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A review of performance of zero energy buildings and energy efficiency solutions

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ABSTRACT

The enhancement of energy performance of buildings has become a pillar of energy policies. The main target is the cut of energy consumption to reduce buildings footprint. This aim is pursued by introducing constrains on building requirements in terms of properties of basic materials and components and exploitation of renewable energy sources. That results in the definition of the zero-energy building (ZEB) concept. The new paradigm introduced new challenges and, at the same time, involved all the different stakeholders in facing the barriers to the diffusion of the novel solutions proposed by the research development.

This paper summarizes the actual state-of-art of whole performance of ZEBs and the related technical solutions, analysing their increasing potential in energy consumption. A collection of the different case studies reported in literature involving ZEBs is presented, compiling an analysis of the performance of the common solutions actually applied. The technologies involved are described discussing their impact in meeting the ZEB requirements. A debate is proposed, pointing out the main aspects deserving further investigations and outlining the critical elements in making the zero-energy target the new standard for the buildings.

1. Introduction

Since the oil crises of the 1970's, the scientific community, along with the worldwide governments, has been debating about the thermal and energy performances of buildings in an attempt to define new strategies for optimization [1]. Despite the efforts already made to face this problem, the subject is still of topical interest. The large number of both scientific publications and international financed projects strongly underlines the interest and the resources invested in the development of energy-efficient buildings [2]. Recent reports on worldwide energy consumption identify three main consuming areas collecting the different contributions: industry, transportation and buildings. Looking at worldwide statistics, the percentages associated to each of the contributions appear to be almost equal. In European countries and US the final energy consumption of building sector amounts to about 40%, which is a predominant portion of the total energy consumption; in China the highest impact is related to the industry sector (see Fig. 1). Moreover, the percentage considered could be further increased by including other aspects in the energy balance, such as the consumption related to people mobility [3] or the fraction of heat and power generation produced by the industry related to the construction of buildings and the heat and power generation.

The elaboration of the country-by-country worldwide statistics provided by the International Energy Agency (IEA) highlights an higher global energy consumption of residential buildings compared to commercial ones, due to the wider portion both in terms of number of buildings and floor area [4]. Residential is the most relevant sector in terms of total energy consumption almost everywhere, with EU countries, US and China at the top of the ranking (Table 1). Meanwhile, commercial sector presents the highest Energy Use Intensity (EUI) due to the high consumption for lighting and appliance, except for China where the space heating is the preponderant. The variability of the EUI (from 79.0 to 404.3 kWh/m^2 for the residential and from 75.9 to 567.6 kWh/m^2 for the commercial buildings) is affected by several factors: climate, social and cultural conditions, technological and economic development and energy policies must be evaluated in a general perspective to face the problem.

These factors are at the basis of the energy consumption habits of

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Nomenclature

ASHP	Air-Source Heat Pump
BAS	Building Automation System
BEMS	Building Energy Management System
BIO	Biomass
BIPV	Building Integrated Photovoltaic
CFL	Compact fluorescent lamp
CHP	Combined Heat and Power
CCHP	Combined Cooling, Heat and power
DC	District Cooling
DH	District Heating
DHW	Domestic Hot Water
EAHE	Earth-to-Air Heat Exchanger
ERV	Energy Recovery Ventilators
EUI	Energy Use Intensity
GHG	Greenhouse Gas Emission
GSHP	Ground-Source Heat Pump
HVAC	Heating Ventilation and Air-Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
HRV	Heat Recovery Ventilator
HP	Heat Pump
Hydro	Hydropower
LC-ZEB	Life Cycle ZEB
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LED	Light Emitting Diode
OLED	Organic Light Emitting Diode
PBT	Payback time
PCM	Phase Change Material
PV	Photovoltaic
PVT	Photovoltaic Thermal
RES	Renewable Energy Source
SHS	Solar Heating/Cooling System
ST	Solar Thermal
TC	Thermal Comfort
TES	Thermal Energy Storage
VAWT	Vertical Axis Wind Turbine
VIP	Vacuum Insulation Panel
VAWT	Vertical-Axis Wind Turbine
WSHP	Water-Source Heat Pump
WWR	Windows to Wall Ratio
ZEB	Zero Energy Building

each country (Fig. 2). The consumption for space and water heating is preponderant in the residential sector. In particular, for EU countries, the percentage related to this service represents more than two-thirds of the total consumption. The EU statistics [5] show a great variance in energy use for this service due to the large spectrum of the climatic conditions, with values lower than 100 kWh/m^2 in southern countries up to value higher than 200 kWh/m^2 in northern countries. Although these values are still high, they have decreased over the years thanks to an energy policies promoting both technological development and changes in the users' behaviour. In US a similar trend for space heating is reported with values ranging between 99 kWh/m^2 and 145 kWh/m^2 moving from southern to northern countries [6]. In Commercial buildings, final energy use is differently weighted and the consumption related to lighting, appliances and other uses rises up to 50% of the total, reaching in US an overall value of about 180 kWh/m^2 [7]. The international statistics underline two sensible issues to find a global standardized approach for the energy efficiency of buildings: one is the trend in the energy consumption not common for different countries, the other is the different final energy use. As a result, that calls for the development of different solutions in the different cases.

The most recent analyses and projections highlight future scenarios in which both total primary energy consumption and CO_2 emissions coming from energy consumption are set to grow [8]. In this field, the energy consumption related to buildings will play a key role [9]. To face this issue, many governments and international institutions, primarily based in the US and EU, have defined different sets of specific rules conceived to reduce the energy consumption of buildings and their environmental impact. This approach directly supports the improvement of energy performances of buildings and promotes the diffusion of solutions involving renewable energies. In this context, the role of Zero Energy Building (ZEB) has established itself as the standard reference for the target achievements in terms of balance between needs and self-sufficiency for a building under service conditions. Data on building, at both international and local level, underline the primary role played by existing buildings in achieving the target of an overall energy reduction for society, mainly because of their high number if compared to new ones, but also related to their poor performance level. Several policies adopted in different countries support the refurbishment of buildings by promoting the diffusion of modern technologies for the improvement of energy performance, reducing their environmental, economic and social impact. Such initiatives are oriented to identify methods and solutions able to match the requirements imposed by new laws [10,11], starting from a detailed analysis of the data collected related to specific building categories (residential [12,13], offices [13], schools [14], public buildings [15]). The main institutions worldwide have supported ZEBs. European and American plans for future developments of cities and energy saving promote the construction of an increasing number of near-ZEBs (i.e. "a building with high energy efficiency" for which "the nearly zero or very low amount

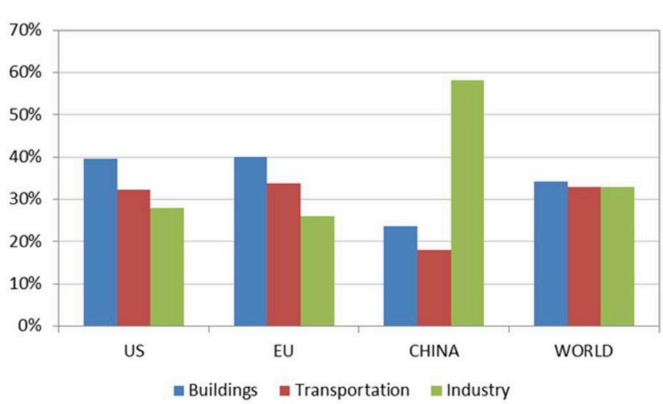

Fig. 1. Final energy consumption by sector referred to 2015. Elaboration from: US, Energy Information Administration, US, 2015; Europe, Eurostat Data 2015; China and World, International Energy Agency report, 2015.

Table 1
Total energy consumption and EUI for eight countries/region of the world. Data elaborated from Ref. [4].

Country	Residential		Commercial	
	Total [EJ]	EUI [kWh/m^2]	Total [EJ]	EUI [kWh/m^2]
ASEAN	4.6	149.3	0.9	199.5
Brazil	1.0	79.0	0.4	285.6
China	14.9	96.6	2.8	75.9
EU-Countries	12.8	177.2	6.5	223.0
India	7.2	160.8	0.6	214.8
Russia	4.7	404.3	1.6	567.6
South Africa	0.6	188.8	0.2	197.7
US	11.2	135.6	8.6	317.1

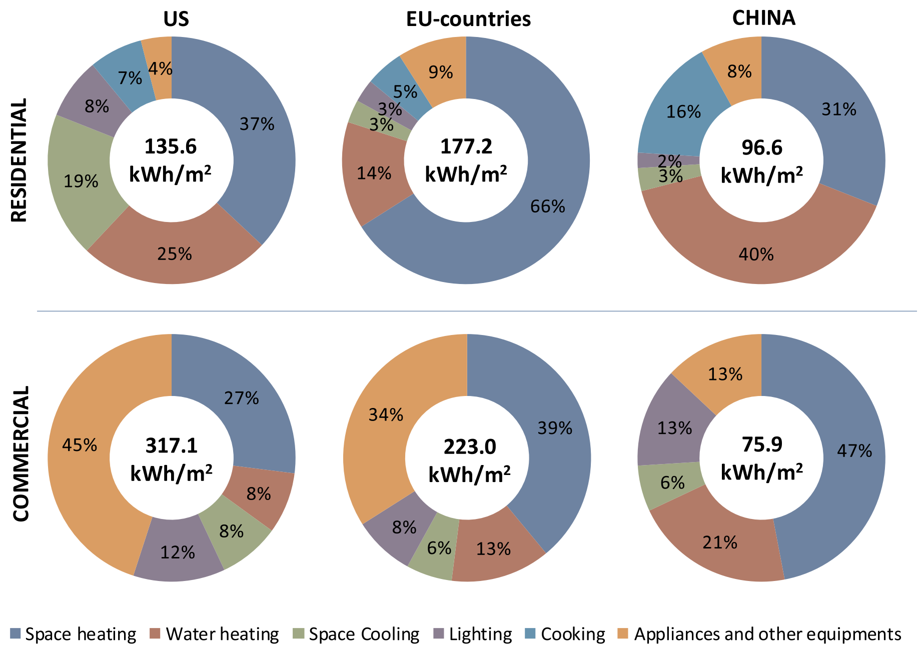

Fig. 2. Final energy consumption by end-use in 2010. Data elaborated from Ref. [4].

of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby") or ZEBs. Public database shows how other countries, such as China, India and Latin American States, which are potentially among the highest energy consumers, are still not in line with this trend even if significant steps have been taken [16,17].

