Doctoral Dissertation
Doctoral Program in Energetics (35th Cycle)

Supporting the launch of advanced technological solutions on the energy-efficient building market through new financial-economic metrics

By

Carola Lingua

* * * * * *

Supervisors
Prof. Stefano P. Corgnati, Supervisor (Politecnico di Torino)
Prof.ssa Cristina Becchio, Co-Supervisor (Politecnico di Torino)
Prof.ssa Marta C. Bottero, Co-Supervisor (Politecnico di Torino)

Doctoral Examination Committee:
Prof. A.B. , Referee, University of….
Prof. C.D. , Referee, University of…
Prof. E.F. , Referee, University of….
Prof. G.H. , Referee, University of…
Prof. I.J. , Referee, University of….

Politecnico di Torino
2024

I hereby declare that the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data. Part of this Ph.D. dissertation was also previously published in journals and conference proceedings cited at the beginning of each chapter.

…………………………………......

Carola Lingua
2024

Summary

Nowadays, buildings play a central role in the clean energy transition for both their ability to save energy and reduce emissions, and their potential to promote health and well-being of occupants. Specifically, taking action on the building sector has become a priority to align with the net zero emissions scenario by 2050, as it accounts for 30% of global final energy consumption and 28% of energy-related CO_2 emissions worldwide. Simultaneously, as people usually spend more than 90% of their time indoors, ensuring satisfactory indoor air quality (IAQ) represents a key measure in the design of future buildings that should be not only smart, able to monitor and manage energy optimally, but also healthy, able to positively influence the health and well-being of their occupants.

These features are the focus of this Ph.D. dissertation as it is set in a specific historical period, which includes the Covid-19 pandemic emergency in 2020 and the Russia-Ukraine war in 2022. Therefore, ensuring an adequate IAQ in the indoor environment for human health and well-being in response to the pandemic, as well as improving energy efficiency in buildings through end-use electrification in response to rising energy prices, are identified as the two main pillars in the design and operation of the building of the future and the main frameworks of the two case studies.

In the light of the above, building technology is widely recognised as the key instrument in improving the energy efficiency and reducing the CO_2 emissions, while ensuring a good IAQ in buildings. This Ph.D. thesis addresses the challenge faced by industrial companies in introducing their technologies and make them competitive in the current building energy market despite the high investment costs that may prevent consumers from investing in them. Therefore, the Ph.D. dissertation aims to guide and support industrial companies in the launch of advanced technological solutions, which play a key role in the design and operation of the building of the future, in the current building energy market.

Two applications are presented and discussed, aiming to address the aforementioned challenges. Starting from the first application, in line with the main targets of ensuring adequate IAQ and promoting human health-related status following the spread of Covid-19, great focus is put on the role of air filtration technologies in reducing the airborne transmission of indoor contaminants. Specifically, this application aims to valorise the benefits offered by the implementation of innovative biocidal and photocatalytic filtration technologies in air handling unit configuration compared to the use of traditional filtering solutions in different school building typologies. The need to economic-financial metrics in the assessment and comparison of alternative technological solutions was demonstrated through the application of the Cost-Benefit Analysis methodology. This tool has proven to be effective in supporting investment decision-making process of industrial companies enabled to demonstrate that the high investment costs associated with the use of innovative filtration technologies can be totally repaid by energy savings and socio-economic benefits (e.g., health and learning performances) in the long-term.

Moreover, the second application of this Ph.D. dissertation, in line with the main challenges of ensuring long-term energy security and achieving a clean energy transition, focuses on the electrification of end-use building energy consumption through the use of renewable energy sources. For this reason, the adoption of heating and cooling systems that rely on a carrier that is no longer gas has led to heat pumps being considered as the key technology for increasing the overall energy efficiency of the system and reducing the environmental impact of the building sector. Contrary to the previous analysis, this study does not rely on economic-financial assessments as the high investment costs of heat pumps are covered by the introduction of financial incentives (e.g., the Superbonus 110% in Italy) that promote their market penetration. Therefore, this application aims to demonstrate the benefits, in terms of energy savings and CO_2 emissions reduction, offered by air-to-water heat pump technologies as an alternative to conventional condensing boilers in typical Mediterranean residential buildings. The development of a step-by-step methodological approach, which includes the definition and computation of specific key performance indicators through the application of a quasi-steady-state simulation, has proven to be effective in supporting industrial companies. In fact, this approach allows to demonstrate the energy and environmental benefits of this technological replacement in both new and existing buildings.

To conclude, this Ph.D. dissertation is the result of a collaboration during these years with an external industrial company with expertise in this field. The

research activity has allowed to identify potential methodological approaches to assess the energy, environmental, and socio-economic benefits of implementing advanced technological solutions in the Heating, Ventilation and Air-Conditioning system. Specifically, the main results of the two applications allowed to support the industrial company to launch its advanced technologies in the building energy market, demonstrating to consumers that the high investment costs were totally repaid by the multiple benefits.

The originality of this Ph.D. dissertation lies in the first application, in which a widely-used evaluation technique was applied within a rarely-explored domain, specifically the energy sector, to assess the overall IAQ and its impacts on occupants' health and well-being. Additionally, another interesting aspect relates to the replicability of the proposed methodology for other emergencies in the future. While the second application addresses a current issue, by providing interest insights into local and non-local energy policies.

Acknowledgment

Looking back on this long journey as a Ph.D. student, I think it was one of the greatest challenges of my life. Despite the difficulties I have encountered over the past years, I have never given up. Today I am gratified to have embarked on this Ph.D. path, which has allowed me to grow professionally and personally, as well as to meet and collaborate with respectable people. I would like to express my gratitude to all the people who have shared these years and this research project with me.

First of all, I would like to thank my supervisor, Prof. Stefano Paolo Corgnati, for giving me the opportunity to get in touch with the world of research and for guiding me along this path with valuable advice. I would also like to thank my co-supervisors, Prof. Cristina Becchio, for the valuable time and for her constant availability and openness to discussion over all these years, and Prof. Marta Carla Bottero, for her collaboration and for sharing her knowledge in the world of financial-economic valuation. A mention also to Sara Viazzo, for her availability and guidance in the use of the simulation software.

To the researchers and industrial partners, I had the privilege of working with during my Ph.D., I would like to express my gratitude. In particular, a personal thanks to Rhoss S.p.A, especially to Leonardo Prendin and Micaela Ranieri for the extensive work over the past few years, which allowed me to develop the case studies presented in this Ph.D. dissertation. Thanks also to Martina Tornabene and Michele Babuin for their constant availability to discussion and debate.

I would like to express my sincere gratitude to all of my colleagues who have shared this journey with me. Thanks to Giulia C., Giulia V., Ilaria, Maria Cristina, and Maria Valentina for their constant support and for always encouraging me during the difficult times I encountered along the path with valuable advice. I thank them because from a working relationship it became a

true friendship. Also, thanks to Federico for his support and collaboration during these years.

A special thanks to all my "BIG" family for always supporting me. I am particularly grateful to my mum, a woman I hold in high esteem and who I would like to thank for always believing in me and supporting me to achieve my goals. Thanks to Davide, not only my brother but also my best friend, for his valuable advice and life lessons.

Last but not least, thank you Giovanni, for being a part of my life and for sharing with me the happiest and the darkest moments during these years. Thanks also to my son, Leonida, for filling my life with joy and happiness.

“To the loves of my life,
always and forever”

To Giovanni and Leonida.

Contents

List of Tables

List of Figures

Chapter 1

Setting the context

"The building sector is crucial for achieving the EU's energy and environmental goals. At the same time, better and more energy-efficient buildings aim to improve the quality of citizens' life and alleviate energy poverty while bringing additional benefits, such as health and better indoor comfort levels, and green jobs, to the economy and society"
European Commission [1]

1.1 The big picture

This section provides an overview of the context in which the Ph.D. dissertation is developed, with the aim of clarifying the choice of topics that will be covered within the following chapters. In particular, the summary includes the main historical events and their key missions from the years before 2019 to the present.

Therefore, **until 2019** the *fight against climate change* was at the forefront of all the political debates in the European Union (EU). In fact, the Kyoto Protocol, which was adopted in 1997 and entered into force in 2005, set the first binding targets for reducing greenhouse gas (GHG) emissions at the international level [2]. Subsequently, the adoption of the first universal Paris Agreement in December 2015 [3], as the main regulatory instrument for the global response to climate change, marked the EU's challenge to keep the global average temperature increase below 2°C (aiming to limit it to 1.5°C compared to pre-industrial levels). Finally, the fight against climate change was also the key mission of the European Grean Deal introduced in 2019, which aims to make Europe the first climate neutral continent in the world by 2050 [4].

The **year 2020** marked a paradigm shift due to the spread of Covid-19 pandemic, declared as a Public Health Emergency of International Concern (PHEIC) by the World Health Organization (WHO) [5]. The EU's mission has shifted from fighting against climate change to prioritising *human health and well-being* in indoor environments. Therefore, providing a healthy and comfortable indoor environment for people, who are required to stay in the same confined spaces for an extended period of time, becomes the primary purpose of buildings in a pandemic emergency. Already in 2018, with the amendments to the Energy Performance of Building Directive (EPBD) [6], a "human-centric approach" for new buildings and renovations of existing ones is encouraged. In addition, to emphasise the key role of occupant in building, the Directive 2018/844/EU introduced the concept of a Smart Readiness Indicator (SRI) to assess how smart a building is also in terms of satisfying the needs of occupants (e.g., health, comfort, well-being, etc.) [6]. Subsequently, with the spread of Covid-19 emergency, ensuring a good indoor air quality (IAQ) and promoting human health-related status become the priority in the design of buildings and in the renovation of existing ones. Moreover, ensuring health and well-being of building users has become a fundamental requirement of many Standards and guidelines introduced in 2020 to support the pandemic response (e.g., the WELL Building Standard v.2 [7]).

In **2022**, the strong impact on the energy market following the war between Russia and Ukraine, led to a sharp increase in energy prices and, thus, necessitated strategic changes in EU policy [8]. The 2022 energy crisis has led to the new challenge of *energy security*, which is at the heart of the European Commission's agenda. Thus, to face the challenge of ensuring long-term energy security in 2023 in order to achieve a clean energy transition, the EU needs to reduce energy consumption, improve energy efficiency, accelerate the deployment of renewable energy, increase gas supply diversification, and strengthen its strategic energy autonomy [9]. For this reason, by focusing on the building sector, the main objective of the new EU policy actions is to improve the *energy efficiency of buildings*. In particular, the electrification of end-use consumption, through the adoption of renewable energy sources (RES), represents the key driver to accelerate the energy transition and decarbonisation of buildings, leading to increased energy efficiency [10]. Among the EU strategies adopted to respond adequately to the energy crisis, the REPowerEU plan [11], launched by the European Commission in May 2022, sets out a series of measures aimed at achieving energy savings, diversifying energy supply, as well as accelerating the deployment of renewable energy in order to rapidly reduce dependence on Russian fossil fuels in buildings.

In the light of the above, Figure 1 presents a simplified graphical representation of the general framework of the thesis with the aim to show the historical period in which the Ph.D. dissertation is developed.

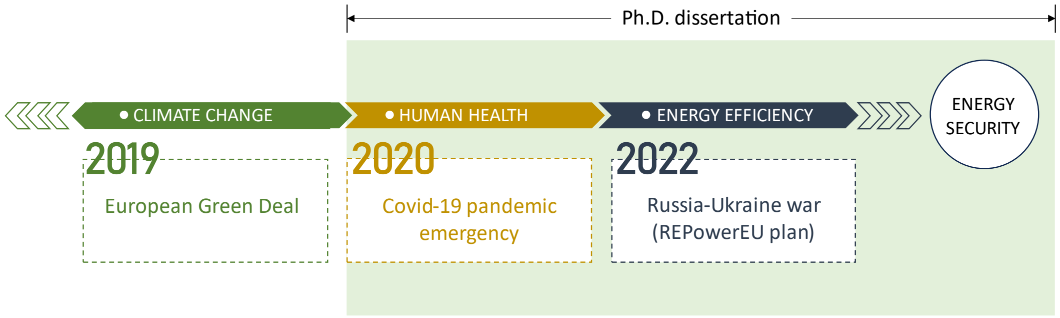


Figure 1: The big picture of the Ph.D. dissertation.

As shown in Figure 1, this Ph.D. dissertation is set in a specific historical period, which is marked by the spread of the Covid-19 pandemic emergency in 2020 and the Russia-Ukraine war in 2022. The characterisation of each periods described above helps to explain the choice of topics discussed in the following chapters. Therefore, the attention to ensure an adequate IAQ in the indoor environment for human health and well-being in response to the pandemic, as well as the improvement of energy efficiency in buildings through end-use electrification in response to the energy crisis, are the key objectives to boost the building of the future (Chapter 2) and the main frameworks of the case studies application (Chapter 4 and Chapter 5).

1.2 Overview of the energy and emissions trends in the building sector

The building and construction sector is well-recognized as the primary source of energy consumption and GHG emissions [12]. As it plays a key role in achieving the EU's energy and environmental targets, this section aims to provide an overview of its total final energy consumption, as well as its operational energy-related carbon dioxide (CO_2) emissions trends.

The 2022 Global Status Report for Buildings and Construction [12] states that the year 2020 marked the largest decrease in CO_2 emissions in the last decade due to the spread of the Covid-19 pandemic. The changes in home and workplace practices, due to the imposed lockdown restrictions, had a significant impact on both energy and emissions trends of the global building sector. In particular, global energy demand in buildings decreased by 1% in 2020 to around 127 exajoule (EJ), while CO_2 emissions from building operations fell 10% in 2020 to around 8.7 gigatons of carbon dioxide ($GtCO_2$), down from around 9.6 $GtCO_2$ in 2019 [13]. In 2021, construction activities returned to pre-pandemic levels and, due to the reopening of workplaces, there is an increase in energy use. As a result, building energy demand has seen the largest increase over the last 10 years, rising by about 4% from 2020 to around 135 EJ [13]. As far as CO_2 emissions from building activities are concerned, they increased by about 5% compared to 2020, to 10 $GtCO_2$, and by 2% compared to the previous peak in 2019 [13]. In detail, the global building sector (residential and non-residential) is responsible for almost

30% of the total final energy consumption (for space heating and cooling, lighting, cooking, etc.) [14]. To the operational energy demand is added the energy used in buildings to produce concrete, steel, and aluminium, which accounts for a further 4% of the final energy demand [14], bringing buildings energy demand to 34% in 2021. Figures 2 and 3 show the share of total final energy consumption by sector in 2022 and the breakdown of building energy consumption by fuel (e.g., biomass, natural gas, electricity, renewables, etc.) from 2010 to 2022, respectively.

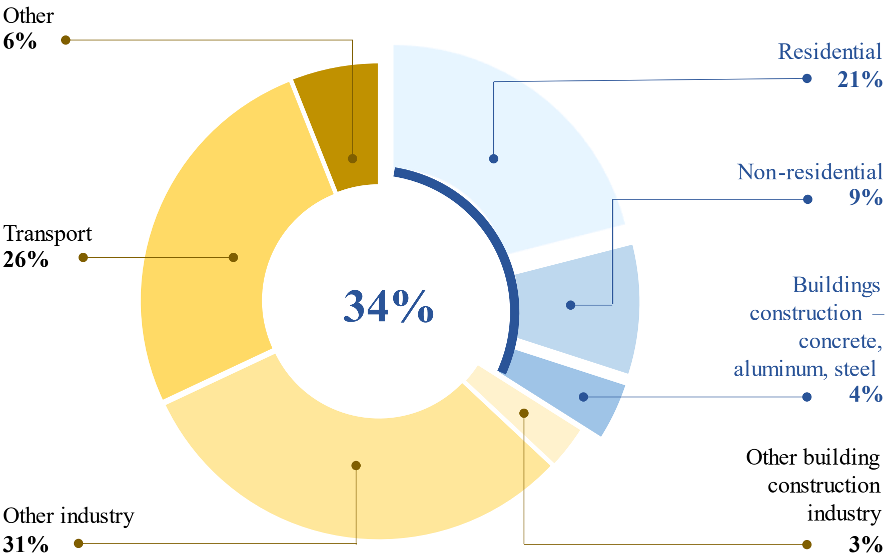


Figure 2: Share of total final energy consumption by sector in 2022. Elaboration from [14].

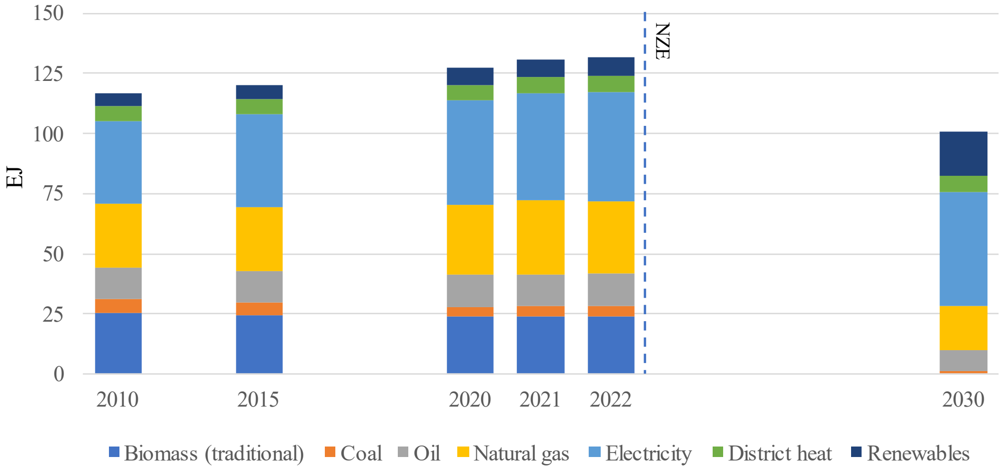


Figure 3: Energy consumption in buildings by fuel, 2010-2022. Elaboration from [14].

Figure 3 shows that electricity accounted for 35% of the total energy consumption in buildings in 2022, which represents a 30% increase from 2010. Despite the ongoing transition from traditional fossil fuels to alternative energy sources (e.g., electricity and renewables), the use of fossil fuels in buildings has increased at average annual growth of 0.5% since 2010. According to the International Energy Agency (IEA), achieving the Net Zero Emissions (NZE) scenario will require a significant reduction of about 25% in energy consumption in buildings and a significant decrease of over 40% in the use of fossil fuels by 2030 [14].

As mentioned before, in 2021, CO_2 emissions from building operations increased by 5% compared to 2020 levels. In detail, the building sector, which include the residential and non-residential buildings, is responsible for about 28% of operational energy-related CO_2 emissions [14]. Direct use of fossil fuels in buildings accounts for about 9% of these emissions, while the remaining 19% is due to electricity use (indirect emissions). The operational energy-related CO_2 emissions are supplemented by emissions from the concrete, steel, and aluminium used in building construction, which account for an additional 6% of global emissions [14]. Which means that in 2021 buildings account for approximately 34% of global operational CO_2 emissions related to energy and processes [12]. Figures 4 and 5 show the share of global energy and process emissions by sector in 2022 and the CO_2 emissions in buildings from 2010 to 2022, respectively.

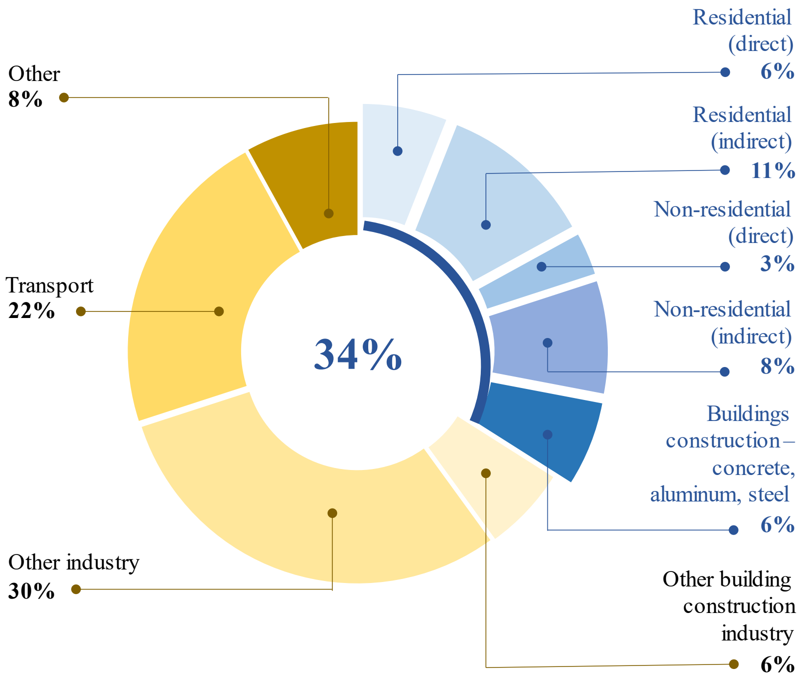


Figure 4: Share global energy and process emissions by sector in 2022. Elaboration from [14].

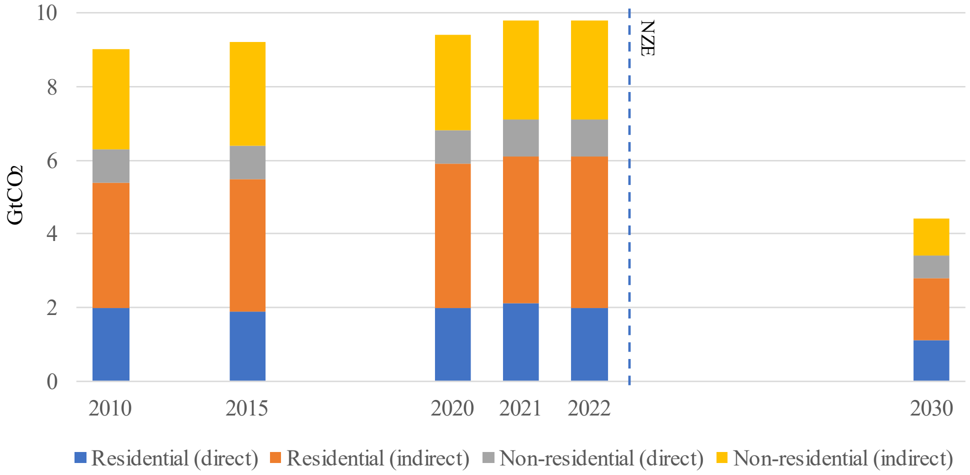


Figure 5: CO_2 emissions in buildings, 2010-2022. Elaboration from [14].

Figure 5 shows that in 2022, buildings emitted 3 $GtCO_2$, while indirect emissions increased to almost 6.8 $GtCO_2$. In detail, direct emissions from building-related activities show a year-on-year reduction in 2022, in contrast to 2015-2021 trend, where they recorded an average annual increase of nearly 1%. In contrast, indirect emissions related to building activities show a growth of about 1.4% in 2022. According to the IEA, in order to meet the NZE scenario, emissions will be reduced by 9% annually until 2030, followed by a reduction of over 50% by the end of that decade [14]. In this context, increasing both the rate and depth of building renovation plays a key role in achieving the 2050 target.

As shown in the projected scenarios in [15], increasing the annual renovation rate to 3%, with deep renovation accounting for 70% of the total, would achieve climate neutrality by 2050. In fact, renovation of existing buildings could reduce the total EU energy consumption by 5-6% and CO_2 emissions by about 5% [16]. However, nowadays about 75% of the EU building stock is energy inefficient, and on average, less than 1% of the national building stock is renovated each year (with rates varying between 0.4% and 1.2% in the different Member States) [16].

In the light of the above, regulations and policy instruments play a key role in introducing ambitious energy saving measures to improve the energy efficiency of buildings, as well as to reduce GHG emissions by promoting the renovation of the existing building stock. The following section aims to summarise the main energy and climate initiatives and regulations adopted at European and Italian national level for the energy efficiency of buildings.

