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Highly advanced modular integration of insulation, energising and storage systems for non-residential buildings

D2.1 FRAMEWORK ON ENERGY EFFICIENT BUILDINGS

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1. Executive summary

Deliverable D2.1 “Framework on energy efficient buildings” presents a framework for various retrofit situations in Europe, reviewing the situation in terms of building stock characteristics and codes for non-residential and residential buildings. Project POWERSKIN+ deals with non-loadbearing curtain walls, which is a domain of non-residential buildings in particular. Use in residential buildings is very limited in Europe, but it may become the preferred rational solution for building envelopes. The deliverable includes building characteristics, building codes and other regulatory measures, preliminary simulation analysis of potential energy savings in the case of POWERSKIN+ application, and an overview of different energy-saving concepts and solutions used in energy efficient building façade systems. The collected data allow determining the strategies for improving the energy and greenhouse gas savings potential of the future POWERSKIN+ solution and model a variety of scenarios of its operational performance on various climate/building solutions. The framework is derived for building retrofit situations. Scenarios for new construction have also been investigated, and in specific aspects of this report are stated separately. Generally, the approaches for retrofits are applicable for new construction as well.

2. Introduction

Energy consumption is growing steadily and exponentially, and according to the 2018 forecast, world energy consumption can be expected to increase by up to 25% between 2018 and 2040. Therefore, energy will become an increasingly desirable and expensive commodity in the coming years. A forecast predicting a reduction in absolute energy consumption is completely unrealistic, which is a proven historical experience [1].

In the EU, the building stock accounts for about 40% of all primary energy use and approximately 36% of CO_2 emissions [2], [3]. It makes buildings the largest and, consequently, the key energy consumer in Europe. Therefore, reducing primary energy consumption in buildings is the main goal of European policies to achieve a sustainable and low greenhouse gas emission economy. To fulfil this goal, the EU commission presented the Directive on the Energy Performance of Buildings (EPBD) in 2002 [4]. In 2010, the EPBD was rearranged and the second version of the EPBD2 [2] was introduced with the 20-20-20 slogan, expressing the European Community's goal of reducing greenhouse gas emissions by 20% in 2020 compared to 1990, reducing the EU energy consumption by 20% and increasing the share of energy produced from renewable sources to 20%.

Moreover, among other things, EPBD2 introduces the concept of nearly zero energy building (nZEB). To be more precise, Article 9 states that all new buildings occupied by public authorities should be constructed in the nZEB building standard from 01.01.2019. For private buildings, the requirement to build new buildings in nZEB standard is postponed for 2 years and starts to act from 01.01.2021. Interestingly, the EPBD2 did not introduce a clear definition of nZEB buildings and, as a result, each European Union state developed its own definition. This, in some cases, causes inconsistencies between the policies of individual countries. For example, the German nZEB does not meet the requirements of the Czech nZEB.

Later, in 2018, the third version of EPBD (EPBD3) was published [3]. It presented a long-term strategy which should bring a significant reduction in greenhouse gas emissions of 40% by 2030 compared to 1990, increase the use of energy from renewable sources with an overall reduction in building energy consumption of up to 32.5% and increase the share of renewable energy use to 32%.

After that, at the end of 2019, The European Commission has presented the European Green Deal, which includes a list of concrete plans to achieve climate neutrality in the EU by 2050. In March 2020, the European Commission adopted a European industrial strategy with a greater ambition to reduce greenhouse gas emissions by 2030, from the original 40% to 55%. The basic precondition for achieving this goal is the decarbonisation of the energy system based on several principles. One of the main principles is to ensure higher energy efficiency of buildings.

Thus, it is clear that special attention is paid to buildings due to the high energy-saving potential caused exactly by the high energy consumption of the building sector at present.

3. Building stock

3.1 Residential buildings share

Today, the residential building stock accounts for 75% of the EU floor space area [5] and represents the biggest segment in the total EU floor space area (Figure 1). However, it should be noted that the share for each country varies considerably from around 86% for Italy and Romania to approximately 66% for Finland and Germany. There are two main groups of buildings within the residential scope, namely single-family houses (SFH) and apartment blocks (AB). The difference between them is that SFH normally accommodates one household, while AB may accommodate two to thirty households. For instance and in some cases, social housing or high residential buildings, AB can have more than thirty households within one apartment block.

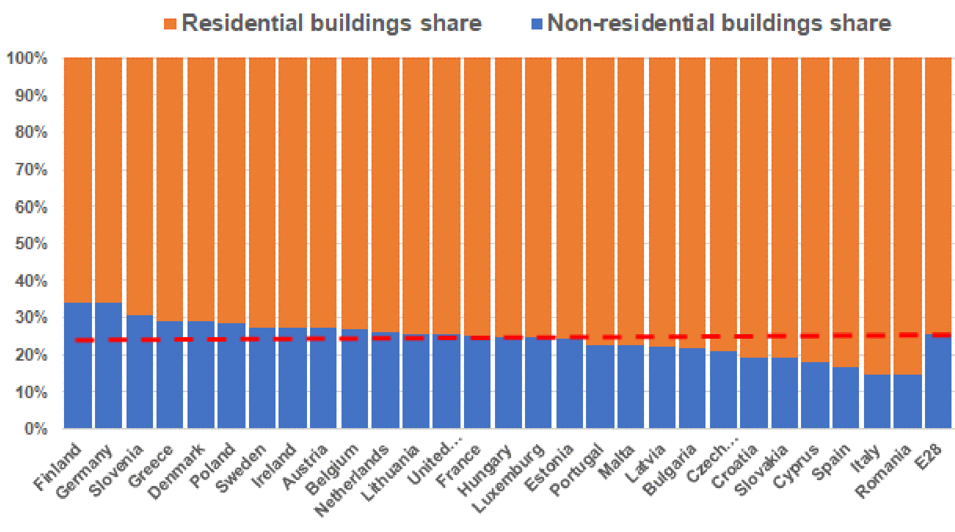


FIGURE 1 SPLIT BETWEEN RESIDENTIAL AND NON-RESIDENTIAL BUILDINGS IN EUROPE. DATA SOURCE: [5]

Using the collected data [5], 51% of residential building stock area is associated with SFH and 49% with AB (Figure 2). Needless to say, the split between SFH and AB varies from country to country. There are countries with approximately the same share between SFH and AB, for instance, Bulgaria, Czech Republic, Slovakia. On the other hand, there are counties with a clearly defined dominated group. In such countries as Cyprus, Netherlands, and the UK, most residential buildings are represented by SFH, while in such countries as Belgium, Italy, and Latvia, the situation is reversed, and most of the residential buildings are represented by AB.

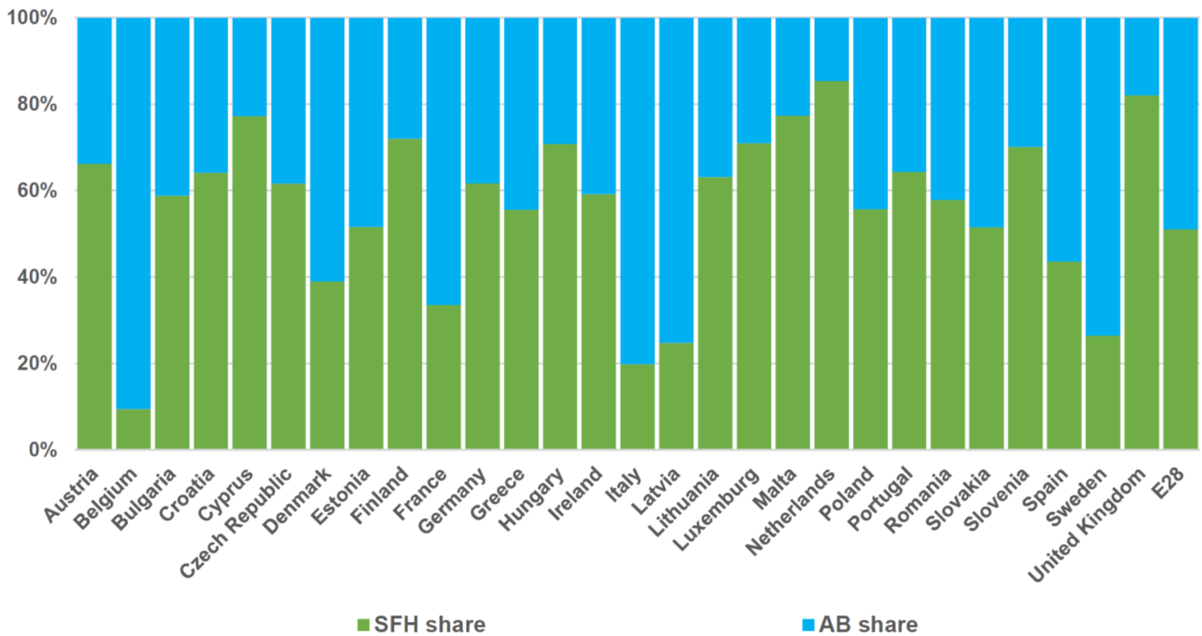


FIGURE 2 SPLIT BETWEEN SFH AND AB WITHIN RESIDENTIAL BUILDINGS IN EUROPE. DATA SOURCE: [5]

3.2 Non-residential buildings share

On the other hand, the non-residential buildings sector accounts for approximately 25% [5] of the total building stock in Europe (Figure 3). Compared to the residential building stock, the main distinctive feature of the non-residential building stock is that it is a more complex and heterogeneous building sector with high diversity in terms of typology. It includes trade facilities, offices, educational facilities, hotels and restaurants, health facilities, and other buildings. Figure 3 presents the share of different non-residential building groups for European countries (based on the floor space area).

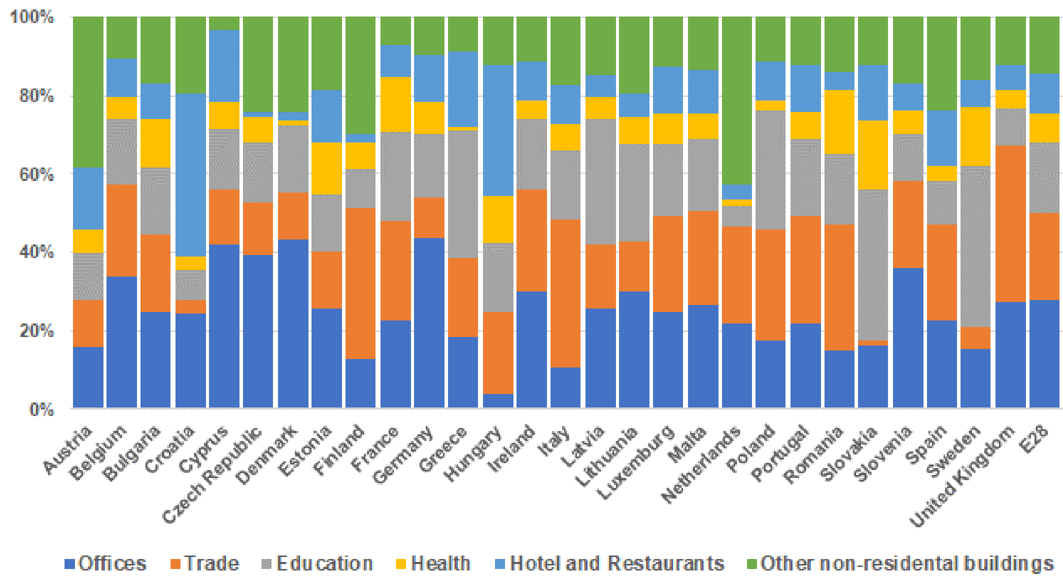


FIGURE 3 BREAKDOWN OF NON-RESIDENTIAL FLOOR SPACE IN EUROPE. DATA SOURCE: [5]

First of all, it is clear that office buildings comprise the largest portion of the non-residential building stock at the European level, corresponding to approximately 28% of the total non-residential floor space. The trade facilities are the second biggest category with a floor space corresponding to 22% of the total non-residential floor space. Educational facilities account for less than 18% of the entire non-residential floor space area. Hotels and restaurants are represented by the next 10% of the total non-residential floor space area, while health facilities account for 8%. The other non-residential buildings are represented by 14% of the total non-residential floor space.

Secondly, it is evident that the distribution of different non-residential building types varies across Europe and many countries reported a large component in the category of other non-residential buildings. It indicates that the categorisation system for non-residential buildings varies significantly from country to country.

In addition to the categorisation system introduced by different European countries, there is also a difference between non-residential building categorization systems presented by different European institutions.

According to the definition presented by the Organization for Economic Cooperation and Development (OECD) [6], a building is regarded as a non-residential building when the minor part of the building (i.e. less than half of its gross floor area) is used for dwelling purposes. Furthermore, OECD states that non-residential buildings comprise: industrial buildings, commercial buildings, education buildings, health buildings, and other buildings.

Eurostat [7], on the other side, presents another definition of non-residential buildings. According to their definition, a non-residential building is a construction that is mainly used or intended for non-residential purposes. To be more specific, Eurostat non-residential building categorization system is as follows: private offices, public offices, wholesale and retail trade, hotels and restaurants, health facilities, education facilities, sports facilities, and other facilities.

According to Ecofys [8], non-residential buildings can be categorised as follows: private offices, trade facilities, gastronomic facilities, health facilities, educational facilities, industrial facilities, public buildings, and other buildings.

Needless to say, that compared to residential buildings where the data are fairly comprehensive, the non-residential buildings stock is far less covered. The main reason is that within the non-residential building sector, there is no clear and unified sector categorization system.

3.3 Building age profile

Buildings across Europe are associated with different time periods [5]. It can be seen from Figure 4 that the historical buildings (typically represented by buildings built up to 1945) and buildings built in the period from 1945 till 1969 demonstrated the highest share in both sectors. It is probably because this period covers more years than over the analysed periods. From 1970 until 2010, the share of different periods is relatively stable and accounts for approximately 12.5% for the residential sector and 12.9% for the non-residential one. It is also evident that the share of buildings built in the last 10 years is the smallest. Two facts can describe it. First of all, the 2007-2009 financial crisis heavily affected the building construction industry. Secondly, the data for this period is incomplete and would be revised in the next few years.

FIGURE 4 AGE PROFILE OF THE BUILDING STOCK IN EUROPE. DATA SOURCE:[5]

It can be concluded that there is not much difference between residential and non-residential buildings stock in terms of buildings age profile.

3.4 Residential energy consumption

According to [9], in 2018 the residential sector was responsible for 26% of the total final energy consumption in Europe or 65% of the total final energy use in buildings. Energy in the residential sector is mainly consumed by space heating - 63.6% of the final energy consumption in the residential sector [10]. Water heating represents 14.8%, while the proportion used for electricity for lighting and electrical appliances is slightly lower, representing 14.1% (Figure 5). Energy for cooking purposes accounts for 6.1%, while space cooling and other end-uses account for 0.4% and 1.0%, respectively.

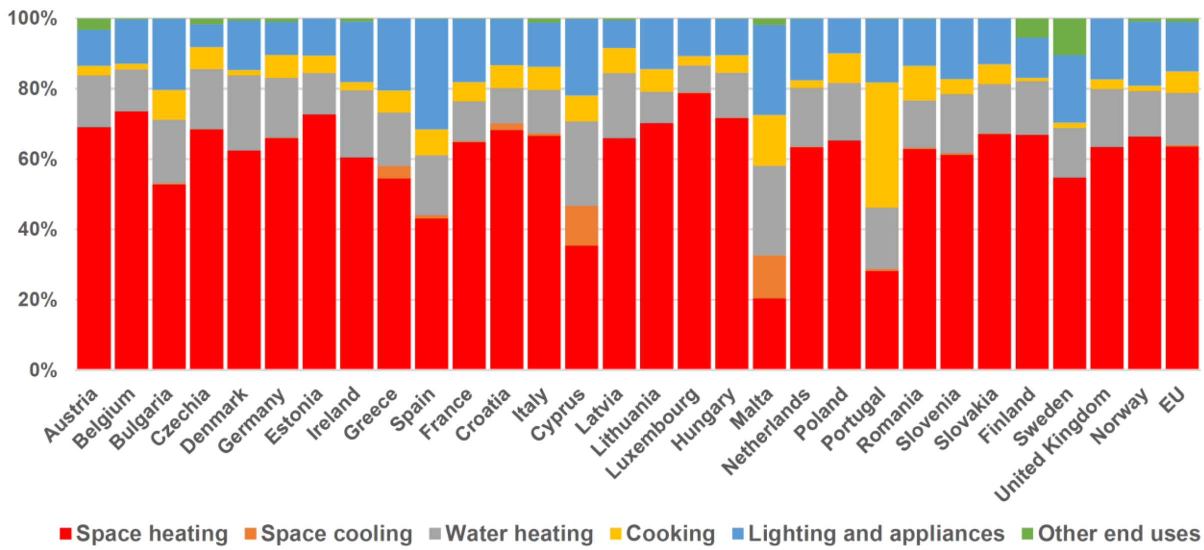


FIGURE 5 SHARE OF FINAL ENERGY CONSUMPTION IN THE RESIDENTIAL SECTOR BY TYPE OF END-USE. DATA SOURCE: [10]

It is clear from Figure 5 that space heating is the most energy-intense end-use in the vast majority of EU countries. It is also clear that this share is less in warmer climates and higher in cold climates. The lowest proportions of energy used for space heating are in Malta (20.4%), Portugal (28.2%), Cyprus (35%), and Spain (43.1%), while the highest is in Luxemburg (78.7%), Belgium (73.5%), Estonia (72.7%), and Lithuania (70.3%).

The final energy consumption used to cover the space heating demand depends on several factors such as the performance of the installed heating system, type of the building envelope, local climatic conditions, and behavioural characteristics. Despite different improvements in heating systems and behavioural characteristics, there is still a large savings potential associated with an improvement in the thermal quality of the building envelope.

As shown in Figure 4, a large share of residential buildings (approximately 39%) are built before 1970, in times with much less strict energy requirements for buildings and building components seen from today's perspective. Only a part of these buildings has undergone major energy retrofits. There is still a large group of buildings, in different fractions among countries, with low insulation levels and inefficient technical systems [11]. Therefore, the oldest part of the building stock contributes greatly to the high energy consumption in the building sector. Older buildings tend to consume more due to their low-performance levels.

Figure 6 shows the data on space heating consumption by the age of buildings for selected countries. First of all, based on this data, it is clear that the largest energy-saving potential is associated with the older building stock. These buildings' poor thermal performance is associated with the absence of appropriate insulation due to the lack of building performance standards (insulation levels) in the respective construction years.

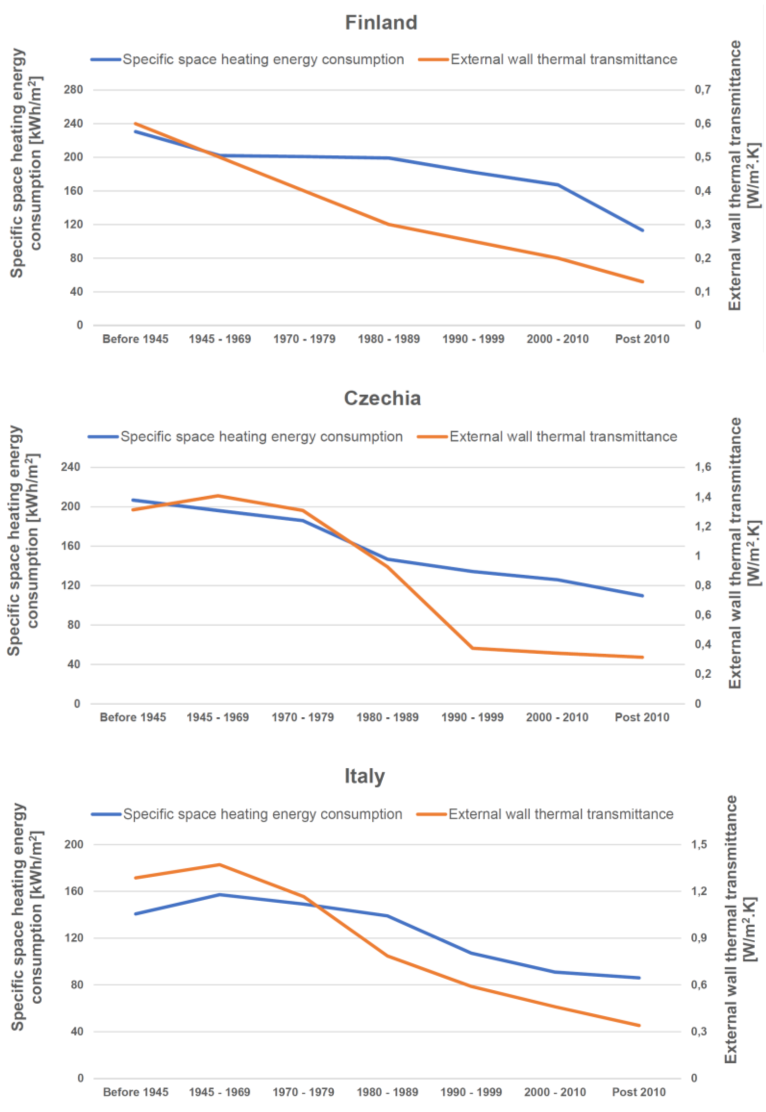


FIGURE 6 AVERAGE SPECIFIC ENERGY CONSUMPTION FOR SPACE HEATING IN TERMS OF FINAL ENERGY USE AND U-VALUE FOR EXTERNAL WALLS VALID IN THE YEAR OF CONSTRUCTION. DATA SOURCE: [5]

Secondly, it is clear that the thermal transmittance (U-value) of the building envelope construction has a significant impact on the building energy performance. Moreover, it is also evident that the implementation of national standards and requirements concerning the energy performance of buildings contribute significantly to an increase in building energy performance.

