lower insulation thickness compared to other thermal insulation on the market. VIP insulation panels are the most effective solution in places where every inch is particularly important. Vacuum insulation panel (Figure 8.12) consists of a micro-porous fumed silica core material (silicon carbide, hydrophilic pyrogenic silica, and polyester fibers), contained within a vacuum-sealed envelope (multi-layer aluminium foil wrapper), manufactured in accordance with prEN 17140. Available in maximum size of 1000 by 1500 mm and a range of thicknesses from 6 to 50 mm, density 180 kg/m^3. VIP can be used as insulation in the following applications: floors, internal and external walls, and roofs. VIP must not be used in applications with heat sources greater than 60°C (BDA Agrement, 2020). Regarding the panel's core material, most VIP manufacturers use fumed silica because of its low thermal conductivity. Nevertheless, looking to reduce costs, other core solutions are being developed such as ones using expanded cork, glass fibre, expanded perlite, aerogel composites, and polyurethane powder (Gonçalves et al., 2020).

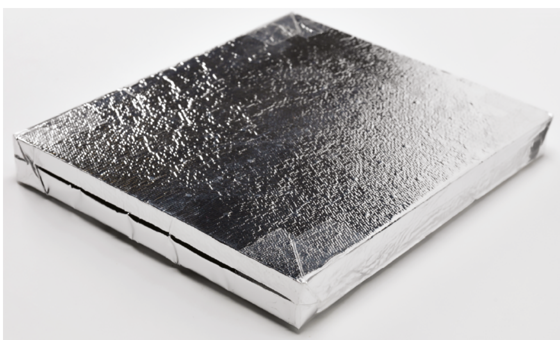

FIG. 8.12. Vacuum insulation panel (Source: BDA Agrement, 2020)

Figure 8.13 presents schematic examples of typical details. VIP characteristics: minimum compressive stress 223 kPa, tensile strength perpendicular to faces 93.6 kN/m^2, reaction to fire – F, declared thermal conductivity – 0.0045 W/(m·K) (BDA Agrement, 2020).