1.3 The regulatory and policy framework for buildings energy efficiency

As mentioned in section 1.2, to reduce GHG emissions and, thus, to achieve the climate neutrality by 2050 and to support the global energy transition of the building sector, a series of energy and climate policies are introduced at European and Italian national level. Figure 6 shows a roadmap of the main European and Italian energy and climate policies for energy efficiency in buildings to guide the reader within the following sections 1.3.1 and 1.3.2.

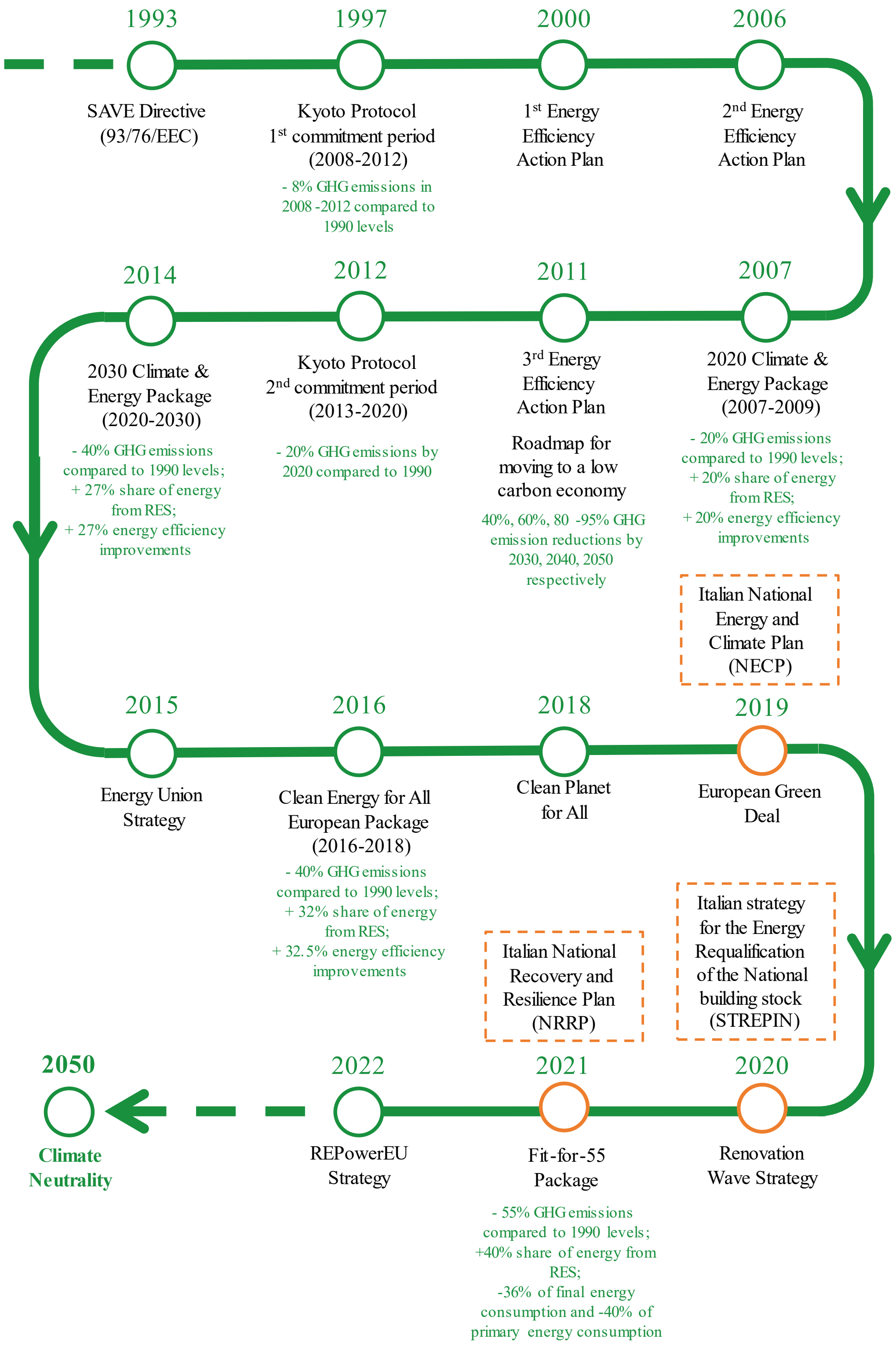


Figure 6: European and Italian national energy and climate policy actions for buildings energy efficiency.

1.3.1 The European context

The first major EU policy on energy efficiency improvements in the building sector was adopted on September 13, 1993. The Directive 93/76/EEC [17], also known as **“SAVE” Directive**, aimed to limit CO_2 emissions, and promote the rational use of energy by requiring Member States (MSs) to implement their energy efficiency measures.

With the adoption of the **1st commitment period of the Kyoto Protocol** [1] on December 11, 1997 (entered into force on February 16, 2005), which established the EU target of 8% reduction in GHG emission reduction during the period 2008-2012 compared to the 1990 levels, a comprehensive set of energy and climate policies were developed to promote energy efficiency. As stated from Claude Turmes [18]: “*energy efficiency must be place at the heart of EU energy policy if we are to have any change of addressing Europe’s energy crisis and we welcome that the Commission has recognised this in the Energy Efficiency Action Plans*”.

In the light of the above, since 2000, the European Commission (EC) has published several **Energy Efficiency Action Plans** (EEAPs) with the aim to reduce energy consumption by improving energy efficiency in buildings. The 2000 Action Plan [19] emphasised the need to amend the SAVE Directive by defining reinforced actions and strengthening existing measures. Furthermore, this plan played a key role in the development of the first Energy Performance of Building Directive (EPBD, 2002/91/EC). In 2006, the 2nd Energy Efficiency Action Plan [20] was published by the European Commission with the aim to outlie a framework of policies and measures to achieve the goal of saving 20% of the EU’s annual primary energy by 2020.

In 2007, following the 2006 Action Plan, the Commission proposed a legislative package, known as **2020 Climate and Energy Package** (2007-2009) [21]. The package aimed to help the EU in achieving its climate and energy targets by 2020. It includes the so-called “20-20-20 targets”, as follows:

- a GHG emission reduction of 20%, compared to 1990 levels;
- an increase in EU energy from RES to 20%;
- an improvement in energy efficiency by 20%.

In 2011, with its "**Roadmap for moving to a competitive low-carbon economy in 2050**" [22], the European Commission set out a plan to achieve the long-term goal of reducing domestic GHG emissions by 80% to 95% by 2050, compared to 1990 levels. The roadmap provided a gradual and effective transition, requiring a national GHG emission reduction of 40% by 2030 and 60% by 2040 [23]. In March 2011, the 3rd Energy Efficiency Action Plan [24] was adopted by the Commission with the aim to encourage energy renovations in the private and public sectors by requiring Member States to renovate at least 3% of public buildings each year [25].

On December 8, 2012, the **2nd commitment period of the Kyoto Protocol** [26] was adopted, running from 2013 to 2020. In line with the “20-20-20 targets”, introduced in 2007, EU countries agreed to achieve a 20% reduction in GHG emissions by 2020 compared to 1990 levels.

In 2014, the European Union established energy and climate targets for the year 2030. The **2030 Climate and Energy Package** [27] outlined the following goals to be achieved in the period 2020-2030:

- a GHG emission reduction of 40% compared to 1990 levels;
- an increase in EU energy from RES to 27%;
- an improvement in energy efficiency by 27%.

In February 2015, the **Energy Union strategy** [28] was adopted with the aim to ensure secure, sustainable, competitive, and affordable energy for all the EU citizens. Specifically, the strategy was based on the following five dimensions: (1) increasing the energy security; (2) strengthening the internal energy market; (3) improving energy efficiency; (4) reducing GHG emissions and (5) supporting research and innovation in the energy sector. This strategy was resulted in the development of several legislative measures, initiatives, and policy packages, among which the **Clean Energy for All Europeans (Clean Energy) package** [4], which was considered the most important legislative measure for energy efficiency. The package, launched by the Junker Commission (2014-2019) in November 2016 and adopted from 2019, updated the following EU targets for 2030:

- a GHG emission reduction of 40% compared to 1990 levels;
- an increase in EU energy from RES to 32%;
- an improvement in energy efficiency by 32.5%.

In addition, the package included eight different legislative acts aimed to accelerate the transition to cleaner energy sources in Europe. Specifically, the main set of directives and regulations for enhancing energy efficiency in the building sector included the Energy Performance of Buildings Directive (2018/844/EU), the Energy Efficiency Directive (2018/2002/EU), the Renewable Energy Directive (2018/2001/EU), and the Regulation on Governance (2018/1999/EU). This section provides a detailed discussion of the aforementioned directives and regulations, which were updated with the introduction of the Fit-for-55 package in 2021.

Among several key initiatives to guide and assist EU strategic priorities for 2019-2021 period, the **European Green Deal** [29] represents the most important one. It was a set of policy and initiatives proposals which includes the Renovation Wave strategy and the Fit-for-55 package. Introduced on January 2019 by the European Commission, it was a roadmap to drive the EU towards a sustainable and climate-neutral economy by 2050.

As part of the European Green Deal, the **Renovation Wave strategy** [30] for Europe was published by the European Commission in October 2020. This strategy aimed to improve the energy performance of existing buildings by encouraging their energy retrofit. Renovating public and private buildings was recognized as a key strategy to drive the decarbonisation of the building sector and to align with the EU’s sustainability targets set for 2050 [31]. As stated by the Commissioner for Energy, Kadri Simson [32]: “*the green recovery starts at home. With the Renovation Wave we will tackle the many barriers that today make renovation complex, expensive and time consuming, holding back much needed action. We will propose better ways to measure renovation benefits, minimum energy performance standards, more EU funding and technical assistance encourage green mortgages and support more renewables in heating and cooling. [...].*”. In fact, more than 75% of the EU's existing buildings were characterised by low energy performance [33] and only 11% was renovated each year with a lack of attention to energy saving, upgrading of technical building systems and installation of renewable energy systems [30]. The Renovation Wave action plan aimed to achieve the at least 55% emissions reduction target by 2030 by reducing “*the buildings' greenhouse gas emissions by 60%, their final energy consumption by 14% and energy consumption of heating and cooling by 18%*” [30], and by doubling the annual renovation rate in the next ten years [32].

The **Fit-for-55 package** [34], which was adopted in July 2021, aimed to translate the climate ambitions of the Green Deal into legislation. This plan replaced the Clean Energy for all European Package, which was initiated by the Juncker Commission (2014-2019), to optimise the European climate policy framework and make it more effective in achieving the 2030 targets. In fact, the overall target of this strategy was to reduce the GHG emissions across all sectors by at least 55% by 2030 [34]. Focusing on the energy sector, the revision of the 2030 targets, which were already approved with the Clean Energy for All Europeans package, included:

- a GHG emission reduction of 55% compared to 1990 levels;
- an increase in EU energy from RES to at least 40%;
- a reduction of final energy consumption by 36% and primary energy consumption by 40%.

On May 18, 2022, the European Commission published the **REPowerEU strategy** [11] in response to the global energy market disruption and the increase in energy prices caused by the war between Russia and Ukraine. The plan aimed to rapidly reduce dependence on Russian fossil fuels and accelerate the green transition, while increasing the resilience of the EU energy system. Specifically, the REPowerEU strategy has planned three actions planned to appropriately respond to the energy crisis [35]: (1) achieving the energy saving through behavioural changes of European citizens; (2) diversifying the energy supply by focusing on alternative sources to gas, oil, and coal; (3) replacing fossil fuels by accelerating the European transition to clean energy through the use of renewables. Among the measures related to renewable energy and energy efficiency, the REPowerEU plan included [36]:

- an increase in EU energy from RES to 45%;
- an increase in the energy efficiency target from 9% (proposed by Fit-for-55 package) to 13%, compared to the 2020 reference scenario.

As mentioned above, the following paragraphs aim to provide a detailed overview of the directives and regulations related to energy efficiency in the building sector, from their entry into force to their latest updates and proposals.

Energy Performance of Buildings Directives

The Energy Performance of Buildings Directives represent a key policy instrument for the EU buildings sector to increase the renovation rate of the existing building stock. The first EPBD was adopted in December 2002 (Directive 2002/91/CE [37]) by introducing a common methodology for the building energy performance calculation. Specifically, the Directive provided the definition of minimum energy performance requirements (Articles 4 and 5), and the introduction of energy performance certificates (EPC) for new and existing buildings (Article 7). In May 2010, the EPBD 2002/91/EC was replaced by the Directive 2010/31/EU [38] which aimed to ensure that minimum energy performance requirements adopted by MSs were harmonized in terms of energy savings and reductions of GHG emissions. This Directive introduced the concept of nearly Zero Energy Building (nZEB) in Article 9 and the cost-optimal methodology in Article 5. The 2018 amendments to the EPBD (Directive 2018/844/EU [6]), as part of the Clean Energy for All Europeans package, aimed to accelerate the decarbonisation of the existing EU's building stock by 2050 by setting strategic national plans for their renovation, which were defined as Long-Term Renovation Strategies (LTRS). Section 1.3.2 focuses on the Italian strategy for the energy requalification of the national building stock. In December 2021, the European Commission proposed a recast of the EPBD as part of the Fit-for-55 package, approved by the European Parliament on March 14, 2023 (EPBD IV recast [39]). The main goal was to reduce buildings' GHG emissions in order to achieve a zero emission building stock by 2050. In particular, the 2023 revised directive increased the European energy efficiency target, requiring EU countries to collectively guarantee a further reduction in energy consumption of 11.7% by 2030, compared to the 2020 reference scenario. Therefore, the total EU energy consumption by 2030 should not exceed 992.5 million tonnes of oil equivalent (Mtoe) for primary energy and 763 Mtoe for final energy [40]. The last EPBD introduced main targets for the building sector, which were summarised in the following bullet list:

- the definition of Zero Emission Building (ZEB), characterised by very high energy performance, in which the low amount of energy consumption is entirely covered by renewable energy sources. ZEB should become the standard for new buildings from 2027 for non-residential and public buildings, and from 2030 for all others (*Article 2*);
- for existing buildings, residential buildings would have to achieve at least class E by 2030 and D by 2033; while non-residential and public buildings would have to achieve the same classes by 2027 and 2030, respectively (*Article 9*);

- long-term renovation strategies are strengthened towards building renovation plans (*Article 3*);
- from January 2024, the purchase and installation of fossil-fuelled generators and the use of fossil-fuelled systems for new buildings and major renovations will no longer be eligible for incentives;
- from 2035, all heating systems currently fuelled by traditional fuels will have to be completely replaced.

On December 7, 2023, the Council and the European Parliament reached a provisional political agreement to revise the new EPBD [41]. The final version presents several changes compared to the text approved by the European Parliament in March 2023. The following bullet list summarised the main changes introduced by [41] :

- EU Member States will have to ensure that residential buildings reduce average energy consumption by 16% by 2030 and 20-22% by 2035. For non-residential buildings, the required reduction is 16% by 2030 and 26% by 2033;
- From 2030, all new buildings will have to be zero emission. For public buildings, this obligation will apply from 2028. The entire existing building stock will have to reach the zero emission standard by 2050;
- The end of fossil fuel heating systems in homes has been postponed from 2035 to 2040. In addition, subsidies for autonomous boilers are scheduled to end by 2025.

On January 15, 2024 the European Parliament's Industry, Research and Energy (ITRE) Committee confirmed the agreement on the revision of the energy performance of buildings directive [42].

Energy Efficiency Directives

The Energy Efficiency Directives (EED) represent a set of policies in the EU aimed to improve energy efficiency. The first EED entered into force in December 2012 (Directive 2012/27/EU [43]) by introducing a set of measures to achieve the 20% energy efficiency target by 2020. Specifically, MSs were required to establish their own national level energy efficiency targets to contribute to the overall EU target. In November 2018, the EED was revised to establish a legal framework for the 2030 energy efficiency targets. As part of the Clean Energy for All Europeans package, Directive 2018/2002/EU aimed to increase the energy efficiency target to 32.5% by 2030 [44]. MSs were required to implement measures to achieve an average annual reduction of 4.4% in their energy consumption by the year 2030 [45]. The revised Energy Efficiency Directive 2023/1791/EU [46], published in the Official Journal in September 2023, represents an important step in the EU's commitment towards energy efficiency. The Directive 2023/1971 was the result of a first revision in July 2021 [47], as part of the Fit-for-55 package, which was subsequently strengthened by an additional proposal in May 2022, within the framework of the REPowerEU plan [35]. Specifically, with the first recast in 2021, the European Commission required MSs to double their annual energy savings commitments from 2024, as well as to achieve 9% more energy savings [48]. Subsequently, the Commission's proposed amendment in 2022, as part of the REPowerEU plan, called for 13% more energy savings by 2030 [48]. Among the changes introduced by the new Directive 2023/1971/EU, in respect to the previous Directives 2018/2002/EU and 2012/27/EU, the main goals were summarised as follow:

- setting a legally binding EU target to decrease the EU’s final energy consumption by 11.7% by 2030, compared to the 2020 reference scenario. This means that the total EU’s energy consumption should be limit to 992.5 Mtoe for primary energy and 763 Mtoe for final energy;
- achieving an average of 1.49% of annual energy savings for the period between 2024 to 2030, equivalent to an annual increase in energy savings from 0.8% to 1.3% (2024-2025 period), at least 1.5 (2026-2027 period) and 1.9% in 2028-2030;
- introducing an annual target for reducing energy consumption in the public sector, set at 1.9%;
- renovating at least 3% of the total surface area of public buildings each year.

Renewable Energy Directive

The Renewable Energy Directives (RED) aim to support the EU’s policy framework for the production and promotion of renewable energy. The Directive 2009/28/EC [49] (also known as RED I) was adopted in April 2009, as part of the 2020 climate and energy package, to assist the EU in achieving its 20% renewable energy target by 2020. National targets were introduced in RED I for all Member States to increase the use of renewable energy sources (RES) in the EU's energy consumption from 12.5% in 2010 to 21.8% in 2021 [50]. In 2016, the European Commission proposed a full recast of RED I, which did not enter into force until June 2018. The Directive 2018/2011/EU [51] (RED II), as part of the Clean Energy for All Europeans package, established a new binding renewable energy target for the EU of at least 32% by 2030. On July 14, 2021, the European Commission proposed an amendment to RED II [52], as part of the Fit-for-55 package, to increase the 2030 target from 32% to 40%. This means doubling the current renewable energy share of 19.7%. Focusing on the building sector, Article 15a of the proposed Directive, sets a new renewable energy target of 49% share of RES in heating and cooling of buildings by 2030 [53]. Subsequently, as part of the REPowerEU plan in 2022, the European Commission proposed an additional revision of RED II to further increase the renewable energy target to 45% by 2030 (above the 40% RES target proposed in July 2021) [35]. In September 2023, the European Parliament (EP) presented its final adopted position on the new Directive, amending the previous Commission’s proposal targets. As reported in [54]: “*Member States shall collectively ensure that the share of energy from renewable sources in the Union’s gross final consumption of energy in 2030 is at* *least 42.5 %. Member States shall collectively endeavour to increase the share of energy from renewable sources in the Union's gross final consumption of energy in 2030 to 45 %*". Finally, in October 2023 the Directive 2023/2413/EU (RED III) [55] was published in the Official Journal of the European Union and it will come into force on November 20, 2023. RED III outlined various innovative approaches for promoting and increasing the share of renewable energies in the Union's energy mix, providing guidance for Member States [55].

Regulation on Governance

In December 2018, the Regulation on Governance of the Energy Union and Climate Action (Directive 2018/1999/EU [56]), which amended several Directives and repealed the Regulation 2013/525/EU on the mechanisms for monitoring and reporting greenhouse gas emissions, entered into force as part of the Clean energy for all Europeans package. The Governance Regulation represents the main instrument through which the EU aimed to achieve its 2030 energy and climate targets. Each MS must comply with the following requirements:

- the development of an integrated National Energy and Climate Plan (NECP) for each ten-year period, starting with the period from 2021 to 2030 [57]. NECPs set out the strategic path envisioned by national policymakers for the forthcoming decade, aiming to plan how each country intends to address energy efficiency, renewable energy and GHG emission reductions, as well as how it means to achieve the national targets;
- by 2020 and every ten years, the submission of a National Long-term Strategy (NLTS), with a perspective of at least 30 years, aiming to fulfil their commitments under the Paris Agreement and align with the objectives of the Energy Union [58]. The Governance Regulation also calls for the development of an EU Long-term Strategy (EU LTS) by the European Commission for the reduction of GHG emissions [59];
- by 2023 and every two years thereafter, the development of an integrated national energy and climate progress report, with the aim of reporting to the European Commission on the status of implementation of its national energy and climate plan [57];

The Governance Regulation required revision in 2021 due to the higher levels of ambition and stricter requirements for energy and climate policies proposed by the Fit-for-55 package and the REPowerEU plan. In July 2021, the EU published the European Climate Law (Regulation 2021/1119/EU [60]), which sets the EU's overall target of achieving the climate neutrality by 2050 and the interim target of reducing GHG emissions by at least 55% by 2030. On June 30, 2021, the European Climate Law came into effect, amending Regulation 2018/1999/EU on the Governance of the Energy Union and Climate Action.

1.3.2 The Italian national context

In accordance with the EU energy and climate policy framework described in the previous section 1.3.1, the main goal of Italy’s energy policy was to reduce carbon emissions in the energy sector by promoting the adoption of renewable energy sources and by increasing the energy efficiency.

In July 2021, the Italian **National Recovery and Resilience Plan** (Piano Nazionale di Ripresa e Resilienza, PNRR) was established by the European Council, as part of the Next Generation EU (NGEU) programme for the period 2021-2026 [61]. It was adopted in response to the Covid-19 pandemic crisis, with the aim to make Italy a more equitable, environmentally sustainable, and inclusive country. The plan was developed along three strategic axes: digitisation and innovation, ecological transition, and social inclusion. It included several financial measures for energy efficiency, in particular for the renovation of the existing building stock and the strengthening of the Ecobonus and Sismabonus tax deductions. The PNRR invested over 15 billion € in the following four measures to improve the energy efficiency of buildings:

- energy and seismic renovation of residential buildings, including social housing, and transformation of the national building stock into nZEB;
- intervention in 290,000 m^2 of offices, courts, and judicial citadels, making 48 structures more efficient;
- construction of about 195 school buildings, reducing energy consumption and cutting annual GHG emissions;
- support the development of 330 km of new efficient district heating networks.

To meet the EU targets, each MS was required to draft a 10-year National Energy and Climate Plan. As mentioned in section 1.3.1, the NECPs were introduced by the Regulation 2018/1119/EU on Governance of the Energy Union and Climate Action. In Italy, the **Integrated National Energy and Climate Plan** (Piano Nazionale Integrato Energia e Clima, PNIEC), as part of the Clean energy for all Europeans package, represented a fundamental instrument that marked the beginning of a strategic change in the Italian energy and climate policy towards decarbonisation, for the period 2021-2030 [61]. The plan aimed to achieve and exceed the EU targets for energy efficiency, energy security, the use of renewable energy sources, the development of the internal energy market, and competitiveness. In [61], the main Italy’s 2030 energy and climate targets were shown as follows:

- the production of energy from renewable sources accounting for 30% of gross final energy consumption by 2030;
- a 43% reduction in primary energy consumption and 39.7% in final energy consumption;
- a reduction of 33% in GHG emissions not covered by the EU Emissions Trading System, compared to 2005.