Finally, although space heating needs in Southern countries (for instance, Italy) are lower due to milder winters, the consumption for space heating is comparable to other countries presented here. This can be an indication of a lack of sufficient thermal insulation in building stock in these countries.

3.5 Non-residential buildings energy consumption

In 2018, the non-residential sector was responsible for 14% of the total final energy consumption in Europe or 32% of the total final energy use in buildings. The average specific energy consumption in the non-residential sector is almost 280 kWh/m^2, while the average specific energy consumption in the residential sector is close to 200 kWh/m^2 (approximately 32% less compared to the equivalent value for the non-residential sector).

Based on BPIE (Buildings Performance Institute Europe) survey results [11], offices and trade facilities represent more than half of the total non-residential energy use in Europe (Figure 7). On the other hand, health facilities and hotels and restaurants with high specific energy consumption are associated with 22% of total non-residential energy use. Educational facilities represent the next 12% of energy use while other buildings account for 12%.

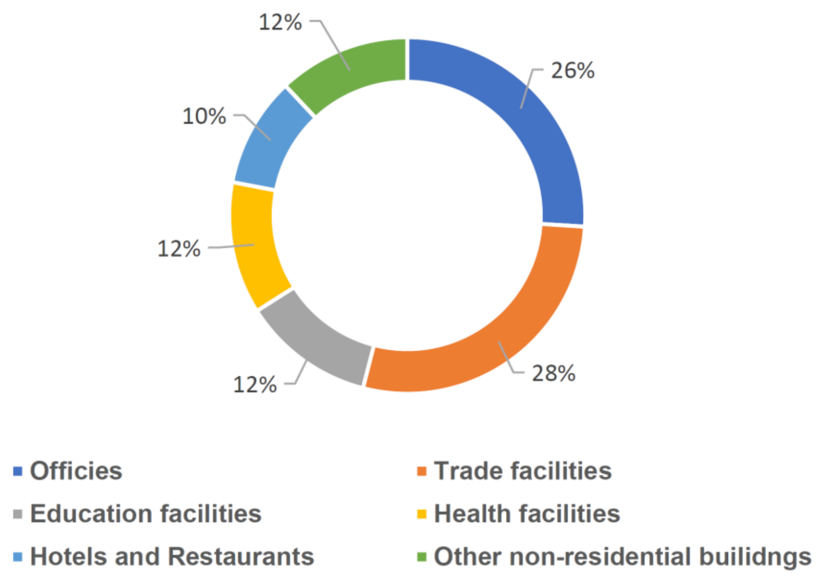


FIGURE 7. FINAL ENERGY USE IN NON-RESIDENTIAL BUILDINGS FOR DIFFERENT BUILDING TYPES. DATA SOURCE: [11]

Needless to say that within the non-residential sector, different specific energy consumption values are expected from country to country and from one building type to another. These variations are clearly illustrated in Figure 8, where the specific energy use is compared for the United Kingdom (UK) and Spain.

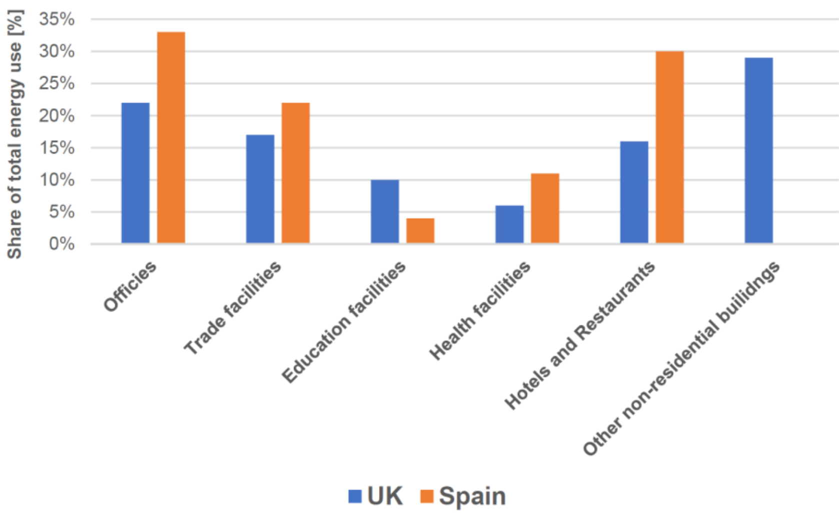


FIGURE 8 FINAL ENERGY USE IN NON-RESIDENTIAL BUILDING TYPES FOR TWO DIFFERENT COUNTRIES. DATA SOURCE: [12]

Understanding non-residential buildings energy consumption is very complex, and to properly analyse it, some main constituents should be introduced. Non-residential building energy consumption is mainly related to space heating, space cooling, water heating, cooking, lighting, and other appliances (Figure 9).

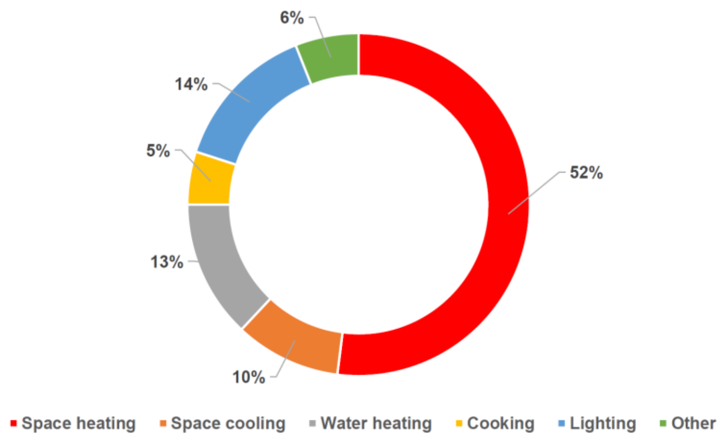


FIGURE 9 AVERAGE SHARE OF FINAL ENERGY CONSUMPTION IN THE NON-RESIDENTIAL SECTOR BY TYPE OF END-USE. DATA SOURCE: [13]

Energy in non-residential buildings is mainly consumed by space heating, as well as in residential buildings. It makes up to 52% of the total non-residential buildings' energy consumption, way ahead of space cooling, lighting, water heating, cooking, and other end-uses. High energy consumption for space heating is partly due to the fact that 75% of the EU's building stock is still energy inefficient (compared to current regulations on the energy performance of buildings), and the rate of building renovation remains very low at around 0.4% to 1.2% per year.

It is evident that the age of the building has a great influence on the building energy performance. Figure 10 visualizes the specific heat energy consumption for space heating for the non-residential buildings sector by the age of construction. It can be seen from the figure that the specific space heating consumption for non-residential buildings decreases from the value of 168 kWh/m^2 for buildings built before 1945 to approximately 95 kWh/m^2 for new buildings [5]. The slight deviations from the trend can be described by the main feature of the non-residential building stock. The non-residential building stock is inhomogeneous. It includes different types of buildings such as trade facilities, offices, educational facilities, etc. Thus, the decrease in space heating consumption in one building sector can be accompanied by an increase in another building sector.

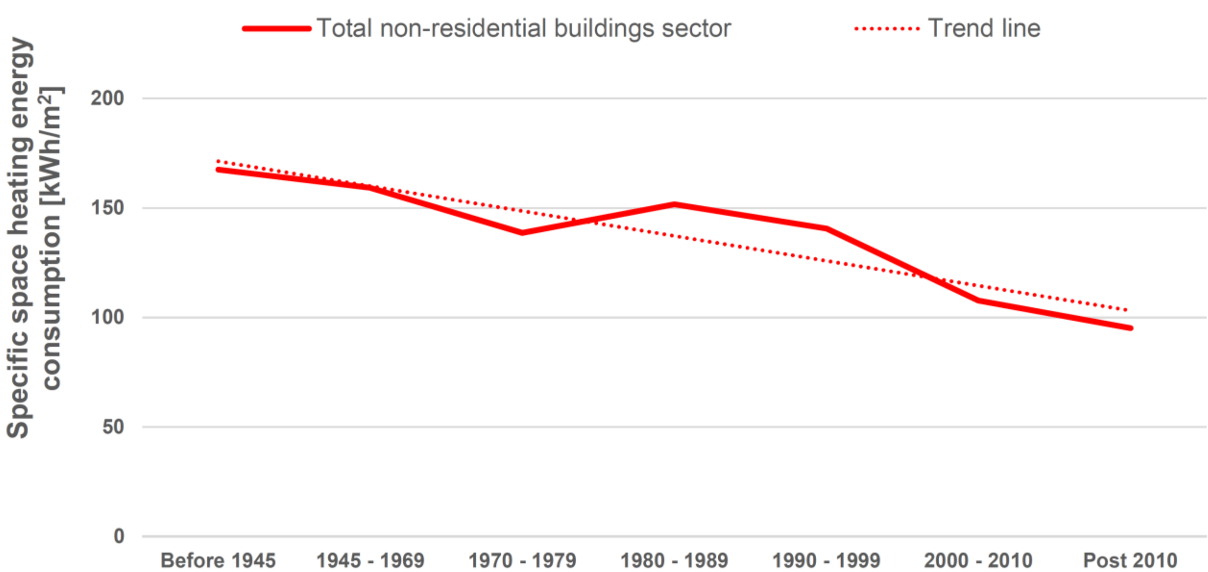


FIGURE 10 DEVELOPMENT OF THE SPECIFIC ENERGY CONSUMPTION FOR SPACE HEATING IN THE NON-RESIDENTIAL BUILDINGS SECTOR. DATA SOURCE [5]

Needless to say that the older part of the non-residential building stock (as well as residential building stock) have higher energy consumption because when they were built, only few or no requirements for energy efficiency existed. Hence, the largest energy-saving potential is associated with the older building stock and its renovation.

As for today, the specific energy consumption for space heating is approximately twice as low for the non-residential sector today as for non-residential buildings built before 1945 [5]. It is clear that the main reason for this decline in specific energy consumption for space heating is the implementation of energy performance requirements. In Sweden, the national requirements for energy performance of buildings were firstly presented as early as 1948. Northern, Western, and Central European countries started introducing or significantly tightened the energy performance building requirements (thermal insulation requirements, air tightness level) around the 1970s after the first oil crisis. Southern countries with no previous embedded regulations for insulation (for instance, Portugal) introduced a 50% reduction in the U-values in 2005 [11].

Figure 11 presents the development of specific energy consumption for space cooling. It indicates a relatively small increase in the specific energy consumption for space cooling during the last 70 years. There are several reasons why specific energy consumption for space cooling increased. The first and probably the main reason is that modern architect's design buildings with larger glazing areas. The second reason is the increased comfort standards of the European population.

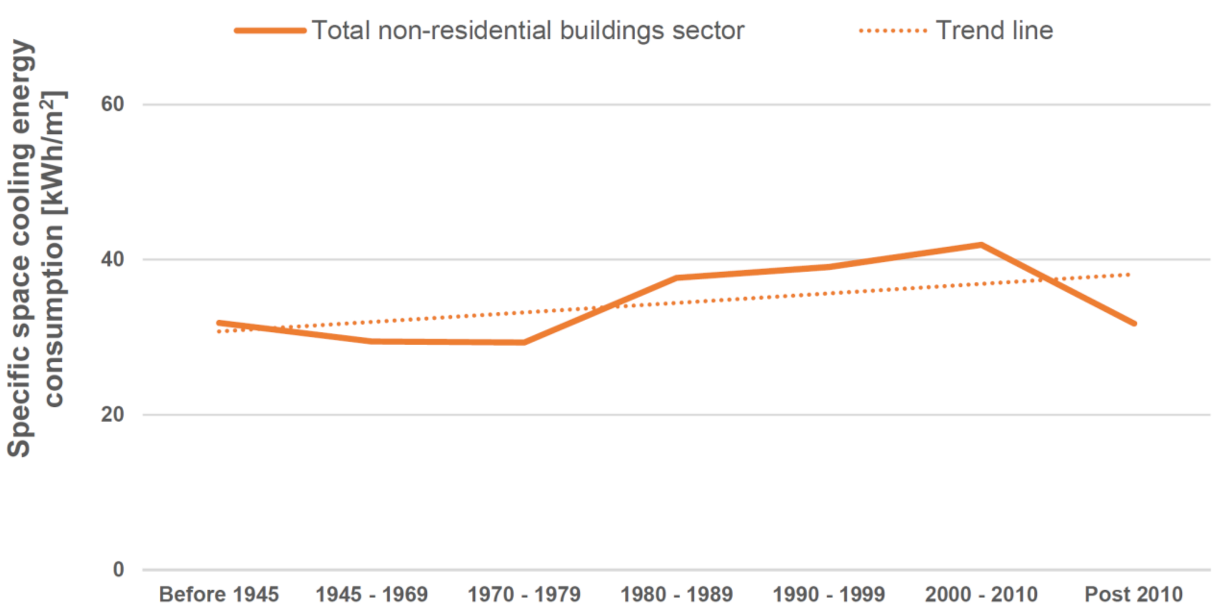


FIGURE 11 DEVELOPMENT OF THE SPECIFIC ENERGY CONSUMPTION FOR SPACE COOLING IN THE NON-RESIDENTIAL BUILDINGS SECTOR. DATA SOURCE: [5]

Although the non-residential building sector has higher specific energy consumption than the residential building sector, comprehensive information and detailed data on the non-residential building sector are still limited in Europe. In general, the data collection process is a time-consuming procedure. In the particular case of non-residential building stock with numerous building categories, the variability of services, and technical information, this process becomes even more complicated and more time-consuming. This fact probably indicates that extensive and detailed data gathering should be provided in this field in the future.

4. Energy efficient building façade systems

The EPBD requires all new buildings in Europe from 2021 to be nearly zero-energy buildings. According to the European Commission definition, "nearly zero-energy building" is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby [2]. The main impact on the overall energy consumption of the building has the building façade. Based on the previous nZEB building's definition, it is evident that two different approaches should be implemented simultaneously for a building façade to achieve nZEB building. First, the façade of the building should be designed to reduce building energy consumption as much as possible (passive energy-saving concept). Second, renewable energy sources should be applied in the façade construction to cover the building energy consumption (active renewable energy generation concept).

4.1 Passive energy saving concept

The first concept is a passive energy-saving concept. It includes three main parts: advanced building envelope, passive heating and cooling technologies, and thermal energy storage.

4.1.1 Advanced building envelope

Building façade plays a crucial role in reducing building energy losses since it separates outdoor and indoor environments. Façade factors related to building energy performance are thermal transmittance U-value, solar heat gain coefficient g-value, and air tightness n_{50}. The improvement of the building façade moves in two ways. The first is the reduction in thermal transmittance, which leads to the reduction in energy losses, especially in a cold climate. It is a simple and effective approach to increase the energy efficiency of the building. The second is to control solar heat gain during the year. The problem is that solar radiation influences energy consumption in different ways in different seasons. In summer, excessive solar heat gain results in higher energy consumption due to the increased cooling load; in winter, solar radiation entering through the transparent parts of the façade can provide passive solar heating; in all seasons of the year the solar radiation improves the daylight quality. Therefore, well-designed solar control devices can significantly reduce the energy consumption of buildings and enhance natural daylight utilization in the indoor environment.

In general, the building façade consists of two parts: a transparent part and an opaque part. The transparent part is responsible for visual comfort (day-lighting and visual contact with the outdoor environment), but usually has a higher U-value than the opaque one. To minimize heat loss through the transparent part, glazing materials with low U-values should be used, for instance, vacuum glazing [14], triple glazing [15] or low-emissivity glazing or coating [16].

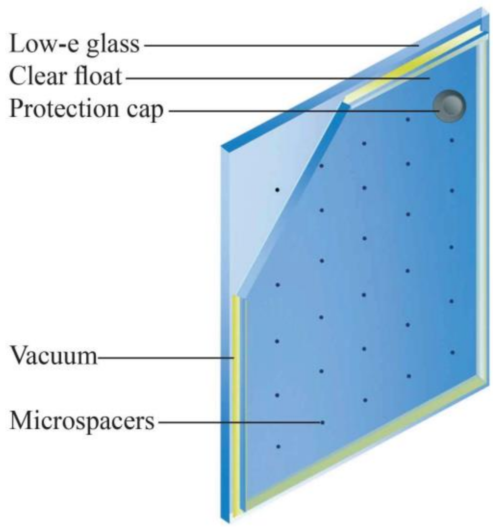


FIGURE 12 VACUUM INSULATION GLAZING - PILKINGTON SPACIA™. IMAGE SOURCE: [17]

On the other hand, the transparent part greatly impacts solar heat gain, which should be managed effectively while visual discomfort and glare are minimized. Many different principles to control the solar heat gain exist and could be successfully used to control solar radiation, from static devices such as overhangs and louvres, automated blinds [18] to static angular selective prismatic glazings [19], films and coating [20] and electrochromic glazing [21].

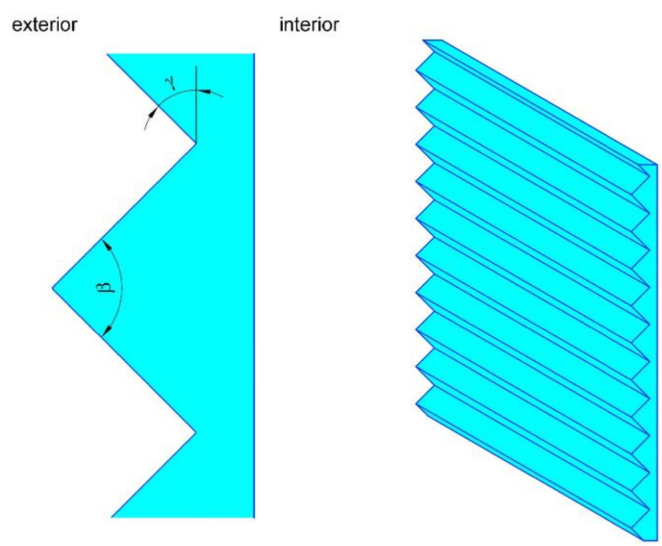


FIGURE 13 GEOMETRY OF STATIC ANGULAR SELECTIVE PRISMATIC GLAZING. IMAGE SOURCE: [19]

The U-value of the opaque part of the façade is also an important factor. It is evident that the focus here is and still will be to achieve the highest physically possible thermal insulation values, that is, the lowest thermal conductivity parameters for the insulation materials. Today, conventional thermal insulation materials like fiberglass, mineral wool, expanded polystyrene, and extruded polystyrene have thermal conductivity values from 0.033 to 0.040 W/m.K. Relatively new and high-tech insulation materials such as vacuum insulation panels [22], gas-filled panels [23], aerogels [24], nano insulation [25], etc., have thermal conductivities approximately between 5 and 10 times (depending on the ageing) lower than traditional thermal insulation materials. This reduction in thermal conductivity is essential to achieve energy-efficient buildings, passive houses, and zero energy or zero-emission buildings.

As a result, the reduction in thermal transmittance and solar heat gain control are considered a relatively simple and highly efficient way that can be applied to façade construction element to increase building energy efficiency. It allows to keep more heat/cool within the building and prevent heat flux with the surroundings.

4.1.2 Passive heating and cooling concepts

As we know (Figure 9), the largest contributor to non-residential building energy consumption is space heating energy consumption. Considering this, passive heating and cooling concepts could be introduced to reduce building energy consumption. Actually, it is one of the oldest ways to reduce heating and cooling consumption. Moreover, these systems could represent suitable alternatives to conventional heating and cooling system for modern and effective buildings. However, it should be noted that the efficiency of these systems depends on site climatic conditions, season and daytime.