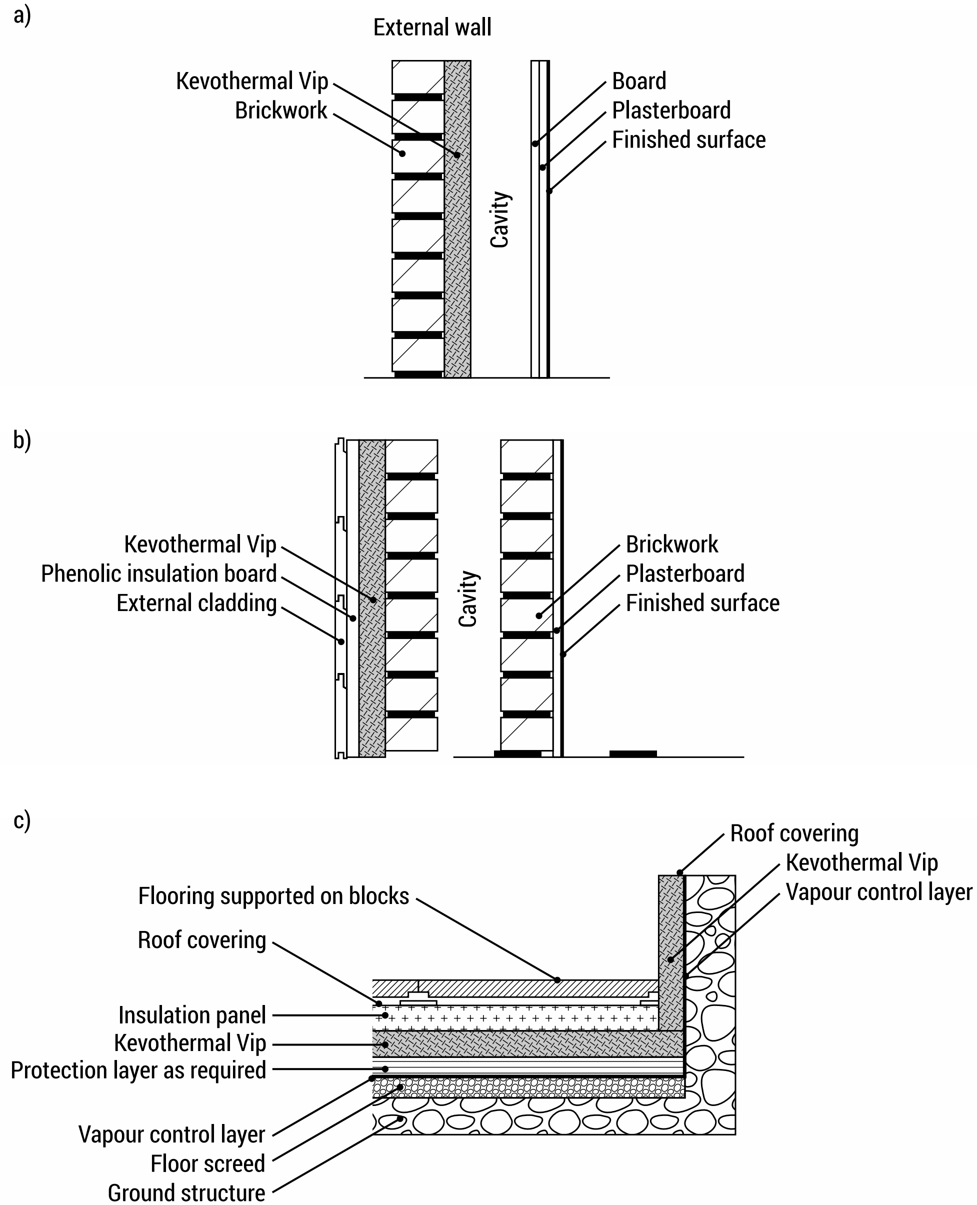

FIG. 8.13. Typical details: (a) – internally insulated external wall detail, (b) – externally insulated external wall detail, (c) – ballasted flat or tapered roof system (Source: BDA Agrement, 2020)

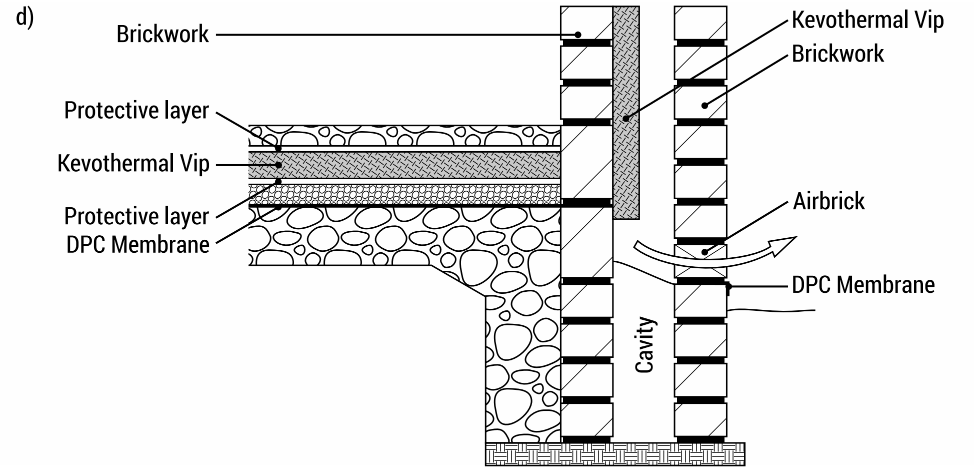

FIG. 8.13. Typical details: (d) – solid concrete ground-based floor (Source: BDA Agrement, 2020)

Energy efficiency of the built environment greatly depends on the performance of the insulating materials used in the building envelope construction. Vacuum insulation panels offer excellent thermal resistance properties that can enhance the energy efficiency of the insulating systems and provide savings in energy consumption.