In section 1.3.1, it was mentioned that the EPBD required Member States to establish strategic policy instruments aimed to renovate their existing residential and non-residential buildings into a decarbonised and highly energy-efficient building stock by 2050. In March 2021, Italy presented its own strategy called the **Italian strategy for the energy requalification of the national building stock** (Strategia italiana per la riqualificazione energetica del parco immobiliare nazionale, STREPIN) [63]. The PNIEC revealed that the building sector is accountable for 45% of the final energy consumption and 17% of CO_2 emissions in our country [63]. The STREPIN have to identify proper ways to ensure adequate financial sources, including the use of tax deductions, and to provide period targets for 2030, 2040 and 2050, as well as progress indicators specifying their functionality with regard to the energy efficiency targets set out in the PNIEC. The Italian LTRS aimed to renovate the private building stock using key financial instruments, such as tax deductions. Specifically, the Italian government launched the so-called Superbonus 110% to promote economic recovery and energy efficiency in the building and construction sector following the Covid-19 pandemic emergency. It was introduced on May 20, 2020, by the Relaunch Decree (Decree-Law 34/2020 [64]) with the aim to encourage specific interventions related to energy efficiency, reduction of seismic risk, installation of photovoltaic systems and installation of infrastructure for recharging electric vehicles in buildings. As reported in the Relaunch Decree, article 119, the energy efficiency measures covered by the Superbonus 110% concern: (1) the thermal insulation of vertical, horizontal, and inclined opaque surfaces of the building envelope with an incidence of more than 25% of the building's gross dispersion area, (2) the replacement of existing winter air-conditioning systems with centralised heating, and/or cooling and/or domestic hot water supply (among which the installation of heat pump technology). Moreover, to benefit from the tax deduction, it was necessary that the interventions comply with the minimum requirements (set out by the Ministerial Decrees of 19 February 2007 [65] and Ministerial Decrees of 11 March 2008 [66]), as well as ensure the improvement of at least two energy classes or the achievement of the highest energy class. This condition must be demonstrated by an EPC, issued before and after the intervention, by a qualified technician. On July 18, 2020, the Relaunch Decree was converted into Law no. 77 of 17 July 2020 [67]. Subsequent regulations and measures, among which the 2022 Budget-Law (Law 234/2021 [68]), introduced substantial changes regarding the extension of the tax deduction. Another important change was introduced by the last 2023 Budget-Law (Law 197/2022 [69]), which provided a reduction in the tax deduction from 110% to 90% for expenses incurred by condominiums from January 2023. More details on Superbonus 110%-related interventions are provided in Chapter 4.

1.4 Problem statement

As described in section 1.3, the current context is characterised by the post-Covid-19 recovery and the global energy transition process. This scenario has led to a growing attention on two main pillars to be integrated in the design of the building of the future: (1) indoor environmental quality (IEQ) issues with the aim of ensuring occupants' health and well-being in the built environment, as well as (2) the role of energy efficiency and electricity in the building sector to achieve the Zero Emission Building target by 2050. The need to achieve these two pillars is discussed in Chapter 2.

On the one hand, the Covid-19 pandemic, declared as a Public Health Emergency of International Concern on 30 January 2020 [5], emphasised the key role of IEQ in promoting human health and well-being. In particular, since the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is identified as the cause of the infectious disease as well as it is mainly transmitted airborne, there is the urgency to improve IAQ due to its significant impact on human health-related status in indoor environments [70]. Even before the pandemic people are used to spend more than 90% of their time indoors [71]; now, with the changes of people habits and the practice of employees working remotely from home due to the lockdown, they are required to stay in the same enclosed space for an extended period of time. With the spread of the Covid-19 pandemic, the attention to the indoor built environment as well as the need to ensure occupants' health and well-being have become key targets for the design and operation of future buildings that will be not only smart - able to monitor and manage energy optimally - but also healthy – able to positively impact the health, well-being, and productivity of its occupants [72]. According to [73], a healthy building can be characterised by the so-called "*9 fundamentals of a healthy building*", which includes all the criteria needed to build an indoor environment able to guarantee human health. Among them, IAQ represents a predominant factor since the indoor pollutant concentration is twice high than outside, thus causing a range of health issues such as adverse short-term health effects (e.g., sick building syndrome symptoms such as headaches, nausea, fatigue, etc.), and long-term consequences (e.g., respiratory and heart disease, cognitive deficit, cancer, etc.) [74]. Already in 2018, with the EPBD 2018/844/EU [6], a "*human-centric approach*" for new buildings and renovations of existing ones is encouraged by shifting the focus from building energy efficiency to the occupants' health inside building. Subsequently, with the spread of Covid-19 emergency, ensuring a good IAQ and promoting human health-related status become the priority for the transition towards healthy and resilient building design. To reach this goal, long-term strategies, among which innovative air filtration technologies installed in Heating Ventilation and Air Conditioning (HVAC) systems, are crucial to mitigate the transmission of SARS-CoV-2 virus or other contaminants in the indoor environment.

On the other hand, the main goal of the global energy transition to reduce the use of primary energy and to increase the use of renewable sources, is pushing the

EU's building energy market towards the electrification of final energy consumption and, thus, towards incentivising the use of renewable technologies [10]. Specifically, the war between Russia and Ukraine had a strong impact on the energy market, leading to a sharp rise in energy prices and, thus, necessitating strategic changes in EU policies. In response to the ongoing global energy crisis, the European Commission presented in 2022 the REPowerEU strategy with which EU intends to take important and stronger measures in the short- and medium-term [36]. The plan sets out a series of measures to rapidly reduced dependence from Russian fossil fuels and accelerated the "green" transition through the use of renewable, more economically and environmentally sustainable sources. Another key policy instrument adopted in 2023, as part of the Fit-for-55 package, was the last recast of the EPBD [39]. It plans: "*EU countries should ensure that the use of fossil fuels in heating systems, [...] should be totally phased out by 2035*" in order to achieve the ZEB target by 2050 [75]. In addition, to support the energy transition of the building sector and, thus, to encourage energy retrofitting investments in buildings, several financial mechanisms are introduced. Focusing on the Italian context, the Relaunch Decree [64] is adopted with the aim of relaunching the country's economy affected by the Covid-19 emergency. The Decree introduces an incentive mechanism, the so-called Superbonus, which increased the tax deduction for building interventions from 50-65% to 110% [64]. It involves a significant amount of actions, including the installation of renewable solutions, among which heat pump technologies, with the aim of encouraging their installation in new buildings or to replace existing heating systems still powered by fossil fuels. In this context, the European and national energy policy framework is driving the current building energy market towards the adoption of all-electric solutions for space heating and cooling.

In the light of the above, it is evident the key role played by technologies in achieving the main European and Italian national targets to boost the building of the future. In both cases, the main problem encountered by industrial companies concerns the high investment costs of such advanced technological solutions, which might prevent consumers to invest on them.

1.5 PhD Objective and research questions

The previous section summarised how the current context, characterised by the post-Covid-19 recovery and the global energy transition, has highlighted the key role played by technologies in achieving the main European and national targets to promote the building of the future. For this reason, this Ph.D. dissertation stems from the strong demand from industrial companies to enhance their technologies in order to make them competitive in the current building energy market. As mentioned in section 1.4, the high investment costs are a major concern for industrial companies, which may deter consumers from investing in their technologies. Therefore, the Ph.D. dissertation aims to guide and support industrial companies in the launch of advanced technological solutions, which play a key role in the design and operation of the building of the future, in the current building energy market.

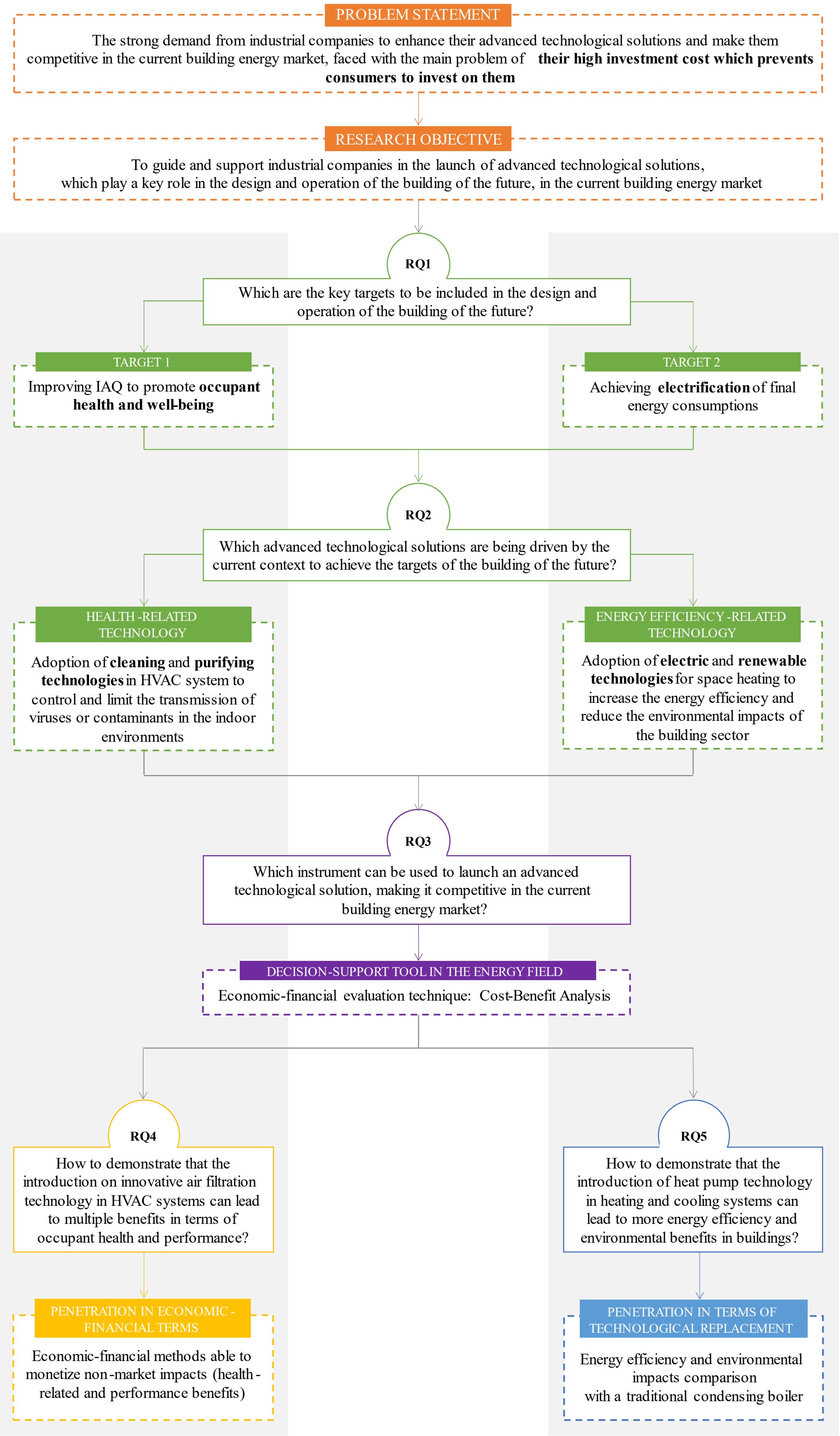
In the light of the above, the following four overarching research questions characterised the whole literature review presented in Chapters 2 and 3:

- *RQ1*: Which are the key targets to be included in the design and operation of the building of the future?
- *RQ2*: Which advanced technological solutions being driven by the current context to achieve the targets of the building of the future?
- *RQ3*: Which instrument can be used to launch an advance technological solution, making it competitive in the current building energy market?

Then, for each case study application presented in Chapters 4 and 5, research questions 4 and 5 are addressed:

- *RQ4*: How to demonstrate that the introduction of innovative air filtration technology in HVAC systems can lead to multiple benefits in term of occupant health and performance?
- *RQ5*: How to demonstrate that the introduction of heat pump technology in heating and cooling systems can lead to more energy efficiency in buildings?

Figure 7 shows a graphical synthesis of the Ph.D. dissertation to guide the reader within the thesis structure showed in the following section. As shown in the figure, the flow of the whole dissertation was characterised by two pillars: IAQ and occupants' health and well-being (on the left), and energy efficiency and electrification in buildings (on the right). These pillars represent the main context of the case studies discussed in Chapters 4 and 5, respectively.


PROBLEM STATEMENT

The strong demand from industrial companies to enhance their advanced technological solutions and make them competitive in the current building energy market, faced with the main problem of **their high investment cost which prevents consumers to invest on them**

RESEARCH OBJECTIVE

To guide and support industrial companies in the launch of advanced technological solutions, which play a key role in the design and operation of the building of the future, in the current building energy market

RQ1

Which are the key targets to be included in the design and operation of the building of the future?

TARGET 1

Improving IAQ to promote **occupant health and well-being**

TARGET 2

Achieving **electrification** of final energy consumptions

RQ2

Which advanced technological solutions are being driven by the current context to achieve the targets of the building of the future?

HEALTH-RELATED TECHNOLOGY

Adoption of **cleaning** and **purifying technologies** in HVAC system to control and limit the transmission of viruses or contaminants in the indoor environments

ENERGY EFFICIENCY-RELATED TECHNOLOGY

Adoption of **electric** and **renewable technologies** for space heating to increase the energy efficiency and reduce the environmental impacts of the building sector

RQ3

Which instrument can be used to launch an advanced technological solution, making it competitive in the current building energy market?

DECISION-SUPPORT TOOL IN THE ENERGY FIELD

Economic-financial evaluation technique: Cost-Benefit Analysis

RQ4

How to demonstrate that the introduction on innovative air filtration technology in HVAC systems can lead to multiple benefits in terms of occupant health and performance?

PENETRATION IN ECONOMIC-FINANCIAL TERMS

Economic-financial methods able to monetize non-market impacts (health-related and performance benefits)

RQ5

How to demonstrate that the introduction of heat pump technology in heating and cooling systems can lead to more energy efficiency and environmental benefits in buildings?

PENETRATION IN TERMS OF TECHNOLOGICAL REPLACEMENT

Energy efficiency and environmental impacts comparison with a traditional condensing boiler

Figure 7: Graphical synthesis of the Ph.D. dissertation: problem statement, objective, and research questions.

1.6 Roadmap and thesis structure

This section aims to guide the readers within the Ph.D. dissertation. After an introduction section that provides an overview of the research topic, the problem statement, the research objective and the research questions, Chapters 2, 3, 4 and 5 represent the main core of the thesis aimed to address to research questions highlighted in the previous section. Figure 8 summarises a graphical representation of the Ph.D. thesis structure.

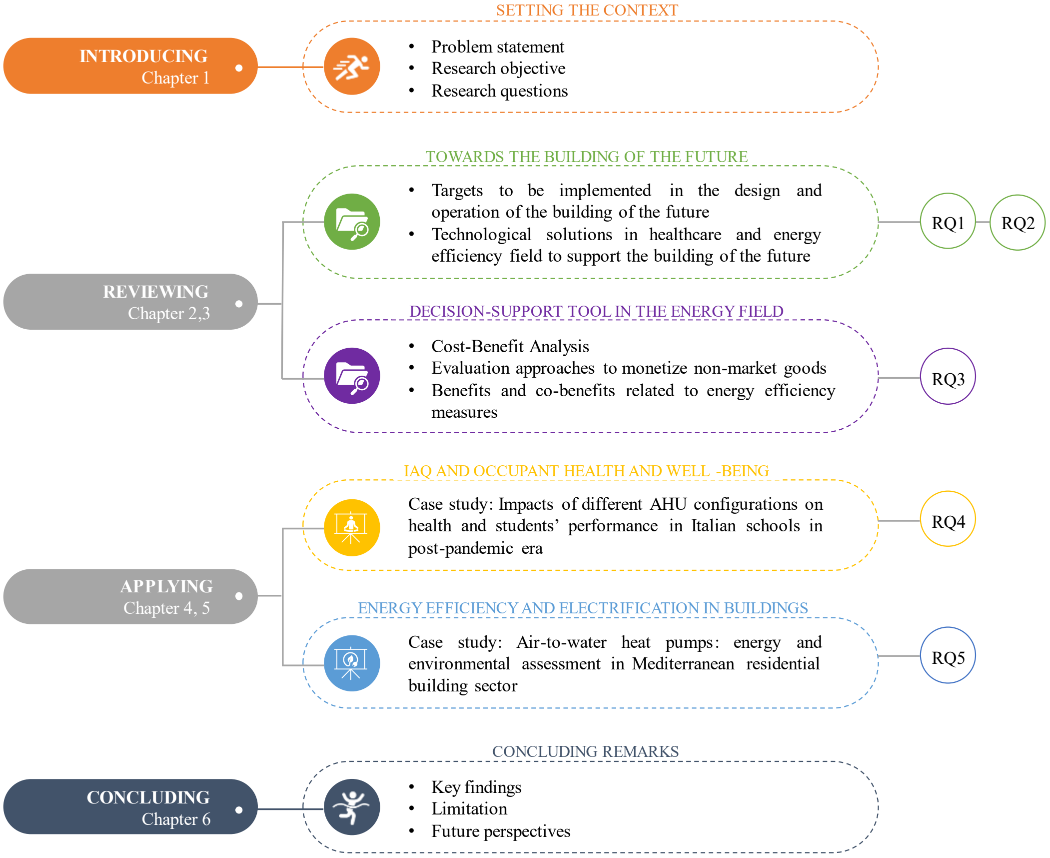


Figure 8: Ph.D. thesis structure.

Specifically, *Chapter 2* provides a detailed examination of the main targets and technological solutions for designing and operating future buildings, in line with the current European and Italian national contexts. The chapter is divided into three main sections, in addition to a brief section providing an overview of the chapter:

- section 2.2 shows the building targets before the spread of Covid-19 pandemic emergency;
- section 2.3 addresses RQ 1, highlighting the importance of integrating two new fundamental aspects into future building design. These pillars are represented by achieving good IAQ for the health and well-being

of occupants, as well as by electrifying final energy consumption in buildings (sections 2.3.1 and 2.3.2, respectively)

- section 2.4 aims to answer RQ 2 by providing an overview of the main technological solutions in the healthcare and energy efficiency fields, driven by the current context. Specifically, section 2.4.1 deals with solutions for the healthcare sector, while section 2.4.2 deals with technologies for energy efficiency in buildings.

Then, in order to answer to the RQ 3, *Chapter 3* highlights the need for research into new decision-support tools in the energy field. In addition to a brief overview section, it is divided into the following five main sections:

- section 3.2 provides an overview of the most used tools in the energy investment decision-making process, with the aim of identifying among them the optimal one in response to RQ 3;
- section 3.3 presents the objective and methodological steps of the Cost-Benefit Analysis (CBA);
- section 3.4 reviews the main economic evaluation approaches used to measure and monetise costs and benefits;
- section 3.5 aims to classify the direct and indirect benefits related to energy efficiency measures in the decision-making framework;
- section 3.6 summarises the economic key performance indicators (KPIs) used to provide a final judgment on the performance of the project.

Chapters 4 and 5 deal with the case study applications, providing to answer RQ 4 and RQ 5, respectively. Specifically, both chapters offer an overview of the background, a detailed methodology description, and the main findings. Finally, the conclusions and future developments are summarised at the end of each section.

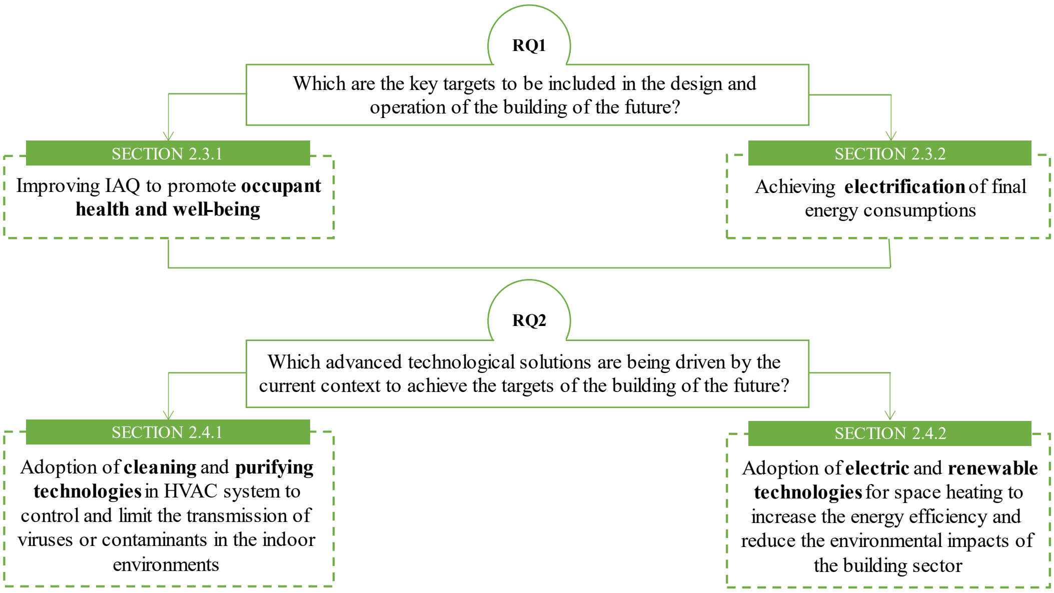
To conclude, *Chapter 6* summarises the main findings and limitations of the whole research, addressing each of the research questions presented above.

Chapter 2

Towards the building of the future

> *"In 10 years, the buildings of Europe will look remarkably different. Buildings will be the microcosms of a more resilient, greener, and digitalised society, operating in a circular system by reducing energy needs, waste generation and emissions at every point and reusing what is needed (...). Buildings will be less energy-consuming, more liveable, and healthier for everybody"*
> *European Commission, COM(2020)662 [30]*

2.1 Overview



RQ1

Which are the key targets to be included in the design and operation of the building of the future?

SECTION 2.3.1

Improving IAQ to promote **occupant health and well-being**

SECTION 2.3.2

Achieving **electrification** of final energy consumptions

RQ2

Which advanced technological solutions are being driven by the current context to achieve the targets of the building of the future?

SECTION 2.4.1

Adoption of **cleaning** and **purifying technologies** in HVAC system to control and limit the transmission of viruses or contaminants in the indoor environments

SECTION 2.4.2

Adoption of **electric** and **renewable technologies** for space heating to increase the energy efficiency and reduce the environmental impacts of the building sector

Figure 9: Structure of Chapter 2.

This chapter presents a literature review on the main targets and technological solutions for the design and operation of future buildings, driven by the current European and Italian national context. Specifically, section 2.2 introduces the pre-Covid-19 building targets. Then, section 2.3 provides a definition of IAQ-resilient building (section 2.3.1), as well as outlines the decarbonisation pathway of the building sector (section 2.3.2) by aiming to answer to RQ 1: *"Which are the key targets to be included in the design and operation of the building of the future?"* Finally, section 2.4 examines the main health-related technologies in HVAC systems (section 2.4.1), as well as the electric and renewable technologies for space heating (sections 2.4.2) driven by the current context to support the design of the building of the future. The last two section aim to address the following research question: *"Which advanced technological solutions being driven by the current context to achieve the targets of the building of the future?"*

Keywords: indoor air quality; IAQ-resilient building; energy efficiency.

Declaration: The topics described in sections 2.3.1 and 2.4.1 were previously published in the following publication:

- **Lingua, C.**; Crespi, G.; Becchio, C.; Corgnati, S.P. Designing IAQ-Resilient Post-Pandemic Buildings. Sustainability (2023), 15, p. 2187. DOI: 10.3390/su15032187 [76].

2.2 The pre-Covid-19 building targets

Reducing energy consumption in new and existing buildings was the most important goal to be achieved before the Covid-19 pandemic emergency. Improving energy efficiency and achieving high energy performance in buildings was, therefore, at the heart of the main European and national strategies to meet future climate and energy policy objectives. In this context, a key measure to reduce energy consumption in buildings was the nearly Zero Energy Building. The concept of nZEB was introduced by the recast of the EPBD (Directive 2010/31/CE [38]) as the new standard for new buildings occupied by public authorities from 2018, while all new buildings from 2020. According to the EPBD recast (Article 2), an nZEB is: "*a building that has a very high energy performance, as determined in accordance with Annex I. The nearly or very low amount 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*" [38]. In particular, Annex I defines that "*the energy performance of a building shall be determined on the basis of the calculated or actual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs to maintain the envisaged temperature conditions of the building, and domestic hot water needs*" [38]. A graphical interpretation of the nZEB definition as set out in Article 2 of the EPBD recast is shown in Figure 10.