A typical example of a passive heating concept is the Trombe wall, a massive wall (sometimes covered by high absorption coating or paint) covered by external glazing with an air-channel between them [26]. The massive wall absorbs and accumulates solar energy. Then, one part of the accumulated energy is transferred to the indoor environment by conduction through the wall. The second part of the accumulated energy is transferred to the building’s indoor environment by the stack (chimney) effect emerging within the air channel between the wall and glazing. The lower temperature air enters the air channel through a hole situated in the lower part of the wall, heated up by the wall, flows upward, and then heated air returns to the room through the hole situated in the higher part of the wall.

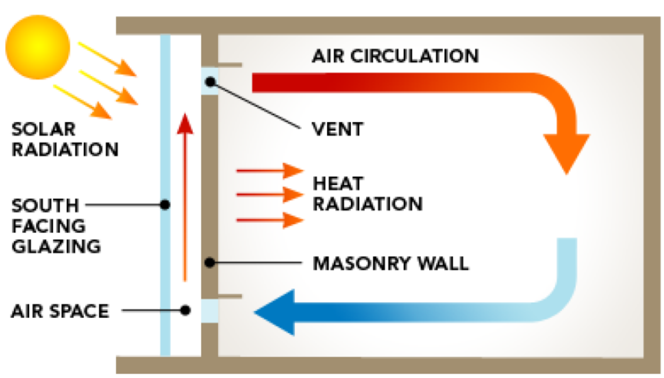


FIGURE 14 TROMBE WALL OPERATION PRINCIPLE. IMAGE SOURCE: [27]

Double skin façade concept is probably one of the most advanced passive heating concepts. It allows using solar energy to provide heat energy and prevent energy losses. In essence, there are three different operation modes of double skin façade [28]. In the first operation mode - open natural convection - air is circulated in the middle cavity because of the stack (chimney) effect. The entrance of air is located in the lower part of the outer skin. The exit, in contrast, is located in the upper part of the outer skin. This mode creates a sufficient thermal resistance between outdoor and indoor environments and the heated air can be used by openings in the middle or upper part for ventilation or space heating purposes. The second operation mode is the closed natural convection mode. In that case, air circulates in the closed gap between the inner and outer parts of the façade caused by natural convection. In that mode, double skin façade reduce to the minimum heat transfer between outdoor and indoor environment. The third operation mode is the forced convection mode. In this mode, the system uses the middle gap to preheat the outdoor air and send it to the room space through the HVAC system.

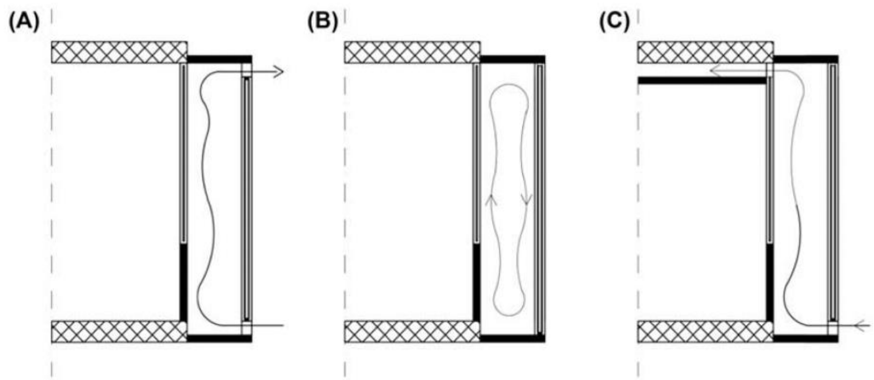


FIGURE 15 DIFFERENT TYPES OF DOUBLE-SKIN FAÇADE ACCORDING TO THE TYPE OF AIRFLOW: (A) OPEN NATURAL CONVECTION, (B) CLOSED NATURAL CONVECTION, (C) FORCED CONVECTION. IMAGE SOURCE: [28]

The next example of a passive concept is a solar chimney. Solar chimneys are generally used to provide natural ventilation, but can also be used for the heating of outdoor air [29]. A solar chimney may be considered as a special case of the Trombe Wall concept because its working principle is very similar. Solar radiation is passed through the glazing, absorbed on the absorber surface, and heated the air in the channel between the absorber and glazing. This causes a stack (chimney) effect and draws the air from below. The difference is that a Trombe wall is a part of a massive external wall normally taken up by glazing, whereas a solar chimney is more general and can be represented by a metal absorber with low mass. Moreover, Trombe Wall is designed mainly for passive heating purposes, while a solar chimney is used mainly for passive ventilation purposes.

In moderate and cold climates, with relatively low night-temperatures in summer, passive night-cooling of buildings by ventilation can be used as a passive technology. The basic concept is relatively simple and includes cooling the building structure during the night to provide a heat sink during the day. This way, it is possible to decrease daytime cooling energy requirements and sometimes cover the whole daytime energy one [30].

4.1.3 Thermal energy storage

One of the most important factors that can increase the efficiency of passive heating and cooling technologies is the design of heat storage. Latent heat storage systems using phase change materials (PCM) can be used as an effective way of storing thermal energy in the façade construction. These materials (PCM) can be successfully combined with, for instance, the Trombe Wall [31]. Typically, Trombe Walls accumulates sensible heat in the massive wall. The application of PCM materials allows to store energy in the latent heat and consequently, for a given amount of heat energy, the wall with PCM material will require less space and will be lighter compared to the original massive wall.

Thermal energy storage technology (such as PCM) can also be successfully combined with night-time cooling [32]. Typically, night-time cooling uses the thermal mass of the building to accumulate cooling energy. On the other hand, modern non-residential buildings (especially office buildings) widely use lightweight construction to increase the total number of building storeys. As a result, the specific thermal mass of the building rapidly decreases and decreases the efficiency of night-time cooling. In that case, the combination of phase change materials integrated into façade and night-time cooling will be a promising solution to decrease space cooling energy consumption.

Table 1 summarises the passive energy concepts used to design energy efficient buildings.

TABLE 1 SUMMARY OF THE REVIEWED PASSIVE ENERGY CONCEPTS

Category	Technology	Principle	Feature	Applicability
Advanced building envelope	Thermal transmittance	Lower U-values lead to a reduction in thermal gains/losses	Highly effective in cold climate	Transparent part: vacuum glazing; triple glazing; low-e glazing. Opaque part: vacuum insulation panel; gas-filled panel; aerogel; nano insulation
	Solar gain control	Control solar gains during the year and improve visual comfort	Highly effective in moderate and hot climates	Transparent part: static overhangs and louvres; textile screens; sun-tracking vertical and roller blinds; static angular selective prismatic glazings, films and coatings; electrochromic glazing
Passive heating and cooling	Trombe wall	Transform solar energy to heat energy for ventilation and space heating purposes	Highly effective in cold climate	Opaque part: Trombe wall
	Double skin façade	Provide additional thermal resistance to the façade and can be used for ventilation purposes	Highly effective in moderate climates	Whole façade

TABLE 1 (CONTINUED)

	Solar chimney	Provide natural ventilation for cooling purposes	Highly effective in moderate climates	Opaque part: solar chimney
	Passive cooling	Night-time cooling	Highly effective in moderate climates	Openings in transparent or opaque parts
Thermal energy storages	PCM materials	PCM materials allow storing more energy, accumulate and release energy when it is needed	Highly effective in combination with other passive/active technologies	Opaque part: integrated PCM materials

4.2 Active renewable energy generation concept

Even after applying various energy passive concepts presented above, there is still more or less energy required for building operation. Thus, this energy consumption could be covered by renewable energy sources to achieve nZEB building standards. As for today, renewable energy represents approximately 20% of the energy consumed in Europe. Moreover, the third version of EPBD (EPBD3) set the very ambitious aim to increase this share to 32% until 2030. The roof area of modern non-residential buildings (especially offices) is limited due to lift housings, ventilation and air conditioning facilities, etc. Therefore, the integration of renewable energy sources into façade construction could help to achieve this aim. The main renewable energy source which the building facade can use is solar energy.

The application of solar energy sources is typically focusing on building-integrated on-site solar power systems. These systems could be broadly specified as solar thermal systems (ST) and photovoltaic systems (PV). The first produces heat energy and the second produces electricity, while buildings need both of them.

Photovoltaic solar systems today are probably the most widely used technology applied to cover the final building energy consumption. It directly converts incident solar radiation into electrical energy by using the photoelectric effect. For modern photovoltaic systems, the efficiency of the conversation varies from 10% to 23%, depending on the type of PV panel and the climatic conditions on site [33]. Modern photovoltaic panels are available in different sizes, shapes, textures, and colours, providing their high acceptance by the public and architects [34]. There are also some technologies of semi-transparent photovoltaic cells that can be applied to the transparent part of façades.

FIGURE 16 SEMI-TRANSPARENT BUILDING INTEGRATED PHOTOVOLTAIC AT THE ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE. IMAGE SOURCE: [35]

On the other hand, solar radiation incidents on photovoltaic cells generate heat as well as electricity. As a result, the cells working temperature increases and the efficiency of energy conversation decreases. Thus, the combination of photovoltaic and solar thermal technologies in one device (PVT collector) is a promising solution to solve this technical issue. It allows producing electricity while removing and utilizing waste heat from the photovoltaic cells. As a result, the operation temperature of photovoltaic cells decreases and thus improves their performance. Moreover, PVT collectors provide an opportunity to increase the total energy production (electricity and heat energy) compared to separate systems installed in the same area [36].

FIGURE 17 PVT HYBRID COLLECTOR. IMAGE SOURCE: [37]

Moreover, the combination of PV panels (as a source of electrical energy) and Peltier cells could provide a promising solar cooling and heating technology. A thermoelectric effect (Peltier effect) causes heat transfer from one side to the other (creating a temperature difference), when a voltage is applied to Peltier cells. If the direction of the current is changed, the heat transfer direction changes too. Hence Peltier cells can be used as heat pumps. As a result, Thermoelectric Peltier systems can be used in summer for cooling purposes (transfer heat energy from interior to exterior) and in winter for heating purposes (transfer energy from exterior to interior. The heating or cooling power of such a heat pump depends on geometric dimensions, the number of the Peltier cells, as well as on the properties of the used materials. The greatest advantages of these systems are small dimensions, quiet and reliable operation, and minimum maintenance requirements. There are also two main disadvantages: the high price of Peltier cells and their low conversation efficiency. On the other hand, the interest in thermoelectric modules is constantly increasing in the last years and the latest research indicated the materials needed to increase the efficiency of Peltier cells.

The direct conversion of solar energy to heat is probably the oldest renewable energy technology used by humans. This is a highly efficient and time-proven technology of solar energy utilization. Flat plate liquid solar thermal collectors play a crucial role in Europe within solar thermal technologies applicable for building integration. Based on the latest report presented by Solar Heating and Cooling Program [38], their share in total installed capacity in operation in Europe is 81.3%. By the end of 2018, the main application of water solar collectors in Europe, based on installed water collector capacity, is the domestic hot water system for single-family houses with the share 63%, followed by large DHW systems and combi systems used for multifamily houses and commercial buildings with the share 30%. Compared with the cumulated installed capacity, the amount of newly installed large DHW systems and combi systems used for multifamily houses and commercial buildings reached 45% of the total newly installed capacity. This may indicate a shift in the application of solar thermal collectors from single-family houses to large applications used for multifamily houses and commercial buildings.

On the other hand, two main issues are related to integrating solar thermal collectors into façade elements. The first issue concerns the architectural integration of a solar water collector. To increase the architectural acceptance of flat plate liquid solar collectors, coloured absorbers [39] and coloured glazings were introduced [40]. It was found that 85% of architects would prefer solar collectors in other colours than black, despite the negative effect of "coloured" collectors on the system performance [41]. The second issue regarding integrating solar thermal systems into façade is the technical integration with the existing water heating system (solar tanks, pipes, pumps, etc.) and connection with other façade elements (solar collector jointing). Moreover, the hydraulic system of integrated solar collectors should be investigated to deal with water pressure differences at different façade levels (heights). This is not a big issue for solar thermal collectors located on the roof, but it is more challenging for solar collectors integrated into façade where special solutions should be used to ensure reliable and high-efficient operation.

FIGURE 18 FACADE INTEGRATED AVENTASOLAR SOLAR THERMAL COLLECTORS. IMAGE SOURCE: [35]

Another active technology that can be used to cover building energy consumption is a Solar Wall – a metal sheet with holes operating as an absorber to heat up the fresh air. The concept of the Solar Wall is as follows: fresh solar-heated air accumulates on the surface of the metal sheet mounted on a building sun-facing exterior wall, pulled through thousands of tiny holes in the air channel between the solar absorber and the building wall and delivered to the building by a fan. These air collectors are typically unglazed or partially glazed, depending on the design temperature difference. The ability to work with different dark colours of façade walls allows for blending in with other façade parts and makes this system more architecturally acceptable [42].

FIGURE 19 SOLARWALL® INSTALLATION ON THE GREATER TORONTO AIRPORT AUTHORITY BUILDING. IMAGE SOURCE: [35]

Table 2 summarises the active energy concepts used to design energy efficient buildings.

TABLE 2 SUMMARY OF THE REVIEWED ACTIVE RENEWABLE ENERGY GENERATION CONCEPTS

Category	Technology	Principle	Feature	Applicability
Solar energy	Photovoltaic system	Convert incident solar radiation to electrical energy	Highly effective in sunny regions, low conversation efficiency	Transparent part: semi-transparent photovoltaic cells Opaque part: photovoltaic panels
	Thermal system (liquid collectors)	Convert incident solar radiation to heat energy	Highly effective in sunny regions, high conversation efficiency	Transparent part: microfluidic glazing, solar thermal Venetian blinds Opaque part: solar liquid thermal collector
	Photovoltaic system + Peltier cells	Depending on the current direction, it transfers heat energy from one side to another	Could provide solar cooling as well as solar heating (with PV panels), low efficiency	Opaque part: Peltier cells, photovoltaic panels

TABLE 2 (CONTINUED)

	Hybrid PVT system	Convert incident solar radiation to electrical energy and thermal energy	Highly effective in sunny regions, high conversation efficiency	Opaque part: PVT collector
	Thermal system (unglazed solar air collectors, partially glazed solar air collectors)	Preheated air used for ventilation and air space heating	Highly effective in cold climate	Opaque part: SolarWall®, MatrixAir®
Environment energy	Thermoelectric effect	Depending on the current direction, it transfers heat energy from one side to another side	Can be used for heating as well as for cooling, low efficiency	Opaque part: Peltier cells

4.3 POWERSKIN+

Given the abovementioned facts, the building envelope plays a significant role in achieving a sustainable and high energy efficiency non-residential building stock, thus helping cut its CO_2 emissions.

Facades, as the main part of a building envelope, considerably impacts the environmental conditions of indoor spaces, the thermal performance of buildings, and subsequently the user’s satisfaction. It is stated that an efficient building is one that can provide a thermally comfortable indoor environment while effectively controlling its energy consumption. This is where POWERSKIN+ comes into the picture.

POWERSKIN+ aims to develop a truly innovative façade solution based on a smart integration of highly energy-efficient components, including super-insulative elements, solar energy harvesting, and active energy storage features, all in one single combined active/passive management system especially addressed for modern non-residential curtain wall retrofitting solutions (Figure 20).

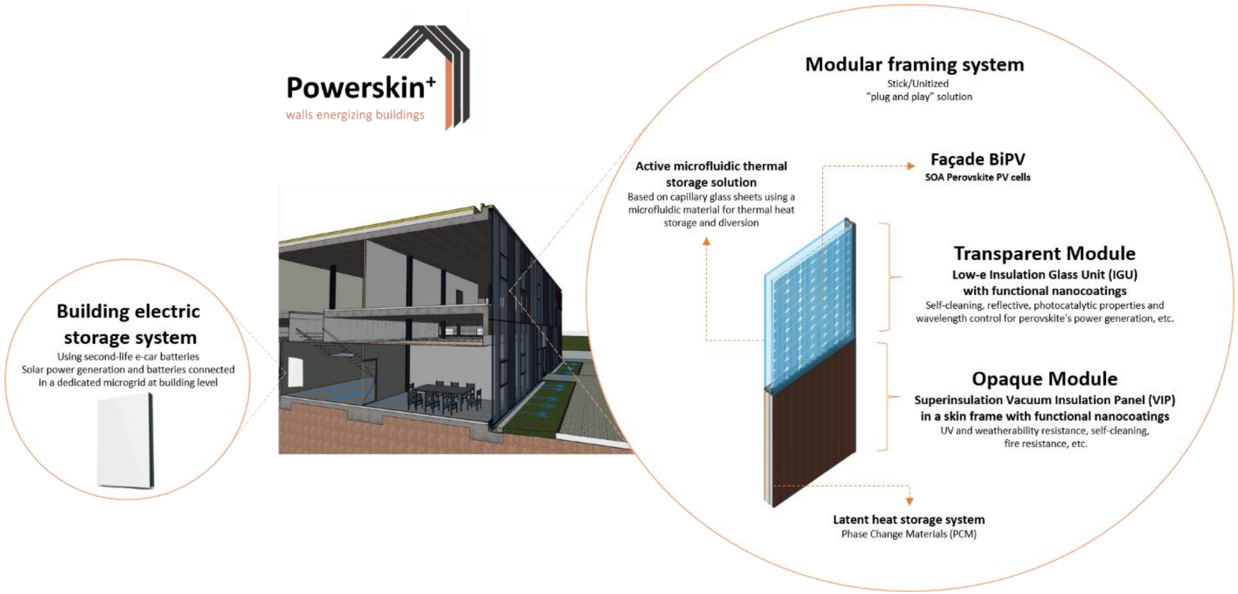


FIGURE 20 POWERSKIN+ CONCEPT

Due to its modular system, different POWERSKIN+ modules and add-on combinations can be set to match any specific needs. In its full upgrade package, POWERSKIN+ targets the deep renovation goals and accelerates the transition to energy plus buildings. It provides a unique all-in-one envelope solution by combining three objectives: insulation/climate control, energy harvesting, and energy storage.

The POWERSKIN+ standard modules designed for nZEB buildings will include:

- A prefab, low-e super-insulation triple glazing IGU transparent module.
- A prefab opaque module incorporating a novel generation of advanced nano super-insulation vacuum insulating panels and an outer functional and aesthetic protective sheet.
- A modern smart framing system to integrate both modules on-site with superior installation cost reductions and designed for its easy disassembly at the end of service, allowing full recycling and recovery of the modules.

The POWERSKIN+ upgrade package will include standard modules with additional functional nanocoatings and solar energy harvesting and energy storage package add-ons aiming for plus energy buildings standards. The portofolio covers:

- An energy harvesting solution to be integrated either on transparent or opaque modules, based on a novel generation of flexible and highly efficient perovskite photovoltaic (PV) cells.
- A dedicated building electric storage system using reused Li-ion batteries from electrical vehicles connected to the PVs and the grid.
- Active and passive latent heat storage and diversion solutions based on a patented glass-glass microfluidic device and on phase change materials (PCM), respectively, for the transparent and the opaques modules.

- Functional smart coatings for both modules, providing self-cleaning, anti-reflective, photocatalytic, UV weatherability and fire resistance features, among many others, whenever required or found appropriate to excel the façade solution capabilities.

5. Building codes

To define the critical requirements that the POWERSKIN+ should fulfil, a literature review collecting information on the relevant national building codes was provided. To be more precise, the literature review concentrated on two different areas and related to:

- Performance-based requirements
- Safety regulations and other legal requirements

5.1 Performance-based requirements

European countries have different regulations, component-based requirements associated with building energy codes, such as maximum thermal transmittance value, air tightness, thermal bridge requirements, etc. A selection of the normative criteria associated with the key requirements is analysed below.

5.1.1 Thermal transmittance

Thermal transmittance values (U-values) greatly impact the building energy efficiency and performance, since it indicates heat losses and gains through the building envelope. Consequently, it contributes to analysing building energy consumption. Limiting the thermal transmittance of major construction elements is the most common thermal performance requirement for buildings. Since POWERSKIN+ is a curtain-wall façade system, the following country by country review will focus on the limit U-values requirements for the curtain wall system. Additionally, to emphasise the difference between conventional wall system thermal requirements and curtain wall system thermal requirements, the research has been extended to include limiting U-values for external walls and windows. Moreover, the analysis also includes the forthcoming changes in the required U-values, which were already announced. Thus, the U-values presented below are the maximum acceptable normative values for the curtain wall construction, external wall, and windows for non-residential buildings (Table 3).