As good as the performance of VIPs is, should a panel be punctured then up to 80% of its insulation performance would be lost. Taking this into account using this technology as internal wall insulation takes a great deal of thought as the likelihood of a fixing being driven into the panels at a later date could be high. In order to overcome this issue Studio Indigo (South Edwardes Square, Kensington, London) designed a system that created an 87 mm clearance between the VIPs and the internal face of the wall. This clearance would allow for internal fixings at a later date without the fear of puncturing the panels. The exact wall (Fig. 8.14a) build-up was as follows – existing wall / 15 mm VIP with 10 mm EPS backing to both sides / 60 mm Gyproc stud / 12 mm Plywood boarding / 12.5 mm Plasterboard / 3 mm skim coat.

a)

b)

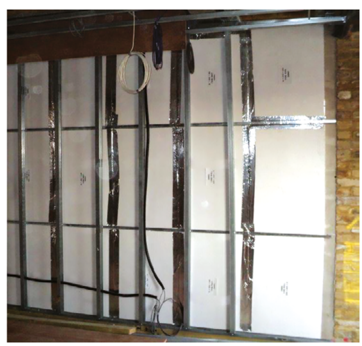

FIG. 8.14. Internal wall insulation: (a) – wall layers, (b) – fixing an L-shaped metal section (Source: KEVOTHERMAL case study 022, 2015)

The I-stud is independent of the external wall, fixed top and bottom with the VIPs fitted behind the studs. To give the I-stud stability they are braced back to the external wall at mid-span. This is achieved by fixing timber noggins between them, then fixing an L-shaped metal section to the timber and back to the wall. To alleviate the chance of puncturing the panels on-site the VIPs were installed after all services and immediately before the Plywood was fixed to the stud (Fig. 8.14b). The VIPs were slotted in place behind the studwork and then using a foil duct tape they were held in place by taping to the appropriate I-stud. The vacuum panels were used only on the external walls of the property and not in internal partitions, where alterations would most likely take place.

References

[1] Amran, Y.H.M., El-Zeadani, M., Lee, Y.H., Lee, Y.Y., Murali, G., Feduik, R. (2020) Design innovation, efficiency and applications of structural insulated panels: A review. *Structures*, 27, 1358-1379. [Online] Available from: https://doi.org/10.1016/j.istruc.2020.07.044 [Accessed on 01.03.2022].

[2] Bai, L., Wang, H., Shi, C., Du, Q., Li. Y. (2017) Assessment of SIP buildings for sustainable development in rural China using AHP-grey correlation analysis. *International Journal of Environmental Research and Public Health*, 14(11). [Online] Available from: https://doi.org/10.3390/ijerph14111292 [Accessed on 01.03.2022].

[3] BDA Agreement BAE-19-124-P-A-UK. (2020) Kevothermal. Vacuum Insulation Panel (VIP).

[4] Boafo, F.E., Chen, Z., Li, C., Li, B., Xu, T. (2014) Structure of vacuum insulation panel in building system, *Energy and Buildings*, 85, 644-653. [Online] Available from: https://doi.org/10.1016/j.enbuild.2014.06.055 [Accessed on 04.03.2022].

[5] Broun, R., Babaizadeh, H., Zakersalehi, A., Menzies, G.F. (2014) Integrated life cycle energy and greenhouse gas analysis of exterior wall systems for residential buildings. *Sustainability*, 6(12), 8592-8603. [Online] Available from: https://doi.org/10.3390/su6128592 [Accessed on 04.03.2022].

[6] Brunner, S., Simmler, H. (2008) In situ performance assessment of vacuum insulation panels in a flat roof construction. *Vacuum*, 82(7), 700-707. [Online] Available from: https://doi.org/10.1016/j.vacuum.2007.10.016 [Accessed on 07.03.2022].

[7] Dhaif, M., Stephan, A. (2021) A life cycle cost analysis of structural insulated panels for residential buildings in a hot and arid climate. *Buildings*, 255, 11(6). [Online] Available from: https://doi.org/10.3390/buildings11060255 [Accessed on 07.03.2022].

[8] Du, Q., Jin, L., Lv J., Cai, C., Zhang, R. (2021) Experimental and numerical studies on the thermal performance of structural insulated panel splines. *Journal of Building Engineering*, 44. [Online] Available from: https://doi.org/10.1016/j.jobe.2021.103334 [Accessed on 07.03.2022].