The aim of this work is to collect the data reported in literature on design and real ZEBs worldwide. The main focus is the recognition of the common features characterizing the different case studies and the evaluation of the effectiveness of the different components in matching the conditions imposed by the ZEB requirements. The parameters involved are evaluated in terms of scalability, validity in different climatic conditions and sustainability facing the different local policies. Moreover, the comparative analysis carried out suggests new methods to overcome current limitations. Another important aspect of this review is the evaluation of retrofitting accessibility of the different solutions proposed for the existing buildings. A large number of existing buildings are still excluded from the energy update for optimization. In particular, in those countries such as in Europe, where a large number of historical buildings are still used for public or private use, the attempt to meet the increasing energy standards required by the policies results to be too expensive or not applicable. On contrary, defining a plan oriented to retrofitting solutions for building efficiency update, even if hard to apply, should contribute in a significant way to an overall reduction in building energy consumption thanks to the large-scale access to such alternative.

2. Literature review

The concept of ZEB was introduced in the early 2000's [18] and strongly emphasized over the years [19]. Thanks to worldwide initiatives, it has rapidly spread worldwide, both in terms of concept and real applications [20]. The new challenge of ZEB performance is a holistic overview in which the building is seen from an energy, environmental and economic perspective [21], in close connection with the built and natural environment and end users [22].

The literature here analysed comprises peer-reviewed papers and books written in English, focused on ZEBs during the time period from early 2000s up to December 2018. The main database that we searched is Scopus, which is the largest database of peer-reviewed literature. In each research string the keywords used for the selection of articles are "Zero Energy Building", "Zero Energy Renovation", "Zero Energy Retrofit". We obtained a total of about 1500 papers from this raw search, excluding the non-authored papers. The issues addressed are heterogeneous and deal with the issue from different points of view: role of ZEBs in mitigating major environmental issues (climate change) and their integration in smart cities, assessment of the whole buildings performance, potentials of specific technical solutions are the most frequent covered topics. Among them we've been concentrating on the references related to the assessment of the performance of whole building. The initial selection was made considering each paper's title, abstract and keywords, with a total of 175 papers extracted. Once this group of papers had been identified, a secondary screening was carried out to refine the selection, based on the full text read of each paper. The criteria adopted for the choice are related to the quality and completeness of data related to: location, thermal properties of the envelope, performance of the generation systems, renewable energy production and overall performance of the building. Only the papers referred to case studies with ZEB performance were considered. Duplications in case studies were avoided by excluding the relative papers. The approach allows to identify and analyse 74 papers, reported in Table 2 in order of year of publication. This list includes all case studies potentially referring to real buildings; laboratory buildings are excluded from the count. More than 50% of case studies are placed in Southern Europe (Italy -IT, Spain -ES, Portugal -PT, Greece -EL- and the islands of Cyprus -CY- and Malta -MT) and 32 are in Italy. In Baltic Region (Sweden -SW, Finlandce -FR, Ireland -IE, United Kingdom -UK). -FI, Norway -NO, Denmark -DK, Estonia -EE, Latvia -LV) and in Eastern Europe (Poland -PL, Romania -RO, Austria -AT, Serbia -SER) 13 and 6 case studies are counted, respectively. Five case studies are placed in Central Europe and United Kingdom (FranFinally, 11 case studies are placed in extra European countries with different climatic condition (United State -USA, Australia -AU, China CH, Singapore, Hong Kong, Middle East and North Africa -MENA, India). The attention of the authors is mainly paid on residential buildings, indeed 43 references analyse this intended use, including hotels. Educational buildings are the second analysed category and tertiary buildings, including commercials, the third one. More than two thirds of case studies focus on the retrofit of existing buildings. Starting from this varied set, in the following chapters the ways the different authors deal with the problem

Table 2
List of analysed references.

Refs	Year	Location	HDD[a]	Building	Use	Intervention	Assessment	Performance
[23]	–	IE - Wexford	2570	Real	RES	New	Measured	Energy, cost, TC
[24]	1956	PL - Warsaw	3201	Real	RES	Retrofit	Calculated	Energy, TC
[25]	1960	ES - Bilbao	1827	Real	RES	Retrofit	Calculated	Energy, cost
[26]	1970	PL - Warsaw	3135	Real Virtual	RES	Retrofit	Calculated	Energy, cost
		PL - Szczecin	3013					
		PL - Suwałki	3641					
[27]	–	Singapore	–	Real	TER	New	Calculated	Energy, cost
[28]	1980	IT - Bologna	2034	Real	RES	Retrofit	Calculated	Energy
		LV - Riga	3648					
		EL - Athens	1169					
[29]	–	ES - Valladolid	2025	Real	TER	New	Calculated	Energy
[30]	–	IT - Bologna	2034	Real	RES	New	Calculated	Energy, TC
[31]	1937	IT - Bologna	2034	Real	RES	Retrofit	Calculated	Energy, cost
[32]	1935–1940	IT - Pavia	2623	Real	RES	Retrofit	Calculated	Energy, cost
[33]	1986	EE - Tallinn	4248	Real	RES	Retrofit	Calculated	Energy
[34]	Before 1900	IT - Agrigento	970	Real	TER	Retrofit	Calculated	Energy
[35]	1960	IT - Milan	2404	Real	TER	Retrofit	Calculated	Energy, cost
[36]	–	EL - Thessaloniki	1788	Virtual	RES	New	Calculated	Energy, cost, LCA
[37]	1992–2006	ES - San Sebastian	1702	Real	RES	Retrofit	Calculated Measured	Energy, TC
[38]	1980	IT - Modena	2055	Real	RES	Retrofit	Calculated	Energy, TC
[39]	Before 1940	IT - Milan	2404	Real	RES	Retrofit	Calculated	Energy, cost
[40]	–	CY - Peyia	720	Real	RES	New	Calculated	Energy
[41]	1940	IT - Turin	2805	Real	EDU	Retrofit	Calculated	Energy, cost
[42]	–	IT - Catania	1215	Real	RES	New	Calculated Measured	Energy
[43]	2004	CY - Nicosia	720	Real	RES	Retrofit	Calculated	Energy, cost
[44]	–	Hong Kong	142	Real	EDU	New	Calculated	Energy
[45]	1970	FI - Helsinki	4367	Virtual	RES	Retrofit	Calculated	Energy, cost
[46]	1921–1945	IT - Turin	2805	Virtual	Hotel	Retrofit	Calculated	Energy, cost, TC
[47]	Before 1900	IT - Naples	1117	Real	EDU	Retrofit	Calculated	Energy, cost
[48]	–	CY - Famagusta	720	Real	EDU	Retrofit	Calculated	Energy, IL
[49]	1930	IT - Treviso	1944	Real	EDU	Retrofit	Calculated	Energy, cost
[50]	1960–1975	IT - Pisa	1415	Real	EDU	Retrofit	Calculated	Energy
[51]	1950–1980	FI - Tampere	4713 2753	Real	RES	Retrofit	Calculated	Energy, cost, LCA
		SER - Belgrade						
[52]	1990	IT - Benevento	1462	Real	EDU	Retrofit	Calculated	Energy, cost, TC
[53]	1960–1979	FI - Lappeenranta	4757	Real	EDU	Retrofit	Calculated	Energy, cost
[54]	1960	IT - Turin	2805	Real	EDU TER	Retrofit	Calculated	Energy, cost
[55]	1946–1964	NL - Maastricht	2486	Real	RES	Retrofit	Calculated	Energy, LCA
[56]	5702	USA - MA	5702	Real	COM	Retrofit	Calculated	Energy
[57]	Before 1900	IT - Agrigento	970	Real	TER	Retrofit	Calculated	Energy, cost
[58]	1950 1977	IT - Lecce	1192	Real	EDU	Retrofit	Calculated	Energy, cost
[59]	–	CH - Tianjin	2865	Virtual	TER	New	Calculated	Energy
[60]	1974	ES - Pontevedra	1370	Real	RES	Retrofit	Calculated	Energy, cost
[61]	–	MENA	0–1508	Virtual	RES	New	Calculated	Energy, cost
[62]	1999	Kuwait	371	Real	EDU	Retrofit	Calculated	Energy
[63]	1990	PT - Porto	1156	Real	RES	Retrofit	Calculated	Energy, cost
[64]	–	Estonia	4208	Real	RES	New	Calculated	Energy
[65]	1960–1977	FI - Southern	4487	Real	RES	Retrofit	Calculated	Energy, cost
		NL - Netherland	2544	Real				
		RO - Timisoara	2592	Real				
		ES - Bilbao	1575	Real				
		SW - Stockholm	3884	Real				
[66]	n.a.	IT - Milan	2404	Real	EDU	Retrofit	Calculated	Energy, TC
[67]	Before 1900	AT - Wien	2468	Real	EDU	Retrofit	Calculated	Energy, cost
[68]	1928	USA - IN	5699	Real	RES	Retrofit	Measured	Energy
[69]	–	MT - Gozo Island	485	Virtual	Hotel	New	Calculated	Energy
[70]	1963	CY - Nicosia	720	Real	RES	Retrofit	Calculated	Energy
[71]	–	IT - Lecce	1192	Virtual	TER	New	Calculated	Energy, cost
[72]	–	IT - Lecce	1192	Virtual	RES	New	Calculated	Energy, cost
[73]	–	EG - Alexandria	327	Virtual	RES	New	Calculated	Energy
[74]	–	IT - Turin	2805	Virtual	RES	New	Calculated	Energy, cost
[75]	1997	EL - Chania	962	Real	TER	Retrofit	Calculated	Energy
[76]	2007–2013	IT - Rome	1385	Real	Airport	Retrofit	Calculated	Energy, cost
[77]	–	CH -Beijing	2865	Virtual	RES	New	Calculated	Energy
[78]	1990	IT - Brescia	2559	Real	EDU	Retrofit	Calculated	Energy
[79]	–	India - New Delhi	–	Real	TER	New	Calculated	Energy, cost
[80]	Before 1900	IT - Treviso	1944	Real	RES	Retrofit	Calculated	Energy, cost
[81]	1970–1990	Estonia	4208	Real	RES	Retrofit	Calculated	Energy, cost
[82]	–	IT - Southern	1456	Virtual	RES	New	Calculated	Energy, cost
[83]	–	FR - Lyon	2334	Real	RES	New	Calculated	Energy
[84]	–	IT - Milan	2404	Real	TER	New	Calculated	Energy
[85]	–	IT - Perugia	2110	Real	TER	New	Calculated	Energy, LCA
[86]	1960	IT - Varese	2234	Real	EDU	Retrofit	Calculated	Energy, cost
[87]	n.a.	PT - Porto	1156	Real	RES	Retrofit	Calculated	Energy, cost

(continued on next page)

Table 2 (*continued*)

Refs	Year	Location	HDD[a]	Building	Use	Intervention	Assessment	Performance
[88]	–	DK - Copenhagen	3060	Real	RES	Retrofit	Measured	Energy
[89]	Before 1900	IT - Siracusa	1102	RES	Hotel	Retrofit	Calculated	Energy, cost
[90]	2008	AU - Queensland	–	Real	RES	New	Measured	Energy, TC
[91]	–	PT - Lisbon	686	Virtual	RES	New	Calculated	Energy, cost
[92]	–	Estonia	4208	Virtual	RES	New	Calculated	Energy, cost
[93]	1980	NO - Oslo	4714	Real	RES	Retrofit	Calculated	Energy, cost
[94]	–	IT - Lecce	1192	Real	RES	New	Calculated	Energy
[95]	–	DK - Aalborg	3149	Virtual	RES	New	Calculated	Energy, cost
[96]	–	UK - Cardiff	2275	Virtual	RES	New	Calculated	Energy

[a] Sources: Eurostat, Eurima

of ZEBs are analysed.