TABLE 3 MAXIMUM ALLOWABLE U-VALUES FOR THE CURTAIN WALL SYSTEMS, EXTERIOR WALLS, AND WINDOWS FOR NON-RESIDENTIAL BUILDINGS WITH AN INTERNAL DESIGN TEMPERATURE OF 21°C

Country	Max U-value [W/m².K]			Source
	Curtain wall	Exterior wall	Windows	
CZ	$0.3 + 1.4f_w, for\ f_w \leq 0.5$[1] $0.7 + 0.6f_w, for\ f_w > 0.5$ $0.25 + 1.2f_w$[2]	0.30 0.25 massive[2] 0.20 light-weight[2]	1.5 1.3[2]	[43]
DE	1.5	0.28 (new)[3] 0.24 (ref)	1.5 (new)[4] 1.3 (ref)	[44]
FR (Zone 1,2)	1.9 (2018)	0.35 (2018) 0.31 (2023)	1.9 (2018) 1.9 (2023)	[45]

TABLE 3 (CONTINUED)

FR (Zone 3)		0.45 (2018) 0.45 (2023)	1.9 (2018) 1.9 (2023)	[45]
BE (Brussel capital region)	2 ($U_{g.max} = 1.1$)	0.24	1.8 ($U_{g.max} = 1.1$)	[46]
BE (Flemish region. Waloon region)	2 ($U_{g.max} = 1.1$)	0.24	1.5 ($U_{g.max} = 1.1$)	[47] [48]
GR (A)	2.10 (new) 2.20 (ref)	0.55 (new) 0.60 (ref)	2.80 (new) 3.20 (ref)	[49]
GR (B)	1.90 (new) 2.00 (ref)	0.45 (new) 0.50 (ref)	2.60 (new) 3.00 (ref)	
GR (C)	1.75 (new) 1.80 (ref)	0.40 (new) 0.45 (ref)	2.40 (new) 2.80 (ref)	
GR (D)	1.70 (new) 1.80 (ref)	0.35 (new) 0.40 (ref)	2.20 (new) 2.60 (ref)	
IT (A)	n/a	0.40	3.00 (ref)	[50]
IT (B)	n/a	0.36	3.00	
IT (C)	n/a	0.32	2.20	
IT (D)	n/a	0.28	1.80	
IT (E)	n/a	0.26	1.40	
IT (F)	n/a	0.24	1.10	
ES (α)	n/a	0.80	3.20	[51]
ES (A)	n/a	0.70	2.70	
ES (B)	n/a	0.56	2.30	
ES (C)	n/a	0.49	2.10	
ES (D)	n/a	0.41	1.80	
ES (E)	n/a	0.37	1.60	
SL	n/a	0.28	1.30[5] (1.60[6])	[52]
PT (1)	n/a	0.50	2.80	[53]
PT (2)	n/a	0.40	2.40	
PT (3)	n/a	0.35	2.20	
PT (4)	n/a	0.70	2.80	
PT (5)	n/a	0.60	2.40	
PT (6)	n/a	0.45	2.20	
PO	0.90	0.20	0.90	[49]
UK	2.2	0.35	2.20	[54]

[1] f_w is the fenestration ratio within the curtain wall – area of the transparent part including related frames divided by overall curtain wall area
[2] new standard is currently under review
[3] average value for opaque part of exterior components
[3] average value for transparent part of exterior components
[4] for wooden or plastic frame
[5] for metal frame

As the values in Table 3 show, there is an evident difference between the values used for Southern and Northern countries, which was expected based on the different climatic conditions and consequently on the different climatic load that the buildings are subjected to. It is also clear that there are countries having different climatic zones (for instance, Belgium, Italy, Spain, Portugal, etc.) and, therefore, different maximum allowed U values for these zones (e.g. Figure 21). The basis of this separation within one country is also directly connected with the different climatic conditions.

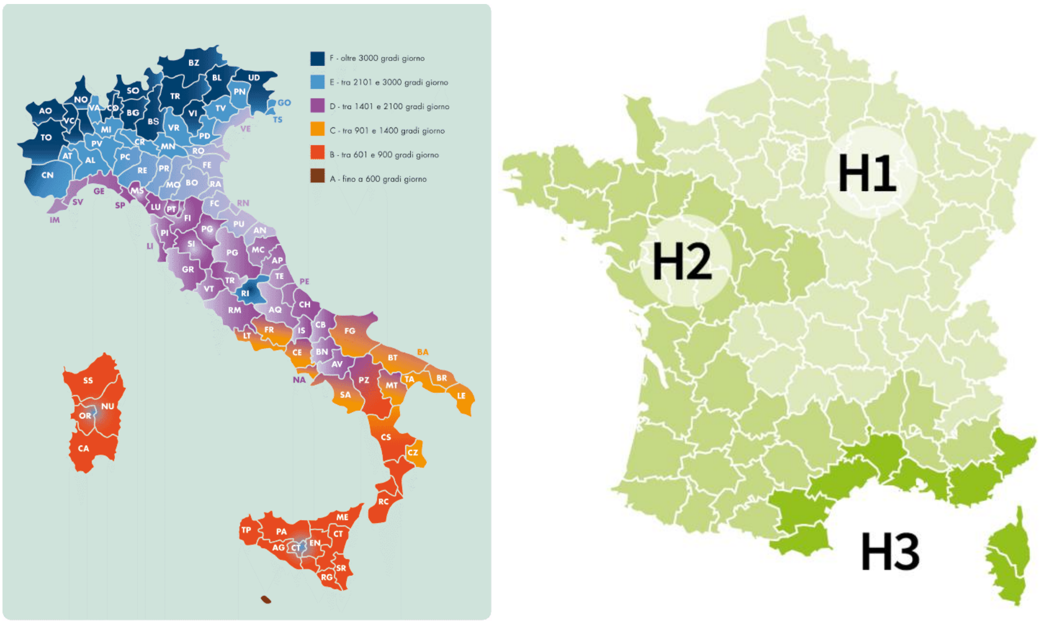


FIGURE 21 CLIMATIC ZONES OF ITALY AND FRANCE. IMAGE SOURCES: [55], [56]

In most European countries, the limit U-values for residential and non-residential buildings are the same. However, in some countries, there is a differentiation between the limits of U-values for residential and non-residential buildings and typically, the values for non-residential buildings are higher than the values for residential buildings.

In some countries (Czech Republic, Germany, Belgium, etc.), the national regulations define a curtain wall as a specific type of construction and, consequently, set a maximum U-value for a curtain wall. Moreover, in the Czech Republic regulations, the maximum U-value for a curtain wall system is defined as a function of the relative area of the transparent part (including the relevant parts of the frame). On the other hand, there is no specific U-value regulation in such countries as Spain, Italy, Portugal, etc.

5.1.2 Air tightness/permeability requirements

Building air tightness, which describes building envelope air leakage resistance, is the next parameter that affects building energy performance. Excessive ventilation may cause considerable energy wastage due to poor construction design, and for this reason, several countries have introduced requirements to limit the air tightness/permeability of buildings.

The European Standard EN 13829 describes the measurement method of air permeability of buildings. Air tightness is normally measured using a pressure test. The measurements are performed in a range of pressure differences and final results are expressed as the value for 50 Pa (4 Pa in France and 10 Pa in The Netherlands). It allows determining the air leakage rate (infiltration airflow rate). The requirement is typically expressed in $m^3/h.m^2$ (where m^2 is the external envelope area), in $l/s.m^2$ in the case of Denmark (where m^2 is the floor area) or in $dm^3/s.m^3$ in the case of Netherlands (where m^3 is the building volume). Table 4 provides an overview of the key requirements regarding air tightness/permeability for European countries. In the international community around passive houses, the $n_{50} \leq 0.6$ 1/h approach is generally used [57].

TABLE 4 AIRTIGHTNESS LEVELS IN BUILDING CODES

Country	Description	Source
AT	$n_{50} \leq 3.0$ 1/h for building without mechanical ventilation and $n_{50} \leq 1.5$ 1/h for buildings with mechanical ventilation	[58]
BE (Brussel)	$n_{50} \leq 0.6$ 1/h for offices and services/schools, $n_{50} \leq 0.6$ 1/h for single family house or flat	[49]
CZ	Recommended values: $n_{50} \leq 4.0$ 1/h for buildings with natural ventilation, $n_{50} \leq$ 1.5 1/h for buildings with mechanical ventilation, $n_{50} \leq 1.0$ 1/h for buildings with mechanical ventilation with heat recovery unit, $n_{50} \leq 0.6$ 1/h for buildings with mechanical ventilation with heat recovery unit (Passive house)	[43]
DE	$n_{50} \leq 3.0$ 1/h for buildings with natural ventilation, $n_{50} \leq 1.5$ 1/h for buildings with mechanical ventilation, $n_{50} \leq 1.0$ 1/h for buildings with mechanical ventilation with heat recovery unit, $n_{50} \leq 0.6$ 1/h for buildings with mechanical ventilation with heat recovery unit (Passive house)	[49]
DK	$n_{50} \leq 0.5$ $l/s.m^2$	[59]
ES	For zones α, A, B: $n_{100} \leq 27.0$ $m^3/h.m^2$; for zones C, D: $n_{100} \leq 9.0$ $m^3/h.m^2$;	[51]
FI	$q_{50} \leq 4$ $m^3/h.m^2$	[60]
FR	$q_4 \leq 0.6$ $m^3/h.m^2$ for single family house, $q_4 \leq 1.0$ $m^3/h.m^2$ for multifamily house, $q_4 \leq 1.7$ $m^3/h.m^2$ for offices, hotels, restaurants, shops, educational and medical facilities, $q_4 \leq 3.0$ $m^3/h.m^2$ other buildings	[61]
LT	For residential buildings, homes for the elderly, hospitals, kindergartens, and public buildings: $q_{50} \leq 3$ $m^3/h.m^2$ for buildings with natural ventilation, $q_{50} \leq 2$ $m^3/h.m^2$ for buildings with mechanical ventilation, $q_{50} \leq 1.5$ $m^3/h.m^2$ for buildings with mechanical ventilation and heat recovery unit For industrial buildings: $q_{50} \leq 4$ $m^3/h.m^2$	[62]
LV	For residential, administrative, educational and medical buildings $n_{50} \leq 2$ 1/h - C, $n_{50} \leq 1{,}5$ 1/h – B, $n_{50} \leq 1$ 1/h – A, $n_{50} \leq 0.6$ 1/h – A+, A++; for trade, sports, culture, hotel and restaurants $n_{50} \leq 2$ 1/h – C, B, $n_{50} \leq 1{,}5$ 1/h – A, $n_{50} \leq 1$ 1/h – A, A++.	[63]
NL	$q_{10} \leq 200$ dm^3/s per 500 m^3 of building area	[64]
PO	$q_{100} \leq 9.0$ $m^3/h.m^2$ (height of building < 55 m) and $q_{100} \leq 3.0$ $m^3/h.m^2$ (height of building > 55 m)	[59]
SI	$n_{50} \leq 3.0$ 1/h for building without mechanical ventilation and $n_{50} \leq 2.0$ 1/h for buildings with mechanical ventilation	[49]
UK	$n_{50} \leq 10$ $m^3/h.m^2$	[54]

5.1.3 Other performance-related requirements

In addition to specifying maximum U-values, several countries have also set limits for maximum permissible thermal bridging. This is generally expressed in W/m.K for linear thermal bridges. Thermal bridges can significantly increase the building energy demand for heating and cooling, and in a building with low energy consumption (for instance, nZEB), thermal bridging can account for a significant proportion of the total heat loss or gain. Thermal bridging is specific to the design and specification and can be complex and time-consuming to calculate. For this reason, some countries allow a default thermal bridging value to be used as a proxy, based upon a percentage (typically 15%) of the overall heat loss calculation.

Thermal bridges can be categorized into two types:

- Linear thermal bridge
- Point thermal bridge

In the case of linear thermal bridges, almost all European countries present reference values for linear thermal bridges and recommendations for avoidance (in some countries through the guidance of avoidance, like, for instance, in the United Kingdom). On the other hand, their limiting is rare despite their significant impact on buildings with low energy consumption. It should be mentioned here that the original reason for analysing thermal bridges was led by the necessity to avoid surface condensation of water vapour in critical areas due to too low surface temperature. The energy-saving driven approach evaluating additional thermal transmittances is relatively new.

It should be clearly distinguished among thermal bridges within an element, e.g. curtain wall panel. These must be integrated into its resulting thermal transmittance. A specific EU standard describes the procedure [65]. The second situation describes the couplings among different building components, which must be analysed separately and expressed as linear or point thermal bridges (Table 5). To make this clearer, the Czech terminology describes the first case as a thermal bridge and the second one as a thermal coupling.

Curtain wall typically characterized by the assembly of parts with very different thermal properties. Neglecting the thermal bridges would lead to unrealistic low thermal transmittances (in the range of 30 – 50%). Here, 2D calculations are necessary – see [65].

TABLE 5 REGULATORY REQUIREMENTS FOR LINEAR THERMAL BRIDGES (COUPLINGS)

Country	Description	Source
BE (Brussel capital region)	Outside corner $\psi \leq -0.10$ W/m.K Inside corner $\psi \leq 0.15$ W/m.K Window and door connection $\psi \leq 0.10$ W/m.K Foundation $\psi \leq 0.05$ W/m.K Balconies $\psi \leq 0.10$ W/m.K	[49]
CZ	Contact of external wall and other structures except openings filling (foundation, another wall, balconies etc): $\psi \leq 0.20$ (0.10[1]) W/m.K Contact of external wall and openings filling: $\psi \leq 0.10$ (0.05[1]) W/m.K Contact of roof and openings filling (roof window etc): $\psi \leq 0.30$ (0.10[1]) W/m.K	[43]

TABLE 5 (CONTINUED)

LT	For residential and non-residential buildings (except industrial buildings) $\psi \leq 0.20$ W/m.K. For industrial buildings $\psi \leq 0.35$ W/m.K	[62]
PT	All zones of any opaque element that constitute a flat thermal bridge zone, namely pillars, beams, shutters, must have a value of the thermal transmission coefficient, calculated in a unidimensional way in the normal direction to the surroundings, not more than double that of the adjacent elements (vertical or horizontal) in the current zone: $\underline{U} < 2 \times U_{adj}$ (closest element)	[59]
[1] new standard is currently under review		

Limiting thermal regulations for point thermal bridges are even less frequent. Only very few countries have requirements for point thermal bridges (for instance Czech Republic requires a point thermal transmittance less than 0.40 W/K). The reason for missing or weak requirements here is a big variety of real situations.

Most building regulations and requirements specify minimum levels of daylight to be achieved in buildings. On the other hand, a large transparent area of the building envelope may cause overheating and, as a result, the building will require space cooling. Therefore, solar heat gain should be controlled, especially in south European countries. Building requirements associated with limiting solar gains vary from simple approaches (for instance, limiting window area or limiting g-value) through detailed simulations to demonstrate the effect of a solar heat gain control strategy. Table 6 presents the limiting values of the maximum window solar gain factor (g-value). In essence, the g-value represents the fraction of incident solar radiation transmitted by a transparent part, expressed as a number between 0 and 1, where 1 indicates the maximum possible solar heat gain, while zero implies no solar heat gain.

TABLE 6 REGULATORY REQUIREMENTS FOR g-VALUE

Country	Description	Source
IT	g-value for glazing components with orientation from east to west through south $g \leq 0.35$	[50]
PO	Low inertia: zone 1 ($g \leqslant 0.15$), zone 2 ($g \leqslant 0.10$), zone 3 ($g \leqslant 0.10$) Medium and high inertia: zone 1 ($g \leq 0.56$), zone 2 ($g \leq 0.56$), zone 3 ($g \leq 0.50$)	[66]

5.2 Safety regulations and other requirements

5.2.1 Impact resistance

For impact resistance, the reference standards in Europe are the EN 12600 (flat glass) and EN 14019 (curtain wall). The EN 14019 defines the standard performance requirements of curtain walling (excluding 'glass in a building' which is classified under EN 12600) under soft body impact load (drop object). The classes are then determined according to the maximum impact load, in terms of drop height, for which the curtain wall does not suffer any breakage, any holing, or any permanent deformation. These classes are – together with the drop height which has to be applied – given in Table 7. It should also be noted that the test should be provided for the internal (I) and external (E) part.

Table 7 Internal (I) and external (E) impact classification

Test class	Associated drop height [mm]
I0/E0	Not tested
I1/E1	200
I2/E2	300
I3/E3	450
I4/E4	700
I5/E5	950

For class 0, there are no requirements for specific resistance to impact loads and the drop height/load criterion is not applicable. For the classification, the impact load position with the lowest result is relevant, considering the results of all impact load positions tested.

5.2.2 Wind load resistance

The design pressures are typically established by the project's structural engineer and are based on the building's exposure classification, the building's height, type, and configuration. The window and curtain wall components need to be designed to resist deflection and failure at the specified design pressure, which is generally calculated according to EN 1991-1-4:2005. However, specific annexes should be investigated to get the wind speed values for the local context depending on the country. Moreover, for high-rise buildings or buildings with irregular shapes, to properly evaluate the effect of wind, the wind tunnel test is prescribed.

There is a special standard related to resistance to wind load for the curtain wall system EN 13116:2001. The standard specifies the structural performance requirements of curtain walling under wind load, both its fixed and openable parts, under positive and negative static air pressure, mainly in terms of allowable deflection and recovery of deformation. Deflections under the design wind load must be less than 1/200 of the length of the longer frame element or 15 mm, whichever is greater.

5.2.3 Water and airtightness

Any type of water leakage or excessive air leakage through a building envelope may cause discomfort to building occupants, excessive condensation on the interior side, etc. At the same time, one of the key performance indicators of any envelope element (including curtain wall system or window) is an appropriate level of resistance to water penetration and air leakage resistance. Moreover, it is evident that any water penetration or excessive air leakage causes problems associated with the in-service performance of building envelopes.

For the watertightness of a curtain wall system, there are two European reference standards. The EN 12154 standard defines the requirements and classification of watertightness performance of both fixed and openable parts of curtain walling under positive air pressure. According to the standard, five classes are defined to adequately cover all locational and regional conditions likely to be experienced. These classes are presented in Table 8 together with the associated test pressure and test duration, which should be applied to ensure that the class is reached. The EN 12155 standard defines the method for determining the watertightness of a curtain wall system, both its fixed and openable parts.

TABLE 8 WATERTIGHTNESS CLASSES ACCORDING TO EN 12154

Class	Pressure levels and test duration [Pa/min]	Water spray rate [l/min.m²]
R4	0/15; 50/5; 100/5; 150/5	2
R5	0/15; 50/5; 100/5; 150/5; 200/5; 300/5	2
R6	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5	2
R7	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5; 600/5	2
RE xxx	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5; 600/5. Above 600/5 in steps of 150 Pa and 5 minutes duration	2

In the case of water leakage at less than 150 Pa, a specimen cannot be classified. A specimen without water leakage at more than 600 Pa is classified as E (exceptional).

For the airtightness of a curtain wall system, there are two European reference standards. The EN 12152 standard defines the requirements and classification of airtightness performance of both fixed and openable parts of curtain walling under positive and negative static air pressure. These classes are presented in Table 9 together with the associated test pressure. The EN 12153 describes the test method to be used to determine the air permeability of curtain walling. It describes how the specimen shall be tested under positive and negative air pressure.

TABLE 9 AIRTIGHTNESS CLASSES ACCORDING TO EN 12152

Max. Pressure P_{max} [Pa]	Allowed permeability related to		Class
	Length of fixed joint [m³/m.h]	Whole area [m³/m².h]	
150	0.5	1.5	A1
300	0.5	1.5	A2
450	0.5	1.5	A3
600	0.5	1.5	A4
>600	0.5	1.5	AE

For an air permeability > 0.5 m^3/m.h or 1.5 m^3/m^2.h at air pressure < 150 Pa, no classification is possible. In the case of air permeability < 0.5 m^3/m.h or 1.5 m^3/m^2.h at air pressure > 150 Pa, the specimen is classified as E (exceptional).

5.2.4 Glazing

There are special requirements for the glass panes located at the height of 1 m from the ground of each floor. It should be toughened, laminated, or both. The list of standards concerning the use of glass in building construction is presented in

Table 10.

TABLE 10 LIST OF STANDARDS CONCERNING THE USE OF GLASS IN BUILDING CONSTRUCTION

Glass type	Standard
Toughened	EN 14179-1, EN 14179-2
Laminated	EN ISO 12543-1, EN ISO 12543-2, EN ISO 12543-3, EN ISO 12543-4, EN ISO 12543-5, EN ISO 12543-6

6. Potential application benefits of POWERSKIN+ façade module

Currently, the estimation of building energy performance plays an important role both during the design phase of a new building and during a building's retrofit. It can be done in various ways, ranging from very detailed dynamic simulations (typically with one-hour time steps) to the simplest steady-state mathematical models with the time step of one month. The main aim of the building energy performance analysis is to determine if a new building or the retrofitted one meets the current local energy regulations and standards.