[9] Ekrami, N., Kamel, R.S., Garat, A., Amirirad, A., Fung, A.S. (2015) Applications of active hollow core slabs and insulated concrete foam walls as thermal storage in cold climate residential buildings. *Energy Procedia*, 78, 459-464. [Online] Available from: https://doi.org/10.1016/j.egypro.2015.11.698 [Accessed on 08.03.2022].

[10] Geng, Y., Han, X., Zhang, H., Shi, L. (2021) Optimization and cost analysis of thickness of vacuum insulation panel for structural insulating panel buildings in cold climates, *Journal of Building Engineering*, 33. [Online] Available from: https://doi.org/10.1016/j.jobe.2020.101853 [Accessed on 10.03.2022].

[11] Gonçalves, M., Simões, N., Serra, C., Flores-Colen, I. (2020) A review of the challenges posed by the use of vacuum panels in external insulation finishing systems, *Applied Energy*, 257. [Online] Available from: https://doi.org/10.1016/j.apenergy.2019.114028 [Accessed on 10.03.2022].

[12] Harris, J., Durdyev, S., Tokbolat, S., Ismail, S., Kandymov, N., Mohandes, S.R. (2019) Understanding construction stakeholders' experience and attitudes toward use of the structurally insulated panels (SIPs) in New Zealand. *Sustainability*, 11(19). [Online] Available from: https://doi.org/10.3390/su11195458 [Accessed on 10.03.2022].

[13] JSC Šilputa (2021a) ICF NEO Thermo blocks installation instructions.

[14] JSC Šilputa (2021b) Catalog of building partitions and construction assemblies. ICF Thermo blocks and Thermo slab. An aid for architects, designers and builders.

[15] JSC Šilputa (2018) Calculation of heat transfer coefficient of linear thermal bridges. JSC Šilputa building insulation technology. Catalog.

[16] JSC Šilputa. (2021c) Catalog of ICF NEO Thermal block detailed drawings.

[17] Kalnæs, S.E., Jelle, B.P. (2014) Vacuum insulation panel products: A state-of-the-art review and future research pathways. *Applied Energy*, 116, 355-375, [Online] Available from: https://doi.org/10.1016/j.apenergy.2013.11.032 [Accessed on 14.03.2022].

[18] KEVOTHERMAL case study 022 (2015) Vacuum Insulation Panels in Construction. Internal Wall Insulation.

[19] Li, M., Lin, Z. (2021) Numerical study of the feasibility of coupling vacuum isolation panels with phase change material for enhanced energy-efficient buildings. *Energy and Buildings*, 251(15). [Online] Available from: https://doi.org/10.1016/j.enbuild.2021.111369 [Accessed on 14.03.2022].

[20] Li, Y., Zhao, Y., Chi, Y., Hong, Y., Yin, J. (2021) Shape-morphing materials and structures for energy-efficient building envelopes. *Materials Today Energy*, 22. [Online] Available from: https://doi.org/10.1016/j.mtener.2021.100874 [Accessed on 14.03.2022].

[21] Murillo, A.M., Abisambra, G.V., Acosta, P.A., Quesada, Q.C., Tutikian, B.F.,Ehrenbring, H.Z. (2021) Comparison of the fire resistance behaviour of structural insulated panels with expanded polystyrene core treated with intumescent coating, *Journal of Materials Research and Technology*, 12, 1958-1969. [Online] Available from: https://doi.org/10.1016/j.jmrt.2021.03.079 [Accessed on 14.03.2022].

[22] Panjehpour, M., Ali, A.A.A., Voo, Y.L. (2013) Structural insulated panels: past, present, and future. *Journal of Engineering, Project, and Production Management*, 3(1), 2-8.

[23] Purasinghe, R., Dusicka, P., Garth, J.S., Dedek, G., Lum, H. (2018) In-plane cyclic behavior of structural insulated panel wood walls including slit steel connectors. *Engineering Structures*, 174. [Online] Available from: https://doi.org/10.1016/j.engstruct.2018.07.027 [Accessed on 14.03.2022].