2.1. ZEB definitions

Before evaluating the technical and methodological approaches adopted to face the optimization of the building energy performances, it is important to define ZEB by understanding its critical aspects. The most important aspect is represented by the capability to give a proper definition of ZEB. Williams et al. [97] provide an extensive list of the current definitions of ZEB, highlighting a certain lack of homogeneity among them and calling for a universally recognized definition. The apparent lack of uniformity is intrinsic in the currently accepted definition of ZEB [98,99], and it is naturally related to several variables affecting the building sector. The absence of a common definition not only affects the possibility of designing an unambiguous profile for the global community and consequently a shared target for a global policy on energy-efficient building, but also raises great difficulties in comparing different solutions coming from different backgrounds. The basic idea is to design a building with zero balance between the energy required for its operation and the energy that can be produced, on- or off-site, by the building itself, under a series of imposed requirements such as, for example, the reduction of the energy demand and the energy produced from renewable sources. Starting from the statement, the identification of the different characteristics defining the ZEB concept is strongly dependent on the chosen approach and the target has to be defined in a very clear way in order to promote and allow an effective approach for the technological evolution of buildings.

The problems associated to the ZEB definition also affect the design of a building: the models of single parts, as well as the assembly of structural and technological solutions are already being widely analysed and reported in detail. The evaluation of the final balance suffers from the complexity of the analyses involved in the final integration and in the identification of parameters. Most of the models proposed for ZEB evaluation and definition take into account the energy performance of buildings in its theoretical self-sufficiency: the power absorbed, for example, is usually considered for the general services integrated in the system (lighting, climate, thermal insulation and hot water availability) without considering the end-user contribution to the power consumption. Recently, an increasing number of studies are approaching the ZEB question from the life cycle point of view, applying Life Cycle analyses (LCC and LCA) [100]. A zero life cycle energy balance in a building means that the sum of primary energy used in operation and the energy embodied in its constituent elements has to be equal to or lower than the energy produced by its renewable energy systems over its lifetime [101]. This approach strongly affects the ZEB effectiveness. The energy need and the potential environmental impacts reduction are strictly related. Although this can be considered a good definition of the ZEB concept, it still overlooks the variation, generally a degradation, of the performances due to both aging and user behaviour.

2.2. The real case studies

The two fundamental requirements to achieve the ZEB target are, on the one hand, the application of energy efficiency measures, related to both building envelope, services and indoor conditions and, on the other hand, power self-sufficiency based on renewable sources. The design approach to meet such requirements depends on both intrinsic and extrinsic variables of the building itself and the context.

New or existing buildings meet needs related to constrains associated to the building itself, while related to the context and the existing features. The building typology, concerning constructive, distributive and functional characteristics, represents a further discriminating factor in dealing with the performance requirements, influencing the choice of the measures to be adopted for energy saving and the use of renewable energy sources. Common approaches can be detected for the reduction of the energy demand, due to the similar requirements imposed by the different local regulations. High insulated envelope, mechanical ventilation, heat pumps and district heating are the most widespread technological solutions [102], according to the hierarchical pathway proposed by Ref. [103].

2.2.1. New buildings

The performances of new buildings are increased over the years as a function of the improvement of both available technical solutions and constraints imposed by the regulations updates. The buildings included in the case studies have different intended uses and are located in different climatic regions characterized by warm, cold and mild climatic conditions. In new constructions, the design of geometry and morphology (shape factor, window-to-wall ratio - WWR) allows to properly handle the loads. The design choices are driven by the balance between energy requirements (thermal losses and solar gains) and internal comfort levels. In colder regions, buildings are generally designed with a low shape factors as to be as compact as possible, aiming the optimization of the thermal flows. The values detected and reported in the case studies are mainly comprised between $0.16\,m^{-1}$ in Ref. [76] and $0.47\,m^{-1}$ in Ref. [71]. In Arumägi et al. [64], the building was designed with a shape factor higher than $0.50\,m^{-1}$, even if the building is located in a cold region, and the achievement of the ZEB requirements was followed working on the envelope and system performance. In warm regions, the orientation and the WWR are investigated measures to manage the overheating risk. The common trend in the case studies is to reduce the WWR minimizing the solar gains, setting values lower than 0.50. Where the energy consumption related to artificial lighting reaches a relevant weight on the overall needs, WWR rises above 0.50 exploiting natural daylighting in combination with management and control systems.

The choice of the best technical solutions for the fulfilment of energy requirements is strongly law-oriented. The examined buildings are mainly placed in European States, relying on local regulatory frameworks on energy efficiency. In these countries, building envelope is developed with the aim at reducing energy losses in winter and limiting overheating in summer. In cold climates the design of envelope with very high-thermal performance, for both opaque and transparent elements, is an essential condition to meet the ZEB requirements. In warm climates, instead, the insulating role of the envelope depends on microclimatic conditions: no or low insulation level is recommended where thermal excursion between day and night is relevant, exploiting the free cooling effect [61]. In mild climates the control of solar radiation through transparent components allows the optimal exploitation of the effect of free gains and ensures a good level of internal comfort conditions, with a maximization in winter and minimization in summer. These results are typically achieved by applying internal or external shading systems (blinds, overhang elements, etc.) operating according to the position of the or using glazing elements with low solar factor. Internal lighting is strictly connected with glazing systems. LED lamps are coupled with the daylighting systems and equipped with control system for the minimization of electric consumption and maximization of visual comfort.

Air circulation management and power supply design emerge as a critical aspect in ZEB achievement. Natural ventilation is the primary solution to take advantage of the natural sources reducing the cooling load and electric consumption but mechanical ventilation is often the preferred solution coupling the mechanical systems with heat recovery units and exploiting the free-cooling benefits.

Concerning the power supply, the review of the literature underlines that ground source heat pumps (HP) coupled with photovoltaic (PV) panels are the most diffused systems. The efficiency of this solution largely increased in the recent years enabling a wider diffusion of PV in almost all the geographical regions as respect to other power production system, but the effectiveness is strongly dependant by the latitude, so that, moving to north, the surface need to satisfy the building power requirements increases, shifting from locally distributed generation to district power management.

Finally, several authors highlight the importance of power consumption and environmental management in buildings. These targets can be achieved using advanced and smart controls of building systems. When evaluating real buildings, the authors' choice comes down to Building Energy Management System (BEMS) solutions in order to manage the technical systems within the building [59,76,79,104]. Control strategies on heating, cooling and ventilation are aimed at ensuring the indoor comfort conditions such as the set-point temperatures and the air flow rate [64,69,71].

2.2.2. Retrofitted buildings

In retrofit interventions more attention has to be paid to the actual characteristics of the existing buildings. The reference literature on

Table 3
Energy consumption and energy production in renovation of residential existing buildings.

Climatic zones[a]	*Ref.*	Energy consumption								Energy production				Target
		Before renovation				After renovation								
		Heat	DHW	Cool	Electr	Heat	DHW	Cool	Electr	PV	ST	Wind	Bio	
		kWh/m²				kWh/m²				kWh/m²				
Zone 1	[25]	47.8	33.6	–	35.0	68.1		–	35.0	8.1	–	–	–	nZEB
	[28]	117.3	–	12.7	–	9.5	–	11.4	–	–	–	–	–	nZEB
		44.2	–	30.9	–	4.2	–	25.3	–	–	–	–	–	nZEB
	[31]	188.0	18.0	–	–	4.7	5.7	–	–	41.2	–	–	–	nZEB
	[32]	232.7	13.3	–	–	13.9	6.39	–	–	6.19	15.4	–	–	nZEB
	[37]	38.4	–	–	22.9	16.1	–	–	22.9	3.6	–	–	–	nZEB
	[43]	35.6	7.4	47.3	15.8	10.8	12.7	9.5	7.3	116.5		–		ZEB
	[60]	266.4	38.9	–	–	45.7	76.4	–	–	–	11.7	–		nZEB
	[63]	335.0		–		84.9		–	–	–	–	–	–	nZEB
		335.0		–		84.9		–	–	84.9	–	–	–	ZEB
	[65]	81.0	33.0	–	9.0	20.0	35.0	–	9.0	12.4	–	–	55.0	nZEB
	[70]	20.8	8.7	126.6	16.5	1.2	8.3	9.2	12.0	34.2	–	–	–	ZEB
	[80]	342.7	44.4	–	45.0	42.3	33.6	–	20.0	6.56		–	–	nZEB
	[87]	237.2	15.0	1.4	12.5	59.5	15.0	1.6	11.1	–	–	89.6	–	nZEB
		134.0	33.0	0.9	44.1	34.72	38.32	1.33	39.1	–	–	113.5	–	nZEB
	[89]	112.0[2]		[2]	24.9	27.0[2]		[2]	24.9	40.1	–	–	–	nZEB
Zone 2	[24]	140.8	69.1	–	88.6	19.7	26.0	–	30.7	58.6	–	–	–	nZEB
	[51]	130	–	5.5	–	55.0	–	3.5	–	–	–	–	–	nZEB
		130	–	13.0	–	35.0	–	8.5	–	–	–	–	–	nZEB
	[65]	177.0	15.0	–	21.0	63.0	15.0	–	8.0	2.0	15.0	–	–	nZEB
Zone 3	[55]	121.7	–	–		55.7	–	–	–	129	–	–	–	LC-ZEB
		81.9	–	–		35.4	–	–	–	134	–	–	–	LC-ZEB
	[65]	107.00	16.0	–	4.0	5.00	6.00	–	7.0	20.5	–	–	–	nZEB
Zone 4	[28]	204.8	–	0.4	–	28.1	–	0.9	–	–	–	–	–	nZEB
	[33]	149.0	30.0	–	35.0	10.0	30.0	–	40.0	4.0	23.0	–	–	nZEB
	[51]	130.0	94.0	–	44.0	19.0	10.0	–	35.0	n.a.	n.a.	–	–	nZEB
	[65]	130.0	51.0	–	44.0	19.0	10.0		35.0	10.8	–	–	–	nZEB
		103.0	29.0	–	10.0	33.0	22.0	–	8.0	n.a.	–	–	–	nZEB
	[81]	131.0	30.0	–	30.0	15.0	30.0	–	35.7	5.5	21.0	–	–	nZEB
	[93]	145.0	–	–	–	24.0	–	–	–	–	16.8	–	–	nZEB
Extra	[68]	159.1	22.3	9.0	31.9	46.7				46.3	–	–	–	ZEB

[2] Primary energy consumption related to space heating and cooling.