It is obvious that local energy regulations and standards differ from country to country. Moreover, there are a few countries in Europe with different climatic zones inside the country and, consequently, different energy regulations and standards for each zone. On the other hand, the POWERSKIN+ project is a European project, so it is necessary to provide the potential application analysis for all countries in Europe. Thus, the concept of representative sites should be introduced. Implementing the concept of the representative sites on a European level will help define the potential benefits of the POWERSKIN+ modules regarding specific climatic conditions of the different climatic zones in Europe.

6.1 Representative sites definition

To determine the representative sites for such a big region as the European Union, the statistical data must be wide enough to cover the whole region. For that reason, the newest climatic data based on a statistical analysis of measured data from 2004 to 2018 for approximately 1500 weather stations in Europe were used. The geographical distribution of the considered weather stations is presented in Figure 22.

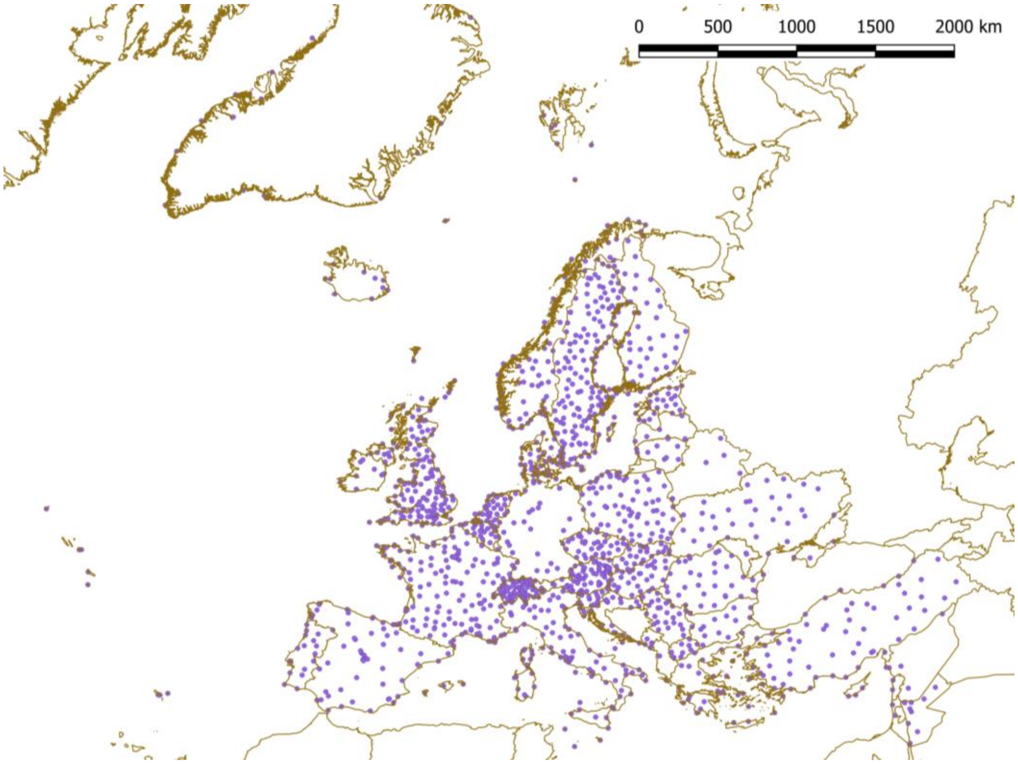


FIGURE 22 THE GEOGRAPHICAL DISTRIBUTION OF THE CONSIDERED WEATHER STATIONS IN EUROPE

In the next step, the detailed dynamic simulations of the reference office room were provided by EnergyPlus simulation software for the considered locations with a timestep of 1 hour. The simulations were conducted for the reference south-oriented office room. It is a 6.3 m wide and 5.3 m deep office room with a ceiling height of 3.4 m (Figure 23).

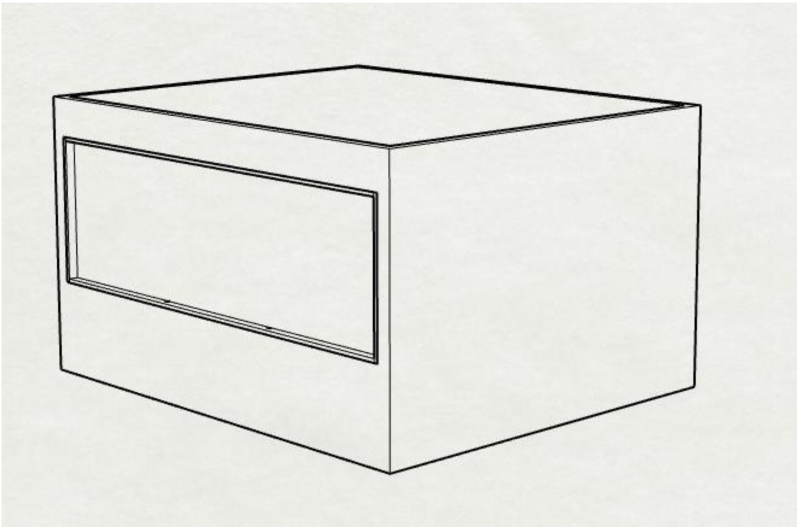


FIGURE 23 THE REFERENCE OFFICE ROOM

All building constructions except for the façade wall, namely internal walls, floor, and ceiling, were considered adiabatic in the simulations. Thus, there is only one external wall, which consists of an opaque and transparent part. A triple glazing represents the transparent part with a U-value of 0.5 W/m^2.K and a g-value of 0.35 W/m^2.K. The glazing to wall ratio for the considered façade is 0.5. The opaque part is represented by a lightweight wall construction with a U-value of 0.2 W/m^2.K. It is assumed that the thermal bridges were minimized using the modern approach in frame construction and the remaining effects of thermal bridges are included in the U-value of the opaque part. The operational parameters and set points of the considered office room are listed in Table 11.

TABLE 11 THE OPERATIONAL PARAMETERS AND SET POINTS OF THE CONSIDERED OFFICE ROOM

Parameter	Description
Occupancy	Five people, Monday to Friday, from 08:00 till 17:00
Heating/cooling/ventilation operation hours	During the occupancy period
Set point temperature for heating	22 °C
Set point temperature for cooling	26 °C
Ventilation rate (ACPH)	0.8
Maximum relative humidity value	60%
Internal heat gains (lighting, laptops, PC, printers, etc.)	12 W/m^2
Solar set point for shading system	200 W/m^2

In Figure 24, the defined space cooling demand is plotted against the defined space heating demand. Based on the results, the examined sites can be categorized according to the heating and cooling demands. The cooling demand of 800 kWh is regarded as the threshold, above which the climate can be characterized as cooling dominated. In parallel, the heating demand of 600 kWh can be regarded as the border of heating dominating climate. Lower values of heating demand and cooling demand indicate lower energy needs for heating and cooling, respectively.

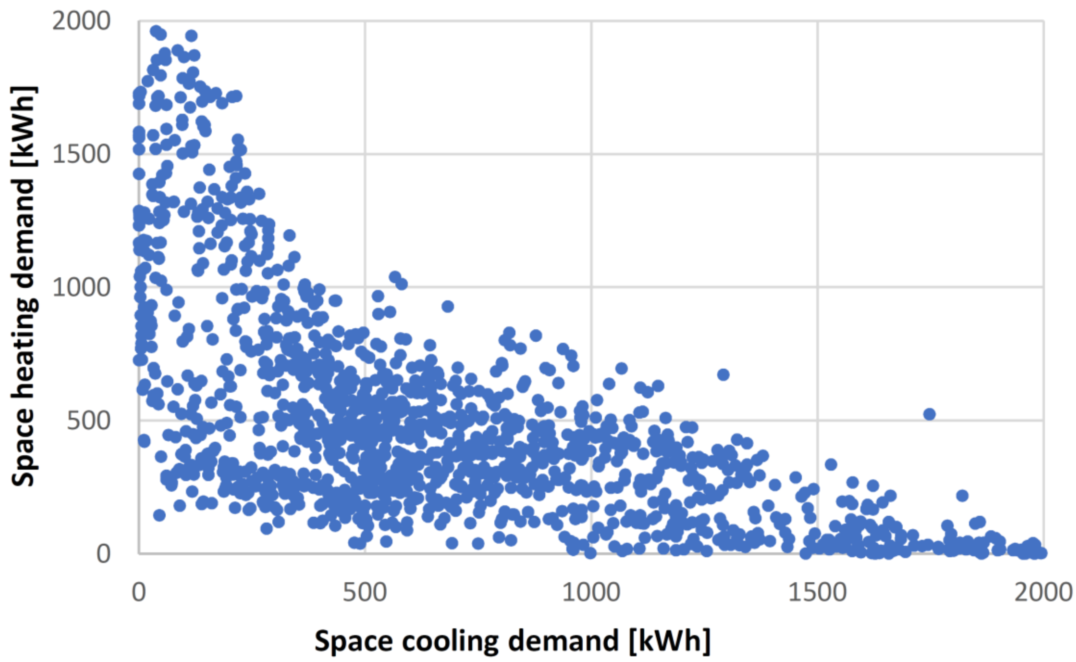


FIGURE 24 THE DISTRIBUTION OF SPACE HEATING DEMAND PLOTTED AGAINST SPACE COOLING DEMAND

Based on this approach, the different climatic groups and their representative sites can be defined by characterizing the heating and cooling demands as low, medium, and high. The proposed scheme is presented in Table 12. The classification of the selected sites in the proposed groups is presented in Figure 25 and in Figure 26. It is worth mentioning that from the selected cities, 9% belongs to the zone with high heating demand (Zone A), 18% belongs to the zone with medium heating demand and low cooling demand (Zone B), 37% belongs to the zone with low heating and cooling demands (Zone C), 15% belongs to zone with low heating demand and medium cooling demand (Zone D), while 19% is part of Zone E (regions with high cooling demand). There is also a group of sites (2%), which are unqualified based on the limits presented above (group F).

TABLE 12 THE PROPOSED ZONE DEFINITION

Group	Group limits [kWh]		Description		Representative site
	HD	CD	HD	CD	
A	> 1200	≤ 400	High	Very low	Oulu (Finland)
B	600 < HD ≤ 1200	≤ 800	Medium	Low	Gdansk (Poland)
C	≤ 600	≤ 800	Low	Low	Prague (Czech Republic)
D	≤ 600	800 < CD ≤ 1200	Low	Medium	Wien (Austria)
E	400	> 1200	Very low	High	Rome (Italy)
F	Unqualified				

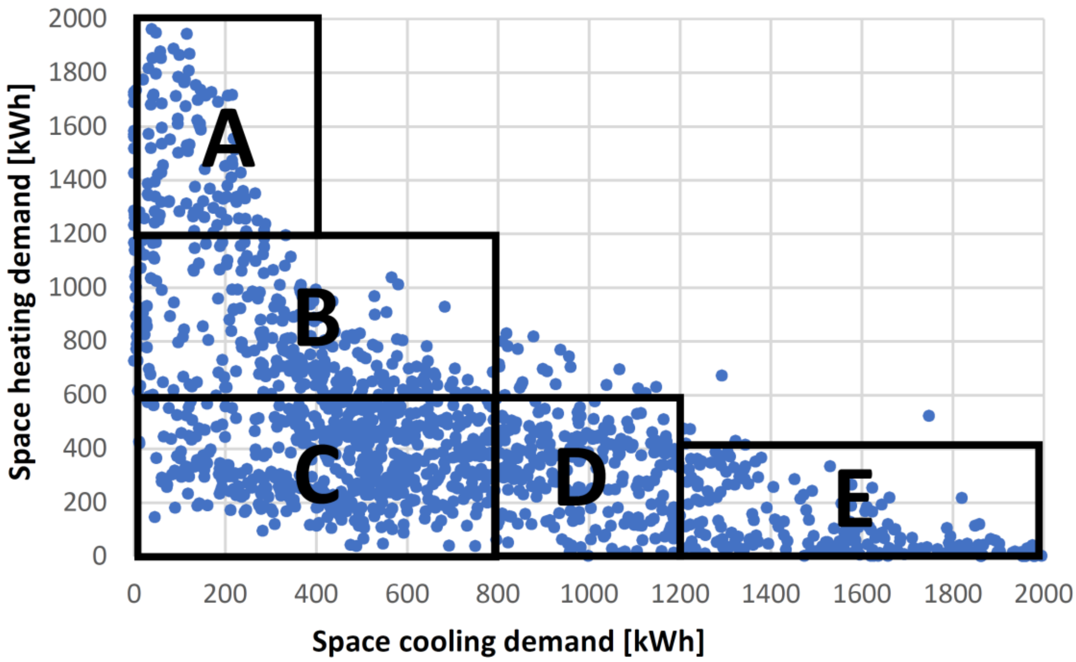


FIGURE 25 THE GROUP DISTRIBUTION OF THE CONSIDERED SITES BASED ON CALCULATED COOLING AND HEATING DEMAND

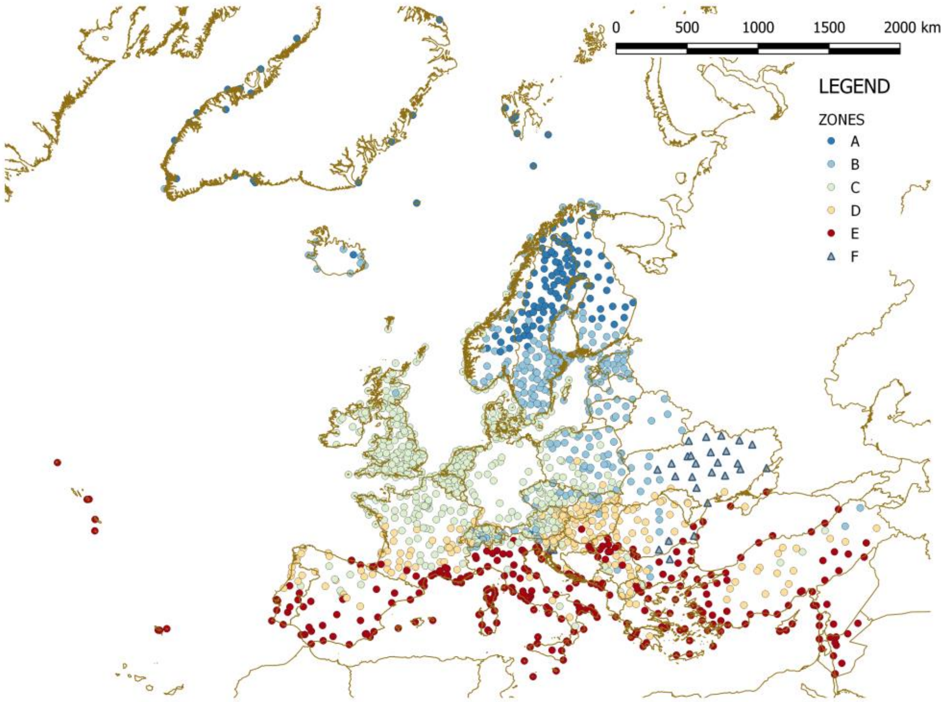


FIGURE 26 THE GEOGRAPHICAL DISTRIBUTION OF SELECTED CITIES AND THEIR CLASSIFICATION INTO CLIMATIC ZONE BASED ON SPACE HEATING AND SPACE COOLING DEMAND

Moreover, it is evident that the proposed climatic zones are similar to the Köppen climate zones classification [67], which is the first and still the most widely used climatic zone classification. It was created based on the concept that native vegetation is the best expression of climate. Different latitudinal zones and seasonality (temperatures and precipitations) were also considered. On the other hand, the proposed climatic zones classification is based solely on space heating, space cooling demand, and reference office room simulations. Finally, both concepts lead to very similar results, although the zone borders do not always match.

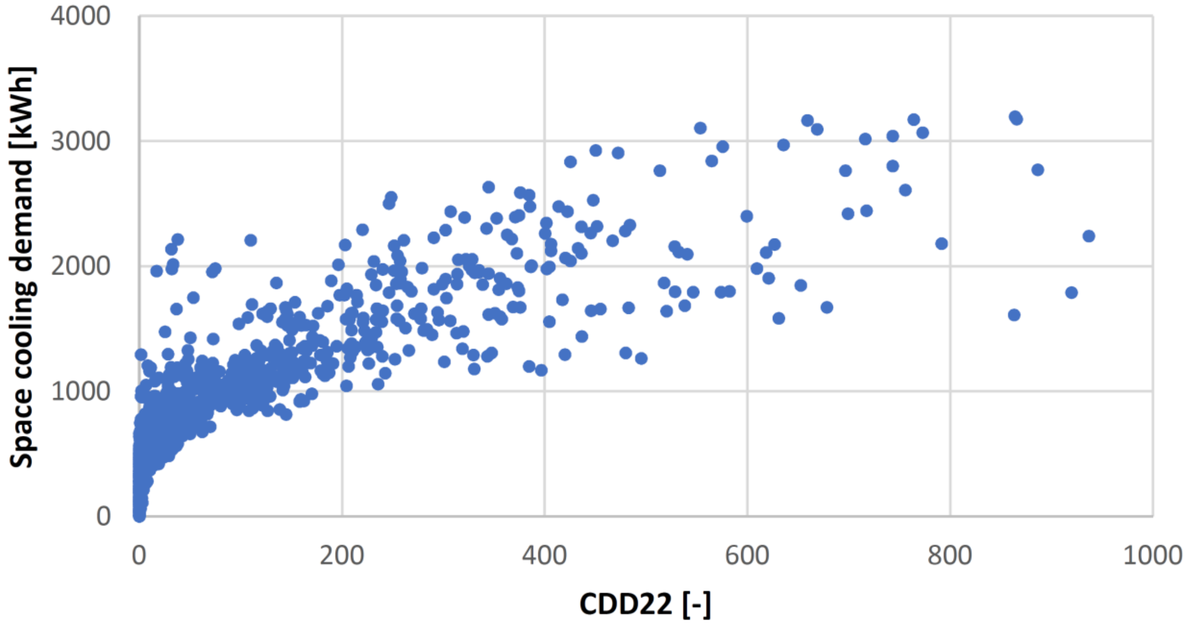
It should also be noted that the European climatic groups' definition presented above is based on the building simulation of the specific office room. It means that the zone borders for the other building typologies and/or boundary conditions will probably differ.

6.2 Proposed climatic zones versus heating degree days and cooling degree days

The different approach that could be used to propose climatic zones is heating degree days (HDD) and cooling degree days (CDD) concepts. In essence, both of these indicators determine the absolute value of the difference between the mean monthly temperature or mean day temperature and base temperature (the indoor air temperature needed to provide comfort in the building). These values allow quantifying the heating (cooling) energy demand for a building in a particular location for a certain period of time.

HDD and CDD are calculated relative to a base temperature — the outdoor air temperature below which a building is needed to heat up or cool down. The choice of baseline temperature clearly depends on the local climate. For instance, Valor et al. [68] in Spain used 10 °C in the case of HDD and 25 °C in the case of CDD. On the other hand, Papakostas et al. [69] used the baseline temperature for HDD from 10 to 20 °C and baseline temperature for CDD from 20 to 27.5. Therefore, it is difficult to choose the right (correct) baseline temperature values for the European regions. This analysis used the baseline temperatures of 15.5 °C and 22 °C suggested by the UK MET-Office for HDD and CDD calculation.

To define the relationship between HDD and CDD with the energy performance of the reference building office, the same climatic data were used (1500 sites) to cover the geographical area of Europe. Figure 27 shows the dependence between the reference office room's simulated heating and cooling demands and the calculated HDD and CDD for the considered sites.