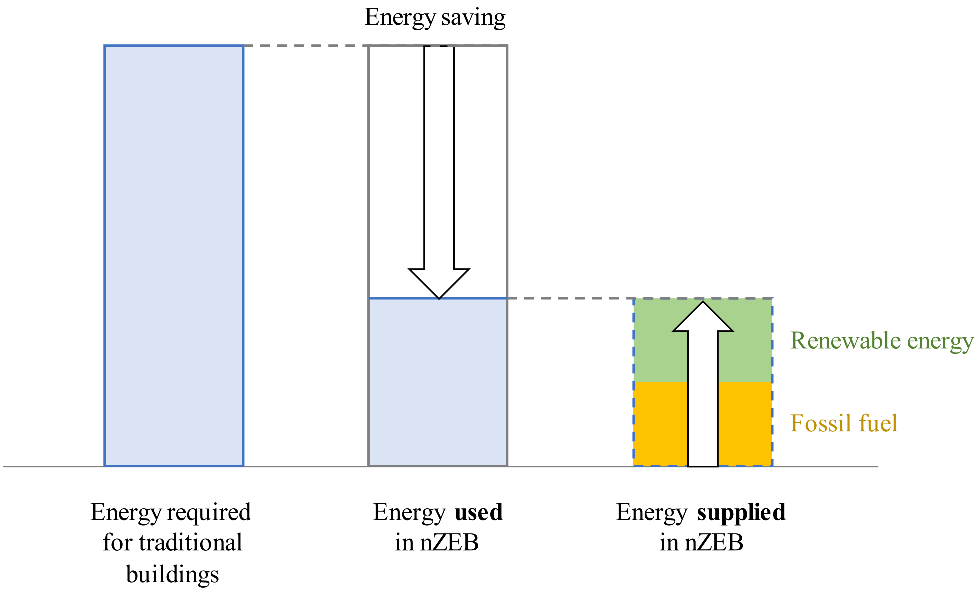


Figure 10: Graphical representation of the nZEB definition according to the EPBD recast. Elaboration from [77].

The EPBD recast did not prescribe a minimum or maximum requirement (i.e., primary building energy use expressed in kWh/(m^2y)), neither a detailed calculation method of the energy consumption for nZEBs, due to the different climatic conditions and local characteristics in each EU's Member State. For this reason, as established by the EPBD recast (*Article 9*), MSs were required to provide their own nZEB definitions in accordance with their national context and climate, to develop specific requirements related to the use of energy from renewable sources, as well as to establish national strategies for increasing the number of nZEBs among new construction or renovation of existing buildings. According to D'Agostino and Mazzarella [78], the MSs had the possibility to define some aspects in the definition of nZEB, such as "*building category, typology, physical boundary, type and period of balance, included energy uses, renewable energy sources, metric, normalization, and conversion factor*". The freedom given to each EU country by the EPBD has led to a variety of terms being used to characterise very low energy buildings with the overall aim of zero energy. Specifically, according to [79], the term "**net zero**" means that the total amount of energy used by the building over a year is equal to the amount of energy from renewable sources produced on-site. Recently, the term "net zero" was replaced by "**zero energy**" for greater clarity and easy communication with the audiences [79]. In addition, the term "**zero energy ready**" is increasingly being used to refer to buildings with low energy requirements and suitable structural and electrical infrastructure, without the need to install photovoltaic (PV) systems at the time of construction [79]. Furthermore, some European countries go beyond the "zero energy" term by targeting "**energy positive**" buildings, also known as PlusEnergy or "Plusenergiehaus" in Germany and as "Bâtiments à énergie positive" in France [79]. There is no official definition of Positive Energy Building (PEB) at European level. However, according to [80], which investigated on the PEB concept, "*a positive energy building is an energy-efficient building that produces more energy than it uses via renewable sources, with high self-consumption rate and high energy flexibility, over a time span of one year. A high-quality indoor environment is an essential element in the PEB, maintaining the building occupants' comfort and well-being. The PEB can also integrate future technologies like electric vehicles with the motivation to maximise the onsite consumption and share the surplus renewable energy*". As reported in [81]: "*Technically, a PEB is a Net ZEB with an increased capacity of the renewable energy generation inside the boundary of the building in order to surpass the annual equality of the net energy balance*". Figure 11 illustrates the different definitions of nearly zero energy, net zero energy, and energy positive buildings, mentioned above.

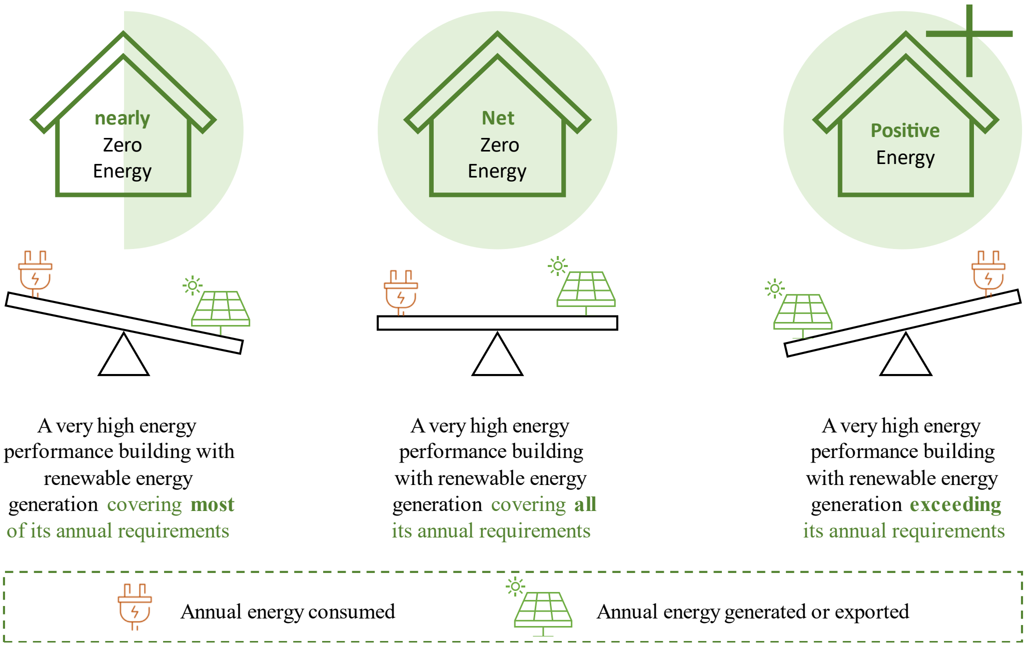


Figure 11: Definitions of nearly, net, and positive energy buildings. Elaboration from [82].

In Italy, the Decree Law 63/2013, converted into Law No. 90 of 3 August 2013 [83], which transposed the European EPBD recast, introduced for the first time a definition of an nZEB as "*a building characterised by a very high energy performance in which the very low or almost no energy demand is covered by energy from renewable sources produced within the system boundary (in situ)*". Regarding the main requirements for an nZEB, they were set out by the Ministerial Decree of 26 June 2015 (D.M. 26/06/2015 [84]), the so-called Minimum Requirements. It introduced the concept of reference building, defined as a building with the same shape, orientation, and basic systems as the real one, and meets all the criteria of the prescriptive compliance method [84]. Therefore, to be classified as an nZEB, a number of requirements must be checked in relation to the reference building. In addition, as established by the Legislative Decree No. 28 of 3 March 2011 [85] on the promotion of the use of RES, the thermal energy system of an nZEB must be designed to cover 50% of the primary energy provided for domestic hot water (DHW), as well as 50% of the sum of the primary energy provided for heating, DHW and cooling, using energy from renewable sources.

2.3 Implementation of nZEB targets

As described in the previous section, the nZEB is a building that established energy efficiency requirements very well, but this is no longer sufficient to respond the new needs. In fact, the future buildings will need to integrate new aspects in order to meet the current targets.

On the one hand, the spread of the Covid-19 pandemic emergency has highlighted the importance of ensuring occupant health and well-being in the built environment. On the other hand, the conflict between Russia and Ukraine and subsequent increase in energy prices has shifted attention towards the adoption of heating and cooling systems that rely on alternative carriers to gas. Thus, the current European and national context has led to two fundamental aspects to be integrated into nZEBs: achieving good IAQ for human health and well-being and electrifying end-use energy in buildings. For this reason, the following sections aim to provide a definition of the IAQ-resilient building (section 2.3.1), as well as to outline the decarbonisation pathway of the building sector (section 2.3.2).

2.3.1 IAQ-resilient building for human health and well-being

As mentioned above, a key aspect to be considered in the design and operation of the building of the future is the need to ensure optimal conditions for occupants' health and well-being in the built environment. While the 2018 amendments to the EPBD [6] had already emphasised this need (as described in section 1.3.1), with the spread of the Covid-19 pandemic emergency the urgency of improving IAQ in enclosed spaces as a transition to healthy and resilient building design is well recognised. It is important to mention that IAQ has long been a major concern and that, similar to the SARS-CoV-2 virus, various pathogens and contaminants (e.g., viruses, bacteria, etc.) can pose risks to human health [86]. However, while existing IAQ standards have traditionally protected individuals against normal contaminant levels, resulting in reduced healthcare expenses and productivity losses, the Covid-19 crisis has highlighted that "*buildings designed to such standards lack the resilience to protect occupants effectively during infectious disease outbreaks*" [87]. As shown by several studies, crowded and poorly ventilated environments were associated with a faster spread of the SARS-CoV-2 virus [88],[89],[90]. Therefore, as reported by the WELL Building Standard [7], ensuring a good level of IAQ for the health and well-being of end-users was identified as a crucial target for post-Covid-19 building construction. In this context, rethinking the built environment by proposing a paradigm based on IAQ-resilience to airborne infections, which can ensure healthier and more adequate living spaces, has become a priority in the design of future buildings. To investigate the implications of an IAQ-resilient building for future transitions, a state-of-the-art literature review was conducted to answer the following two questions: *"(i) what does the resilience of the built environment mean?*" and *"(ii) How can the existing resilience definitions and features be extended to IAQ?*". While previous literature was predominantly focused on the impacts of extreme weather conditions and catastrophic natural events (e.g., earthquakes, high winds, floods, and fires), there was a notable lack of knowledge on resilient responses to pandemic Covid-19 in the built environment, which is the main focus of this review. The literature was collected from various search platforms, such as Google Scholar, Science Direct, and PubMed, as well as from journals, books, and conference papers. More insights into the methodology used for this literature review are presented in [76].

Since the early 1900s, the concept of resilience was applied across several fields, including organizational, social, economic, engineering domains. As shown by [91], the term resilience represented the "*capacity to persist in the face of change, to continue to develop with ever-changing environments*". Another definition reported in [92] explained the resilience as "*a system's readiness in reacting towards disruptive events*"; similarly, it is defined as "*the ability of a system to recover from adversity*" [93]. Focusing on the energy domain, the IEA [94] reported a detail definition of the concept of resilience as "*the capacity of the energy system and its components to cope with a hazardous event or trend, to respond in ways that maintain its essential functions, identity and structure as well as its capacity for adaptation, learning and transformation. It encompasses the following concepts: robustness, resourcefulness, recovery*". Table 1 shows a summary of various definitions of built environment resilience.

Table 1: Definitions of resilient buildings. From [76].

Reference	Definition
[95]	*"A resilient built environment as one designed, located, built, operated, and maintained in a way that maximizes the ability of built assets, associated support systems (physical and institutional) and the people that reside or work within the built assets, to withstand, recover from, and mitigate the impacts of threats"*
[96]	*"Buildings resilience could be seen as an ability to withstand the effects of earthquakes, extreme winds, flooding and fire, and their ability to be quickly returned after such event"*
[97]	*"A building's ability to withstand severe weather and natural disasters along with its ability to recover in a timely and efficient manner if it does incur damages"*
[98]	*"The capacity of the city (built infrastructure, material flows, etc.) to undergo change while still maintaining the same structure, functions and feedback, and therefore identity"*
[99]	*"A single building is resilient if it has the ability to quickly adapt to changes in conditions and continue to function*

	smoothly”
[100]	*“The building is defined to be resilient if it is able to prepare for, absorb, adapt to and recover from the disruptive event”*
[101]	*“A resilient building is a building that not only is robust but also can fulfil its functional requirements during a major disruption. Its performance might even be disrupted but has to recover to an acceptable level in a timely manner in order to avoid disaster impacts”*
[102]	*“A resilient built environment will ensue when we design, develop and manage context sensitive buildings, spaces and places that have the capacity to resist or change in order to reduce hazard vulnerability, and enable society to continue functioning, economically, socially, when subjected to a hazard event”*
[103]	*“Resilience in buildings [...] is framed as the ability of the building to serve the occupants’ needs in times of crisis or shocks. [...] The capacity of a building to sustain atypical operating conditions in disaster situations, rather than succumbing to building failure, is the critical measure of its resilience”*
[104]	*“The ability of a building to prepare for, withstand, recover rapidly from, and adapt to major disruptions due to extreme weather conditions”*
[105]	*The concept of resilience in the built environment is understood as “the ability of any urban system, with its inhabitants, to maintain continuity through all shocks and stresses, while positively adapting and transforming toward sustainability”*

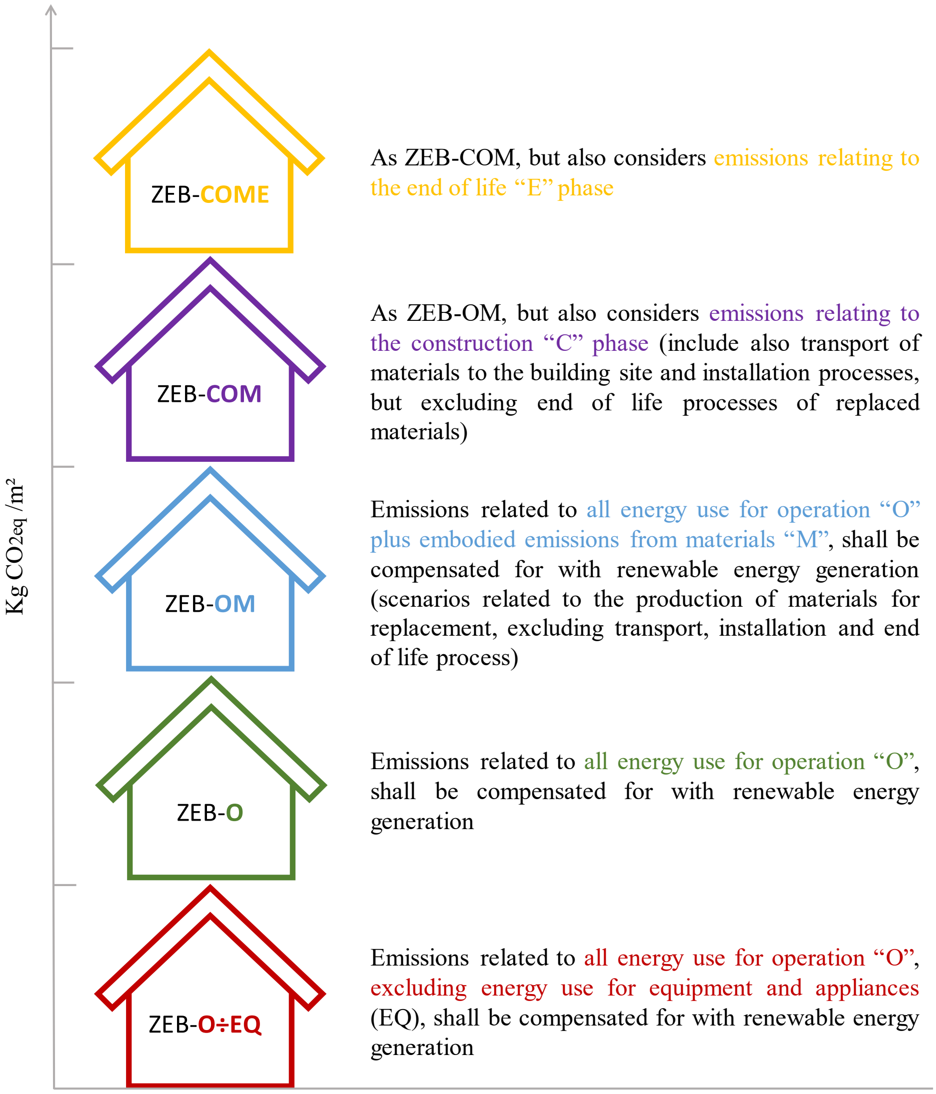
According to [106], Table 1 shows that there is still no common definition of resilience in the built environment. From the above literature review is evident that the resilience of buildings to various dangers, including natural disruptive event (e.g., earthquakes, extreme winds, floods, fire, etc.) and “*atypical operating conditions*”, was generally related to the concepts of adaptation, recovery, and resistance. Furthermore, the increasing impact of natural disasters has brought resilience to the forefront of attention, highlighting its close relationship with sustainability in building design. In fact, the concept of resilience was increasingly discussed in literature as a paradigm that should be adopted alongside sustainability [107],[111]. As reported in [107], the impact of climate change has led to the adoption of both sustainability and resilience paradigms in the built environment. As highlighted by the authors, the difference between the two concepts was that “*whereas sustainability encourages reduced impacts on the environment to avoid changes, resilience encourages adaptation to change*” [107]. In addition, another definition of the two concepts was shown by [112]. The authors suggested that “*sustainability focuses on future stability, while* *resilience represents readiness for the potential disasters of the dynamic and unpredictable future*". While the literature mainly associates the concept of resilience in the built environment with natural hazards, it is important to note that other types of disruptions, such as air pollution and pandemics, can also impact on the resilience of a building [113],[114]. Specifically, the spread of the Covid-19 pandemic has increased people's awareness on the health risks they are exposed to in the indoor environment (e.g., pathogens such as viruses and bacteria, indoor pollutants, etc.).

Therefore, the second part of this literature review focuses on expanding the concept of resilience to include IAQ and health-related concerns. The goal is to address the second question and provide guidance on how to design future buildings to be resilient to IAQ issues. As reported by [109], Covid-19 pandemic emergency required new targets in the design and renovation of resilient buildings, among which guaranteeing health and safety, reducing energy consumption and environmental impact, ensuring occupants' comfort and well-being. According to [90], the authors suggested a more "*human-centred design*" for future buildings in order to preserve occupants' health from future epidemics. Therefore, to face epidemics or other type of emergencies in the future, it was crucial to increase the resilience of post-pandemic building design [115]. Focusing on IAQ resilience related to the Covid-19 pandemic's disruptions, [111] assessed the resilience of residential buildings and their ability to "*withstand future pandemics' social, economic, and health-related challenges*". They defined specific pandemic-resilient sustainability indicators to evaluate buildings' readiness to face potential future health-related threats [111]. Among the several pandemic resilient indexes identified by the authors, air quality indicators (e.g., efficiency of air filtration systems against pathogen, monitor and control indoor air pollution, control the airflows in micro spaces, and level of natural ventilation) played a crucial role in the health of occupants during lockdowns [111]. Similarly, [116] developed and applied a new quantitative assessment framework for IAQ resilience in a school building. The framework resulted in a resilience score metric that integrates all resilience aspects, such as absorptivity, recovery, and impact, with the main pollutants relevant to the built environment (e.g., CO_2, VOCs, $PM_{2.5}$, PM_{10}) [116]. The authors in [117] referred to the concept of infection-resilient environments, which involved constructing buildings that can minimise the risk of disease transmission to support public health during and beyond the Covid-19 pandemic. In addition, as reported by [117], mitigating the risk of infection and achieving a more resilient building design required long-term improvements in buildings able to "*create indoor environments that support our health and well-being*" in the face of various possible airborne diseases (e.g., epidemics, pandemics, seasonal flu, etc.).

To summarise the main findings of the above literature review, an IAQ-resilient building can be defined as a building able to provide healthier and more suitable living spaces, while at the same time adapting to the new needs of occupants (e.g., the practice of working from home arising from Covid-19 pandemic). Specifically, the main focus of an IAQ-resilient building design should be the development of an IAQ management plan for the built environment. This includes giving significant importance to passive measures, ventilation and filtration requirements, as well as to the control and regulation of indoor humidity and temperature in order to safeguard occupants from the risk of airborne infection. It is important to note that improving IAQ may result in increased energy consumption in buildings. Therefore, it is essential that the new IAQ-resilient design and operation strategies are aligned with sustainability goals and climate change mitigation efforts, finding the right balance between IAQ and energy consumption. For this reason, IAQ-resilient buildings require the adoption of suitable engineering and architectural solutions, which can effectively reduce the risk of airborne diseases and ensure high levels of IAQ, while meeting the energy efficiency criteria. These aspects are further explored in section 2.4.1.

2.3.2 The path through building decarbonisation

As mentioned above, in addition to ensuring optimal conditions for occupants' health and well-being in the built environment, the design and operation of future buildings must also consider the crucial role of electrification in the decarbonisation of the building sector. The term “*decarbonisation*” is used to define the process of reducing or eliminating GHG by replacing the use of fossil fuels with renewable energy sources (e.g., solar, wind, geothermal energy) [118]. In particular, the decarbonisation of the building sector represents a key driver in the Europe energy transition process since, as said by the Commissioner for Energy Kadri Simson [119]: “b*uildings are the single largest energy consumer in Europe, using 40% of our energy, and creating 36% of our greenhouse gas emissions. That is because most buildings in the EU are not energy efficient and are still mostly powered by fossil fuels*”. A series of legislative initiatives, among which the REPowerEU strategy introduced in 2022, were adopted by the European Commission to reach the target of reducing GHG emissions of at least 55% by 2030 compared to 1990, with the overall aim of achieving climate neutrality by 2050 [11]. With the introduction in 2023 of the Energy Performance of Building Directive recast (EPBD III [39]), the European Commission upgrades the European building stock from nearly Zero Energy Building, which represents the current building standard from 2011, to Zero Emission Building set as the future building target by 2030 in order to reach the global climate neutrality goal. In detail, as established by Article 7, all new public buildings and new buildings must be zero emission from 2027 and 2030, respectively; while all existing buildings by 2050 [39]. According to the Directive, a ZEB is “*a building with a very high energy performance, where the very low amount of energy still required is fully covered by energy from renewable sources generated on-site, from a district heating and cooling system*” [39]. Due to a lack of internationally agreed official definition of ZEB, as well as since the requirements to achieve carbon neutrality in the building sector are not evident, MSs referred to a variety of terms used to characterise zero or very low emissions buildings. Different definitions of “**zero emission**” was arisen from literature; in [121], authors referred to zero emission building as "*an energy-efficient building with on-site renewable energy generation that can export enough energy to compensate for the carbon footprint of the building's own energy and material consumption in a life-cycle perspective*". While, at the Research Centre on Zero Emission Buildings [122], Zero Emission Building was defined as "*a building that produces enough renewable energy to compensate for building's GHG emissions over its life-cycle*". In detail, the study illustrated the five ZEB ambition levels defined on the number of phases of a building's life cycle that were considered (Figure 12).



As ZEB-COM, but also considers emissions relating to the end of life "E" phase

As ZEB-OM, but also considers emissions relating to the construction "C" phase (include also transport of materials to the building site and installation processes, but excluding end of life processes of replaced materials)

Emissions related to all energy use for operation "O" plus embodied emissions from materials "M", shall be compensated for with renewable energy generation (scenarios related to the production of materials for replacement, excluding transport, installation and end of life process)

Emissions related to all energy use for operation "O", shall be compensated for with renewable energy generation

Emissions related to all energy use for operation "O", excluding energy use for equipment and appliances (EQ), shall be compensated for with renewable energy generation

Figure 12: Different ZEB ambition levels. Elaboration form [123].