[a] Climatic zones.

- Zone 1: Southern Europe, temperate climate with hot summer
- Zone 2: Eastern Europe, temperate/humid continental climate with warm summer
- Zone 3: Central Europe, temperate climate without dry season and warm summer
- Zone 4: Baltic region, cold climate with cold summer
- Extra: Extra European countries

these buildings is wider respect to the new ones both in terms of geographic location and year of construction. Table 3 (residential buildings), Table 4 (educational buildings) and Table 5 (tertiary buildings) summarize the results of the analysis in terms of energy consumption, after and before the renovation, renewable energy production, and energy target achieved. The case studies are grouped as a function of the climatic conditions by aggregating the climatic zones proposed in Refs. [105,106] reported in Table 2. The analyses lead to some common considerations related to the adopted solutions.

Thermal insulation of both opaque and transparent envelope is the common denominator of the retrofit. The improvement of the thermal performance of the opaque elements is sought mainly through the application of external or internal insulation systems, as a function of the existing, typically historical, constraints. In particular contexts, the thermal insulation of existing elements is obtained by filling the walls, roofs and floors cavities with insulating materials or using very thick insulating materials to achieve the performance requirements [68]. In some cases, professionals rely on new technologies for improving the performance of the building envelope. In the refurbishment of a historical Danish multi-family building [88], the improvement of thermal performance of building envelope is obtained by installing innovative solutions such as VIPs and aerogel panels on the interior of walls and in window reveal. In AbuGrain et al. [48], the refurbishment of the building envelope provides the installation of PCM for the reduction of cooling loads. The insulation thicknesses and the technological solutions in some cases, implies the achievement of performances well below half of such value levels [38,45,53,65,66,81,93]. Likewise, the assessment of the current state of existing windows allows the optimization of the interventions from the energy and economic point of view, by replacing only low-performance elements [67]. Solar shading systems are used to optimize both solar gains and internal lighting by acting on the thermal performance of the glazing system using either fixed devices or automated solutions, in particular in mild climate, to control free gains [48,62,70,87] and in buildings where the indoor lighting control is relevant [55,76]. The reduction of energy needs is an unavoidable condition of the building retrofit, but attention must be paid to the specific boundary conditions and to the economic feasibility of the intervention: in Ferrari et al. [35] the increase of the thermal insulation level beyond the standard is not economically convenient.

The control of the ventilation is a crucial aspect in buildings refurbishment both in terms of infiltration and energy losses. The envelope of existing buildings could face with critical issues and cannot guarantee the required levels of air permeability because of the increase of infiltration. In this case, the first step is to restore the air tightness of the envelope with measures targeted to glazing and opaque elements. The choice of the best solution for ventilation system has to take into account the structural and technological limits related to the building shape and morphology, the degree of invasiveness of the refurbishment intervention, in addition to the energy, environmental and economic requirements. A twofold trend can be noticed between southern and northern countries as far as residential buildings are concerned: in the former, the exploitation of natural ventilation with standardized air flow rates, in the latter, mechanical ventilation is the preferred solution. Holopainen et al. [65] highlight how northern countries, such as Finland and Sweden, have gained extensive experience in implementing ventilation systems for residential buildings. In buildings with natural ventilation, the installation of mechanical systems often requires a deep renovation of the building shape and morphology [38,68,81]. As far as the educational category and buildings with different intended uses are concerned, mechanical systems are the most common technology used for the ventilation of the indoor environment. With respect to the hygro-thermal conditions and the indoor air quality, the satisfaction of a large number of users requires the use of technologies able to manage several climatic variables (temperature, humidity, pollutants, CO_2, etc.).

From the point of view of energy generation, refurbishment strategies are similar to those observed for new buildings: HP with different energy sources (air, water or ground) coupled with PV panels is the most common solutions. However, alternative solutions are adopted to reach the ZEB requirements. The residential building is the most heterogeneous category under this point of view. Traditional [81,87] and biomass boilers [60,65], Combined Heat and Power (CHP) [38] and district heating (DH) systems [65] are suitable solutions for ZEBs. The high energy performances of such systems make them suitable to reduce the energy demand without previous refurbishment of the building envelope. In Patiño-Cambeiro et al. [60], the substitution of the existing electric heater with an high performance gas or biomass boiler guarantees a consistent reduction of the primary energy demand higher than 50%. However, as in the case of interventions on the envelope, these technologies alone are not enough to reach the ZEB requirements. Technical solutions for the improvement of both the envelope and the technological systems have to be integrated and embedded for the common goal. The control strategies of the building flows have to be considered among them. The new European Directive on building energy performance emphasizes the importance of the buildings smartness for enhancing energy savings, benchmarking and flexibility. The application of control strategies will become mandatory to achieve the indoor comfort conditions [37,86] and to manage the energy consumptions [68].

As shown by the common definitions, a ZEB requires the exploitation of renewable sources. Among them solar radiation is the most diffuse source and PV panels are the widest solutions thank to the possibility of self-production and energy exportation to the grid. At the same time, PV usually match the needs for retrofitting use being self-

Table 4
Energy consumption and energy production in renovation of educational existing buildings.

Climatic zones[a]	*Ref.*	Energy consumption								Energy production				Target
		Before renovation				After renovation								
		Heat	DHW	Cool	Electr	Heat	DHW	Cool	Electr	PV	ST	Wind	Bio	
		kWh/m^2				kWh/m^2				kWh/m^2				
Zone 1	[50]	222.9	0.6	–	31.0	23.5	0.0	–	15.9	4.8	–	–	–	nZEB
	[58]	227	54	67	67	76	54	22	24	5.7	–	–	–	nZEB
		203	60	95	48	49	60	52	24	n.a.	–	–	–	nZEB
	[66]	202.7	–	–	35.32	22.66			18.53	45.30	–	–	–	nZEB
	[78]	104.7[a]	–	[a]	–	65.3[a]		[a]	–	49.2	–	–	–	nZEB
	[86]	108.7	–	–	–	~38	–	–	–	~38	–	–	–	nZEB
Extra	[62]	348[b]	–	[b]	[b]	136.6[4]		[b]	[b]	154.3	–	–	–	ZEB

[a] Primary energy consumption related to space heating and cooling.
[b] Primary energy consumption related to space heating and cooling and electric services.

Table 5
Energy consumption and energy production in renovation of existing buildings with different intended uses.

Climatic zones[a]	*Ref.*	Energy consumption								Energy production					Target
		Before renovation				After renovation									
		Heat	DHW	Cool	Electr	Heat	DHW	Cool	Electr	PV	ST	Wind	Bio	Hidro	
		kWh/m^2				kWh/m^2				kWh/m^2					
Zone 1	[34]	~12.5	–	~12.5	~40.0	~2.8	–	~1.2	~16.0	~20.0	–	–	–	–	ZEB
	[35]	159.7[a]	–	[a]	[a]	66.6[a]	–	[a]	1	58.0	–	–	–	–	nZEB
	[57]	120.29				21.92				60.65	–	–	–	–	nZEB
	[75]	8.0	–	29.0	38.7	5.0	–	5.0	23.9	14.5	–	12.5	–	–	nZEB
Extra	[56]	378				164				~87	–	~39	~23	~45	ZEB

[a] Primary energy consumption related to space heating and cooling and electric services.

standing elements easily installed and embodied into the buildings. If the energy performance of the technology is not questioned even in a life cycle perspective [55], attention must be paid on the economic feasibility of such systems [32]. The system has to be designed for the real needs of the building to overcome this issue [34]. Even if solar radiation is the most common renewable source, wind energy can be exploit if specific boundary conditions are met. The characteristics of the built environment (giving rise to a more turbulent and reduced wind flow), the climatic conditions of the site (in terms of wind speed), the intermittence of the energy source (the highest wind velocity occur often in winter) besides the characteristics of the building itself (designed to augmented wind speed) affect the choice of such solution [109].

Lighting and equipment consumption represents a non-negligible percentage of the overall energy requirement of a building, especially in the tertiary sector [35]. The use of artificial lighting and control systems is often required to achieve the optimal indoor visual comfort of users. The use of LED, CFL or low-energy bulb coupled with luminance/presence control is the optimal practice to significantly reduce the energy needs. The use of high efficiency appliances is also mandatory.

The so far carried out analyses lead to the following considerations. The first is that building renovation and design cannot be analysed under a single point of view but have to be investigated from a multi-domain perspective, where energy, indoor environmental quality (IEQ) and pollutant emissions compete on the same level. The systemic approach for the achievement of ZEB standard where all the technical solutions are integrated with each other and with the built environment, is equally significant. The actual availability of materials, technical solutions and systems requires a multi-objective assessment where the energy performance are compared with other aspects, first of all the economic one. Finally, strategic is to be able to balance the overall contributions and select the best intervention scenario. Some evaluating methodological approaches and instruments can lead the analyses. Cost-optimal analysis is the most suitable technique for this purpose, considering the cost related to the whole life cycle of an intervention; multi-objective optimization and multi-criteria decision techniques widen the field of application of the analysis through the choice of the optimal solution as a function of the improvement of the considered performances. The CO_2 and greenhouse gas emissions (GHG) quantification affect the environmental impact of buildings by considering both the emissions released during the operational phase and during the whole life service. LCA is adopted to quantify the potential impacts of the different possible scenarios of retrofit and design: in high performance buildings, the embodied quantities (energy, emissions) can play a significant role in the overall balance.