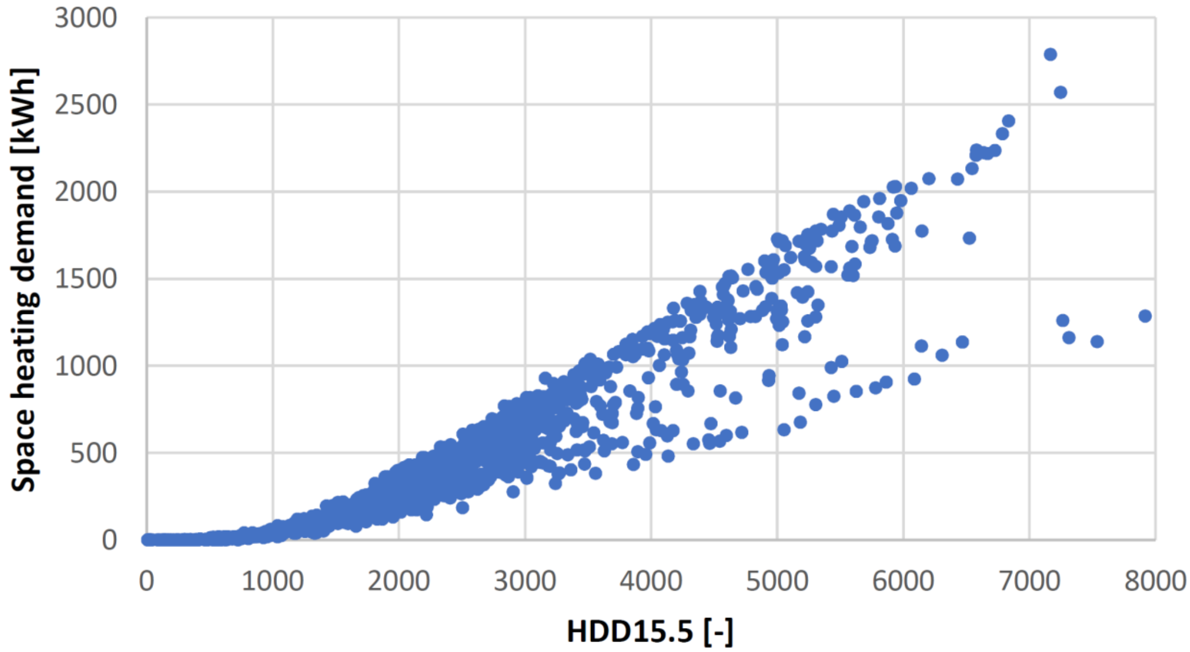


FIGURE 27 THE DEPENDENCE BETWEEN SIMULATED HEATING AND COOLING ENERGY DEMANDS AND CALCULATED HDD AND CDD FOR THE CONSIDERED SITES

First of all, it is evident from the figure that the correlation between CDD22 and space cooling demand is very weak, according to the value of the Pearson correlation coefficient (*r* = 0.81). Generally, correlation coefficient values less than +0.8 or greater than -0.8 are not considered significant. This indicates that a predictive model cannot be developed to calculate space cooling demand based on CDD22 values. There are few possible reasons for this fact. First of all, the space cooling demand is influenced by several climatic variables (air temperature, air absolute humidity, solar irradiation). The second reason is that one general base temperature cannot be used to characterise space cooling demand for the whole European continent region. The third reason for the very weak correlation is that the base temperature of 22 °C is very high and does not correlate to the indoor office temperature and, consequently, the space cooling demand.

Secondly, Figure 27 indicates that there is a strong correlation between HDD15.5 and space heating demand, according to the value of Pearson correlation coefficient of 0.93. This points out that a predictive model could be created for the calculating of space energy demand on the basis of HDD15.5, on the contrary to the CDD22 and space cooling demand. The main reason for such a strong correlation is that heating energy demand is mainly dependent on the outdoor air temperature. Therefore, space heating is highly correlated with the HDD index.

In conclusion, it should be noted that the concept of CDD22 and HDD15.5 cannot be used to propose representative sites. It should also be noted that the analysis presented above is based on the building simulation of the specific office room. It means that the zone borders for the other building typologies and/or boundary conditions will probably differ.

6.3 Potential energy savings

To evaluate the potential energy contribution of the proposed POWERSKIN+ façade module, the annual space heating demand and space cooling demand were analysed for the artificial office rooms (Figure 11) for the proposed sites and under specific energy performance levels. Six different artificial office rooms were defined for each of the representative sites (Oulu, Gdansk, Prague, Vienna, and Rome). The first five office rooms were determined based on the different construction period and, consequently, on the energy performance requirements for that period. The evolution of the required U-values for the different building constructions for the considered sites is presented in Annex A. The sixth artificial office room was defined as the retrofitted office room with the modern POWERSKIN+ façade module (Table 13 – Table 17). The other construction parameters and operation conditions were presented in 6.1 and Table 11. This approach allowed us to analyse the potential contribution of the POWERSKIN+ façade module for different climatic zones and for different time-period buildings. Afterwards, the results were extrapolated to the European scale. This way, it was possible to consider the whole variety of differences in the European Union and simultaneously keep the necessary working demand relatively small.

It should also be noted that historical buildings (typically represented by buildings built up to 1969) could have a significant heritage value. While installing modern POWERSKIN+ façade modules may not always be possible for these buildings, the analysis focused on buildings built after 1969.

TABLE 13 THE BUILDING CONSTRUCTION PROPERTIES OF THE ARTIFICIAL OFFICE ROOMS PROPOSED FOR OULU (CLIMATIC ZONE A)

Building	Construction period	Opaque part U-value [W/m².K]	Transparent part U-value [W/m².K]	Transparent part g-value [-]
A1	1970-1979	0.75	2.50	0.80
A2	1980-1989	0.35	2.10	0.80
A3	1990-1999	0.28	2.10	0.80
A4	2000-2009	0.25	1.40	0.70
A5	2010-2020	0.17	1.00	0.50
POWERSKIN+		0.098	0.80	0.30

TABLE 14 THE BUILDING CONSTRUCTION PROPERTIES OF THE ARTIFICIAL OFFICE ROOMS PROPOSED FOR GDANSK (CLIMATIC ZONE B)

Building	Construction period	Opaque part U-value [W/m².K]	Transparent part U-value [W/m².K]	Transparent part g-value [-]
B1	1970-1979	1.16	3.70	0.80
B2	1980-1989	0.75	3.70	0.80
B3	1990-1999	0.55	2.70	0.80
B4	2000-2009	0.30	2.00	0.70
B5	2010-2020	0.24	1.20	0.50
POWERSKIN+		0.098	0.80	0.30

TABLE 15 THE BUILDING CONSTRUCTION PROPERTIES OF THE ARTIFICIAL OFFICE ROOMS PROPOSED FOR PRAGUE (CLIMATIC ZONE C)

Building	Construction period	Opaque part U-value [W/m².K]	Transparent part U-value [W/m².K]	Transparent part g-value [-]
C1	1970-1979	1.08	4.76	0.80
C2	1980-1989	0.89	3.70	0.80
C3	1990-1999	0.50	2.70	0.80
C4	2000-2009	0.30	2.60	0.70
C5	2010-2020	0.30	1.50	0.50
POWERSKIN+		0.098	1.08	0.30

TABLE 16 THE BUILDING CONSTRUCTION PROPERTIES OF THE ARTIFICIAL OFFICE ROOMS PROPOSED FOR VIENNA (CLIMATIC ZONE D)

Building	Construction period	Opaque part U-value [W/m².K]	Transparent part U-value [W/m².K]	Transparent part g-value [-]
D1	1970-1979	1.20	3.00	0.80
D2	1980-1989	1.00	2.50	0.80
D3	1990-1999	0.50	1.90	0.80
D4	2000-2009	0.50	1.90	0.70
D5	2010-2020	0.35	1.70	0.50
POWERSKIN+		0.098	1.08	0.30

TABLE 17 THE BUILDING CONSTRUCTION PROPERTIES OF THE ARTIFICIAL OFFICE ROOMS PROPOSED FOR ROME (CLIMATIC ZONE E)

Building	Construction period	Opaque part U-value [W/m².K]	Transparent part U-value [W/m².K]	Transparent part g-value [-]
E1	1970-1979	1.15	5.70	0.80
E2	1980-1989	0.78	5.70	0.80
E3	1990-1999	0.78	5.70	0.80
E4	2000-2009	0.50	3.20	0.70
E5	2010-2020	0.36	2.35	0.50
POWERSKIN+		0.098	1.08	0.30

To provide calculations of the total space heating demand and space cooling demand, the simulation software Energyplus was used. The climate data used in the analysis were taken from [70]. The climatic conditions of the considered sites are listed in Table 18.

TABLE 18 CLIMATIC CONDITIONS OF THE CONSIDERED SITES

Annual values	Oulu (Finland)	Gdansk (Poland)	Prague (Czech Republic)	Vienna (Austria)	Rome (Italy)
Latitude	65.01° N	54.35° N	50.08° N	48.20° N	41.89° N
Mean ambient temperature	3.7 °C	9.1 °C	10.2 °C	11.2 °C	16.3 °C
Minimum ambient temperature	-28.1 °C	-14.1 °C	-11.3 °C	14.0 °C	-3.0 °C
Maximum ambient temperature	28 °C	30.1 °C	34.7 °C	38 °C	34 °C
Global Horizontal Irradiance	796 kWh/m²	1130 kWh/m²	1130 kWh/m²	1233 kWh/m²	1735 kWh/m²
Global Tilted Irradiance (South, 90°)	649 kWh/m²	880 kWh/m²	783 kWh/m²	833 kWh/m²	1223 kWh/m²

The results of the modelling are outlined in Table 19 and Table 20, where the values in parentheses indicate the relative difference between the buildings under consideration (1 - 5) and the reference building (PS+).

TABLE 19 SPECIFIC SPACE HEATING DEMAND AND RELATIVE POTENTIAL ENERGY SAVINGS FOR THE CONSIDERED CLIMATIC ZONES AND CONSTRUCTION PERIODS

Construction period	Specific space heating demand [kWh/m²]				
	A (Oulu)	B (Gdansk)	C (Prague)	D (Vienna)	E (Rome)
1970-1979	107 (67%)	82 (71%)	81 (59%)	33 (68%)	27 (92%)
1980-1989	85 (59%)	75 (69%)	63 (53%)	27 (60%)	25 (91%)
1990-1999	83 (58%)	54 (57%)	43 (30%)	17 (37%)	25 (91%)
2000-2009	64 (46%)	40 (41%)	41 (35%)	19 (42%)	12 (81%)
2010-2020	54 (35%)	29 (18%)	28 (18%)	19 (42%)	9 (74%)
POWERSKIN+	35	23	18	11	2

TABLE 20 SPECIFIC SPACE COOLING DEMAND AND RELATIVE POTENTIAL ENERGY SAVINGS FOR THE CONSIDERED CLIMATIC ZONES AND CONSTRUCTION PERIODS

Construction period	Specific space cooling demand [kWh/m²]				
	A (Oulu)	B (Gdansk)	C (Prague)	D (Vienna)	E (Rome)
1970-1979	8 (20%)	12 (6%)	19 (6%)	42 (27%)	64 (19%)
1980-1989	8 (28%)	12 (6%)	20 (12%)	43 (28%)	62 (18%)
1990-1999	8 (29%)	13 (17%)	22 (20%)	43 (28%)	62 (18%)
2000-2009	9 (32%)	14 (20%)	21 (15%)	40 (23%)	61 (16%)
2010-2020	6 (23%)	13 (15%)	20 (11%)	36 (13%)	56 (8%)
POWERSKIN+	6	11	18	31	51

Firstly, simulation results confirmed that the largest energy-saving potential is associated with the older building stock in terms of space heating demand. Older buildings tend to consume more energy due to their low energy performance levels. Therefore, the application of modern POWERSKIN+ façade for these buildings has high energy-saving potential. As for modern buildings, the energy savings potential is lower. The main reason for this is the implementation of energy standards and requirements for buildings (effect EPBD implementation and previous standards). The implementation of energy standards leads to a reduction in space heating demand and, consequently, to a reduction in potential energy savings in the case of POWERSKIN+ implementation. Therefore, to increase the value in POWERSKIN+ standard solutions for new buildings, it is evident that active renewable energy generation and storage strategies should be implemented (upgrade add-ons).

Secondly, Table 19 and Table 20 indicate that Southern countries (Spain, Italy, Portugal, etc) have high energy saving potential for all construction periods regarding space heating. On the other hand, these buildings do not have a sufficient level of thermal insulation in their building stock due to milder winters. As a result, implementing the highly efficient POWERSKIN+ façade modules will significantly decrease space heating demand in relative values, but this reduction may not be so essential in absolute values. On the other hand, the implementation of POWERSKIN+ in Southern countries has a certain potential in terms of space cooling energy savings. Nevertheless, the reduction in space cooling demand is not highly significant. Again, to make the most value possible of the POWERSKIN+ solution in Southern countries, active renewable energy generation and storage strategies should be implemented. Moreover, in the case of photovoltaic system application, the electrical energy can be directly (without storing) used to cover space cooling demand because most of the time photovoltaic production profile matches with the space cooling demand profile.

The situation is the opposite in terms of relative potential energy savings in space cooling demand in Northern and Central European countries. Due to the low space cooling demand caused by moderate summer, any improvement in absolute values will cause high energy saving potential in relative values, but this reduction is not so significant in absolute values. On the other hand, it is evident that the implementation of POWERSKIN+ in Northern and Central European countries will significantly reduce space heating demands.

7. Adaptability analysis

7.1 Thermal performance

When adapting a building envelope to the new thermal standards, the U-value is the key parameter to be considered. Its development in different countries is described in this report. In the building envelope, two basic types of construction are identified: transparent and opaque. Whereas in the case of adapting the transparent parts, the only option is to exchange them for new elements meeting the standard requirements, in the case of opaque parts, it is also possible to add new insulating layers (ETICS). The exchange of the whole opaque part is also an option in the case of curtain walls.

Adding the same thermal insulation layer to different baseline constructions does not result in the same U-value difference. Different insulation materials naturally vary in their thermal and environmental characteristics. These characteristics for the selected materials are summarized in Table 21.

TABLE 21 SELECTED INSULATION MATERIALS CHARACTERISTICS

Material	Density	Thermal conductivity	Carbon footprint (GWP)	PEI
	[kg/m^3]	[W/m.K]	[kgCO$_{2,ekv}$/kg]	[MJ/kg]
EPS	16	0.035	4.205	105.073
XPS	32	0.040	5.840	96.514
PU polyurethane	45	0.025	4.307	99.265
Glass wool – high density	80	0.038	1.380	47.315
Glass wool – low density	22	0.036	1.494	45.534
Rock wool – high density	155	0.045	0.920	23.157
Rock wool – low density	70	0.040	1.082	20.192
Wood fibre – low density	120	0.050	0.062	1.1449
Wood fibre – high density	380	0.090	0.062	1.1449
Aerogel	140	0.017	4.200	173.07
Vacuum insulation panel (VIPs)	170	0.006	8.551	227.6*

* value extrapolated from the data acquired for a 4.5 kg panel (1 m^2)

As mentioned before, the same thermal insulation layer for different baseline constructions does not result in the same U-value difference. The required thickness of the new insulation level can be calculated using:

$$d_{insulation} = \left(\frac{1}{U_{original}} - \frac{1}{U_{required}}\right) \times \lambda_{insulation}$$

An example of results for EPS (λ = 0.035 W/m.K), wood fibre with high density (λ = 0.090 W/m.K) and VIPs (λ = 0.006 W/m.K) are shown in Table 22, Table 23, and Table 24. The values are stated in centimeters. The thickness stated in the tables does not respect the standard production dimensions and are calculated to precisely match the target U-value.

TABLE 22 THICKNESS OF A NEW EPS INSULATION LAYER REQUIRED TO ACHIEVE A TARGET U-VALUE BASED ON THE BASELINE U-VALUE (IN CENTIMETERS)

Original U-value [W/m².K]	Target U-value [W/m².K]								
	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
5.0	2.8	3.2	3.7	4.3	5.1	6.3	8.1	11.0	16.8
4.5	2.7	3.1	3.6	4.2	5.1	6.2	8.0	10.9	16.7
4.0	2.6	3.0	3.5	4.1	5.0	6.1	7.9	10.8	16.6
3.5	2.5	2.9	3.4	4.0	4.8	6.0	7.8	10.7	16.5
3.0	2.3	2.7	3.2	3.8	4.7	5.8	7.6	10.5	16.3
2.5	2.1	2.5	3.0	3.6	4.4	5.6	7.4	10.3	16.1
2.0	1.8	2.1	2.6	3.3	4.1	5.3	7.0	9.9	15.8
1.5	1.2	1.6	2.0	2.7	3.5	4.7	6.4	9.3	15.2
1.0		0.4	0.9	1.5	2.3	3.5	5.3	8.2	14.0
0.9			0.5	1.1	1.9	3.1	4.9	7.8	13.6
0.8				0.6	1.5	2.6	4.4	7.3	13.1
0.7					0.8	2.0	3.8	6.7	12.5
0.6						1.2	2.9	5.8	11.7
0.5							1.8	4.7	10.5
0.4								2.9	8.8
0.3									5.8

TABLE 23 THICKNESS OF A NEW WOOD FIBRE (HIGH DENSITY) INSULATION LAYER REQUIRED TO ACHIEVE A TARGET U-VALUE BASED ON THE BASELINE U-VALUE (IN CENTIMETERS)

Original U-value [W/m².K]	Target U-value [W/m².K]								
	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
5.0	7.2	8.2	9.5	11.1	13.2	16.2	20.7	28.2	43.2
4.5	7.0	8.0	9.3	10.9	13.0	16.0	20.5	28.0	43.0
4.0	6.8	7.8	9.0	10.6	12.8	15.8	20.3	27.8	42.8
3.5	6.4	7.4	8.7	10.3	12.4	15.4	19.9	27.4	42.4
3.0	6.0	7.0	8.3	9.9	12.0	15.0	19.5	27.0	42.0

TABLE 23 (CONTINUED)

2.5	5.4	6.4	7.7	9.3	11.4	14.4	18.9	26.4	41.4
2.0	4.5	5.5	6.8	8.4	10.5	13.5	18.0	25.5	40.5
1.5	3.0	4.0	5.3	6.9	9.0	12.0	16.5	24.0	39.0
1.0		1.0	2.3	3.9	6.0	9.0	13.5	21.0	36.0
0.9			1.3	2.9	5.0	8.0	12.5	20.0	35.0
0.8				1.6	3.8	6.8	11.3	18.8	33.8
0.7					2.1	5.1	9.6	17.1	32.1
0.6						3.0	7.5	15.0	30.0
0.5							4.5	12.0	27.0
0.4								7.5	22.5
0.3									15.0

TABLE 24 THICKNESS OF A NEW VIP INSULATION LAYER REQUIRED TO ACHIEVE A TARGET U-VALUE BASED ON THE BASELINE U-VALUE (IN CENTIMETERS)

Original U-value [W/m².K]	Target U-value [W/m².K]								
	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
5.0	0.5	0.5	0.6	0.7	0.9	1.1	1.4	1.9	2.9
4.5	0.5	0.5	0.6	0.7	0.9	1.1	1.4	1.9	2.9
4.0	0.5	0.5	0.6	0.7	0.9	1.1	1.4	1.9	2.9
3.5	0.4	0.5	0.6	0.7	0.8	1.0	1.3	1.8	2.8
3.0	0.4	0.5	0.6	0.7	0.8	1.0	1.3	1.8	2.8
2.5	0.4	0.4	0.5	0.6	0.8	1.0	1.3	1.8	2.8
2.0	0.3	0.4	0.5	0.6	0.7	0.9	1.2	1.7	2.7
1.5	0.2	0.3	0.4	0.5	0.6	0.8	1.1	1.6	2.6
1.0		0.1	0.2	0.3	0.4	0.6	0.9	1.4	2.4
0.9			0.1	0.2	0.3	0.5	0.8	1.3	2.3
0.8				0.1	0.3	0.5	0.8	1.3	2.3
0.7					0.1	0.3	0.6	1.1	2.1
0.6						0.2	0.5	1.0	2.0
0.5							0.3	0.8	1.8
0.4								0.5	1.5
0.3									1.0

In the case of modular curtain walls, the addition of thermal insulation is not a viable approach. In these cases, either the thermal insulation within the system or the whole façade system can be replaced. The first approach preserves the rest of the façade and is less financially demanding but inherits the flaws of the original and probably outdated system. The most significant problem in this solution is the neglect of thermal bridges. The quality of the joint solutions and framing systems in the older facades corresponds to the thermal insulation level in the original system. Also, the materials used in the facades deteriorate in time and therefore lose their thermal characteristic. The deterioration of the materials may also negatively affect the airtightness of the façade, causing further heat losses.

Song et al. [71] suggest that for an opaque curtain wall, the thermal bridges can account for the effective U-value increase of the façade as high as 200% when compared to each other. However, this study considers only two different opaque panel types combined with two types of joints. The variability of the effective U-value can be much higher when considering other joint types and also panel sizes as the ratio between the main planar construction area and the area/length of thermal bridges affects the resulting heat loss.

Therefore, the latter option is preferred and recommended. The replacement of the entire curtain wall system allows to minimize heat losses in the complex point of view, and the effect on operational energy consumption can be maximized. Furthermore, the façade system replacement also allows the integration of new technologies such as energy harvesting and also building wirings integration.