Another term used to define low emission buildings was "**net zero emission**". In [124], the authors explained the aim of a net zero emission building as follow: "*the overall goal of a net zero emission building (NZEB) is that all emissions related to the energy use for operation as well as embodied emissions from materials should be offset by on-site renewable energy* generation". In their definition, they specify that "*the addition of the word "net" indicates that energy can be exported from and imported to the building, and that the net energy or* *emission balance is calculated over a specific period of time, usually a year*" [124]. The term "**zero carbon**" was used to define a building in which the "*building-incorporated services include all energy demands or sources that are part of the building fabric at the time of delivery, such as the thermal envelope (and associated heating and cooling demand), water heater, built-in cooking appliances, fixed lighting, shared infrastructure and installed renewable energy generation*" [125]. Two different definitions of "**net zero carbon**" were shown by [126], according to the type of intervention. For new buildings and major renovations, the term "net zero" meant that "*the amount of carbon emissions associated with a building's product and construction stages up to practical completion is zero or negative, through the use of offsets or the net export of on-site renewable energy*"; instead, for all building in operation, it meant that "*the amount of carbon emissions associated with the building's operational energy on an annual basis is zero or negative. A net zero carbon building is highly energy efficient and powered from on-site and/or off-site renewable energy sources, with any remaining carbon balance offset*" [126]. Finally, the term "**zero-carbon-ready**" was increasingly used to refer to highly energy efficient buildings that use renewable energy sources or rely on energy provide by sources (e.g., electricity or district heating) that will be completely decarbonised by 2050 [127]. As reported by IEA [127]: "*a zero-carbon-ready building will become a zero-carbon building by 2050, without any further changes to the building or its equipment*". In order to avoid the delay that affected the implementation of nZEB definition in the EU Member States, the methodological framework that should characterise the ZEB definition (e.g., the system boundaries, the calculation methods and timeframe, the main indicators and metrics) was identified and presented by [128].

Among the different strategies for reducing energy-related CO_2 emissions, electrification was the key driver to achieve decarbonisation goals. Specifically, as reported by [129], "*electricity is an important pillar of building sector decarbonisation"*, as well as it led to other multiple benefits including an affordable and reliable energy system thanks to electricity produced from RES, an increased efficiency in energy use, and an improved air quality due to reduced pollutant emissions in energy end-uses [130]. According to IEA, electrification meant "*replacing technologies or processes that use fossil fuels, like internal combustion engines and gas boilers, with electrically-powered equivalents, such as electric vehicles or heat pumps*" [131]. In the building sector, electrification of space heating was considered one of the main contributors to CO_2 emission reductions [131], as almost half of the global energy use in buildings was used for space heating [132]. Therefore, heat pumps were recognised as the key technology for achieving sustainable heating in buildings, replacing fossil-fuel-based boilers. They were also the main driver for reducing emissions in the Net Zero Emissions (NZE) scenario by 2050 [133]. The key role of this electric technology is further discussed in section 2.4.2.

2.4 Technological pathways to support the building of the future

Once the key characteristics of the future building were defined, such as high energy efficiency, all-electric and autonomous features, low CO_2 emissions, and able to meet the needs of end-users while ensuring IAQ-resilience for the health and well-being of occupants, this section explores the main technological solutions that can support the design of such a building in achieving the targets outlined in the previous section 2.3.

2.4.1 Health-related technologies in HVAC systems

As mentioned in section 2.3, the spread of Covid-19 pandemic emergency has emphasised the urgency to improve IAQ for ensuring health and well-being of occupants who spend most of their times in indoor spaces. To increase IAQ resilience of indoor environments with the aim of designing and operating buildings to be healthier and more IAQ-resilient for the future, it was crucial to consider long-term strategies able to mitigate the spread of contaminants (e.g., SARS-CoV-2 virus) [109]. According to [90], the main strategies to improve IAQ included "*source controlling, designing ventilation systems, and air cleaning*". Several studies have shown that the design of a building's ventilation system and the use of cleaning and purifying technologies were crucial in controlling and limiting the transmission of the SARS-CoV-2 virus, thereby improving IAQ [115],[134],[135]. This aspect was also emphasised by the U.S. Environmental Protection Agency (EPA) [136], which recommended improving indoor air ventilation and filtration systems in buildings as fundamental components to prevent the spread of Covid-19. In particular, proper ventilation strategies (e.g., natural ventilation through window opening or mechanical ventilation using HVAC systems) were the most effective for diluting and removing indoor air contaminants [137], as well as for ensuring occupants' health and well-being in the built environment [107].

Focusing on various mechanically ventilated building studies in the literature [137],[138],[139], the key role of air filtration systems (e.g., mechanical filtration or biofiltration technologies) and other air purification techniques (e.g., Ultraviolet Germicidal Irradiation (UVGI) system and bipolar ionization) properly installed in HVAC system was emerged with the aim of ensuring a healthy IAQ for occupants and protecting the Air Handling Units (AHUs) from viruses or bacteria by reducing their transmission in the indoor environment. Specifically, mechanical filtration was widely used in HVAC systems to improve IAQ through the installation of high efficiency particulate air (HEPA) filters [140]. This type of filter was recommended in buildings due to its high efficiency to remove at least 99.97% of airborne particles (e.g., pollen, mould, bacteria, etc.) with a size less than 0.3 μm [141]. While HEPA filters were effective in improving IAQ, they can also become a source of contamination due to microorganisms surviving and proliferating on the filter media [142],[143]. As demonstrated by [144], air filters were identified as the main source of contamination among the components of a ventilation system. To solve this problem, as well as in response to the spread of the Covid-19, the demand for antimicrobial filtration technologies able to reduce the microbiological growth on the filter media was increased. As shown by [145], the use of a tungsten trioxide (WO_3)-based photocatalyst placed on a filter's media, combined with visible LED light, enabled the elimination of harmful agents, including the SARS-CoV-2 virus. Specifically, the experimental results showed that the infectious load of SARS-CoV-2 was reduced by 100% after 30 minutes of treatment. Similarly, [146] and [147] demonstrated that the use of a titanium dioxide (TiO_2) photocatalyst, combined with ultraviolet (UV) lighting, was an effective antimicrobial agent for the inactivation of SARS-CoV-2. As mentioned before, biofiltration technology is becoming increasingly popular among air filtration systems due to its economic, environmental, and social benefits [115]. Thanks to its ability to absorb CO_2, NO_2, and SO_2, this type of filter was especially used in polluted environments to increase occupants' health and performance [148].

Air purification was another effective method for improving IAQ and preventing the spread of airborne viruses. It was defined as a system that "*can inactivate the germicides as well as remove the pollutants with high efficiency*" [134]. Among the various techniques, UVGI appliances and bipolar ionization were the most common used in enclosed spaces [149]. The UVGI technology used Type C ultraviolet light (UV-C) to inactivate bacteria and viruses [150]. Several studies in the literature shown the efficiency of direct UV-C against the SARS-CoV-2 virus; in [151], the authors demonstrated that the Covid-19 could be inactivated by a small dose of UV-C irradiation (about 3.7 mJ/cm^2). Similarly, as shown by [152], UV-C sources were able to inactivate more than 90% of the SARS-CoV-2 virus in indoor environment. Despite its evident advantages, it was important to note that this technology, which was based on UV light, may posed potential hazards to human health. Finally, bipolar ionization (also called needlepoint bipolar ionization) was another air purification technique that can be installed in HVAC systems. This system effectively reduced airborne contaminants from the air using electrostatic force [153].

2.4.2 Electric and renewable technologies for space heating

As mentioned in section 2.3, improving the energy efficiency of buildings is a key objective of current European policy actions towards achieving climate neutrality and decarbonising the building sector. Specifically, the role of electricity and, therefore, the adoption of heating and cooling systems that rely on a carrier that is no longer gas have a growing attention. Heating in buildings was responsible for 4 gigatonnes of CO_2 emissions per year, equal to 10% of global emissions [154]. Fossil fuels accounted for 63% of global energy used for building heating, among which natural gas was the most widely used energy source, accounting for 42% of the heating energy demand in 2022 (around 40% in the European Union) [132]. To align with the NZE scenario, substantial changes were required. This transition entailed reducing the current share of fossil fuels for heating, aiming to bring it down to around 45% by 2030 [132]. Achieving this objective will require a transition towards electric and renewable heating technologies. In this context, heat pumps were considered the central technology to meet decarbonisation in the current energy transition process. In fact, thanks to their power supply from low-emission electricity, heat pumps were recognized as promising technologies for increasing the overall energy efficiency of the system as well as for reducing the environmental impact of the building sector [133]. According to [155], the deployment of heat pumps could reduce the energy-related emissions of buildings by 10-15%. In addition, as reported by the IEA "*heat pumps have the potential to reduce global carbon dioxide emissions by at least 500 million tons in 2030*" [154]. Despite their long-term savings, the high initial investment costs of heat pumps can discourage consumers. However, in recent years, the heat pump market has experienced a strong growth thanks to the introduction of financial incentives (e.g., the Superbonus 110% in Italy) to promote their installation in buildings. Therefore, the global heat pump sales increased by 13% in 2021 compared to 2020 level [154], and by 11% in 2022 compared to the previous year [133]. The European Union represented the most rapidly expanding market globally for this technology, with an increase of 34% in 2021 and almost 40% in 2022 (around 3 million installations) [156]. Figure 13 shows the number of heat pumps sold in each EU country in 2022.

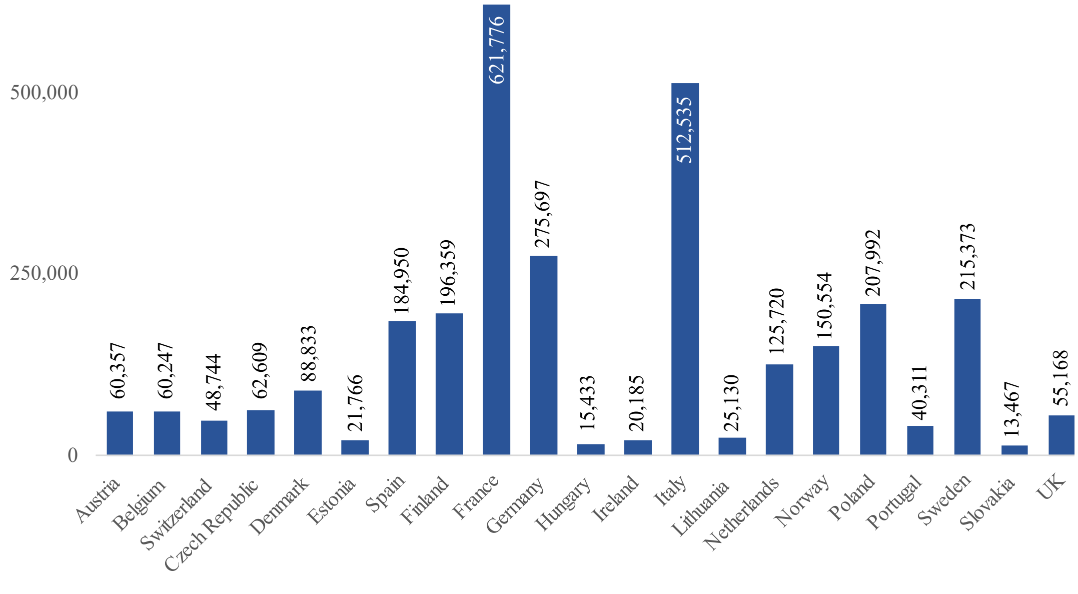


Figure 13: Number of heat pumps sold in 2022 per EU country. Elaboration from [157].

As shown in the figure above, the leading European markets for heat pumps in 2022 were France (621,776 units sold), Italy (513,535 units sold), Germany, (75,697 units sold), Sweden (215,373 units sold), and Poland (207,992 units sold). This surge in heat pump sales played a key role in reducing the demand for natural gas in 2022. As part of the REPowerEU plan to reduce the EU's dependency on imported fossil fuels, the European Commission called for a doubling of the rate of heat pump deployment in buildings with the goal of reaching 10 million heat pumps installed by 2027 and a fourfold increase in the number of heat pumps by 2030 [132]. To conclude, as said by the IEA Executive Director Fatih Birol: "*heat pumps are an indispensable part of any plan to cut emissions and natural gas use, and an urgent priority in the European Union today*" [154].

After an introduction to the European heat pump market, the main characteristics of these technologies are presented. A heat pump was a highly efficient system as it used energy from renewable sources (e.g. air, water, ground) and drastically reduces CO_2 emissions compared to a traditional appliance (i.e. gas or boiler) [133]. Thanks to the possibility of reversing its cycle, it can be used both for winter and summer air conditioning as well as for DHW production [158]. According to the type of thermal source used, heat pumps can be classified as aerothermal, geothermal or hydrothermal, depending on whether they use air, ground or water respectively [158]. Specifically, according to IEA [132], the main characteristics of the above heat pumps are shown:

- The **aerothermal heat pump** is the most popular type of heat pump thanks to its low investment cost. However, the efficiency of this type of heat pump depends on the outside air temperature. In addition, on the basis of the type of exchanger, it is divided into air-to-air, if the distribution terminals use air (split or fan coils), and air-to-water, if the exchange medium is water (radiators or radiant panels).
- The **geothermal heat pump**, also known as ground-to-water heat pump, uses the ground's heat as its primary source of energy. Its advantage over the aerothermal heat pumps is the constant temperature. This also gives control over the efficiency of the machine and, therefore, over consumption and running costs, which are much less susceptible to climatic variations.
- The **hydrothermal heat pump** is also called water-to-water heat pump because it uses water as both the heat source and the heat transfer fluid. This type of heat pump is less affected by fluctuations in air temperature and, therefore, provides more reliable performance. However, it has a higher initial investment cost. These machines can be used for both air conditioning (summer and winter) and DHW production.

Finally, it is necessary to combine a heat pump with a suitable distribution system able to transport and remove heat within rooms. Depending on the distribution fluid used in the room (i.e. air or water), different distribution terminals are required. The main advantages and disadvantages of each distribution terminal are listed below:

- Radiators with a water inlet temperature of 70°C and an outlet temperature of 50°C are the most common heat distribution system in the home. Nowadays, the use of low-temperature radiators, which allow the water temperature to be raised to 55°C, is increasing. However, radiators do not provide summer cooling.

- Fan coil is a water-to-air heat exchanger which uses a fan to draw air from the room, filter it and return it to the room after heat exchange with the water circulating in the system. They require a water temperature of around 45/40°C in the winter and 7/12°C in the summer. In addition, these type of distribution terminals allow individual control of the room temperature.
- Radiant panels consist of plastic or copper pipes that are usually installed under the floor. The large surface of the panel means that it can use water at much lower temperatures than radiators. Typically, the water supply temperature is around 35°C in winter and 18 to 20°C in summer.

Figure 14 provides an overview of the various typologies of heat pumps and distribution terminals described above.

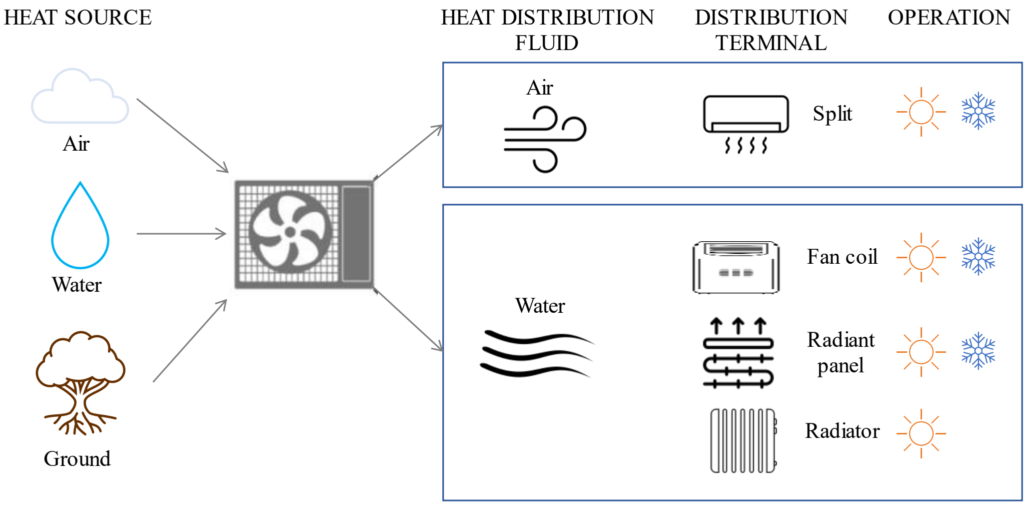


Figure 14: Various heat pumps typologies and distribution terminals. Elaboration from [159].

Chapter 3

Decision-support tool in the energy field

3.1 Overview

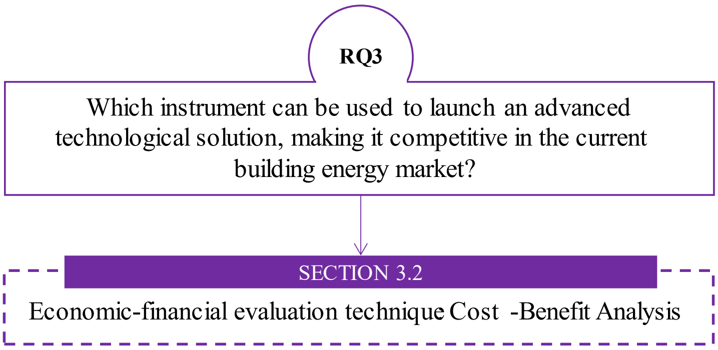


Figure 15: Structure of Chapter 3.

This chapter highlights the need for research into new decision-support tools in the energy field. Specifically, section 3.2 provides an overview of the most used tools in the energy investment decision-making process, with the aim of identifying among them the optimal one in response to RQ 3: "*Which instrument can be used to launch an advanced technological solution, making it competitive in the current building energy market?*". Once the Cost-Benefit Analysis has been identified as the most suitable method, section 3.3 presents the main implications of the tool, its objectives and methodological steps, highlighting the need to move from a cost-optimal methodology to a Cost-Benefit Analysis to combine the financial and the economic dimensions. Then, section 3.4 provides an overview of the main economic evaluation approaches used to measure and monetise non-market impacts. In section 3.5, the direct and indirect benefits related to energy efficiency measures are classified in the decision-making framework. Finally, section 3.6 presents the main key performance indicators used in the CBA.

Keywords: Decision-making methods, Cost-Benefit Analysis, key performance indicator, non-market impact.

Declaration: The topics described in this chapter were previously published in the following publication:

- Cakan, M.; Becchio, C.; Corgnati, S.P.; Mazzarella, L.; Quiles, P.; Ekren, O.; Yay, T.; Dell'Anna, F.; Bottero, M.; **Lingua, C.**; Toksoy, M.; Aktakka, S.; Karadeniz, Z.H.; Saglam, S.; Arisoy, A. Design Strategies for Residential Buildings in Mediterranean Regions - Part 2. European Guidebook 31. Federation of European Heating, Ventilation and Air Conditioning associations (REHVA), 2021 [160].

3.2 Decision-making methods applied in energy investment

According to the literature [161],[162],[163], Life Cycle Assessment (LCA), Cost-Benefit Analysis and Multi-Criteria Analysis (MCA) were recognised as the most frequently methods used in the planning and management of energy-related decision problems. Therefore, by considering their different evaluation criteria, the aforementioned tools can support the decision-making process of an investment project. Specifically, as further described in section 3.3, contrary to financial methods (e.g., the cost-optimal methodology), CBA and MCA can include co-benefits in their assessment [164]. For this reason, this section focuses on the explanation of the most used tools in energy investment decision-making process, the Cost-Benefit Analysis and the Multi-Criteria Analysis, highlighting their application in various studies in the literature. Specifically, this section aims at identifying among them the optimal solution in response to RQ 3.

The **Cost-Benefit Analysis** is a key tool for measuring the effectiveness of an investment decision, as it can translate all the impact categories into monetary values [161]. Specifically, the evaluation allows the combination of financial (e.g., the impact on the main actors involved in the investment) and economic (e.g., the impact on society as a whole, including environmental impacts, health, well-being, etc.) analysis. In this way, the CBA can identify the "*actions with the lowest social cost or the highest net social benefit*" [161]. As presented in section 3.6, different economic performance indicators are available in the literature to perform the final judgement of an investment decision. In addition to the Net Present Value (NPV) and the Internal Rate of Return (IRR) indicators used in conventional financial analysis, the Benefit-Cost ratio (BCR) is "*the most widely used indicator of the social profitability of a project*" [165]. In addition, as reported by [166], CBA can be used at different scales of analysis, including "*at the technological component level, at the building level and at district/city level*". At the technological component level, [167] applied the BCR indicator to demonstrate the benefits of installing an antibacterial filter for AHU units in office building. Specifically, the authors shown that the higher investment and maintenance costs of this innovative filtering technology can be fully repaid by the benefits in terms of increased worker productivity and reduced healthcare costs [167]. Similarly, in [168], the authors found that the additional investment costs of higher filter efficiency could be repaid by monetising the health-related benefits. At the building level, according to [166],[169], a multi-dimensional approach of the CBA was used to advice a building manager to the possible impact of air quality on human health and well-being. In addition, a study conducted in a Beijing residential area applied the CBA methodology framework to assess the economic sustainability of energy efficiency retrofit in existing buildings [170]. Finally, at the district scale, an evaluation approach based on CBA was proposed by [162], with the aim of addressing the energy requalification of a new Net Zero-Energy District (NZED) located in Italy. The CBA allowed to combine the energy and the socio-economic performance (e.g., GHG emission reduction, green jobs creation, real estate valorisation) impacts in this evaluation project. As demonstrated by [171], the CBA represents a suitable tool for the assessment of a project from a social and economic perspective. In this study, the CBA was applied with the aim of assess the efficiency of proposed smart city solutions.

This preliminary literature review shows that the main limitations of the CBA methodology relate to the monetary valuation of costs and benefits. Therefore, it is difficult to express all benefits in monetary terms, especially those related to non-market goods (e.g., environmental impacts, health, well-being, etc.). For this reason, as stated by [161], “*the analysis is often restricted to only monetized aspects such as capital, operation and maintenance costs*”. On the other hand, the CBA has proven to be a key tool in the decision analysis between different alternatives by providing a single criterion as an output that is easy and comprehensible to decision makers. A more detail description of the methodological steps involved in the CBA framework will be explained in the following section 3.3.

The **Multi-Criteria Analysis**, also known as Multi-Criteria Decision-Making (MCDM) or Multi-Criteria Decision Analysis (MCDA), aims at defining the best alternative by considering multiple qualitative and quantitative criteria simultaneously in the decision-making problems [172]. In [173], with the aim of helping professionals select and deploy 4.0 technologies for energy sustainability, the authors used a behavioural approach with MCDA. In another study, a composite index of territorial resilience was developed by combining MCDA and dynamic modelling to assist decision-makers in planning and managing resilient territorial systems [174]. According to the literature [162],[175],[176], MCDA approaches can be grouped into the following three theories proposed by [177],[178]: (i) utility function, (ii) outranking relation and (iii) sets of decision rules. The utility-based theory involves methods that unify information into a single parameter, and it was developed in the 1970s by [179]. Among these methods, the Multi Attribute Utility Theory (MAUT) was applied by [180] to compare different alternative of energy generation technologies in Turkey based on four groups of criteria (i.e., economic, technical, environmental, and socio-economic). In addition, the Analytical Hierarchy Process (AHP) is an alternative method to the previous one, belonging to the family of utility-based theory. This methodology was used in [181], for estimating and ranking the economic, social, political, technical, administrative and geographic barriers to develop renewable energy sources in rural areas of Nepal. Similarly, in Germany, the AHP approach was adopted to establish neighbourhoods at high risk of fuel poverty [182]. The second theory, also known as the outranking relation theory, includes methods for checking whether "*alternative a is at least as good as alternative b*", based on comparisons between pairs of options [183]. This family group is widely used in the energy decision-making process, and it includes the ELimination Et Choix TRaduisant la REalité (ELECTRE) method and the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE). The latter method was used by [184] to evaluate different energy retrofitting scenarios at the district scale. Similarly, in [165], the PROMETHEE methodology was adopted to compare four alternative scenarios of electricity generation technologies in Greece. With regard to ELECTRE, it is a widely used decision-making method among the MCDA. At the building level, ELECTRE III method was applied in [185] to help the decision-maker find the best cost/energy compromise between multi-energy alternative sources in a family house. The decision was based on "*economical, energetically and environmental criteria*" (i.e., costs, energy consumption and CO_2 emission). According to the literature, ELECTRE III was also used in various applications at the district [186] and technological components scale [187]. Finally, the decision rule theory develops a "*preference model in the form of rules derived from examples*" [188] (i.e., Dominance-based Rough Set Approach (DRSA)).