3. Applied technical solutions

Technical solutions are divided in three main subcategories: energy efficiency measure aimed at reducing the energy demand, renewable energy source for the reduction of the energy supply and control systems. The summary here reported is not exhaustive of all the possible options studied and reported in literature for each specific component of the building. However, the technologies considered, are the ones currently used in the real study cases reported. The chapter provides an overview of the most suitable technologies to reach the ZEB target and the possible correlation with the context and achieved (or potential achievable) quantitative performance targets.

3.1. Energy efficiency measures

The energy efficiency measures allow the reduction of the energy demand of buildings. This section analyses the main passive and active solutions needed to reach ZEB goals. The reduction of energy needs requires a design process focused on the maximization of the effects offered by the different passive solutions involved in the process [110]. Moreover, the design of passive components affects the development of active solutions for energy management and control of the operation modes to optimize the IEQ [111], minimizing power consumption.

3.1.1. Passive solutions for space heating and cooling, lighting and other equipment

Literature on passive design concerning buildings is extensive [112] and the related technical solutions are broadly analysed and applied [113]. The main goal of passive systems is the reduction of the energy needs, pursued exploiting the thermal performance of materials, buoyancy mechanism, thermal inertia and evaporative effect [114]. Several strategies are related to the adoption of advanced building envelope. In Table 6 a summary of the characteristics of the analysed technologies is presented.

A number of different parameters affects the energy need of buildings, related to morphological, geometrical and thermo-physical parameters. The design of the building fabric has a direct effect on the building performance. Among the design parameters the WWR plays a major role on building consumption. In Ref. [115], the authors calculate a weight of WWR on cooling and heating loads of about 20% and 11%, respectively. The reduction of the WWR up to values close to 10% is the best solution to reduce heating and cooling consumption, regardless of the weather conditions [116]. However, the result changes if the overall performance of a building are taken into account both in term energy services (i.e. lighting) and indoor requirement (i.e. daylight) [117]. In this conditions the performance of the glazing systems (thermal transmittance, solar heat gain coefficient) is the driving force affecting the WWR value: the better the performance the greater the WWR [117,118].

The common strategies for the improvement of the performance of the building envelope are mainly related to its thermal insulation focusing on opaque and transparent elements, glazing and coating systems for the rooftops [119]. The thermal insulation of the building is designed to take into account: climate, annual balance in heating and

Table 6
Summary of the characteristics of passive solutions for space heating and cooling, lighting and other equipment.

Solution	Performance	Technique	Results	Cost	Mode/climate	Constrains	Ref.
Design factor	Optimization of windows size respect to opaque element to reduce energy consumption and improve visual comfort	WWR	Values between 10% and 30% provide the best energy reduction and comfort results	–	Lower values for reduce cooling load	Type of glazing system, shading properties, façade exposition	[115–118]
Thermal insulation	Increase thermal resistance of building envelope to reduce losses and gains	Aerogel	Low conductivity (0.013–0.014 $Wm^{-1}K^{-1}$), optical properties	High	Better in heating mode	Thermal bridge, dust production, long term performance	[123–125]
		VIP	Very low conductivity (0.004 $Wm^{-1}K^{-1}$)	High	Better in heating mode	Moisture penetration, thermal bridge, long term performance, panel shape	[131,132]
Thermal energy storage	Latent heat storage and release	PCM	Reduce temp. fluctuation, shift and reduce peak load, improve storing effect	High	Better in cooling mode	Melting temperature	[134–136]
Passive heating cooling	Exploit natural ventilation and solar radiation to heat and cool	Trombe wall	Heating and cooling load reduction	Medium	Both heating and cooling mode	Overheating risks	[149–151]
		Solar chimney	Cooling and ventilation load reduction	Medium	Better for cooling mode	Ventilation	[152]
	Reduction of solar albedo of surface, improve permeability	Green roof/wall	Reduce solar gain, improve U-value, storm water mitigation	High	Better for cooling mode	Structural behaviour, type of plants, maintenance	[155–158]
		Cool roof	Reduce solar gain	Medium	Better for cooling mode	Long term performance	[160,161]
	Pre-heat or cool supplied air	EAHE	Reduce heating and cooling consumption	Medium	Better for heating mode	Electricity consumption of fans	[163,164]
	Exploit daylight	Daylight system	Reduce electric consumption for lighting, improve human well-being	Low	Better in sunny region	Type of glazing system, shading properties, control strategies, glare risk	[166,167]

cooling needs and relative costs [120] and is strongly affected by the existing legislative framework. The common strategy recorded among the analysed case studies in chapter 2 is the increasing of the insulation thickness, up to value lower than those prescribed by the current legislative framework. The opportunity to integrate thermal, environmental, comfort and economic requirements has fostered the optimization of some insulation materials and technical solutions with high thermal performance [121]: aerogels, VIPs and PCMs, in the last few years have undergone a technological upgrade able to make them suitable for the achievement of the ZEB target, even if issues related to durability, costs and installations need to be further investigated [122]. Thermal conductivity of aerogel is between 0.013 and 0.014 $Wm^{-1}K^{-1}$ [123], but due to the high costs, this solution was applied only to cases with limited available volumes [123–125]. New materials, based on cheaper aerogel and light aggregates together with novel production processes, are under study to achieve improved insulating performances together with competitive prices [126–129]. Aerogels can be used as translucent or transparent insulation materials because of their combination of low thermal conductivity and high transmittance of daylight and solar energy with remarkable advantage from and sustainable point of view [130]. Similarly, VIPs are characterized by thermal conductivity values close to 0.004 $Wm^{-1}K^{-1}$ [131] allowing the use of very thin insulating layers. Some current technological limits of VIPs (panel shape, thermal bridge, etc.) and the high costs still limit the use of such a solution [132], but new solutions based on composite cores and silica aerogel are under investigation to overcome this issue [133]. PCMs exploit the physical mechanism related to the thermal inertia storing and releasing heat. This allows a reduction in terms of energy requirements for heating/cooling and a damping effect in the power absorption for climate control, preserving the comfort for the end-user [134]. The efficiency of PCM-based systems depends on several factors: the climatic and external conditions, the intrinsic characteristics of the material and the installation characteristics (mode and positioning) [135]. The melting point and the ventilation conditions are essential to guarantee the correct phase change process achieving a reliable reduction of overheating [136]. The material efficiency is strongly affected also by its thermal conductivity. Its natural low thermal conductance limits the thermal exchange [137] so, new PCMs with improved exchange properties are currently under investigation [138]. The use of PCM for glazing or shielding panels has interesting applications thanks to the low thermal conductance able to successfully decouple the cold from the outside in winter and solar heating in summer [139].

Gupta et al. [140] provide an exhaustive collection of the passive solutions and the possible interaction/integration between heating and cooling. Generally, these solutions are applied in warm and moderate climates. Technologies able to exploit natural ventilation, for example, are in general preferred thanks to the low impact on energy consumption [141]. The ventilation of a building using passive or natural methods is a commonly used technique due to the low running costs and improved indoor environments for occupants [142]. Several technologies exploit natural ventilation to improve building performance. Trombe walls are a typical passive solar technology used both for winter heating and summer cooling, depending on the configuration of glazing surface and Trombe wall vents [143]. The integration of Trombe wall with PCMs improves the thermal inertia of the system while also improving the performance in heating season [144]. Recent developments in design [145], the combination with other technologies, such as solar chimney [146], solar shadings [147] and PV modules [148], improve the performance of the system in cooling mode. Trombe walls have improving effect on energy consumption, humidity of interior spaces and indoor thermal comfort [149], with a recorded energy saving of 20% in moderate climate [150] up to more than 40% in warm region [151]. Solar chimney is a traditional technology mainly applied for passive cooling in warm climate. The technology, known for decades over the years, has been applied within buildings in order to improve the energy performance and comfort level often coupled with other passive (such as earth to air heat exchanger) or active solutions (such as solar collectors or PV panels). Applications of the cited solutions highlight how with an appropriate the system is able to satisfy the cooling demand, guarantee the thermal comfort conditions and improve the performance of the solar technologies [152]. Fig. 3 shows the classic design of a Trombe wall, a solar chimney and their working mechanism.

Cool and green represent consolidated solutions for efficient roofs. Their performances depend on climate and design [153,154]. Green roofs reduce solar heat gains, improve albedo with respect to traditional tiles or bitumen membrane and evapotranspiration processes [155–157]. They also contribute to the global thermal insulation of the roof thanks to thermal properties of growing media [158]. Cool roofs, instead, represent a proper solution to reduce summer solar heat gains thanks to their reflective properties [159], and they can be successfully applied both in warm [160] and temperate climates [161].

Heat exchangers are a suitable technology to reduce heating and cooling loads by exploiting the thermal storage of a medium used as a reservoir and the thermal properties of a transfer fluid. In building heating, cooling and ventilation, Earth to Air Heat Exchangers (EAHEs) allow the use of ground heat stored for the reduction of thermal loads by pre-heating or cooling the air supplied [162]. The technology exploits the ground thermal storage through pipes buried underground. EAHEs can be used either as stand-alone or auxiliary systems, providing an enhancement of the performance of the main climate control system. The EAHE can be coupled with HP or a mechanical ventilation system providing an efficiency improvement and maximizing the operating energy saving, with a significant reduction both in cooling consumption (about 30–50% in Ref. [163]) and annual consumption (about 25–40% in Ref. [164]).

Finally, the energy demand for lighting is strongly related to the characteristics of the transparent building envelope, so the optimum cooling, heating and lighting energy balance can only be reached through an integrated approach combining lighting and thermal aspects [165]. The relative cost in terms of energy consumption due to lighting increases with the increase of the energy performance of the building. The lighting energy demand can be minimized based on three key factors: optimization of daylighting, reduction of lighting power and activation time. Passive solutions in lighting are related to the exploitation of sunlight with different approaches according to the physical phenomena of light propagation used by the technological systems [166]. A careful design has to consider the potential of natural sunlight paying attention to both glazing and shading system in order to optimize the indoor visual comfort, managing internal gains and reducing the needs for artificial lighting [167].