7.2 Environmental performance

The environmental impacts, such as carbon footprint and embodied primary energy, depend on the mass of the material used. Based on the required thickness calculated in the previous tables, the calculation of these parameters is shown in the following ones. For the sake of illustration, only the results for achieving the target U-values of 0.2 – 0.6 W/m^2.K with the baseline U-value of 3 W/m^2.K are stated. The effect of thermal bridges in curtain walls means that the below described environmental performance of façade retrofits does not fully reflect curtain walls retrofit as much as it describes ETICS solutions.

TABLE 25 EXAMPLE OF ENVIRONMENTAL CHARACTERISTICS FOR THE CHOSEN INSULATION SCENARIOS

	GWP [kg$CO_{2,ekv}$/m^2]					PEI [MJ/m^2]				
Target U-value [W/m^2.K]	0.6	0.5	0.4	0.3	0.2	0.6	0.5	0.4	0.3	0.2
EPS	3.1	3.9	5.1	7.1	11.0	78.9	98.7	128.3	177.6	276.3
Wood fibre	2.8	3.5	4.6	6.4	9.9	52.2	65.3	84.8	117.5	182.7
VIP	11.6	14.5	18.9	26.2	40.7	309.5	386.9	503.0	696.5	1083.

The carbon neutrality calculation of thermal insulation (the time required for the carbon footprint to be offset by the difference of the heat loss in the heating season) should also include the carbon footprint of the insulation installation. Above, only the material footprint is stated and the installation characteristics may vary based on the building location. The primary energy neutrality can vary due to location as well. In both parameters cases, the emission factor of the heating fuel used in the building (varies by country) and the system efficiency play their role. These parameters should be evaluated when choosing the appropriate insulation strategy.

The savings in the GWP and PEI, offsetting the embodied CO_2 and primary energy, can be calculated based on the improvement of the U-value as the difference between the original and target U-values and on the local annual heating degree days. The product of the multiplication of these two values represents the annual heat loss reduction. The annual heat loss reduction multiplied by the emission factors and primary energy factors represent the annual GWP and PEI savings.

7.3 POWERSKIN+ curtain wall system

When a building façade retrofit using the POWERSKIN+ system is envisioned, its adaptability should be considered, focusing on different areas. The most relevant are the structural and technological adaptability, which are to some extent intertwined. Adding functionalities such as energy harvesting to the façade, for example, may require additional structural adaptations (passes through existing structures other than the façade itself).

7.3.1 Structural adaptability

From the structural perspective, facades can be built as part of the buildings' load-bearing structure or as curtain walls. Curtain walls can be divided into self-bearing, filling, or hanged (Figure 28). In this regard, POWERSKIN+ aims to provide a solution for lightweight non-load-bearing curtain wall and double skin façade systems and has, therefore, no load-bearing function.

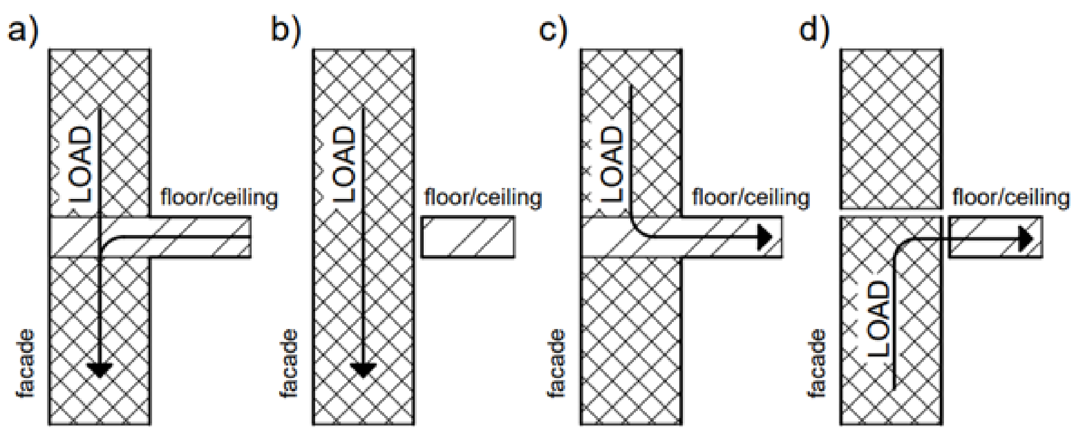


FIGURE 28 TYPES OF FACADES: a) LOAD-BEARING, b) SELF-BEARING CURTAIN WALL, c) FILLING CURTAIN WALL, d) HANGED CURTAIN WALL

A large part of non-residential buildings built in the period from 1970 onwards is built with curtain wall facades. However, some non-residential buildings have a load-bearing façade, or their façade is a combination of load-bearing structure and curtain walls. The fact that the POWERSKIN+ system is intended for non-load bearing applications does not disqualify those buildings for its use. The first option is to use POWERSKIN+ to replace the current curtain walls or opaque elements integrated in the load bearing structure (also, the sill part of the façade can be eventually replaced, as the load bearing function is secured by the lintel above the window). In this option, the replacement must be, in most cases, carried out together with the additional insulation of the rest of the façade in order to maximize the retrofit effect on energy efficiency as well as to avoid thermal bridging and condensation within the contact of well-insulated POWERSKIN+ and the original façade.

FIGURE 29 BUILDING COMBINING A LOAD-BEARING FAÇADE AND CURTAIN WALLS (LEFT); BUILDING WITH A LOAD BEARING FAÇADE (RIGHT)

Another possibility is to create a double skin façade using the POWERSKIN+ modules as the outer skin. In this case, the thermal parameters of the POWERSKIN+ using technologies such as vacuum insulation or PCM would have a small efficiency and lower-performing alternatives can be used. However, other parts of the POWERSKIN+ premium solutions, such as the low-carbon bio composite framing system, nanocoatings, and energy harvesting and electric storage systems, do not lose their potential and can add significant added value for double-skin retrofit solutions. An example of such is shown in Figure 30 (on a residential building).

FIGURE 30 DOUBLE SKIN FAÇADE WITH ORIGINALLY LOAD-BEARING FAÇADE. IMAGE SOURCE: [72]

If a façade to be retrofitted is a curtain wall system, the adaptability is easier and it allows the utilization of the whole POWERSKIN+ potential in terms of thermal insulation and also energy harvesting. As the building is already equipped with curtain walls, the structural integration of POWERSKIN+ modules and add-on solutions does not pose any significant problems, and it allows the planners and professionals to integrate any new curtain wall. A decision has to be made, whether the type of curtain wall (filling or hanged) should remain or should be changed. In the case of filling curtain walls, the thermal bridging must be solved during the design stage, as in any filing curtain wall upgrades. While considering integrating POWERSKIN+ energy harvesting and active latent heat storage diversion add-ons, minor structural tasks may occur regarding the need for connections to the building systems.

7.3.2 Technological adaptability

Integration of the POWERSKIN+ system into retrofitted buildings will significantly affect the heating and cooling energy consumption. As these consumptions may decrease significantly after the envelope retrofit (even without considering the energy harvesting and storage), the pre-retrofit building energy systems may become over-dimensioned. Even though these systems would be able to facilitate the lower energy demand, heating and cooling systems become generally inefficient and prone to failures when running on only a fraction of their capacity. Therefore, the POWERSKIN+ integration should be done in parallel with the building services retrofit and based on an overall planning of energy savings. In some cases, the heating elements were physically connected to original curtain walls (Figure 31). In general, a very good on site investigation should be performed before any definitive decisions about the design and management of the retrofit action.

A major building services retrofit induced by the POWERSKIN+ incorporation is a prerequisite for considering integrating its energy harvesting and storage add-ons, as most of the buildings built since the 1970s do not harvest energy, let alone use it in their operation.

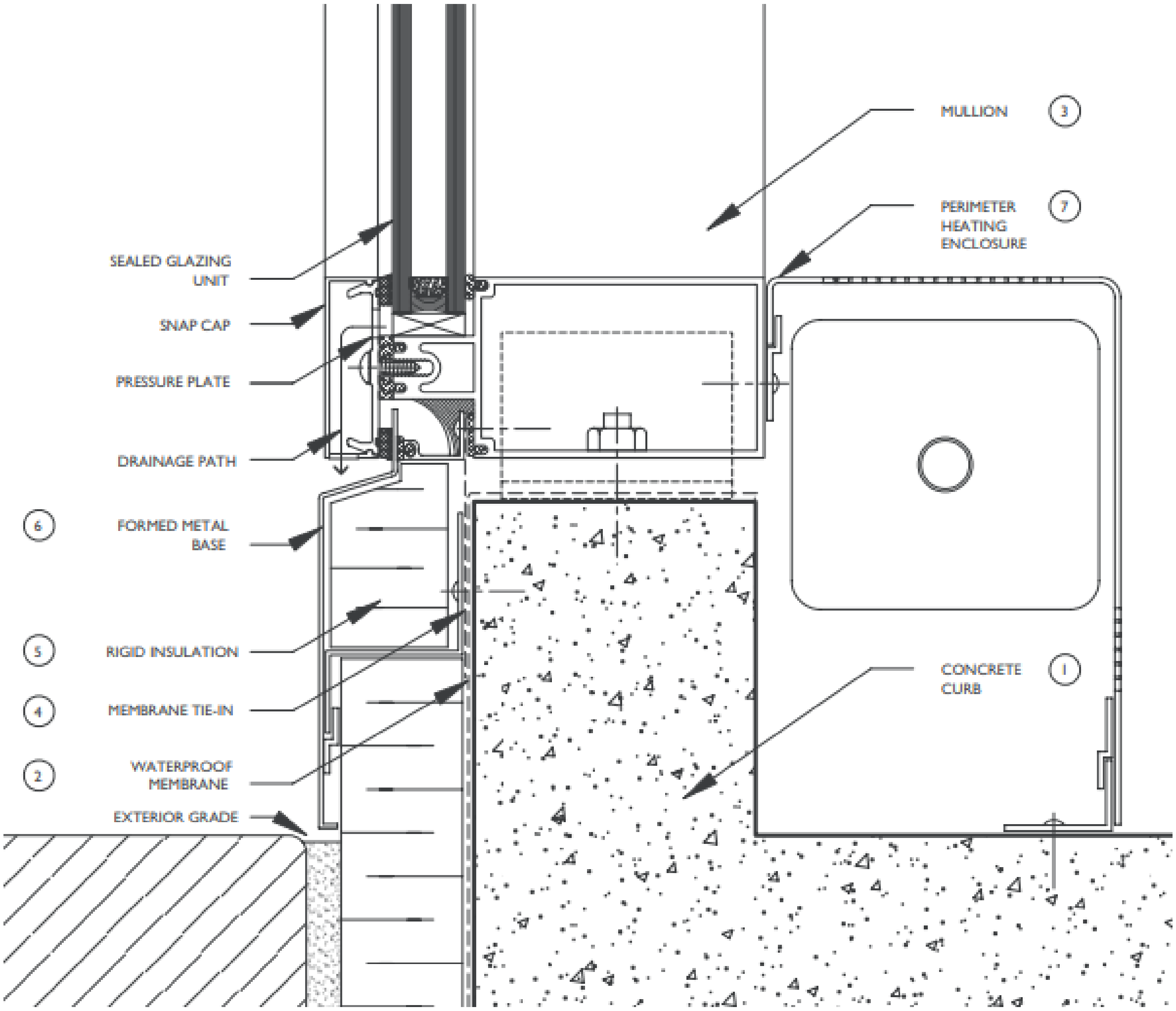


FIGURE 31: CURTAIN WALL SECTION WITH FIXED PERIMETER HEATING. IMAGE SOURCE: [73]

8. Conclusion

The report presents a framework for various retrofit situations in Europe, reviewing the situation regarding building stock characteristics for non-residential and residential buildings. There are approximately 131 million buildings within the Member States of the European Union. The vast majority of these buildings are residential ones (119 million against 12 million of non-residential uses). However, if measured by floor area, the residential building stock accounts for approximately 75% of the total, with the remaining 25% being non-residential buildings. In terms of buildings age, 43% of non-residential buildings and 39% of residential buildings were built pre-1970 within the EU, before the widespread adoption of energy efficiency measures. Energy in non-residential buildings is mainly consumed by space heating, as well as in residential buildings.

The report also includes the preliminary simulation analysis provided for different climatic conditions and different building construction periods. The data collected indicate a high potential for energy efficient retrofit of buildings built before 1990 throughout the EU. Therefore, applying state-of-the-art POWERSKIN+ façade solutions for these buildings allows to fully exploit the energy savings potential. As for the modern buildings or for Southern countries, the energy savings potential is lower. Therefore and in these cases, the energy harvesting and storage potential of POWERSKIN+ façade becomes dominant. Finally, the collected data allows determining the strategies for improving the energy and greenhouse gas savings potential of the future POWERSKIN+ solution and model a variety of scenarios of its operational performance on various climate/building solutions.

9. Annex A. The evolution of the required U-values for different building construction periods for the considered sites

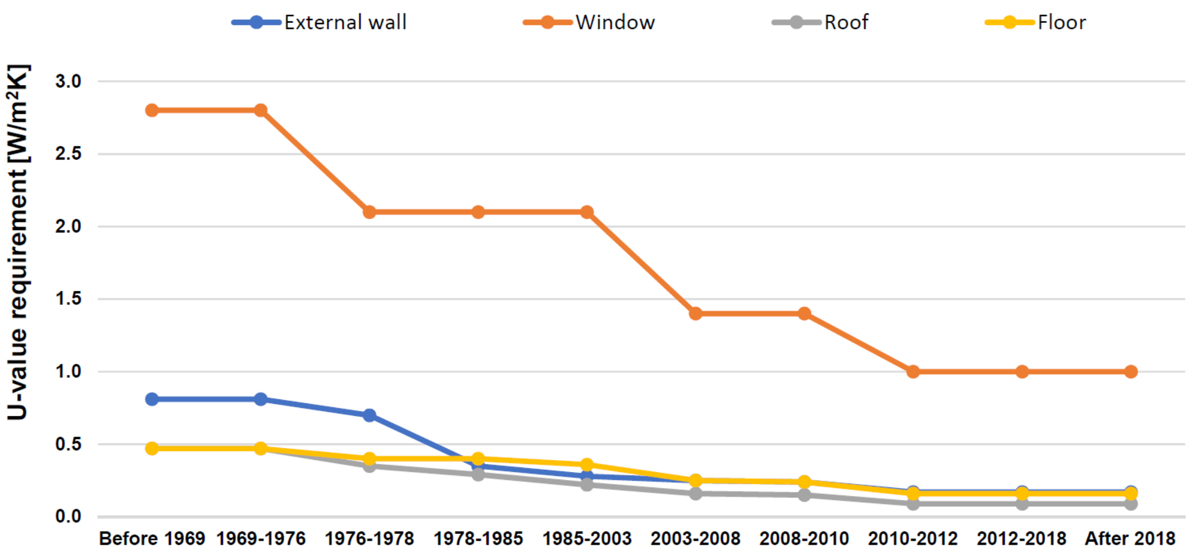


FIGURE 32 DEVELOPMENT OF THE REQUIRED U-VALUES FOR DIFFERENT BUILDING CONSTRUCTION PERIODS IN FINLAND. DATA SOURCE: [60]

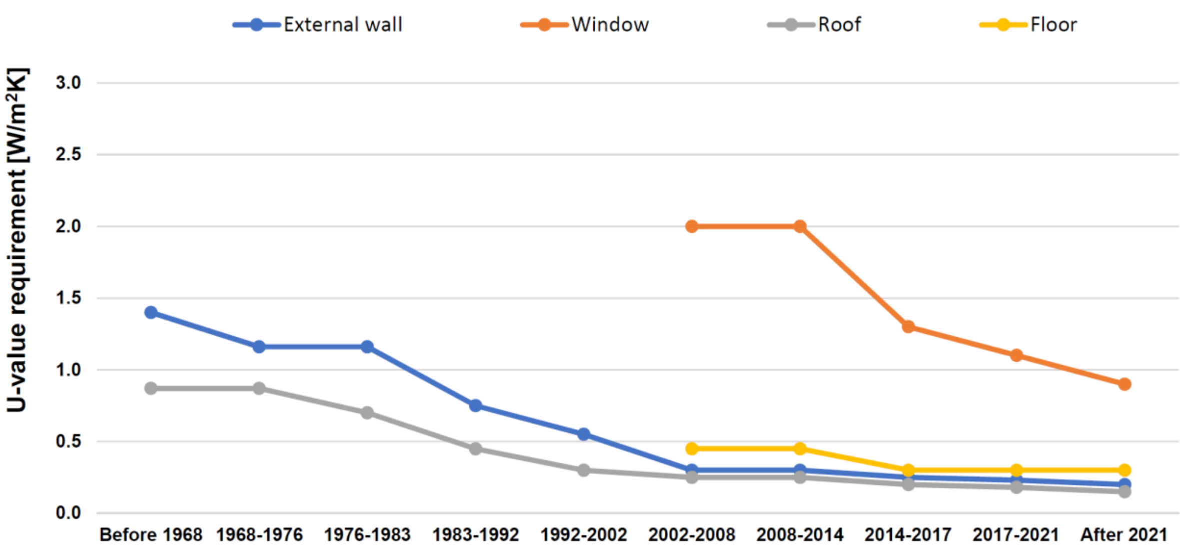


FIGURE 33 DEVELOPMENT OF THE REQUIRED U-VALUES FOR DIFFERENT BUILDING CONSTRUCTION PERIODS IN POLAND. DATA SOURCE: [74]

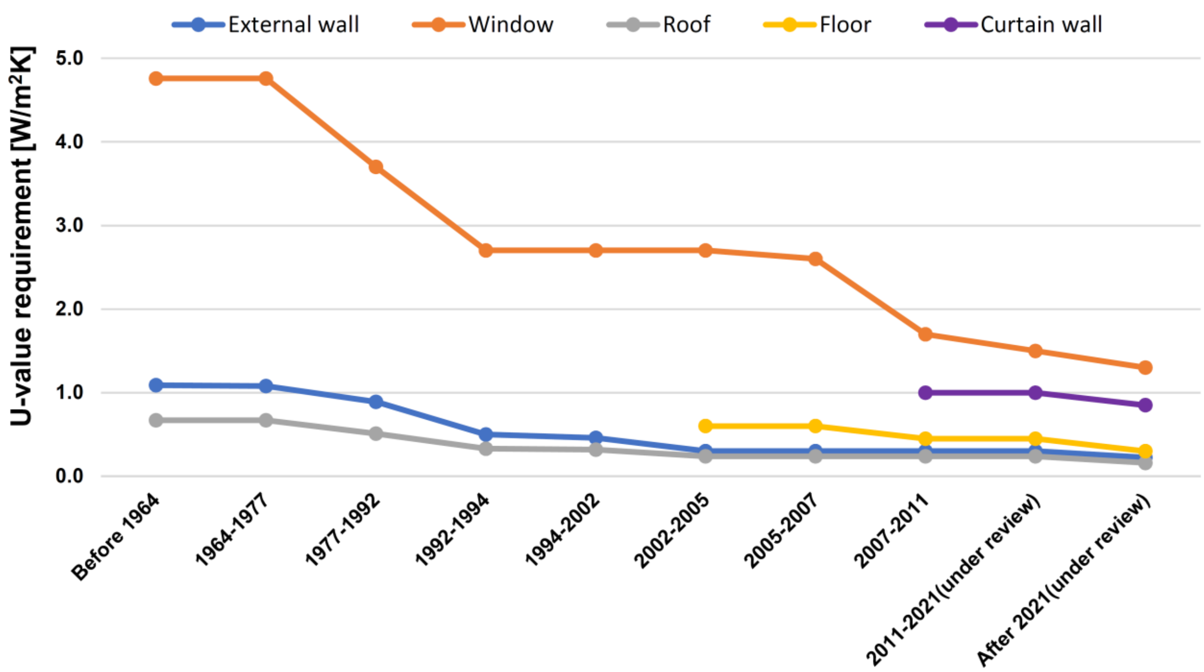


FIGURE 34 DEVELOPMENT OF THE REQUIRED U-VALUES FOR DIFFERENT BUILDING CONSTRUCTION PERIODS IN THE CZECH REPUBLIC. DATA SOURCE: [75]