To summarise the main advantages and limitations with respect to the CBA, the output of the MCDA is expressed in terms of a performance score rather than a monetary value. In addition, as the MCDA method does not provide a single indicator, the results are more difficult to understand. In contrast, with the application of the MCDA, it is possible to integrate various perspectives from the different stakeholders participating in the decision-making process.

The literature review explored in this paragraph allows to identify the optimal solutions in response to RQ 3. Specifically, the CBA has proven to be the most suitable decision-making tool to launch an advanced technological solution making it competitive in the current building energy market. In fact, as demonstrated through the application case study in Chapter 4, CBA provides a single economic indicator that can be easy and comprehensible to decision-makers who are not expert in the energy field.

3.3 From cost-optimal methodology to Cost-Benefit Analysis

According with the transition towards a more “human-centred” approach to building design and operation, the 2018 amendments to the EPBD introduces a new SRI [6]. The purpose of this SRI is to assess the ability of buildings to use advanced technological solutions to ensure occupant satisfaction [6]. As these technologies require a significant initial investment cost by the building owner or the building manager, it is essential to explore new decision-support tools (section 3.2) that are able to consider not only their financial aspects, but also to include externalities (e.g., health-related and performance benefits) in their evaluation.

The cost-optimal methodology, introduced by Directive 2010/31/EU [38], allows the evaluation of different energy efficiency solutions and packages considering not only energy-architectural variables but also financial ones (e.g., investment costs, maintenance costs, etc.). Specifically, the concept of cost-optimality is defined in Article 2.14 of the EPBD as: "*the energy performance level which leads to the lowest cost during the estimated economic lifecycle*" [38]. In order to assess the financial performance (global cost) of the selected package combinations, the European standard EN 15459-1:2017 [189] is proposed as a reference. The global cost formula is shown in Equation 1:

$$C_g(\tau) = C_I + \sum_j [\sum_{i=1}^{\tau} \left(C_{a,i}(j) \times R_d(i) \right) - V_{f,\tau}(j)] \ [€] \tag{1}$$

where, $C_g(\tau)$ is the global cost referred to the initial year τ_0 [€], C_I is the initial investment cost [€], $C_{a,i}(j)$ is the annual cost for component j at year i [€/y] (including running costs and replacement costs), $R_d(i)$ is the discount rate for year i [-], $V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period [€] (referred to the initial year τ_0).

As shown by the equation above, the total cost considers the initial investment cost of implementing the energy efficiency measures, to which are added the running costs, i.e., the annual costs (energy costs, ordinary and extraordinary costs related to maintenance, replacement costs) over the life of the investment until the end of the analysis, when the intervention itself can assume a residual value.

As explained above, the cost-optimal methodology is based only on financial analysis, so it is not suitable for this purpose. Therefore, there is a need for the implementation of an economic analysis which is sensitive to both positive and negative externalities of different types [190]. As stated by the European Commission in [191], “*socio-economic benefits should be included in the objectives and evaluation of a project*”. In this way, in accordance with the results from section 3.2, the Cost-Benefit Analysis was found to be an effective method to support the investment decision-making process from a social perspective thanks to its ability to combine the financial and the economic dimensions, quantifying all the disadvantages (costs) and advantages (benefits) of a project [192]. In detail, the CBA methodology includes the following six steps, as shown in Figure 16.

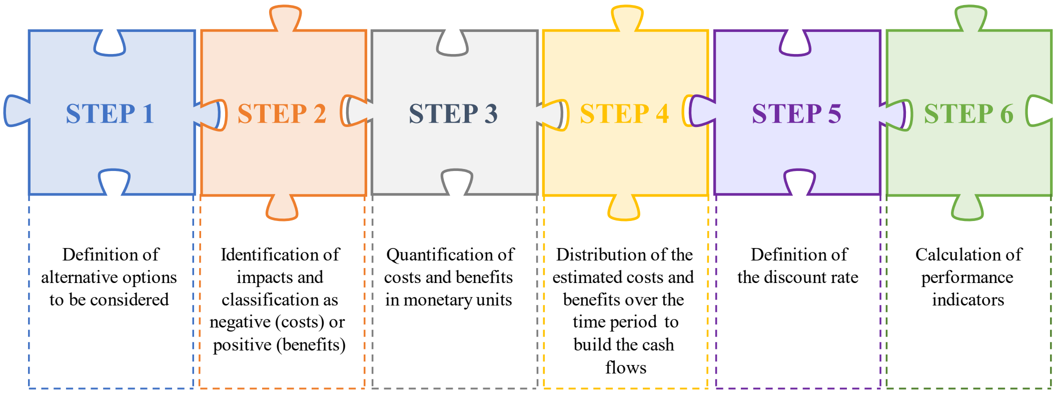


Figure 16: CBA methodology steps.

The following sections aim to present the main methodological steps of the CBA as shown in Figure 16. Specifically, section 3.4 presents different valuation support techniques to monetise the economic disadvantages (direct and indirect costs) and advantages (market and non-market benefits) of a project. Then, section 3.5 identifies the main benefits and co-benefits for different beneficiaries related to energy re-qualification operations in buildings. Finally, the economic key performance indicators used to provide a final judgment on the performance of the project are summarised in section 3.6.

Regarding the definition of step five, there is no established scientific standard for the selection of the discount rate (e.g., 5%, 7%, 10%, etc.) or the time frame to be included in the analysis (e.g., 15, 20, 30 years, etc.) [193].

3.4 Valuation techniques to measure and monetise co-impacts

The key objective of a CBA is to define all the economic impacts (costs or market and non-market benefits) associated with a project, by quantifying them in monetary terms. Specifically, the CBA methodology considers both direct and indirect costs and benefits. The next sections aim to provide an overview of the main financial valuation techniques for assessing costs (section 3.4.1) and the economic evaluation techniques for estimating non-market benefits (section 3.4.2).

3.4.1 Financial valuation techniques for costs estimation

According to [194], the evaluation of the costs associated with a project is based on a financial analysis that considers investment, maintenance, operational, replacement, and disposal costs. For this reason, the Life Cycle Cost (LCC) technique is considered the main financial valuation approach for estimating direct costs. It is defined by ISO 15686-5:2008 [195] as a tool to support the decision-making process during the design phase. As reported by [196], LCC is "*an approach for quantifying short/long term costs and benefits (these last usually represented by savings), along the whole life cycle of alternative design solutions*". The main objective of LCC is to assess alternative options with different investment, operational, maintenance, and replacement costs. Equation 2 shows the LCC formula, distinguishing between the cost items mentioned above:

$$LCC = C_i + \sum_{t=0}^{N} \frac{C_o + C_m}{(1+r)^t} \mp V_r \left(\frac{1}{(1+r)^N}\right) \tag{2}$$

where, C_i is the investment cost, C_o the operational cost, C_m the maintenance costs, t is the year when the cost incurred, N represents the numbers of years of the period considered, r is the discount rate, and V_r is the residual value of the components.

Various techniques were emerged around this primarily financial concept, aiming to incorporate sustainability considerations into the assessment. These methods include Life Cycle Assessment, Life Cycle Sustainable Assessment (LCSA), and Social Life Cycle Assessment (SLCA). These recent advances have facilitated a shift in the assessment of energy systems, moving from a focus on energy efficiency to a broader perspective towards socio-economic efficiency.

According to [197], the first step in conducting a LCC analysis involves the identification and quantification of all the initial investment costs (e.g., design and development costs, costs for material, testing and packaging costs, etc.) associated with alternative options. The second step is to define all the future operating costs on an annual-based (e.g., energy consumption of various plant systems). The third step involves the inclusion of maintenance costs (i.e., money required to maintain the original performances of a building or system), and repair costs (i.e., unanticipated expenditure required to extend the life of a building or system without replacing it) of alternative solutions in the LCC. Finally, replacement costs usually arise when a building system or component reaches the end of its useful life (e.g., the replacement of a boiler to maintain the operational status of the building). In addition, initial costs should be included in the overall LCC analysis at their full value in the first year. On the other hand, it is essential to discount operating, maintenance and replacement costs to their present value in order to include them in the LCC.

3.4.2 Economic evaluation methods for non-market benefits estimation

After the financial assessment, it is necessary to proceed to an economic analysis to include the non-market impacts of a project. According to [72], the quantification and monetisation of non-market impacts (e.g., health-related and performance benefits) requires great effort. The most common economic evaluation methods used in the CBA analysis to quantify and monetise the non-markets benefits can be divided into three main techniques: Stated Preference (SP), Revealed Preference (RP), and Benefit Transfer (BT).

The **Stated Preference approach** employs survey techniques to assess the preferences of people, typically within the environmental domain. Through the development of a questionnaire, these techniques allow researchers to directly inquire about individuals' Willingness To Pay (WTP) or Willingness To Accept (WTA) for a specific outcome. Among the stated preference techniques, the Contingent Valuation Method (CVM) [198] and the Choice Modelling (CM) [199],[200] are the most commonly used to value non-market goods in monetary terms.

The **Revealed Preference approach** examines the choices of individuals, assuming that consumers' preferences are revealed by their actual purchasing behaviour. Within the RP techniques, the Hedonic Pricing (HP) [201] and the Cost of Illness (COI) [202] methods are the main evaluation techniques used to examine individual choice. The COI approach is used in healthcare to calculate health-related benefits in terms of avoided costs to individuals or society [167]. In fact, this method allows the identification and measurement of all the costs associated with a disease, including direct costs (e.g., medical care expenditures, hospitalisations, etc.), indirect costs (e.g., absenteeism), and intangible costs (e.g., pain, emotional distress, etc.). The most widely used methods for estimating indirect costs include the Human Capital Approach (HCA) [203], which assesses the productivity lost when employees are absent from work due to the illness occurrence, and the Friction Method (FM) [204], which assesses the time it takes for another employee to replace the sick employee.

Finally, the **Benefit Transfer method** is used to estimate the economic value of non-market impacts by transferring available information from completed studies [205].

3.5 Benefits and co-benefits related to building energy performance measures

The term co-benefits is often used in the context of energy efficiency investments to refer to the full range of externalities (positive or negative) that such investments may generate for different stakeholders. As explained by the Intergovernmental Panel on Climate Change (IPCC), co-benefits are "*the benefits from policy options implemented for various reasons at the same time, acknowledging that most policies resulting in GHG mitigation also have other, often at least equally important, rationales*" [206].

In decision-making frameworks, the assessment of benefits and co-benefits plays a key role. For this reason, this section focuses on classifying the main direct and indirect benefits associated with building energy efficiency measures (EEMs). In Figure17, the benefits and co-benefits of energy efficiency measures are grouped according to five main categories of beneficiaries identified by [207].

The first category is represented by companies (**utilities**) involved in the generation and distribution of energy, which may benefit from reduced energy costs and insurance savings. The second beneficiary is the **public finance and government authorities**, which can benefit from reductions in hospitalization costs and tax revenues. The third actor is represented by the **building occupants**; their benefits include lower energy consumption costs and improved IEQ and health conditions. The fourth category encompasses **society and environment**, whose benefits include a reduction in CO_2 emissions and an increase in urban vegetation. Finally, the last beneficiary is the **investor**, who benefits from the increase in the value of the property. The following paragraphs provide a detailed description of some benefits and co-benefits shown in Figure 17 (e.g., reduced GHG emissions, increased real estate value, improved IEQ and health conditions, and introduced subsidies and incentives) related to EEMs in building energy retrofit projects.

Reduced GHG emissions

Improving energy efficiency and achieving high energy performance in buildings are at the heart of the main European and national strategies to achieve the future climate targets related to GHG emissions reduction. The main GHG emitted by human activities is CO_2, followed by methane (CH_4) and other GHGs such as nitrous oxide (N_2O) and fluorinated gases (F-gases). To compare the impact of different GHGs, the IPCC introduced the concept of Global Warming Potential (GWP) by providing a common unit of measurement [208]. This indicator quantifies how much a specific quantity of a greenhouse gas contributes to global warming over a specified timeframe (typically 100 years) when compared to the impact of CO_2 [208]. In this way, GHGs can be calculated as CO_2 equivalents (CO_2-eq), defined by as "*the amount of carbon dioxide emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas or a mixture of GHGs*" [209]. For this reason, to estimate the emission costs for each energy carrier, the amount of CO_2 generated per unit of kilowatt-hour (kWh) consumed should be multiplied by the cost value of a ton of CO_2-eq [190].

Increased real estate value

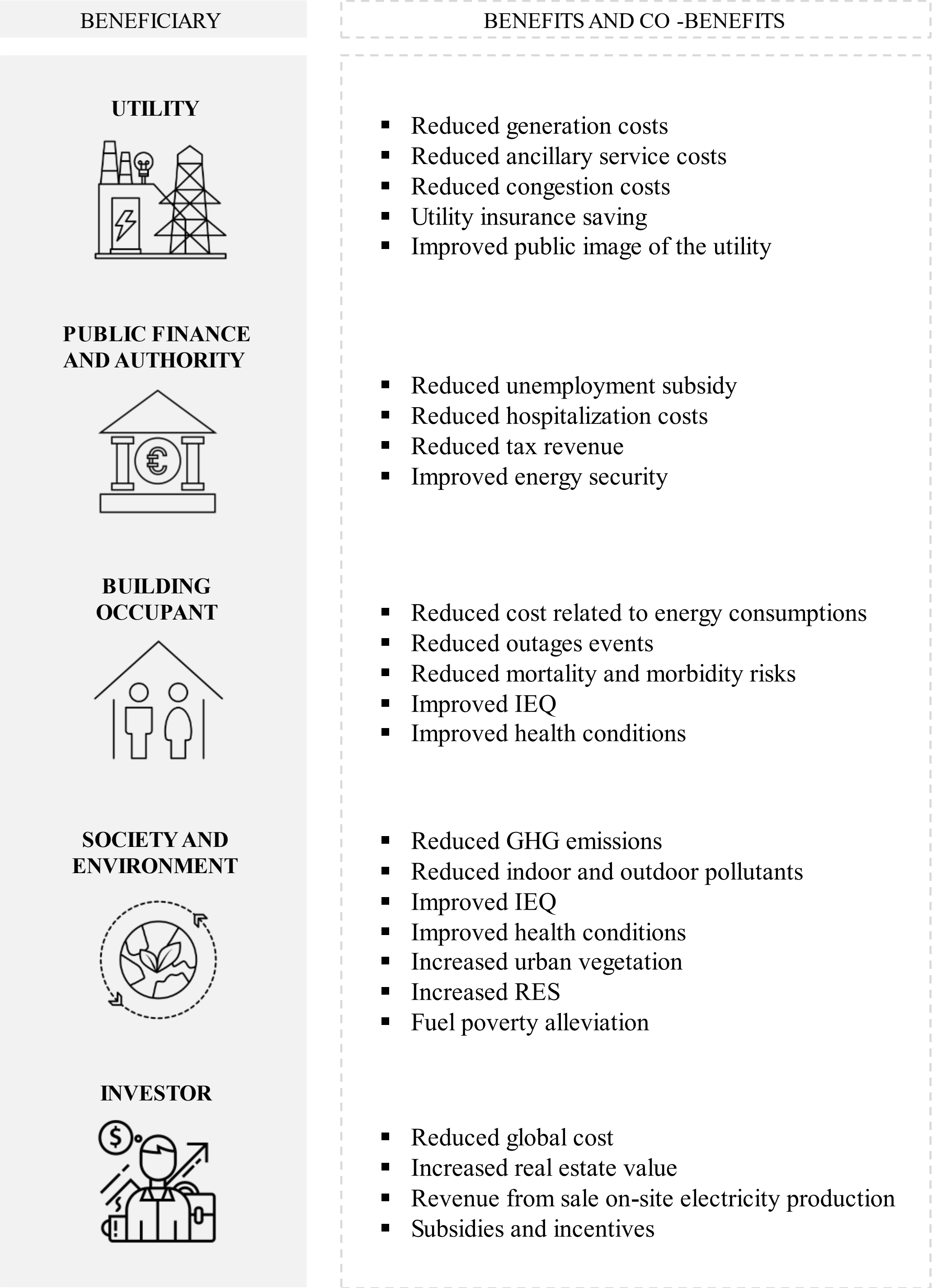
A further benefit derived by EEMs in building energy retrofits is the increase in real estate value. In fact, as reported by [210] and [211], retrofit measures create a new property market in line with the current demands of the green economy, leading to an increase in property value. There is evidence that both individuals and companies are willing to pay higher rents for properties with better energy performance [212]. In addition, investors and property owners need to explore the value of green building certification in increasing the property value, as well as stimulating the real estate market by increasing rents and sales prices. This added value can be monetised according to the hedonic pricing theory, which includes green value among the attributes that influence the market price of real estate [213].

Improved of indoor environmental quality and health conditions

The IEQ in buildings has a major impact on the health, comfort, and work performance of their occupants. Therefore, indoor air quality, thermal comfort, acoustics, and daylight levels are crucial factors to consider in order to ensure the quality of life and overall well-being of building occupants. As suggested by [192], retrofitting measures to improve building performance are expected to result in energy savings by reducing energy demand and increasing indoor comfort. In addition, several studies in the literature have shown how to quantify the benefits of improving IEQ. According to [214], the CVM was used to estimate the expected WTP per decibel (dB) reduction in external noise exposure. The CVM was also applied in [215] to estimate consumers' WTP for reducing health-related problems in homes. In another study related to the impact of cold homes on health issues, the authors highlight the key role played by retrofit measures (e.g., envelope insulation, heating system improvements) in improving occupants' well-being and reducing respiratory and cardiovascular diseases [216]. Finally, as reported by the IPCC [217], significant health benefits in terms of respiratory disease and air pollution reduction can be achieved by improving the efficiency of fossil fuel-fired systems in combination with RES. At the macroeconomic level, the COI methodology helps to capture the positive health benefits by translating them into savings to public finances through reduced hospitalisation and pharmaceutical costs [218].

Introduced subsidies and incentives

Among the benefits for investors, government incentives and subsidies for retrofitting buildings or for installing renewable energy technologies are crucial. In fact, these incentives can help investors in overcoming significant initial costs, thereby reducing the payback period, and allowing them to realise a return on their investment more quickly. For example, in 2020, the Italian government introduced a financial incentive, known as Superbonus 110%, to involve a significant amount of actions including the installation of renewable solutions (heat pump technologies) with the aim of encouraging their installation in new buildings or replacing existing heating systems still powered by fossil fuels [64].



BENEFICIARY	BENEFITS AND CO -BENEFITS
UTILITY	▪ Reduced generation costs ▪ Reduced ancillary service costs ▪ Reduced congestion costs ▪ Utility insurance saving ▪ Improved public image of the utility
PUBLIC FINANCE AND AUTHORITY	▪ Reduced unemployment subsidy ▪ Reduced hospitalization costs ▪ Reduced tax revenue ▪ Improved energy security
BUILDING OCCUPANT	▪ Reduced cost related to energy consumptions ▪ Reduced outages events ▪ Reduced mortality and morbidity risks ▪ Improved IEQ ▪ Improved health conditions
SOCIETY AND ENVIRONMENT	▪ Reduced GHG emissions ▪ Reduced indoor and outdoor pollutants ▪ Improved IEQ ▪ Improved health conditions ▪ Increased urban vegetation ▪ Increased RES ▪ Fuel poverty alleviation
INVESTOR	▪ Reduced global cost ▪ Increased real estate value ▪ Revenue from sale on-site electricity production ▪ Subsidies and incentives

Figure 17: Benefits and co-benefits of energy efficiency measures in buildings. Elaboration from [160].

3.6 Key performance indicators in CBA

In the previous section 3.4, all costs and benefits associated with a project or technology are evaluated to establish the CBA. According to [192], only the initial investment costs and benefits (e.g., increase in real estate value) are considered in the first year, and then the maintenance, energy and operating costs and all other benefits (e.g., reduction in GHG emissions, indoor environmental quality, etc.) are included from the second year. The CBA allows different economic indicators to measure the performance of a project, such as the NPV, IRR and the discounted BCR. According to [219], each indicator is shown in Equations 3, 4 and 5 respectively.

In calculating NPV, the estimation process of discounting cash flows allows the equivalent value of flows to be determined at the start of an investment across various periods. Therefore, the NPV is described in Equation 3 as follows:

$$NPV = \sum_{t=1}^{n} \frac{F_t}{(1-r)^t} - C_0 \tag{3}$$

where n represents the analytic horizon (usually 30 years), t refers to the cash-flow period, F_t stands for the net cash inflow during period t, C_0 refers to the initial investment costs, and r indicates the discount rate. If NPV is greater than zero, the investment benefits surpass the corresponding costs, implying that the project can enhance welfare.

As the NPV does not provide an indication of the capital invested as an economic cost, the IRR is used as the discount rate to make the NPV equal to zero and to balance the positive and negative flows. Equation 4 provides a description of the IRR indicator:

$$NPV = 0 = \sum_{t=1}^{n} \frac{F_t}{(1+IRR)^n} - C_0 \tag{4}$$

where n represents the analytic horizon, t refers to the cash-flow period, F_t stands for the net cash inflow during period t, C_0 refers to the initial investment costs, and IRR is the International Rate of Return. For the investment to be economically feasible, the IRR must exceed or equal a specific threshold of acceptance.

The discounted BCR indicator is evaluated to improve the assessment of socio-environmental impacts. The BCR is calculated by discounting the value of both benefits and costs, according to Equation 5:

$$BCR = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}} \tag{5}$$

where n represents the analytic horizon, t refers to the cash-flow period, B_t is the benefit in period t, C_t is the cost in period t, and r is the discounted rate. The BCR is an economic indicator which quantifies the production of social benefits for every euro spent. If the BCR is major than 1, the project is considered appropriate as the benefits exceed the costs. The higher the indicator, the greater the benefits exceed the costs.

Chapter 4

IAQ and occupant health and well-being

4.1 Overview

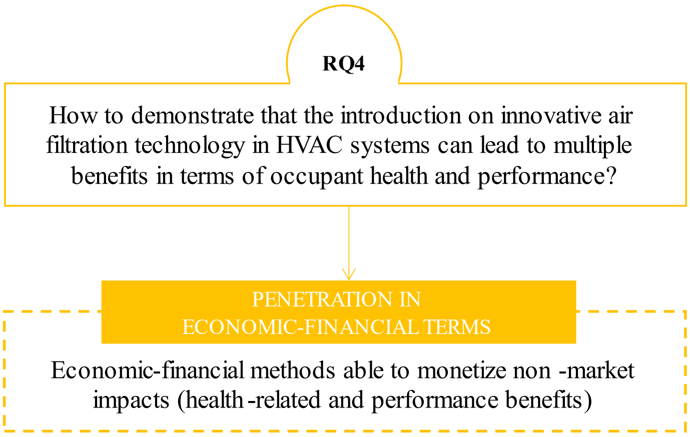


Figure 18: Structure of Chapter 4.

The following chapter aims to demonstrate, through an application case study in educational buildings, the need of transitioning towards an integrated approach rather than a financially driven assessment. In fact, this approach will enable the quantification and monetisation of benefits in terms of energy savings and reduction of negative impacts on student and teacher well-being and performance. Specifically, Chapter 4 provides a detailed response to RQ 4: "*How to demonstrate that the introduction on innovative air filtration technology in HVAC systems can lead to multiple benefits in terms of occupant health and performance?*". The following structure is presented: section 4.2 provides an overview of the main context and objective of the case study, while section 4.3 outlines the methodology used to answer RQ 4. In section 4.4, the characteristics of the case study are defined, followed by the presentation of the main fundings and conclusions in sections 4.6 and 4.7, respectively.