3.1.2. Active solutions for space heating and cooling, lighting and other equipment

According to the state-of-art, conventional HVAC units are responsible of almost half of the total of energy consumption a building. However, improving the control system [168] or using specific energy-efficient strategies, such as thermal energy storage (TES), recovery of exhaust heats, evaporative technologies, the energy performance of HVAC systems can be largely improved [169]. Huang et al. [170] provide a review of the main mechanisms adopted in the last decades to improve the performance of HVAC systems. TES systems are addressed as an effective solution for space and water heating, space cooling and air conditioning [171]. Chilled water, ice and PCM are common storage medium types [172]. In active TES cooling the optimization of the control driving the mechanical systems and the exchange fluid used to charge and discharge the storage tank allow improving efficiency of the system. Similarly, PCMs can be integrated to improve the performances of systems such as: HVAC, domestic hot water, ventilation, radiant floor heating, chilled ceiling or solar cooling facilities [173]. HVAC are often coupled with energy recovery systems designed to reduce the energy consumed for space heating and cooling by recovering potential wasted energy even if the energy savings must be balanced against the electrical power consumed by fans. The choice of the best recovery technology is driven by the climatic conditions. In Ref. [174], the effectiveness of heat and energy recovery ventilators (HRV, ERV) is investigated in 11 cities in Southern Europe, in a warm climate with medium relative humidity. Under these climatic condition, the RVs provide a reduction in energy demand between 20% and 40%: ERV is suitable when the relative humidity is higher than 30%, in the other conditions HRV is the best solutions. A cross country analysis in USA about the effectiveness of RV in buildings detects an energy saving potential between 16% and 21% [175]. Radiant heating/cooling systems are widely used thanks to the high integration capability and the high ratio between thermal comfort and energy efficiency. Literature references record a variable range of energy saving from 10% up to 80% due to system configuration and the adopted control strategies [176]. The design of the system requires the use of forced air systems and humidity controllers to prevent wetting phenomena or indoor air quality (IAQ) degradation [177]. A significant fraction of the ZEB energy demand for air conditioning is attributable to ventilation. Mechanical ventilation is used to control the flow rate to manage the ventilation heat losses and, at the same time, it is an effective means to prevent indoor air quality degradation [178]. Variable air volume systems are a more suitable technology in low energy buildings

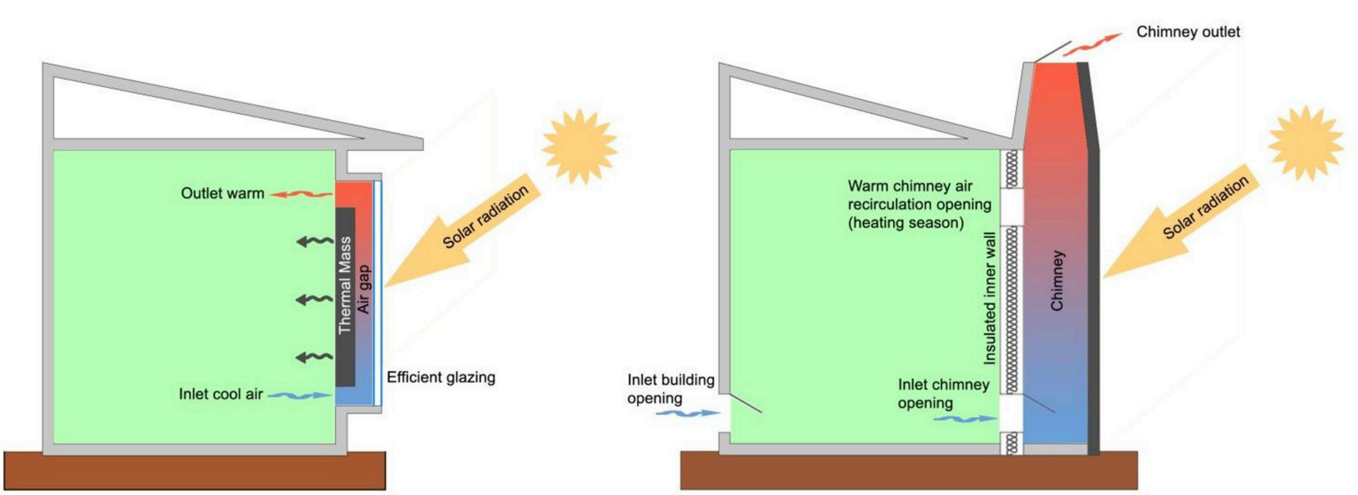

Fig. 3. Passive technologies for heating and cooling: working mechanism in heating mode of a Trombe wall (left) and in cooling mode of a solar chimney (right).

supplying air volume at a constant temperature in order to meet the demand caused by the changing heat load in the conditioned space [179]. They can achieve energy savings between 17 and 38%, compared to the constant air volume system, starting from a control algorithm specifically designed to supply the minimum air flow rate to guarantee thermal comfort, IAQ, and reduce stratification and energy consumption [180,181].

For what concerns the energy consumption related to lighting, LED lamps are the most efficient technology with regard to lighting power aspects. In fact, compared to standard incandescent lamps, LED lamps have a luminous flux that is about 6 times higher (90 vs 15 lm/W) [182] and lower heat production due to the absence of IR and UV radiation production [183], reducing at the same time the indoor cooling needs. Organic material based LEDs (OLEDs) components have been recently developed, reaching a mean luminous efficiency of 74 lm/W, with a peak value of 124 lm/W using a 3D light extraction system from the glass substrate [184]. Finally, in a ZEB, the consumption related to appliances and other plug loads represent an important part of the overall building consumption. Lighting and equipment consumption are optimized by using efficient systems and by carefully scheduling the use of load appliances, in order to maximize the use of energy from renewable sources [185]. In this case, users play an active role by adopting an energy saving-oriented behaviour. In Table 7 a summary of the characteristics of the analysed technologies is presented.

3.2. Power supply and generation systems

3.2.1. Solar and wind energy

PV technologies are currently the most widely used renewable systems in the building sector, since the use of active solar energy is one of the main strategies applied to provide on-site renewable energy [186]. Technical characteristics, performances and critical factors affecting PV efficiency are well known and analysed [187]. The technology has gained significant attention from policymakers in numerous countries thanks to the high readiness level reached [188]. PV technology, indeed, has the main advantage of an easy scalability with a linear growth of the electrical power output with the exposed surface. The potential of PV technologies is reported by several authors highlighting good results both from the energy [189] and environmental [190] point of view. The positive characteristics of the technology along with a favourable legislative framework has allowed a rapid growth of the PV market as the preferred renewable system for the energy generation in buildings. Alongside the classic PV panels, several technologies have arisen in order to maximize their potential and allow the diffusion in different contexts. The photovoltaic-thermal (PVT) technology, using thermoelectric cooling modules, allows to manage the solar cell temperature (known as a critical variable in PV performance), taking advantage of the heat waste collected to produce hot water: the system, indeed, is designed to keep the PV panel at the optimal temperature for the solar radiation absorption, increasing the overall conversion efficiency [191]. Building-integrated photovoltaic (BIPV) has been recently drawing the attention of the building sector due to its versatility [192]. These PV modules are designed to be integrated into the building envelope to replace traditional passive construction elements, such as roof and façade cladding, windows, blinds and shading elements, in order to convert them into active power generators. The energy performance of BIPV modules is affected by several factors: ambient temperature, shadowing effect, installation mode and positioning. Even though the technical characteristics and the performance of BIPV have increased over the last few years, high costs of production and high labour charges are the main barriers to the spread of this technology [193].

Another important limit to the solar technology is related to the reliability of the power output of the systems. Solar-generated electricity cannot be exactly forecasted, since variable meteorological processes introducing a significant timing variability in production.

Table 7
Summary of the characteristics of active solutions for space heating and cooling, lighting and other equipment.

Solution	Performance	Technique	Results	Cost	Mode/climate	Constrains	Ref.
HVAC	Charge and discharge storage tank	Active storing system	Optimize system efficiency	High	Better in cooling mode	Melting temperature	[172,173]
	Recover sensible and latent heat	Heat recovery	Best results in heating mode	High	Better in heating mode	Relative humidity, fans electrical consumption	[174,175]
	Exploit radiant and convective principle for heating and cooling	Radiant heating and cooling	TC at lower air temperaturefor heating, and at higher air temperature for cooling	Medium	Better in heating mode	Condensation risk, coupled with mechanical ventilation	[176,177]
	Variable air volume systems	Vary airflow at a constant temperature	Supply minimum air flow rate to guarantee thermal comfort, IAQ, and reduce stratification and energy consumption	High	Both in heating and cooling mode	Control strategies	[180,181]
Lighting	LED	Long service life, high efficiency	High luminous flux, low heat production, reduce electricity consumption, reduce thermal load	Medium	–	Control strategies, design	[182,183]
	OLED			High	–		[184]
Appliance	High efficiency appliance	High efficiency	Reduce electricity consumption	Medium	–	Control strategies	[185]

Moreover, PV electricity generation and consumption do not have the same profile and this mismatch leads to a significant export of the locally generated energy to the grid. Energy storage systems are the potential solution to overcome problems associated to the intermittency of the renewable sources. It has been demonstrated that in a warm Mediterranean climate, the correct design of an energy storage system leads to a consistent reduction (76 and 78,3%, respectively) of energy delivered to and consumed from the grid; even though this system is still not cost-effective [194]. In Sweden, the price of electricity, feed-in electricity and battery, were taken as parameters for the sizing of a battery to be used in multi-story residential building. Such calculation shows that the addition of a battery reduces the payback time of the system and increases the consumption shared on site, providing at the same time benefits for the power grid [195].

Solar Heating/Cooling System (SHS) is the collective name for a wide number of devices designed for converting the solar radiation into useful heat using air [196] or water [197] as vector fluid. SHSs successfully fulfil the heat demand of buildings reducing at the same time CO_2 emission. A wider diffusion of solar collectors is related to residential buildings, where energy for domestic hot water (DHW) production has an important weight in the overall energy need of the building. Several studies confirm that the thermal efficiency of water-based solar thermal collectors is higher than air-based ones due to the specific heat capacity of water, and the flat plate collector appears to be the most commonly applied solution [198]. Researches were conducted in order to optimize the efficiency of SHSs by using nano-materials [199] and nano-fluids [200]. PCMs can be applied to improve the thermal energy storage of both systems [201,202]. TES appears to be the fundamental component for such solar energy use [203], operating to store solar heat when it is not required and therefore minimizing the fuel consumption for boilers [204]. Solar energy can also be exploited to produce cooling power: compared to heating applications, solar technology better fulfils cooling requirements, especially in conjunction with solar peaks [205]. A wide review of the technologies involved in solar cooling developments is provided by Al-Alili et al. [206]. Despite the large number of installations reported, a satisfactory analysis of the costs involved in this technology is still unavailable: current data seem to indicate that, so far, this is not a cost-effective alternative to the traditional vacuum compressor. Integrated modules, adopting either adsorption or desiccant cycles, are emerging solutions for small-scale solar cooling applications [207].