[24] Rajagopalan, N., Bilec, M.M., Landis, A.E. (2010) Residential life cycle assessment modeling: comparative case study of insulating concrete forms and traditional building materials. *Journal of Green Building*, 5(3), 95-106. [Online] Available from: https://doi.org/10.3992/jgb.5.3.95 [Accessed on 16.03.2022].

[25] Solomon, A., Hemalatha, G. (2020) Characteristics of expanded polystyrene (EPS) and its impact on mechanical and thermal performance of insulated concrete form (ICF) system. *Structures*, 23, 204-213. [Online] Available from: https://doi.org/10.1016/j.istruc.2019.10.019 [Accessed on 16.03.2022].

[26] Thongcharoen, N., Khongtong, S., Srivaro, S., Wisadsatorn, S., Chub-uppakarn, T., Chaowana, P. (2021) Development of structural insulated panels made from wood-composite boards and natural rubber foam. *Polymers*, 13(15). [Online] Available from: https://doi.org/10.3390/polym13152497 [Accessed on 16.03.2022].

[27] Uriarte, A., Garai, I., Ferdinando, A., Erkoreka, A., Nicolas, O., Barreiro, E. (2019) Vacuum insulation panels in construction solutions for energy efficient retrofitting of buildings. Two case studies in Spain and Sweden. *Energy and Buildings*, 197, 131-139. [Online] Available from: https://doi.org/10.1016/j.enbuild.2019.05.039 [Accessed on 04.04.2022].

[28] VanderWerf, P.A., White, J.G.A. (1998) Choosing an insulating concrete form system. *Concrete construction*, 1-4.

[29] Verma, S.K., Anand, Y., Gupta, N., Jindal, B.B., Tyagi, V.V., Anand, S. (2022) Hygrothermal dynamics for developing energy-efficient buildings: Building materials and ventilation system considerations. *Energy and Buildings*, 260(1). [Online] Available from: https://doi.org/10.1016/j.enbuild.2022.111932 [Accessed on 01.04.2022].

[30] WEB–1: Wikimedia Commons. (2022) [Online] Available from: https://commons.wikimedia.org/wiki/File:%D0%9F%D0%B5%D0%BD%D0%BE%D0%BF%D0%BB%D0%B0%D1%81%D1%82.jpg [Accessed on 10.03.2022].

[31] WEB–2: SIPs Technical Bulletin. Structural Timber Association. Building Solution in Timber. (2014) [Online] Available from: https://www.thesipcompany.com/assets/downloads/sta-sips-technical-bulletins-1-structure.pdf [Accessed on 01.03.2022].

[32] WEB–3: ApaCAD.org. (2022) [Online] Available from: https://www.apacad.org/cad-details?f=Structural+Insulated+Panels [Accessed on 10.03.2022].

[33] WEB–4: Tikri namai. (2022) [Online] Available from: http://tikrinamai.lt/sipnamai/technines-charakteristikos/ [Accessed on 10.03.2022].

[34] WEB–5: PCA Americas Cement Manufacturers. (2022) [Online] Available from: https://www.cement.org/cement-concrete/paving/buildings-structures/concrete-homes/building-systems-for-every-need/insulating-concrete-forms-(ICFs) [Accessed on 14.03.2022].

[35] WEB–6: Continuing Education. (2021) [Online] Available from: https://continuingeducation.bnpmedia.com/pdf/courses/L850C2653.pdf [Accessed on 01.04.2022].

[36] WEB–7: Nearby Engineers. Improving Efficiency with Insulated Concrete Forms. Author: Nick Natsoulis (2021) [Online] Available from: https://www.ny-engineers.com/blog/improving-efficiency-with-insulated-concrete-forms [Accessed on 01.04.2022].

[37] WEB–8: Pro Crew Schedule. Increasing Energy Efficiency with Insulated Concrete Forms (ICFs) [Online] Available from: https://www.procrewschedule.com/increasing-energy-efficiency-with-insulated-concrete-forms-icfs/ [Accessed on 01.04.2022].

[38] WEB–9: Moderni izoliacija. (2022) [Online] Available from: https://izoliacija.com/produktas/vip-izoliacija/ [Accessed on 04.04.2022].

LIST OF TABLES

LIST OF FIGURES