Keywords: air filter, schools, healthy building, learning performances.

Declaration: the topics described in this chapter were previously published in the following publications:

- Becchio, C.; Corgnati, S.P.; Crespi, G.; **Lingua, C.** Impacts of different AHU configurations on health and students' performance in Italian schools in post-pandemic era. *Sustainable Energy Technologies and Assessments 60*, 2023, p. 103479. DOI: 10.1016/j.seta.2023.103479 [220].
- Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F.; Fabi, V.; **Lingua, C.**; Prendin, L.; Ranieri, M. (2019). Effects on energy savings and occupant health of an antibacterial filter. In: Proceedings of CLIMA 2019, REHVA 13rd HVAC World Congress, Bucharest, Romania, 26 May 2019. DOI: 10.1051/e3sconf/201911102056 [167].
- Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F.; Fabi, V.; **Lingua, C.**; Prendin, L.; Ranieri, M. (2019). The effects of indoor and outdoor air pollutants on workers productivity in office building. In: Proceedings of CLIMA 2019, REHVA 13rd HVAC World Congress, Bucharest, Romania, 26 May 2019. DOI: 10.1051/e3sconf/201911102057 [221].
- Becchio, C.; Corgnati, S.P.; Fabi, V.; **Lingua, C.**, Prendin, L.; Ranieri, M. (2019). Costs and benefits of antibacterial filter and its effects on energy saving, human health and worker productivity. In: Proceedings of 51st AiCARR International Conference, the human dimension of building energy performance, Venice, Italy, 20 February 2019 [222].

4.2 Background

In recent years, there was an increased focus on the health of building occupants. This was influenced by the recent Covid-19 pandemic, which highlighted the inefficiency of HVAC systems and the need for buildings to be prepared to respond to this challenge. As early as 1987, the WHO [223] estimated that 50% of the indoor biological contamination originated from the HVAC system. Furthermore, several studies have identified HVAC systems as a major source of indoor pollution [224],[225],[226]. Then, with the Covid-19 widespread, the inadequacies of existing AHUs were highlighted by putting a strain on the HVAC system. In fact, while HVAC systems are typically managed to minimise energy use in buildings, the focus during the outbreak was on providing the right indoor conditions for the health and performance of users [227]. As the risk of infection is higher in crowded and poorly ventilated spaces, these considerations are essential in public environments (e.g., offices, hotels, schools, commercial buildings, etc.) [228]. In response to the global crisis and in order to identify appropriate measures to minimise the risk of SARS-CoV-2 transmission indoors, international and national building authorities and associations have issued specific guidelines for the correct design, operation and management of HVAC systems [72]. Among the various guidelines, common preventive measures include: (i) extending the operating hours of the systems; (ii) proper settings of relative humidity and temperature set-points; (iii) increasing the outdoor air rate and improving ventilation airflow patterns reducing the proportion of recirculated air to reduce the risk of virus transport and avoid cross-contamination; (iv) the use of ancillary equipment, including air filters, ultraviolet germicidal irradiation systems for disinfection and portable air cleaners [72],[229]. Although these measures reduce the risk of airborne transmission, they have a significant impact on energy consumption. For example, a 50% increase in heating demand was measured when the ventilation rate was increased from 0 to 50 $m^3/(h \cdot person)$ [230]. Similarly, the cost of HVAC systems increases by 2% to 10% when the outdoor air rate is increased from 2.5 to 10 $L/(s \cdot person)$ [231]. In addition, the effect of extended HVAC schedules on energy consumption was investigated in [229], revealing a 128% increase in energy consumption when comparing normal and pandemic periods. Therefore, restoring conventional HVAC system operation requires the implementation of innovative technological solutions that deliver favourable outcomes in terms of energy efficiency, indoor air quality, and occupant health and productivity.

This study aims to investigate the benefits of advanced biocidal and photocatalytic filtration technologies installed in AHUs in non-residential buildings, not only to improve IAQ control, but also to enable energy savings through the use of conventional HVAC operating strategies. However, while the adoption of such technology has potential benefits, its high investment costs may deter consumers from investing in it. According to [72], "*evidence-based research*" capable of quantifying the multi-domain impacts of these innovative technologies (e.g., social, economic, and environmental consequences) is required. Therefore, as energy investment decisions are still driven by financial decisions, there is a need to include externalities (e.g., occupant health and productivity) in their assessment. To this end, CBA has proven to be an effective tool to support energy investment decisions, monetising the benefits of AHU configurations equipped with innovative technological solutions and demonstrating that their higher investment costs could be fully recouped in the long-term by the energy and socio-economic benefits [166],[169]. While energy benefits can be easily quantified by simulating or measuring energy use, monetising health and performance benefits is more straightforward [72]. According to [232], the benefits associated with providing healthy indoor environments can be quantified by focusing on three main aspects: the increase in property value, the increase in occupant productivity, and the reduction in health-related costs for either individuals or society. The authors in [168] examined air filtration solutions and found that the increased cost of investing in higher filter efficiency can be balanced by monetising the associated health benefits. In a similar study, [167] reported that the installation of antibacterial filters resulted in increased employee productivity and reduced healthcare costs, which fully covered the higher investment and maintenance costs.

School buildings are widely recognised as important sites for SARS-CoV-2 transmission due to their high occupant densities, seating arrangements and frequent contact between occupants, coupled with long periods spent indoors [227],[228]. Therefore, creating a healthy classroom environment must be a priority to promote the health and performance of both students and teachers. According to a study in Swedish schools [233], the authors show that poor indoor air quality has a direct impact on teachers' and pupils' health, increasing "*the societal burden through health costs, absenteeism, poor academic performance and productivity losses*". Furthermore, a study conducted by [234] found high levels of CO_2 in the classrooms of three schools in Kuwait. This indicates poor IAQ, which poses significant health risks to pupils and negatively affects their academic performance. These findings were also confirmed by [235], which showed that poor classroom air quality has a significant impact on students' cognitive abilities and skill development. According to a Norwegian study on the respiratory health of schoolchildren, children exposed to CO_2 levels above 1,000 parts per million (ppm) had a higher risk of developing a dry cough [236]. In addition, the authors in [237] highlighted critical limitations of the previous literature, indicating areas requiring future research; among them, "*the socio-economic consequences of the effects on children's health and performance in classrooms should be considered*".

In light of the above, the present study focuses on the Italian context, where schools generally have an unsatisfactory IAQ. The originality of the study lies in the application of a widely-used evaluation technique in a rarely-explored domain, specifically the energy sector, to assess the overall IAQ and its impacts on the health and well-being of occupants. Specifically, the aim of this study is to develop a CBA to estimate the health and learning impacts resulting from two AHU configurations installed in Italian schools. These configurations are representative of both Covid-19 (C) and post-Covid-19 (PC) conditions. By examining different cost-benefit monetisation methods, the study aims to demonstrate the need to move from a financially focused analysis of alternative solutions to a more comprehensive approach. This approach should include the ability to evaluate, quantify, and monetise individual and societal advantages in terms of energy savings and minimised negative impacts on student health and performance.

4.3 Methodology

This section presents the CBA framework used for the evaluation of the aforementioned AHU configurations and the techniques used to quantify costs and benefits. As described in Chapter 3, CBA provides an assessment in monetary terms of the advantages and disadvantages of a project or technology by integrating financial and economic components. In particular, the study presents its fundings through the application of the BCR indicator, which allows the comparison between different options and a reference scenario in order to determine the most advantageous solution. Therefore, the ΔBCR between PC and C configurations (the latter identified as the reference scenario) is calculated as shown in Equation 6:

$$\Delta\text{BCR} = \frac{\sum_i B(i)_{PC} - \sum_i B(i)_C}{\sum_i C(i)_{PC} - \sum_i C(i)_C} \tag{6}$$

where $B(i)_{PC}$ and $B(i)_C$ represent the discounted benefits of the post-Covid-19 and Covid-19 i-th configurations, respectively [€/y]; $C(i)_{PC}$ and $C(i)_C$ are the discounted costs of the post-Covid-19 and Covid-19 i-th configurations, respectively [€/y]. If the ΔBCR is greater than 1, this means that the incremental benefit exceeds the incremental cost over the reference option.

4.3.1 Financial impacts estimation

Based on an LCC analysis, a financial evaluation is carried out to estimate all the costs associated with the AHUs. These costs, which are standardised at a constant interest rate, include investment, maintenance, disposal, and replacement items. In addition, the energy impact assessment includes the electricity consumption used by fans and the energy sources used by generators to provide heating (e.g., heat pump) and cooling (e.g., chiller) for the AHU coils. Specifically, the energy consumption of fans is calculated for both C and PC configurations according to Equation 7:

$$Energy\ consumption_{fans} = SFP \times Q_v \times h \text{ [kWh]} \tag{7}$$

where SFP is the specific fan power of the air movement system [kW·s/m^3] obtained by dividing the total electrical power absorbed by the fans (P_{supply} + P_{return}) by the airflow rate (Q_v), Q_v is the airflow rate [m^3/s], h represents the total AHU operating hours.

For both C and PC configurations, Equation 8 shows the calculation of the energy consumption of the hot and cold AHU coils:

$$Energy\ consumption_{coils} = \frac{P_{hot\,(or\ cold)} \times h}{\eta_{gen}} \text{ [kWh]} \tag{8}$$

where $P_{hot\,(or\ cold)}$ represents the hot or cold coils power [kW], h is the total AHU operating hours, while η_{gen} is the efficiency of the generation system used for heating and/or cooling applications.

Therefore, the overall energy consumption is evaluated by adding the energy consumption of fans (Eq. 7) and coils (Eq. 8). Then, the total energy consumption is converted into an energy cost by multiplying it by the unit price of the energy source (0.20 €/kWh). The difference between the resulting energy costs for the C and PC configurations represents the energy impact. As mentioned above, it is important to clarify that the use of the ΔBCR can lead to financial impacts that are either costs (if higher than the reference scenario) or benefits (if lower than the reference scenario).

4.3.2 Health-related impacts estimation

According to [238], the economic burden of a disease on society is evaluated using the COI method, which identifies, measures, and evaluates the costs associated with the disease. The COI methodology is used in this study to calculate the healthcare-related benefits, specifically the avoided costs to individuals and society [239]. As described in Chapter 3, the COI can be divided into three categories: (i) direct costs; (ii) indirect costs; (iii) intangible costs. According to [240], the first category involves both healthcare and non-healthcare expenses related to the treatment of the illness; indirect costs include the productivity losses due to the sick patient's absence from work; while intangible costs are related to psychological consequences.

Due to a lack of data, this case study focuses only on direct and indirect costs excluding intangible ones. To calculate the direct costs (C_d) related to both students and teachers, the following Equation 9 is used:

$$C_d = C_{treatment} \times t_{treatment} \times i \text{ [€]} \tag{9}$$

where $C_{treatment}$ represents the healthcare costs for treating students/teachers [€/day], $t_{treatment}$ is the duration of treatment [day], i is the average incidence of the disease among students/teachers [%].

The HCA method [203] is used to calculate indirect costs (C_i). In a study conducted in a school setting, the authors report that student absenteeism from school can be calculated in economic terms as a proportion of the educational services provided by teachers that remain an unused resource by the student due to illness [241]. In other words, the indirect costs are related to the teacher's educational output (in economic terms) that cannot be used by the student due to illness. This share of unused educational services can be expressed in monetary terms according to Equation 10:

$$C_i = ((I_{PA} \times n_{teachers}) / t_{school} / n_{students}) \cdot t_{treatment} \cdot i \text{ [€]} \tag{10}$$

where I_{PA} represents the mean annual per capita income from Public Administration employment, i.e., the average yearly salary of a teacher [€/y], t_{school} refers to the school duration [days/y], while $n_{students}$ indicates the total number of students in the case study, $t_{treatment}$ is the duration of treatment, which is equal to the days of absence from school [days], i is the average incidence of disease among the students [%].

After estimating the direct and indirect costs associated with the disease infection, the proportion of social costs avoided due to the presence of filtering solutions (providing health benefits for the PC configuration) is calculated using Equations 11 and 12 for students and teachers, respectively.

$$Health\ benefit_{student} = (C_d + C_i) \times \%_{inactivation} \times t_{ambient,student}\ [€] \quad (11)$$

$$Health\ benefit_{teacher} = C_d \times \%_{inactivation} \times t_{ambient,teacher}\ [€] \quad (12)$$

where C_d and C_i represent the direct and indirect costs [€], $\%_{inactivation}$ denotes the percentage of filter inactivation of a specific virus or bacteria, and $t_{ambient,student}$ and $t_{ambient,teacher}$ refer to the time spend by students and teachers in the classroom, respectively [%].

Indirect costs are calculated only for students, without considering any possible quota resulting from teacher absenteeism.

4.3.3 Learning performance impacts estimation

To assess the impact of classroom air quality on academic performance, a correlation between IAQ and learning outcomes is required. Students' academic performance is typically assessed based on their ability to successfully complete typical school tasks. In particular, according to [242], measures such as the speed and accuracy at which schoolwork is completed are commonly used as markers.

The present study investigates the correlation between indoor CO_2 concentration and student performance levels, using a fixed air flow rate through the analysed AHUs. Specifically, the estimated relationship between the CO_2 concentration in the classroom and the speed of schoolwork is calculated using Equation 13 [242]:

$$R_{speed} = (1.5 \times 10^7 \times C_{CO_2}{}^2) - \left(0.0005 \times C_{CO_2}\right) + 1.3002 \quad [\%] \quad (13)$$

where R_{speed} is the relative speed at which schoolwork is performed [%] and C_{CO_2} represent the indoor carbon dioxide concentration [ppm].

As shown in Equation 13, to assess the performance of schoolwork, classroom CO_2 concentration is required. It can be calculated according to Equation 14:

$$C_{CO_2} = C_{out} + \frac{(n_{students} \times G_{CO_2,student}) + (n_{teachers} \times G_{CO_2,teacher}) \times 10^6}{q_v \times (n_{students} + n_{teachers})}\ [ppm] \quad (14)$$

where C_{out} is the outdoor CO_2 concentration [ppm], $n_{students}$ and $n_{teachers}$ are the number of students and teachers in classroom, $G_{CO_2,student}$ and $G_{CO_2,teacher}$ are the CO_2 generation rate per student and teacher, respectively [L_{CO_2}/(person)], and q_v is the fixed ventilation rate [L_{air}/ (s·person)].

Then, once the relative speed for both the C and PC configurations has been provided, Equation 15 is used to assess the students' performance benefit for each configuration:

$$Performance\ benefit_{student} = \left(R_{speed} \times I_{PA} \times \frac{n_{teachers}}{n_{students}}\right) \times n_{students}\ [€] \tag{15}$$

where R_{speed} represents the performance of schoolwork in terms of relative speed [%], I_{PA} is the annual average salary of a teacher [€/y], and $n_{students}$ and $n_{teachers}$ are the number of students and teachers in classroom, respectively.

The learning performance benefit of students is improved thanks to the presence of innovative filtering solutions within the PC configuration. This is quantified by annual revenue based on the share of educational services provided by teachers.

4.4 Case study

Applying the CBA methodology described in the previous section, the performance of two AHU configurations installed in four different types of Italian schools, including pre-school, primary school, junior-high and high school, was assessed. The analysis compared the benefits of innovative air filtration technologies installed in the AHU during normal condition with the management of the AHUs during pandemic emergency. Figure 19 shows the Covid-19 AHU configuration. It consists of two standard ISO Coarse 55% pre-filters [243], one on external air (1), the other one on return air (2), while on the supply air it is installed a standard ISO ePM1 50% filter (3) [243].

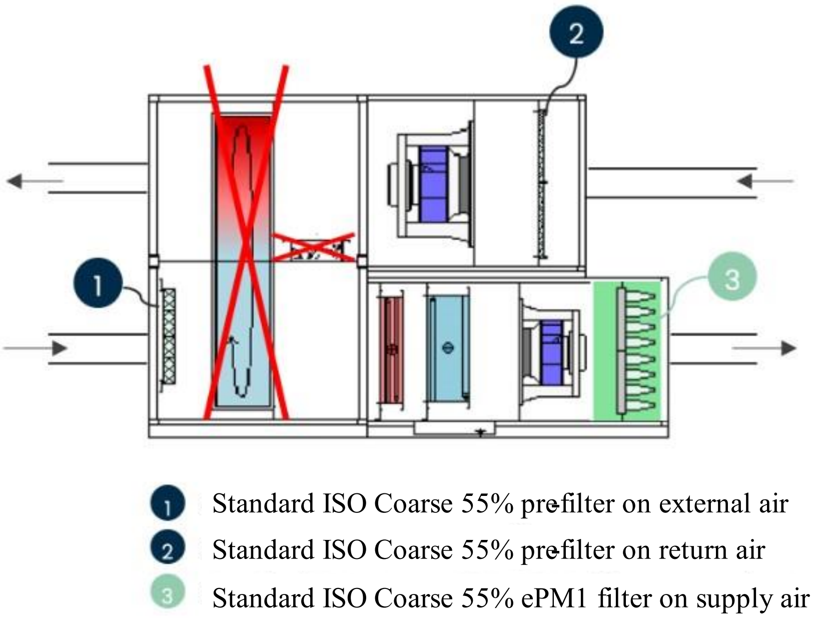
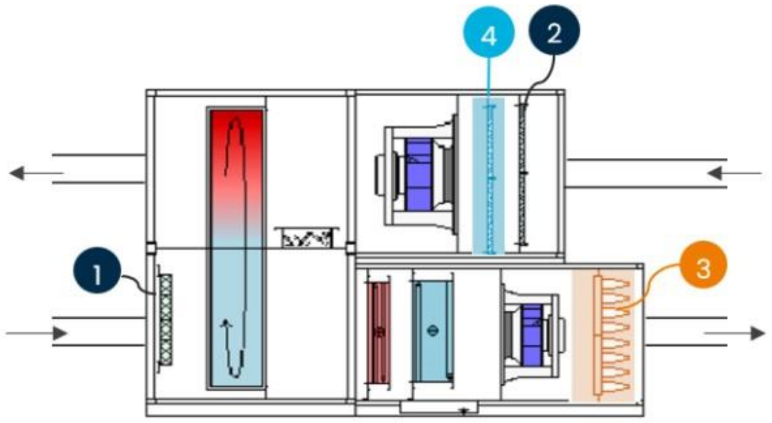


Figure 19: Covid-19 AHU configuration. From [220].

To avoid any cross-contamination, the rotary heat recovery system was deactivated, and the recirculation damper was closed, allowing the AHU to operate at 100% outdoor air rate.

In contrast, as shown by Figure 20, the post-Covid-19 configuration consists of two standard ISO Coarse 55% pre-filters [243], one on external air (1), the other one on return air (2), a biocidal ISO ePM1 50% filter for supply air (3), and a photocatalytic filter for recirculated air (4). In this scenario, the rotary heat recovery system was in operation, with a 50% recirculation rate. As described in [167], the biocidal filter included an additional decontamination process to eliminate airborne microorganisms (e.g., bacteria, moulds, viruses, and algae) from the air. The bactericidal capacity of the biocidal filter was evaluated for two types of bacteria, namely Staphylococcus Aureus (Gram-positive) and Escherichia Coli (Gram-negative) [244]. As demonstrated by [244], this filter was able to reduce Staphylococcus Aureus by 98% within 24 hours, and Escherichia Coli by 53% within 16 hours, ultimately reaching 90% reduction after 24 hours of contact with the filter. Furthermore, the nanoparticles in this filter exhibited an effective reactivity towards gaseous substances. Within the group of gases, the biocidal filter can reduce the concentration of CO_2 in indoor environments by approximately 1%, NO_2 concentration by 5% and SO_2 concentration up to 20%.

The photocatalytic filter within the PC configuration employed a photocatalyst process consisting of tungsten trioxide (WO_3) and visible Light Emitting Diodes (LED), eliminating the need for UV light [245] and the presence of harmful agents in the air, such as the SARS-CoV-2 virus. As stated by [245], the system required low energy usage and maintenance requirements. According to laboratory testing, the photocatalytic filter was assumed to have the ability to fully deactivate the infective charge of the SARS-CoV-2 virus within 30 minutes [245]. Furthermore, the photocatalytic filter had the capability to detect bacteria, including Staphylococcus Aureus and Escherichia Coli, with a 99% reduction rate over 24 hours. It also showed a reduction of 33.3% against adenovirus within 8 hours. With regard to its capability for reacting against gaseous substances, the photocatalytic filter had the ability to decrease the concentration of CO_2 by roughly 12.5% in 60 minutes. However, it was ineffective against other gases (e.g., NO_2 and SO_2).



① Standard ISO Coarse 55% pre-filter on external air
② Standard ISO Coarse 55% pre-filter on return air
③ Biocidal ISO ePM1 50% filter on supply air
④ Photocatalytic filter on return air

Figure 20: Post-Covid-19 AHU configuration. From [220].

Both the C and PC configurations were set up to serve 7 classrooms, each measuring approximately 50 m^2. Each classroom was occupied by 1 teacher and 24 students, with a fixed airflow rate of 7.9 L/(s·person), as reported in [246]. To assess the variances in costs and benefits associated with each type of school, the same analysis was performed for the four case studies presented in the following table. Table 2 shows the main characteristics of the different school typologies considered for this study.

Table 2: Different school typologies and related parameters. From [220].

	Pre-school (3-5 years)	Primary school (5-10 years)	Junior high school (10-13 years)	High school (12-18 years)
School days	186 days/year	205 days/year	205 days/year	205 days/year
Daily opening hours	7 hours/day	5 hours/day	6 hours/day	6 hours/day

Table 3 provides data on the power required by fans and by heating and cooling coils for air treatment. As can be seen from the data, the use of a recirculated air system and heat recovery resulted in lower heat loads for the PC configuration, as indicated by the data. Specifically, 50% of outside air and 50% of recirculated air were considered during the calculations. In this case, only 50% of the air flows through the heat recovery system, causing a significant pressure drop that compensates for the presence of the photocatalytic filter in the exhaust. In contrast, the C configuration did not include either element, in line with the emergency countermeasures implemented during the pandemic.

Table 3: AHU configurations data from real systems. From [220].

	Fans absorbed power [kW]		Coils requested power [kW]	
	Supply (P_{supply})	Return (P_{return})	Heating (P_{hot})	Cooling (P_{cold})
C configuration	1.44	0.96	42.1	44.9
PC configuration	1.05	0.80	4.70	27.7

For the calculation of the electricity consumption used by fans in both C and PC configurations, a total airflow rate (Q_v) of 5,000 m^3/h (equal to 1.4 m^3/s) was considered for each case study typology.

Furthermore, it is crucial to specify for the AHUs comparison that the C configuration was supposed to remain operational 24 hours per day, whereas the PC configuration should only be activated during occupancy, with an extra two hours for the AHU pre-activation phase. The following Table 4 aims to summarise the total AHU operating hours per each school typology.

Table 4: AHU operating hours for each school typology.

	Pre-school (3-5 years)	Primary school (5-10 years)	Junior high school (10-13 years)	High school (12-18 years)
C configuration	4,464 h	4,920 h	4,920 h	4,920 h
PC configuration	1,714 h	1,505 h	1,647 h	1,647 h

Both configurations were fully electric, with the heating and cooling coils served by a heat pump and a chiller using the average performance (η_{gen}) of commonly available technology markets. The Coefficient Of Performance (COP) and Energy Efficiency Ratio (EER) were assumed to be equal to 4 [84].

To conclude, the CBA was developed over a period of 10 years. As recommended by the European Commission [247], benefits and costs were actualised using an annual discount rate of 3%.