Wind energy can be considered a complementary renewable source to reach the ZEB target. Wind turbines, transforming mechanical energy in electric energy, provide a positive contribution to the building energy balance. The most important factors regarding the effectiveness of a wind system are the characteristics of the turbine plant and the shape of both building and of its surroundings in relation to wind pattern. In relation to the capability of orienting wind turbine, there are generally two main mechanisms: yawning (free-standing) and non-yawning system (fixed). A non-yawning building integrated turbine can, if properly designed, generate at least twice as much energy from the prevailing wind than a 'free-standing' equivalent turbine thanks to the local acceleration of wind velocity [208]. Lee et al. demonstrate that vertical wind flows that arise with high turbulence in urban areas could affect the output power of a small vertical-axis wind turbine (VAWT) [209]. In particular, VAWTs accept wind from any direction with the advantage of avoiding the yawning system, which is costly and could fail during operation [210], having reduced power losses due to temporary changes in wind direction [211]. An omni-directional turbine can be located where winds are turbulent and where wind direction changes often: for this reason, in urban areas, VAWTs have an advantage with respect to horizontal axis turbines and are less noisy, which is an important aspect in urban areas [212]. In Table 8 a summary of the characteristics of the analysed technologies is presented.

Table 8
Summary of the characteristics of solar and wind technologies.

Solution	Performance	Technique	Results	Cost	Mode/climate	Constrains	Ref.
Solar energy	Convert solar energy in electricity	PV panels	Reduction of fossil fuel consumption	Medium or low (with incentives)	Better in sunny regions but widely used in several countries	Building and site shading, temperature, solar forecast, grid connection, peak production	[189,190]
		BIPV	Reduction of fossil fuel consumption, reduction of raw materials	Medium	Better in sunny regions but widely used in several countries	Building and site, shading, temperature, solar forecast, grid connection, peak production	[192,193]
	Convert solar energy in electricity and heat	PV/T	Optimization of PV cell temperature, production of hot water, high efficiency	High	Better in sunny regions but widely used in several countries	Building and site, shading, temperature, solar forecast, grid connection, peak production	[191]
	Convert the solar energy into heat using air or water	Solar heating	Reduction of fossil fuel for heating/DHW	Medium	Better in sunny regions but widely used in several countries	Building and site (shading), solar forecast, fluid vector	[196,197]
		Solar cooling	Reduction of fossil fuel for cooling	High	Better in sunny regions but widely used in several countries	Building and site (shading), solar forecast, technology	[206]
Wind energy	Convert wind energy in electricity	Wind turbine	Yawing and VAWT are the best solutions for building integration	High	Better in windy region	Building and site, wind forecast	[208,209]
Energy storage	Store electrical energy for deferred consumption	Electrical battery	Reduction of energy delivered to and consumed from the grid	High	Function of the RES	Charging and discharging, shiftable loads, electricity price	[194,195]

Table 9
Summary of the characteristics of HPs, DH/DC and bioenergy technologies.

Solution	Performance	Technique	Results	Cost	Mode/climate	Constrains	Ref.
HP	Compression and expansion of a working fluid	ASHP	Reduction of heating and cooling consumption	Medium	Both heating and cooling mode	Electricity price (often coupled with PV), frosting and defrosting in winter	[214,215,218]
		WSHP-GSHP	Reduction of heating and cooling consumption, constant earth temperature and COP	High	Both heating and cooling mode	Electricity price (often coupled with PV)	[216,217,219]
DH/DC	Centralisation of energy production and distribution to individual units	CHP and tri-generation	Exploit several fuels (waste or excess heat or electricity), multi-generation	High	Both heating and cooling mode, electricity	District network, urban policy	[221–223]
Bioenergy	Generate heat and electrical power with a single fuel	Biomass generator	Reduction in CO2 emissions	Low	Better in heating mode	Primary energy weighting factors, ultrafine particulate emission	[232–234]

3.2.2. Heat pump, district heating and cooling and bioenergy

The European directives on the use of RES identify the aerothermal, hydrothermal and geothermal energies as renewables. Heat Pumps (HP) exploit these sources to transfer heat to buildings by reversing the natural flow of heat from higher to lower temperature [213]. HPs are classified according to the heat sources and the heat sinks. Air source HPs (ASHP) are widespread in the building sector: among these, air-to-water appears to be a suitable technology in case of energy retrofit of buildings, since the air source is available everywhere. These kinds of HPs are easy to install and relatively cheap, but their performance suffers the climatic conditions, especially in winter [214]. Studies carried out on housing building stock show a potential energy saving between 20% and 40% [215]. Water and Ground Source HPs (WSHP and GSHP) are attractive solutions, thanks to the constant earth's temperature as a heat source in a heating mode and a heat sink in a cooling mode, but they are limited by the presence on site of the primary geothermal energy source. This characteristic causes this solution to be unevenly distributed [216]. A cross country analysis in Europe confirms the average energy saving potentials with values between 20% and 40% [217]. In general, HPs have proven beneficial in terms of costs and efficiency when associated to other renewable sources. Field tests and studies demonstrate that energy performance and the economic feasibility of HPs can be enhanced through the combination with multi-energy sources, such as RES [218,219].

District Heating/Cooling (DH/DC) can provide efficiency, environmental and operation cost benefits to the communities and is an enabling solution that can support low energy buildings. District energy plants would be able to provide low-temperature domestic hot water, heating or cooling of buildings using waste or excess heat or electricity coming from different sources [220]. In fact, district energy systems have higher efficiency if compared to individual heating/cooling ones due to the possibility to efficiently manage and control the overall energy grid. Combined Heat and Power (CHP) system is the most common technology in DH/DC producing at the same time thermal and electric energy with a consequent reduction of CO_2 emission resulting from the implementation of multi-generation energy conversion technologies [221,222]. Tri-generation system is a suitable technology to extended operational time of a power plant, reducing CO_2 emissions and enhancing economic investments performance compared to a standard gas-based CHP system [223]. The integration of renewable energies, such as solar energy, HPs and biomass, in the district energy system improves the energy, environmental and economic performances of the system allowing the ZEB target [224,225]. Scandinavian and Baltic countries are frontrunner in this field. These countries demonstrate an enduring policy on environmental and energy-related issues. Their experiences allowed to detect the main influencing factors and to identify the potential application of these technologies [226–228]. Some studies [229,230] underscore significant energy benefits associated to the use of excesses of heat delivered from different typologies of renewable energy plants such as solar heating, HPs or wasted heat with an improvement of economic investments and operating time of the system. Micro-CHP and biomass heater are also suitable technologies to be integrated in a single building for reaching ZEB target. Micro-CHP can work as a generator enslaved of a single building or as multiple generators enslaved of a cluster of buildings. Sibilio et al. [231] studied the potential penetration of micro-CHP in the sector suggesting the maximum exploitation of the thermal portion and the use of the cogeneration devices for more than 4000 h/yr.

Biofuels and biomass can be qualified as ZEB resources since they provide a consistent reduction in CO_2 emissions and an improvement in economic saving [232]. Using the weighting factors established by the current standards, biomass generators are the most advantageous solutions. However, the real sustainability of these sources represents a topic still open: some countries like Denmark and Switzerland, for example, discourage the use of biomass as fuels by adopting strict weighting factors, comparable to the ones associated to hydrocarbons

[233]. Bio-fuels are used in the heating mode, for DHW production and in the mixed mode as source of a CHP/CCHP plant. Biomass stoves are installed in low energy buildings as the main generator or as supplementary heating systems. Particular attention must be paid to the ultrafine particulate emissions coming from the biomasses combustion; so, appropriate ventilation systems have to be designed and installed [234]. In CHP/CCHP plant, biomass and biofuels find wide application both in district heating, as discussed below, and as generator in a single building. In this latter field, encouraging results are provided for biomass-CHP with low power-to-heat ratio even if in a cost-optimal perspective HPs are still the best solutions [235]. In Table 9 a summary of the characteristics of the analysed technologies is presented.

3.3. Control and management strategies

Building Automation System (BAS) and the related systems for optimization and control are fundamental for reaching the ZEB target and maintaining user-acceptable comfort levels [236]. At the same time, BAS is still considered a challenge for the development of ZEB target. BAS is pervasive within the building and it is applied for the optimal management and control of different services and devices: HVAC, DHW, lighting and shading systems, energy conversion and storage (heating and cooling), onsite power generation, monitoring and data management, communications and safety management [237]. The saving capability in HVAC consumption, related to the comfort level achievable through several control technologies, displays an impressive percentage up to 40% of energy saving associated to efficient occupancy-based control strategies if compared to typical control strategy based on static schedules and fixed internal set points [238]. These results, theoretically obtained through building calculations, must be evaluated in operational conditions by performing an experimental analysis of the building. Michailidis et al. [239] applied a general adaptive optimization system to two different office buildings in Germany (continental climate and high-inertia building) and Greece (Mediterranean climate and low-inertia building) demonstrating how it is possible to improve thermal comfort and energy saving through adaptation to different contexts. Papantoniu et al. [240], instead, applied a web-based, multi-step optimization approach to a Hospital to predict the hourly set-point of temperature in order to achieve an energy saving of 40 kWh/m^2. Energy saving and IEQ are strongly affected by the operation of HVAC systems: so, advanced HVAC control systems are crucial strategies to maintain high-quality indoor thermal comfort with low energy consumption. Some other studies provide a summary of the strategies adopted in HVAC control [241,242]. Advanced controls have been widely used in recent years [243]; among these, the Model Predictive Control is the technology of choice thanks to the high performance compared to "classic" control [244,245]. Soft computing techniques are also applied in HVAC control. Artificial Neural Network, Genetic Algorithm Fuzzy Logic, and their combined use are implemented in HVAC control in order to overcome the non-linear nature of these systems [246].

Building Energy Management System (BEMS) represents another solution in which control algorithms are embedded, as overviewed by McGlinn et al. [247]. Its structure consists of different layers [248]: the "sensor and actuating" infrastructure, allowing the connections with the built environment through sensors to detect the external variables and actuators to change the state of the environment, represent the first step. Then, there are the "middleware", integrating the previous infrastructure with a common interface; "the process engineering", representing the computational core of the system, receiving information from sensors and transmitting the relevant actions to the actuators; and the "user interaction interface", supporting the interaction with final users. The potentials of BEMS is well documented both in terms of energy saving [249] and environmental impact [250]. The advent of the Internet of Things provides new perspectives thanks to a widespread communicating-actuating network where the devices are deeply interconnected [251]. In these terms, the scientific literature provides useful applications of the potentials of this technology [252,253].