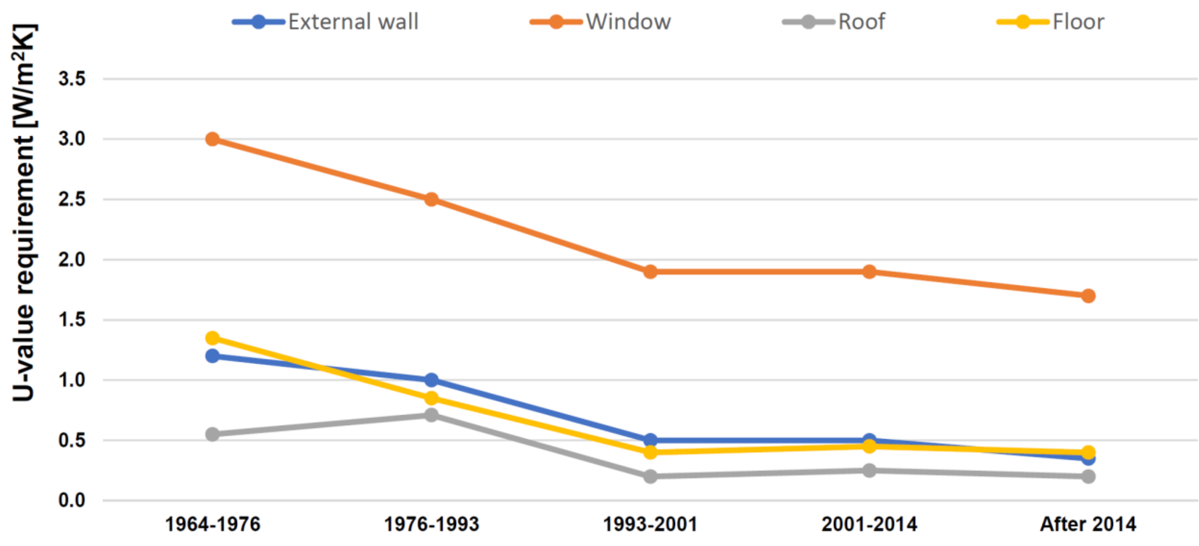


FIGURE 35 DEVELOPMENT OF THE REQUIRED U-VALUES FOR DIFFERENT BUILDING CONSTRUCTION PERIODS IN AUSTRIA (VIENNA). DATA SOURCE: [58]

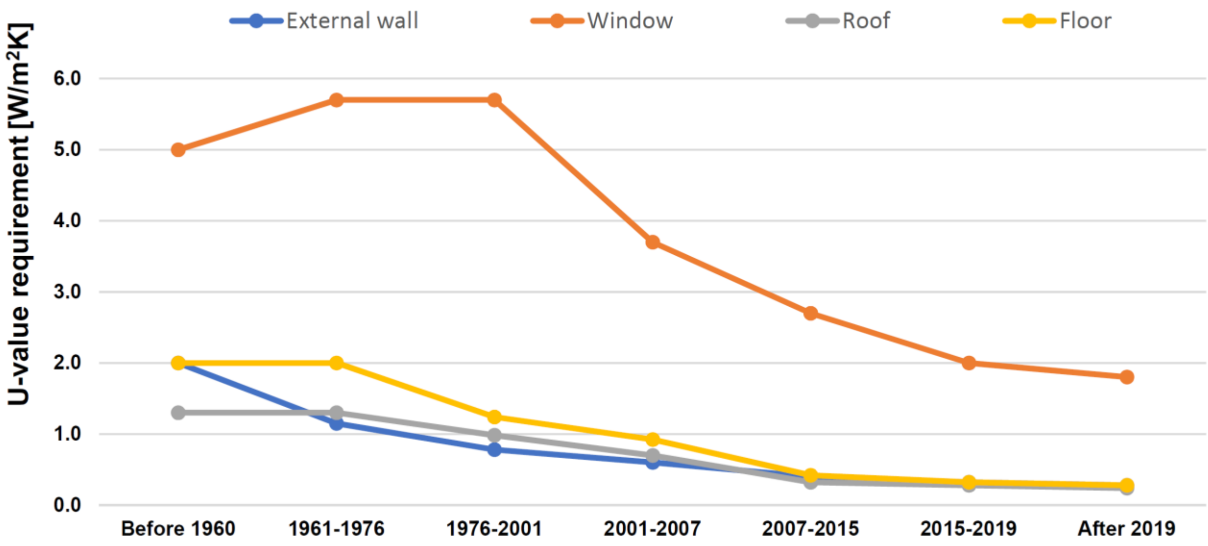


FIGURE 36 DEVELOPMENT OF THE REQUIRED U-VALUES FOR DIFFERENT BUILDING CONSTRUCTION PERIODS IN ITALY (ROME). DATA SOURCES: [76], [77]

References

[1] IEA and AIE, *World Energy Outlook 2018*. OECD, 2018.

[2] "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings." OJ L 153, pp. 13–35, 2010.

[3] "Directive (EU) 2018/844 of the European Parliament and of 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." OJ L 156, pp. 75–91, 2018.

[4] "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings." OJ L 1, pp. 65–71, 2002.

[5] S. Pezzutto *et al.*, "Hotmaps Project, D2.3 WP2 Report – Open Data Set for the EU28," 2018. [Online]. Available: www.hotmaps-project.eu.

[6] "Organisation for Economic Co-operation and Development. Glossary of statistical terms - Non-residential buildings." https://stats.oecd.org/glossary/detail.asp?ID=1833.

[7] "Eurostat. Glossary: Building." https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Building.

[8] S. Schimschar, J. Grözinger, H. Korte, T. Boermans, V. Lilova, and R. Bhar, "Panorama of the European non-residential construction sector." Ecofys, p. 88, 2011.

[9] "Eurostat. Energy consumption and use by households," 2020. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200626-1.

[10] "Eurostat. Share of final energy consumption in the residential sector by type of end-use, 2018," 2020. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Share_of_final_energy_consumption_in_the_residential_sector_by_type_of_end-use,_2018_(%25).png.

[11] M. Economidou *et al.*, "Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings," 2011.

[12] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy Build.*, vol. 40, no. 3, pp. 394–398, Jan. 2008, doi: 10.1016/j.enbuild.2007.03.007.

[13] C. Balaras, E. Dascalaki, K. Droutsa, M. Micha, S. Kontyiannidis, and A. Argiriou, "Energy use Intensities for Non-Residential Buildings," in *Proceedings of the 48th International HVAC&R Congress*, Dec. 2017, pp. 369–389, doi: 10.24094/kghk.017.48.1.369.

[14] P. C. Eames, "Vacuum glazing: Current performance and future prospects," *Vacuum*, vol. 82, no. 7, pp. 717–722, Mar. 2008, doi: 10.1016/j.vacuum.2007.10.017.

[15] H. Manz, S. Brunner, and L. Wullschleger, "Triple vacuum glazing: Heat transfer and basic mechanical design constraints," *Sol. Energy*, vol. 80, no. 12, pp. 1632–1642, Dec. 2006, doi: 10.1016/j.solener.2005.11.003.

[16] B. P. Jelle, S. E. Kalnæs, and T. Gao, "Low-emissivity materials for building applications: A state-of-the-art

review and future research perspectives," *Energy Build.*, vol. 96, pp. 329–356, Jun. 2015, doi: 10.1016/j.enbuild.2015.03.024.

[17] E. Cuce and P. M. Cuce, "Vacuum glazing for highly insulating windows: Recent developments and future prospects," *Renew. Sustain. Energy Rev.*, vol. 54, pp. 1345–1357, Feb. 2016, doi: 10.1016/j.rser.2015.10.134.

[18] T. E. Kuhn, C. Bühler, and W. J. Platzer, "Evaluation of overheating protection with sun-shading systems," *Sol. Energy*, vol. 69, pp. 59–74, 2001.

[19] B. Sourek, V. Jirka, V. Shemelin, and T. Matuska, "Experimental characterization of glazing with glass prisms," *Sol. Energy*, vol. 158, pp. 440–447, 2017, doi: https://doi.org/10.1016/j.solener.2017.08.087.

[20] R. S. Zakirullin and S. N. Letuta, "A smart window for angular selective filtering solar radiation," *Sol. Energy*, vol. 120, pp. 585–592, 2015.

[21] A. Cannavale, U. Ayr, F. Fiorito, and F. Martellotta, "Smart Electrochromic Windows to Enhance Building Energy Efficiency and Visual Comfort," *Energies*, vol. 13, no. 6, p. 1449, Mar. 2020, doi: 10.3390/en13061449.

[22] R. Baetens *et al.*, "Vacuum insulation panels for building applications: A review and beyond," *Energy Build.*, vol. 42, no. 2, pp. 147–172, Feb. 2010, doi: 10.1016/j.enbuild.2009.09.005.

[23] R. Baetens, B. P. Jelle, A. Gustavsen, and S. Grynning, "Gas-filled panels for building applications: A state-of-the-art review," *Energy and Buildings*, vol. 42, no. 11. Elsevier Ltd, pp. 1969–1975, Nov. 01, 2010, doi: 10.1016/j.enbuild.2010.06.019.

[24] S. R. Hostler, A. R. Abramson, M. D. Gawryla, S. A. Bandi, and D. A. Schiraldi, "Thermal conductivity of a clay-based aerogel," *Int. J. Heat Mass Transf.*, vol. 52, no. 3–4, pp. 665–669, Jan. 2009, doi: 10.1016/j.ijheatmasstransfer.2008.07.002.

[25] T. Gao, L. I. C. Sandberg, and B. P. Jelle, "Nano insulation materials: Synthesis and life cycle assessment," in *Procedia CIRP*, Jan. 2014, vol. 15, pp. 490–495, doi: 10.1016/j.procir.2014.06.041.

[26] Z. Hu, W. He, J. Ji, and S. Zhang, "A review on the application of Trombe wall system in buildings," *Renewable and Sustainable Energy Reviews*, vol. 70. Elsevier Ltd, pp. 976–987, Apr. 01, 2017, doi: 10.1016/j.rser.2016.12.003.

[27] Meadowlark. Design+Build, "Passive Energy Strategies. Passive House." https://www.meadowlarkbuilders.com/green-building/techniques-materials/advanced-building/passive-energy-strategies.

[28] R. Norouzi and R. Motalebzade, "Effect of Double-Skin Façade on Thermal Energy Losses in Buildings," in *Exergetic, Energetic and Environmental Dimensions*, Elsevier, 2018, pp. 193–209.

[29] D. J. Harris and N. Helwig, "Solar chimney and building ventilation," *Appl. Energy*, vol. 84, no. 2, pp. 135–146, Feb. 2007, doi: 10.1016/j.apenergy.2006.07.001.

[30] N. Artmann, H. Manz, and P. Heiselberg, "Climatic potential for passive cooling of buildings by night-time ventilation in Europe," *Appl. Energy*, vol. 84, no. 2, pp. 187–201, Feb. 2007, doi: 10.1016/j.apenergy.2006.05.004.

[31] V. V. Tyagi and D. Buddhi, "PCM thermal storage in buildings: A state of art," *Renew. Sustain. Energy Rev.*,

vol. 11, no. 6, pp. 1146–1166, Aug. 2007, doi: 10.1016/j.rser.2005.10.002.

[32] E. Solgi, R. Fayaz, and B. M. Kari, "Cooling load reduction in office buildings of hot-arid climate, combining phase change materials and night purge ventilation," *Renew. Energy*, vol. 85, pp. 725–731, Jan. 2016, doi: 10.1016/j.renene.2015.07.028.

[33] A. K. Pandey, V. V. Tyagi, J. A. Selvaraj, N. A. Rahim, and S. K. Tyagi, "Recent advances in solar photovoltaic systems for emerging trends and advanced applications," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 859–884, Jan. 2016, doi: 10.1016/j.rser.2015.09.043.

[34] A. Røyset, T. Kolås, and B. P. Jelle, "Coloured building integrated photovoltaics: Influence on energy efficiency," *Energy Build.*, vol. 208, p. 109623, Feb. 2020, doi: 10.1016/j.enbuild.2019.109623.

[35] P. Bonato *et al.*, "State-of-the-art and SWOT analysis of building integrated solar envelope systems," *IEA SHC Task*, vol. 56, 2019.

[36] T. Matuska, B. Sourek, V. Jirka, and N. Pokorny, "Glazed PVT Collector with Polysiloxane Encapsulation of PV Cells: Performance and Economic Analysis," *Int. J. Photoenergy*, vol. 2015, pp. 1–7, 2015, doi: 10.1155/2015/718316.

[37] M. van Veen, "Photovoltaic thermal hybrid solar collector," *Solar2Power*. https://solar2power.pt/photovoltaic-thermal-hybrid-solar-collector/.

[38] W. Weiss and M. Spörk-Dür, "Solar heat worldwide," *IEA Sol. Heat. Cool. Program.*, 2019.

[39] T. N. Anderson, M. Duke, and J. K. Carson, "The effect of colour on the thermal performance of building integrated solar collectors," *Sol. energy Mater. Sol. cells*, vol. 94, no. 2, pp. 350–354, 2010.

[40] J. Boudaden, R. S.-C. Ho, P. Oelhafen, A. Schüler, C. Roecker, and J.-L. Scartezzini, "Towards coloured glazed thermal solar collectors," *Sol. Energy Mater. Sol. Cells*, vol. 84, no. 1–4, pp. 225–239, Oct. 2004, doi: 10.1016/J.SOLMAT.2004.02.042.

[41] W. Weiss and I. Stadler, "Facade integration – a new and promising opportunity for thermal solar collectors," in *Industry Workshop*, 2001, pp. 59–63, Accessed: Jun. 03, 2020. [Online]. Available: http://www.task7.iea-shc.org/data/sites/1/publications/task26-proceedings-delft.pdf#page=59.

[42] A. Cali *et al.*, "A report of Task 14 Air Systems Working Group: low cost high performance solar airheating systems using perforated absorbers," *Washingt. Int. Energy Agency*, 1999.

[43] *ČSN 73 0540-2 Tepelná ochrana budov - Část 2: Požadavky*. Praha: ÚNMZ, 2011.

[44] "Gesetz zur Vereinheitlichung des Energieeinsparrechts für Gebäude und zur Änderung weiterer Gesetze," *BGBl. I*, vol. 37, p. 1728, 2020.

[45] R. Bordier, N. Rezai, and C. Gachon, "EPBD implementation in France. Status in December 2016." Concerted action. Energy performance of buildings, 2018.

[46] "Vademecum reglementering EPB-werkzaamheden. Gids van de eisen en procedures van de reglementering inzake EPB-werkzaamheden in het Brussels Hoofdstedelijk Gewest," 2017.

[47] "U-values from 2018 version (Flanders, Belgium)." Flemish Government, FlemishEnergy Agency (VEA), p. 1, 2018, [Online]. Available: https://www.energiesparen.be/sites/default/files/atoms/files/epbuwaarden2018.pdf.

[48] B. Fourez *et al.*, "EPBD implementation in Belgium – Walloon Region. Status in January 2017." Concerted action. Energy performance of buildings, 2018.

[49] E. Maldonado, Ed., *Implementing the Energy Performance of Buildings Derective (EPBD). Featuring County Reports*. Lisbon: ADENE, 2015.

[50] "Ministerial Decree 26/06/2015, Calculation Methodologies of the Building Energy Performance and Minimum Requirements for Buildings." Ministry of Economic Development, pp. 1–8, 2015.

[51] "Real Decreto 732/2019, de 20 de diciembre, por el que se modifica el Código Técnico de la Edificación, aprobado por el Real Decreto 314/2006, de 17 de marzo.," *Boletín Oficial del Estado*. Ministerio de Fomento, pp. 140488–140674, 2019.

[52] "Akcijski načrt za skoraj nič-energijske stavbe za obdobje do leta 2020 (AN sNES)." Ministrstvo za infrastrukturo, 2015.

[53] "Portaria n.º 379-A/2015," *Diário da República, 1.ª série — N.º 207*. Ministério do Ambiente Ordenamento do Território e Energia, pp. 9196(14)-9196(17), 2015.

[54] S. Polley, "Approved Document L: Conservation of fuel and power," in *Understanding the Building Regulations*, Routledge, 2012, pp. 203–246.

[55] G. M. Calvi, L. Sousa, and C. Ruggeri, "Energy Efficiency and Seismic Resilience: A Common Approach," in *Multi-hazard Approaches to Civil Infrastructure Engineering*, Cham: Springer International Publishing, 2016, pp. 165–208.

[56] T. De, N. Dans, and L. E. Logement, "La réglementation thermique," pp. 1–6, 2018.

[57] PHI, "Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard," *Passiv. House Inst.*, pp. 1–27, 2016, [Online]. Available: https://passiv.de/downloads/03_building_criteria_en.pdf.

[58] "OIB- Richtlinie 6. Energieeinsparung und Wärmeschutz." Österreichisches Institut für Bautechnik, 2019.

[59] E. Kontonasiou *et al.*, *Indoor air quality, thermal comfort and daylight*. Buildings Performance Institute Europe (BPIE), 2015.

[60] "Tasauslaskentaopas 2018. Rakennuksen lämpöhäviön määräystenmukaisuuden osoittaminen." YMPÄRISTÖMINISTERIÖ, 2017.

[61] "La perméabilité à l'air des bâtiments." SAINT-GOBAIN, Vaujours, p. 24, 2012.

[62] "Noteikumi par Latvijas būvnormatīvu LBN 002-01 'Ēku norobežojošo konstrukciju siltumtehnika,'" *Latvijas vestnesis*, vol. 125, no. 5443. Latvian Cabinet of Ministers, pp. 2005–2010, 2015.

[63] "STR 2.01.02:2016 „Pastatų energinio naudingumo projektavimas ir sertifikavimas"," *D1-754*. Lietuvos Respublikos aplinkos ministerija, Vilnius, p. 273, 2020.

[64] "Kwaliteitsrichtlijn Metalen gevels en daken 2020. Deel 2: Technische richtlijn," *Kwaliteitsrichtlijn*. p. 173, 2020.

[65] "SIST EN ISO 12631:2017 - Thermal performance of curtain walling - Calculation of thermal transmittance (ISO 12631:2017)." .

[66] "Portaria n.º349-B/2013," *Diário da República, 1.ª série — N.º 232*, vol. 1ª Série, no. 18. Ministério do Ambiente Ordenamento do Território e Energia, pp. 6624-(18) a 6624-(29), 2013.

[67] H. E. Beck, N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg, and E. F. Wood, "Publisher Correction: Present and future Köppen-Geiger climate classification maps at 1-km resolution," *Sci. Data*, vol. 7, no. 1, p. 274, Dec. 2020, doi: 10.1038/s41597-020-00616-w.

[68] E. Valor, V. Meneu, and V. Caselles, "Daily Air Temperature and Electricity Load in Spain," *J. Appl. Meteorol.*, vol. 40, no. 8, pp. 1413–1421, Aug. 2001, doi: 10.1175/1520-0450(2001)040<1413:DATAEL>2.0.CO;2.

[69] K. Papakostas, T. Mavromatis, and N. Kyriakis, "Impact of the ambient temperature rise on the energy consumption for heating and cooling in residential buildings of Greece," *Renew. Energy*, vol. 35, no. 7, pp. 1376–1379, Jul. 2010, doi: 10.1016/j.renene.2009.11.012.

[70] D. B. C. Lawrie and K. Linda, "Development of Global Typical Meteorological Years (TMYx)," 2019.

[71] J.-H. Song, S.-H. Park, M.-J. Park, J.-H. Lim, and S.-Y. Song, "Influence of Thermal Bridges on the Insulation Performance of Curtain Wall Panel Systems," *J. Asian Archit. Build. Eng.*, vol. 14, no. 3, pp. 741–748, Sep. 2015, doi: 10.3130/jaabe.14.741.

[72] L. F. B. da Silva, E. Thomaz, and L. A. de Oliveira, "Ventilated cladding systems: structural and drainability performance criteria," *Ambient. Construído*, vol. 18, no. 3, pp. 341–358, Sep. 2018, doi: 10.1590/s1678-86212018000300285.

[73] "Canada Mortgage and Housing Corporation (CMHC). 2004. Glass and Metal Curtain Walls: Best Practice Guide and Building Technology," p. 257, 2004.

[74] "BUILD2LC Project. Boosting Low Carbon Innovative Building Rehabilitation in European Regions. State of Art, SWOT analysis and identification of needs. Region: Podkarpackie," 38AD.

[75] C. Hůlka, "Vývoj a závaznost tepelně-technických požadavků," *Dektime*, vol. 1, pp. 34–42, 2007.

[76] D. A. Bournas, "Concurrent seismic and energy retrofitting of RC and masonry building envelopes using inorganic textile-based composites combined with insulation materials: A new concept," *Compos. Part B Eng.*, vol. 148, pp. 166–179, Sep. 2018, doi: 10.1016/j.compositesb.2018.04.002.

[77] V. Corrado, I. Ballarini, S. P. Corgnati, and N. Talà, "Building Typology Brochure--Italy," *Fasc. sulla Tipol. Edil. Ital.*, pp. 1–117, 2011.