4. Discussion

In a scenario where buildings play a major role in the energy consumption and GHG emissions, ZEB projects are due to find an effective way to optimize energy use and, at the same time, to reduce the ecological footprint of buildings. Most of the literature reports a growing number of case studies of built solutions and methodological approaches useful to support the decision-making process for ZEB design. However, part of the studies is still focused on the different issues that still stand in the way of the achievement of the goals. The analysis carried out suggests the presence of relations between design parameters and technological choices not only related to building performance criteria but also to broader criteria involving aspects far from technical ones. Considering both the wide-spectrum characteristics and the specific peculiarities of each building, the potential list of design factors that influence the building performance could be extremely long. However, several key factors are common to the buildings and have a higher impact on their performances. Legislative framework, climate, urban context and socio-economic features play a crucial role on the market penetration of ZEB approach and have to addressed with a systemic approach as to avoid mutual negative rebounds [254].

The legislative framework expresses the national or international political will through the definition of minimum performance requirements, economical investments or supports and methodological decisions designing. A first consideration falls within the "national definition" of the ZEB requirements allowing the states the freedom to define different targets preventing standardized or shared methodological approaches towards the achievement of design and control of buildings ZEB. The identification of the system boundaries, the energy services to be included and the RES to be implemented, the calculation methodologies and the numerical indicators are still arguments on which there is no common consensus [255]. Therefore, experiences and results are very diversified, both in countries where a legislative framework exists and even more in those without specific laws, and difficult to compare. The situation is related to the lack of a common definition on ZEB as discussed in paragraph 2.1. For instance, in the UK, Norway the ZEB targets coincide with zero carbon standard, in France and Denmark with positive-energy buildings and in the Netherlands with net zero-energy buildings. The same problem may be faced when defining numerical indicators such as the requirements for the primary energy demand [256]. In addition, the political will may strongly pilots the design choices through legislative and financial instruments. The literature review identifies a mutual influence between energy policies and economic issues expressed through incentives. Several authors highlighted how the economic feasibility of a ZEB is strictly related to the availability of financial supports able to minimize the payback time of the investments. In fact, considering the actual average energy costs for the different countries and the investments related to the technologies involved in an energy efficient building, the payback time can be estimated in the range of 25 years. Such a time, increased by the performance degradation of the different components, comes ever closer to the lifetime proper of the building. As an example, the solar technology can be considered: the introduction of favourable tax regimes coupled with its greater adaptability to the buildings characteristics promoted a larger diffusion of this technology. As a result, half of overall solar capacity installed is deployed on buildings. Such policy affected a large number of related sectors of economy worldwide, from the productive to the electricity market. Whether, from a technical point of view, the diffusion of such technologies appears necessary to reach the target of the energy policy, from an economic point of view, the current electricity market has been negatively affected. As a consequence the penetration of solar solution on the market slowed down [257].

The optimal design of a ZEB depends on many factors influenced by complex relation between buildings, environment and climate. Buildings represent a significant source of greenhouse gas emissions, insofar as the changing climate impacts on building performances and occupants' comfort. It means that buildings and energy systems simulated and implemented today will shape building's GHG emissions for the coming 25 years and beyond. As building energy simulations are involved in the process of ZEB design, one of the first actions is, for instance, to use future hourly weather data files, considering the predictable climate changes from today to the end of life of the simulated buildings. Climate is the most relevant geographic factor in the achievement of ZEB performances. The climatic conditions vary significantly across and within the countries critically influencing the transition rate to ZEBs. As a consequence, the complexity of a simultaneous minimization of energy consumption for heating and cooling, DHW, lighting and the maximization of electric and thermal energy production is different in relation to the geographic context. Climate naturally impacts on the most suitable technological choices for a ZEB. As reported in the tables of paragraph 3, each technical solution can be more or less suitable for a specific climate but in compliance with the literature review in not possible to define a single relation between them. Indeed the carried out analyses provide preferred solutions driven by the different climates. So, for instance, high insulation levels are preferred in cold climate, but low U-values still meet in warmer climate [71,72]. Solar technologies are more suitable in sunny regions but PV and solar panels are installed at all latitudes and longitudes. Climate therefore has importance within the design choices, but other factors have to be taken into account to reach the ZEB goal. What certainly needs to be considered in relation to the climate are the future perspectives on climate change that should affected the future performance of buildings. Whether the scenarios foreseen by the IEA were realised (an ambitious scenario with an average temperature increase of 2 °C or a baseline scenario based on the actual statistics where the temperature increase reaches 6 °C up to 2050) there would be a generalized increase in annual temperature and in extreme weather conditions, implying the necessity of an ever-increasing attention to this issue. Such an issue is only mentioned in the analysed literature, but it underlines the need to analyse the ZEB performance over a wide time horizon, compatible to the life of the building, considering both the impact of buildings on climate change and the consequent effects on the energy behaviour of the building.

The geographical context, meaning placement, orientation, shape and morphology of buildings, also affected the development of urban areas. Urban areas are extremely complex environment where the presence of overlapping effects constitutes a constraint in the development of low energy impact solutions. Mutual synergies are created between the urban context and the buildings affecting the behaviour and characteristics of both. In highly urbanized environments, the availability of renewable resources is influenced by the morphology and characteristics of the surroundings shifting generally towards high-efficiency envelope and plant technologies in order to cope with the limits associated to the access to RES. The availability of RES depends on both climatic and environmental conditions. These sources can be used for on-site or off-site plants producing either electric or thermal renewable energy resulting in an opportunity for a ZEB solution. However, technologies exploiting the wind, hydro or geothermal energy have limitations with regard to their applications in dense urban environments:

- Wind has a great fluctuation in terms of intensity and direction. As a consequence, a wind resource has not the characteristics for a stable/reliable power supply to the building. Moreover, the non-predictable/periodical character of the source make it difficult to be modelled. So, wind plants are suitable only for specific sites and are usually associated to districts;
- Geothermal power is a stable and reliable source. However, it requires a wide underground pipe network available only in new buildings or buildings located in adequate wide open areas;
- Hydro power requires a constant water flow from a stream (natural or artificial). This requirement is quite difficult to satisfy in most of the cities, so hydro power plants are used as main providers for territorial power distribution.

Typically, urban effects such as urban overheating or rainfall water management influence the choice of technological solutions aimed at mitigating their impact: green solutions such as green roofs or façade or cool solutions can be widely used.

User's behaviour is one of the most influential aspects and, at the same time, an unpredictable variable in the forecast of building performance. In this field, techniques of other disciplines are exploited to describe the complex interaction between users and buildings and improve the internal conditions for user's satisfaction. The control and management techniques (described in paragraph 3.3) are aimed at this purpose.

A final driving force coming out from the analyses performed on the literature data is related to the ZEB costs in many terms. The economic feasibility is a crucial criterion for the penetration of ZEB into the market. The optimization of project costs is the result of evaluations carried out on the whole building trying to consider its entire life cycle and the boundary conditions (climate, urban environment, availability of renewable resources, etc.). The cost-optimal methodology allows to make wide-ranging evaluations from a temporal point of view, considering a life cycle perspective, and identifying the options offering the best energy balance to costs rating. An evaluation considering all the characteristics of the building allows the design of a technological package where extra costs for one technology are balanced by the savings associated to another. In a scenario in which the aim is to improve the functional requirements, the life cycle cost becomes of critical importance and the effectiveness of the design solutions, also in terms of cost-optimization, cannot be separated from this type of analysis.

The collected references show that a systematic approach to these issues is still in its early stage and is encountering many obstacles related to the difficulties of integrating the data produced by the analysis of individual components.

5. Conclusions

The review conducted so far highlights several issues related to high-efficient buildings, with the main focus on ZEBs. The number and quality of research studies shows an advanced technological evolution of the solutions applied to achieve such a standard. Active and passive technologies for space heating and cooling are tested worldwide and their reliability in reducing energy consumption and improving usability conditions is proven, both in controlled environments and in real operating conditions. The use of innovative materials (PCM, VIP, aerogel, etc.) combined with traditional solutions offers a promising approach to face the ZEB problem. Active service systems are applied to guarantee both energy savings and IEQ levels. Renewable energy sources are fundamental for a ZEB development: solar, geothermal, bioenergy and wind are exploited to produce the energy to meet the building's needs. The availability of sources, conversion efficiency and related costs are all issues still affecting the RESs. These issues can be partially overcome with an integrated design approach, considering the boundary conditions of the building system and the constrains affecting the building performance, followed by a cautious commissioning phase aimed at verifying the actual state performance. The design of advanced controls gives one more chance to improve the behaviour of each single technical element, the energy and environmental performance of buildings and the interaction with the energy grid.

The outstanding element is the worldwide interest in the subject of energy efficiency in buildings and, in particular, in the development of solutions enabling a zero, optimistically positive, balance between the needs and the self-provided sources of a building. The debate shows that further efforts are needed in order to make the diffusion of ZEBs and the related goals of the energy policy actions fully effective. This interest and the timelines chosen for the achievement of the target, strongly affects the research and development of new effective technologies capable of yielding results. The analyses carried out allow to identify different challenges that are still open for the ZEB. The greatest challenge in the near future is the capability to bridge the existing gap between design and modelling and the completed building. In other words, the real performance has to comply with the requirements of the design phase to guarantee the constancy of performance over the years and under unforeseen external conditions. Considering a broader time horizon, the challenge is the capability of buildings to respond to the climate change ensuring a social, economic and environmental reliability. These are complex challenges involving both the refinement of models, choosing different parameters, considering ageing degradation rate during the lifespan, effect on the energy market, next to a larger diffusion of technical solutions able to achieve high performances.

The sustainability of materials, processes and systems are in the process of becoming an important parameter for every human activity. In the case of buildings, the improvements still to be implemented and the expected effects on human environmental footprint are so extensive that the constraints related to sustainability are still weak. In view of future developments, the study of new processes enabling the optimization of the ratio between improvements and costs, meant in terms of sources consumption will help to create new areas of research and development.

ZEB is the current standard for the building sector playing an important role thanks to its ever-evolving applications. New challenges have to be addressed by all involved stakeholders in order to keep ZEB an openly discussed and continuously updated subject.

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