4.4.1 Financial valuation

The financial analysis accounted for the annual energy consumption expenses of C and PC configurations, as well as the investment, maintenance, replacement, and disposal costs of each filter installed in both configurations. The cost items related to the other components of the AHUs were not included as they are the same for both configurations. Real market data was used for the assessment of expenditure on AHUs and filters. Specifically, to assess the energy costs linked to the AHU configurations, an electricity price of about 0.21 €/kWh was used [248]. While the main costs associated with each filter technology are shown in Table 5. The duration in brackets indicates the number of months the filter will operate before maintenance or replacement is required.

Table 5: Costs related to each air filter technologies. From [220].

	Standard pre-filter ISO Coarse 50%	Standard filter ISO ePM1 50%	Biocidal filter ISO ePM1 50%	Photocatalytic filter
Investment cost	20 €	120 €	310 €	600 €
Maintenance cost	50 € (2 months)	0 €	0 €	50 € (2 months)
Replacement cost	20 € (4 months)	120 € (8 months)	310 € (8 months)	600 € (40,000 h)
Disposal cost	0.5 €	0.5 €	0.5 €	0.5 €

As shown in the table above, it is important to emphasised that the investment cost of the biocidal filter ISO ePM1 50% is more than double that of the standard filter ISO ePM1 50%. In contrast, the cost of the photocatalytic filter is almost twice that of the biocidal filter. The total investment costs for the two AHUs, including the filter costs shown in Table 5, are 15,700 € and 16,670 € for the C and PC configurations, respectively. This cost item is exclusively accounted for in the initial year of the CBA.

With regard to the pre-filter ISO Coarse 50%, both configurations include two pre-filters (as shown in Figures 19 and 20). Therefore, considering that the two pre-filter has to be serviced 3 times a year, because the other 3 times it is directly replaced, the total maintenance and replacement cost is 300 € and 120 € for each year, respectively. Consequently, as the two pre-filter require to be replaced 3 times per year, the total disposal cost amounts to 3 € annually.

Furthermore, the maintenance costs of both the standard and biocidal filter ISO ePM1 50% are equal to 0 € because no maintenance is done on these filters, but they are directly replaced after 8 months of operation. Consequently, the replacement cost related to standard and biocidal filter ISO ePM1 50% is 120 € and 310 € in the first year, respectively. While in the second year they are replaced twice resulting in replacement costs of 240 € and 620 €, respectively. For the same reason, the disposal costs for both filters are equal to 0.50 € in the first year and 1 € in the second year (the same pattern is repeated in the following years for both maintenance and disposal costs).

Finally, as the photocatalytic filter requires maintenance 3 times a year, resulting in a yearly maintenance cost of 150 €. Exceptions occur in the fifth and tenth year, when the filter is replaced, and therefore maintenance is only required twice at a cost of 100 € each time. A replacement cost of 600 € has to be considered every five years of operation, as well as a filter disposal cost of 0.50 €. Accordingly, replacement and disposal costs are considered only twice in the CBA.

4.4.2 Health benefits evaluation

To evaluate the health benefits for both students and teachers associated with the presence of innovative filtering technologies in the PC configuration, the COI method was applied by estimating the economic impact, in terms of direct and indirect costs, associated with respiratory diseases caused by viruses (including SARS-CoV-2 virus and Adenovirus), and bacteria (including Staphylococcus Aureus and Escherichia Coli). In fact, as mentioned above, the biocidal filter ISO ePM1 50% installed in the PC configuration was effective against Staphylococcus Aureus and Escherichia Coli bacteria with a reduction capacity of 98% and 90% in 24 hours, respectively [244]. The photocatalytic filter in the PC configuration was capable of completely inactivating the infectious load of the SARS-CoV-2 virus within 30 minutes, as well as detecting bacteria, including Staphylococcus Aureus and Escherichia Coli, with a reduction rate of 99% over 24 hours [245]. It also showed a 33.3% reduction against Adenovirus within 8 hours.

SARS-CoV-2 virus and Covid-19 disease

The SARS-CoV-2 virus was known to be the cause of Covid-19, the name of the disease that was associated with the virus. A range of clinical manifestations, from asymptomatic to critically ill, can occur in patients infected with SARS-CoV-2 virus. According to [249], clinical manifestations can be categorised as follows: (1) asymptomatic infection, mild and/or moderate disease, including patients requiring home treatment to avoid hospitalisation; (2) severe disease, including patients requiring hospitalisation and, if necessary, oxygen therapy; and (3) critical disease, including patients requiring intensive care unit (ICU) treatment [249]. Depending on the severity of the disease, different types of treatment were recommended. For the first category, treatment was usually based on three different types of medication: paracetamol, non-steroidal anti-inflammatory drugs (NSAIDs) such as aspirin or ibuprofen, which were used for fever or muscle pain, and monoclonal antibodies, which were only allowed for patients over 12 years old [250]. Covid-19 required hospitalisation for an average of 11.3 and 15 days for severe and critical diseases, respectively [251]. Table 6 summarises the main cost parameters used to calculate the direct healthcare costs associated with Covid-19 disease.

Table 6: Real data used to calculate direct health costs per patient associated with Covid-19 disease. From [220].

	Direct costs per patient	Source
Cost of home treatment for patients with mild/moderate disease:		
- paracetamol	5.40 €	[252]
- NSAID	16.90 €	[252]

- monoclonal antibodies	1,500 €	[253]
Daily cost of hospitalization for patients with severe disease	709.7 €	[251]
Daily cost of hospitalization in ICU for patients with critical disease	1,680.6 €	[251]

For both students and teachers, the total direct costs associated with each case study were calculated in the same way. First, the average weekly Covid-19 incidence by age group in Italy for 2021 was calculated using data from [254]. The incidence rate was resulted equal to 0.14% for students aged 3 to 9 and 0.19% for students aged 10 to 19. These data were then used to estimate the average annual Covid-19 incidence for students in the four case studies by multiplying them by the number of weeks in a year. Specifically, considering 52 weeks in a year, the average annual Covid-19 incidence rate is 7.4% for students aged 3 to 9 and 9.8% for students aged 10 to 19. Subsequently, based on data on the age distribution of teachers in different school years [255], the average annual Covid-19 incidence for teachers was estimated equal to be about 7% for all the case studies. Furthermore, according to [254], the percentage distribution of students in relation to the severity of the illness can be summarised as follows: about 99% of cases were treated at home, hospitalization was required for 0.5% to 0.9% based on student age groups, and approximately 0.02% received treatment in the ICU. For those students who did not require hospitalisation, it was assumed that 70% would require home treatment with paracetamol and 30% with NSAIDs. While the percentage distribution of teachers was assessed according to [256], resulting in 96% of cases treated at home, 3.5% hospitalised, and 0.5% required ICU hospitalisation. For the percentage of teachers who did not require hospitalisation, it was assumed that 68% would require home treatment with paracetamol, 30% with NSAIDs and the remaining 2% would be treated with monoclonal antibodies. Once the direct costs were estimated for each severity disease category according to Equation 9, the sum of the costs derived from home treatment, hospitalisation, and ICU hospitalisation for both students and teachers provided a comprehensive view of the total direct costs associated with each case study.

Indirect costs were estimated using the average annual per capita income from employment in the Public Administration, which is 28,351 € for school staff [257]. According to Equation 10, the indirect costs were calculated by considering the days of absence from school equal to the 21 days of quarantine. As mentioned in section 4.2, the calculation of indirect costs was performed only for students, not considering the quota potentially associated to teachers’ absence from school. Figure 21 shows the direct and indirect costs associated with Covid-19 for both students and teachers in each case study.

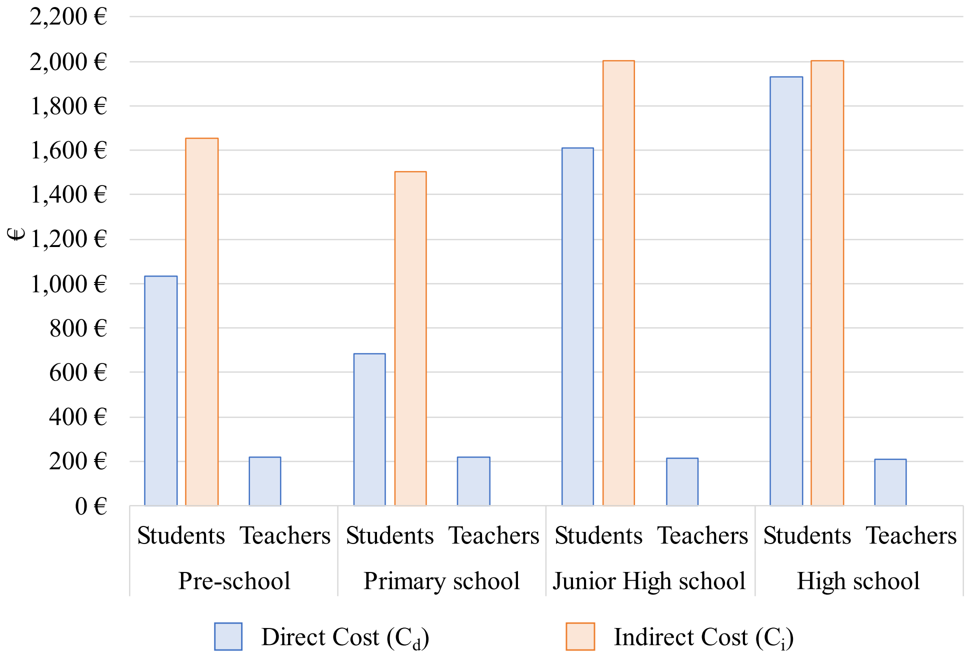


Figure 21: Direct and indirect cost associated to Covid-19 disease for the different school typologies.

Finally, the health benefits of the PC configuration in each case study were assessed by calculating the proportion of costs avoided due to the presence of the photocatalytic filter. According to Equation 11, to estimate the health benefits related to students, the costs (direct and indirect) were summed and then multiplied by the percentage of SARS-CoV-2 virus filter inactivation (100% due to the presence of the photocatalytic filter in the PC configuration) and the proportion of time that both students and teachers spend in the classroom (15% in pre-school, 13% in primary school, and 12% in junior high and high schools, based on the number of school days and the time spent inside daily, as shown in Table 2). For the evaluation of the health benefit related to teachers, only the direct costs were considered in accordance with Equation 12.

The overall health benefit of each case study in terms of cost reduction due to the presence of the photocatalytic filter in the PC configurations comprise the combination of health benefits for students and teachers (Figure 25).

Staphylococcus Aureus, Escherichia Coli, Adenovirus and Community-Acquired Pneumonia disease

According to the National Institute of Health (NIH) [258], the pneumonia was a respiratory infection that affects one or both lungs and is caused by bacteria or viruses. Specifically, viral pneumonia accounted for about 30% of all pneumonia cases in adults and 20% in children (aged from 0 to 18 years) [259]. Consequently, bacterial pneumonia accounted for the majority of pneumonia cases in both adults (70%) and children (80%). According to epidemiological criteria, pneumonia can be divided into Community-Acquired Pneumonia (CAP), which occurred outside hospitals; Hospital-Acquired Pneumonia (HAP), which occurred in the hospital environment and has clinical symptoms after 48 hours of hospitalisation; and Ventilator-Associated Pneumonia (VAP), which occurred 48 hours after endotracheal intubation [260]. In this study, the focus is on CAP, as the school environment is the setting for all the research. According to [261], CAP can be attributed to several bacteria and viruses divided as follows: Streptococcus pneumoniae (10-60%), Chlamydophila pneumoniae (5-43%), Mycoplasma pneumoniae (13-37%), Hemophilus influenzae (2-12%), Legionella (2-12%), Staphylococcus Aureus (1-10%), Gram-negative (10%, e.g., Escherichia Coli), and viruses (15-36%, e.g., Adenovirus). For the purpose of the analysis, only Staphylococcus Aureus, Escherichia Coli and Adenovirus were considered, as they were the main bacteria and viruses against which innovative filter solutions in PC configuration were effective. Specifically, according to the percentages above, the study considers Staphylococcus Aureus to be responsible for 6% of CAPs, as well as Escherichia Coli and Adenovirus for 10% and 15%, respectively.

According to [262], CAP was diagnosed by auscultating the lungs with a stethoscope and reading the chest radiography (two chest x-rays are required for the treatment of pneumonia, one at the beginning and one at the end of any type of treatment). Depending on the organism responsible, antibiotics or antiviral drugs were administered to the patient [262]. In detail, as reported by [263], clinical manifestations can be categorised as follows: (1) low severity CAP, including patients who require home treatment to avoid hospitalisation; (2) intermediate or high severity CAP, including patients who require hospitalisation and, if necessary, oxygen therapy. Depending on the severity of the disease, different types of treatment were recommended. For patients who required home care, the treatment varied according to the type of microorganism responsible for the inflammatory process; bacterial CAP was usually treated with antibiotics (e.g., amoxicillina), while viral CAP treatment usually relied on two different types of medication: paracetamol and NSAIDs (such as aspirin or ibuprofen) [262]. In this category of patients, additional costs associated with outpatient management should also be considered [264]. As mentioned above, the second category included patients who required hospitalisation. For both adults and children, the average hospital stay for CAP was about 10 days [265]. Table 7 summarises the main cost parameters used to calculate the direct healthcare costs per patient associated with both bacterial and viral CAP.

Table 7: Real data used to calculate direct health costs per patient associated with bacterial and viral CAP. Elaboration from [167].

	Direct costs per patient	Source
Cost of home treatment for patients with bactericidal CAP: - antibiotic	6.50 €	[252]
Cost of home treatment for patients with viral CAP: - paracetamol	5.40 €	[252]

- NSAID	16.90 €	[252]
Chest radiography ticket cost (1)	31 €	[266]
Cost for outpatient management	182 €	[264]
Daily cost of hospitalization for adults with complications (2) (> 17 years old)	3,558 €	[267]
Daily cost of hospitalization for adults without complications (>17 years old)	2,291 €	[267]
Daily cost of hospitalization for children (< 17 years old)	1,948 €	[267]

(1) chest radiography ticket cost (15.50 €, to be considered twice)

(2) complications include acute respiratory distress syndrome, lung abscesses, sepsis

For both students and teachers, the total direct costs associated with each case study were calculated in the same way. First, the average annual incidence of CAP by age group was calculated using data from [268]. This resulted in an incidence rate of 1.85% for 2-5 years, 1.4% for 5-10 years, 0.95% for 10-13 years, and 0.65% for 13-18 years. Subsequently, according to [269], the average annual CAP incidence among teachers was estimated to be 0.9% for all the case studies. Furthermore, the percentage distribution of students in relation to the severity of illness was derived from [270]. The authors showed that 0.3% of the cases required hospitalisation and, consequently, the remaining 99.7% were treated at home. In the same way, the percentage distribution of teachers was assessed according to [269], resulting in 8% of cases requiring hospitalisation and 92% being treated at home. For the percentage of teachers requiring hospitalisation, it was assumed that the hospitalisation rate for CAP with complications is 60%, while the remaining 40% represents the hospitalisation rate for CAP without complications [265].

Once the direct costs were estimated for each severity disease category according to Equation 9, the sum of the costs derived from bacterial and viral CAP home treatment and hospitalisation, for both students and teachers, provided a comprehensive view of the total direct costs associated with each case study.

As for the estimation of indirect costs associated to Covid-19, the average annual per capita income from employment in the Public Administration (28,351 €) was used to assess the indirect costs associated to CAP. According to Equation 10, the indirect costs were calculated by considering the days of absence from school, which correspond to the average hospital stay (10 days). Figure 22 shows the direct and indirect costs associated with CAP for both students and teachers in each case study.

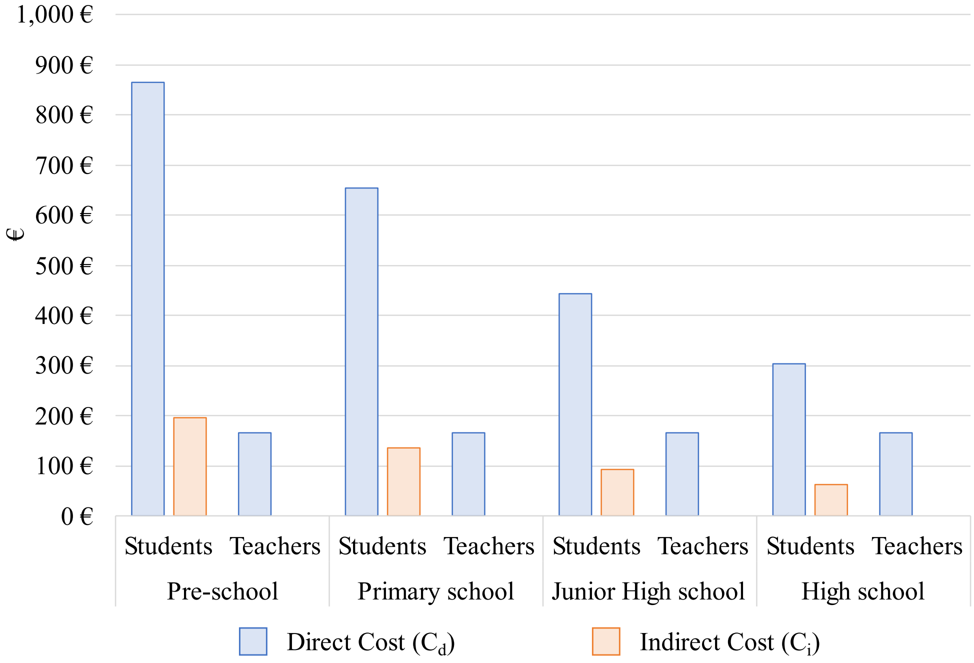


Figure 22: Direct and indirect cost associated to CAP disease for the different school typologies.

Finally, the health benefits of the PC configuration in each case study were assessed by calculating the proportion of costs avoided due to the presence of the biocidal and photocatalytic filters. Specifically, since both the biocidal and photocatalytic filters were able to reduce the presence of Staphylococcus Aureus and Escherichia Coli in the environment, the highest filtration capacity among the filters presented in the PC configuration was considered, which correspond to 99% reduction of both bacteria thanks to the presence of the photocatalytic filter. On the other hand, only the photocatalytic filter was effective against Adenovirus, with a reduction of 33.3%. Each of these percentages was multiplied by the percentage of responsibility of each bacterium or virus in causing CAP (6% Staphylococcus Aureus, 10% Escherichia Coli and 15% Adenovirus) in order to define the percentage of reduction of bacteria and viruses in all the case studies. Then, according to Equation 11, to estimate the health benefits related to students, the costs (direct and indirect) were summed and then multiplied by the sum of the percentage of bacteria and virus reduction due to the use of photocatalytic filter (equal to 20.3%) and the proportion of time spent by both students and teachers in the classroom (15% in pre-school, 13% in primary school, and 12% in junior high and high schools, based on the number of school days and the time spent inside daily, as shown in Table 2). For the evaluation of the health benefits related to teachers, only the direct costs were considered according to Equation 12.

The overall health benefits of each case study in terms of cost reduction due to the presence of biocidal and photocatalytic filters in the PC configurations included the combination of health benefits for students and teachers (Figure 25).

4.4.3 Students’ learning performance evaluation

As reported in section 4.3.3, the present study investigates the correlation between indoor CO_2 concentration and student performance levels in terms of relative speed. Specifically, to evaluate the relative speed of schoolwork, it was necessary to measure the CO_2 concentration in the classroom. According to Equation 14, the CO_2 concentration for the C configuration was calculated to be 750 ppm, considering the CO_2 generation rate of 0.0039 L/(s·person) for students and 0.0052 L/(s·person) for teachers [84]. Subsequently, the CO_2 concentration in the C configuration was reduced based on the highest CO_2 filtration capacity among the filters presented in the PC configuration, which was 12.5% due to the presence of the photocatalytic filter, in order to evaluate the indoor CO_2 concentration in the PC configuration. After calculating the CO_2 reduction capacity in the PC configuration as 94 ppm, the vale obtained was subtracted from the CO_2 value in the C configuration, resulting in 656 ppm. Subsequently, according to Equation 13, the relative speeds of each configuration were calculated. The results showed that the students' performance increased by 3% in the PC configuration compared to the C configuration. Finally, the student performance benefit for each AHU configuration was calculated using Equation 15, considering the average annual salary of teachers (I_{PA}) which amounts to 28,351 € [223]. The benefit obtained for each AHU configuration was the same for all the case study typologies.

Teachers' productivity was not evaluated in this study, as no link with indoor CO_2 concentration was identified in the current literature.

4.5 Results and discussion

This section provides the results of the CBA application, starting with the evaluation of the main costs associated with both C and PC AHU configurations, as well as the quantification of the main impacts (either negative or positive).

According to section 4.4.1, the investment, maintenance, replacement, and disposal costs of each filter installed in both C and PC configurations are estimated. As the costs of the AHUs vary yearly depending on the characteristics of each filter installed (Table 5), Figure 23 shows the annual total costs over a 10-year period related to both C and PC AHU configurations.

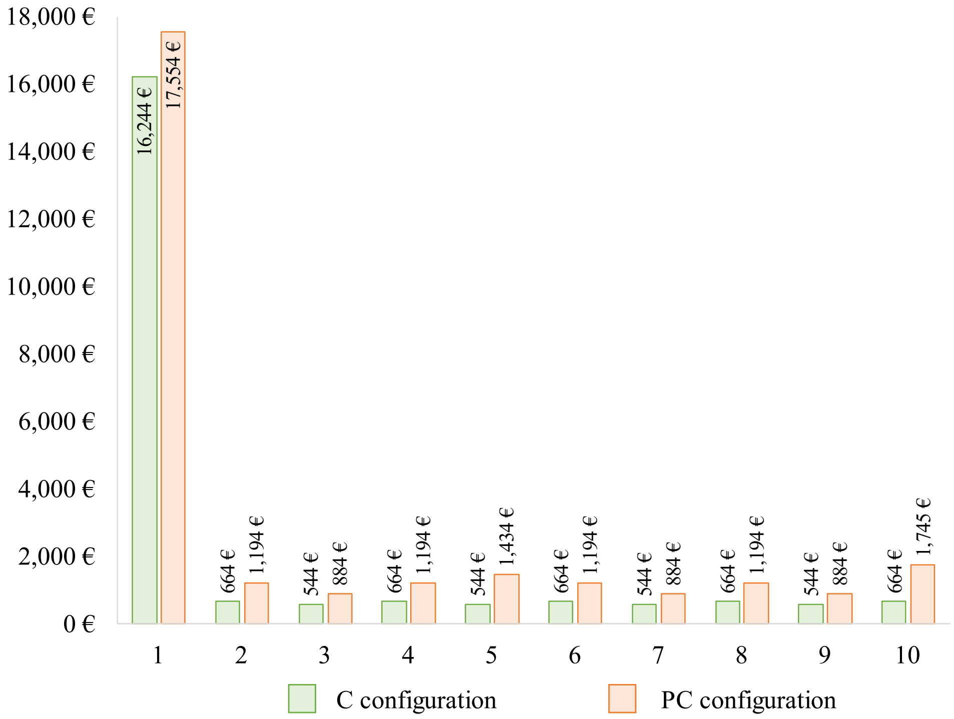


Figure 23: Total costs per year related to C (green) and PC (red) AHU configurations.

The total costs associated with each AHU configuration are the same for all case study typologies. As shown in the figure above, the costs are higher in the PC configuration than in the C configuration due to the presence of both the biocidal ePM1 50% and the photocatalytic filters which require higher investment, maintenance, and replacement costs according to Table 5.

According to section 4.3.1, the energy impact assessment includes the electricity consumption used by fans (Eq. 7) and the energy sources used by generators to provide heating and cooling for the AHU coils (Eq. 8). For all the case study typologies, Figure 24 shows the main results for the C and PC configurations regarding electricity consumption. Specifically, the electricity consumption of the fans is approximately 11,000 kWh/y and 3,000 kWh/y for the C and PC configurations, respectively. While the coils consume approximately 51,000 kWh/y and 55,000 kWh/y in the C configuration for heating and cooling purposes, respectively. In the PC configuration, the electricity consumption related to hot and cold coils is around 2,000 kWh/y and 11,000 kWh/y, respectively.

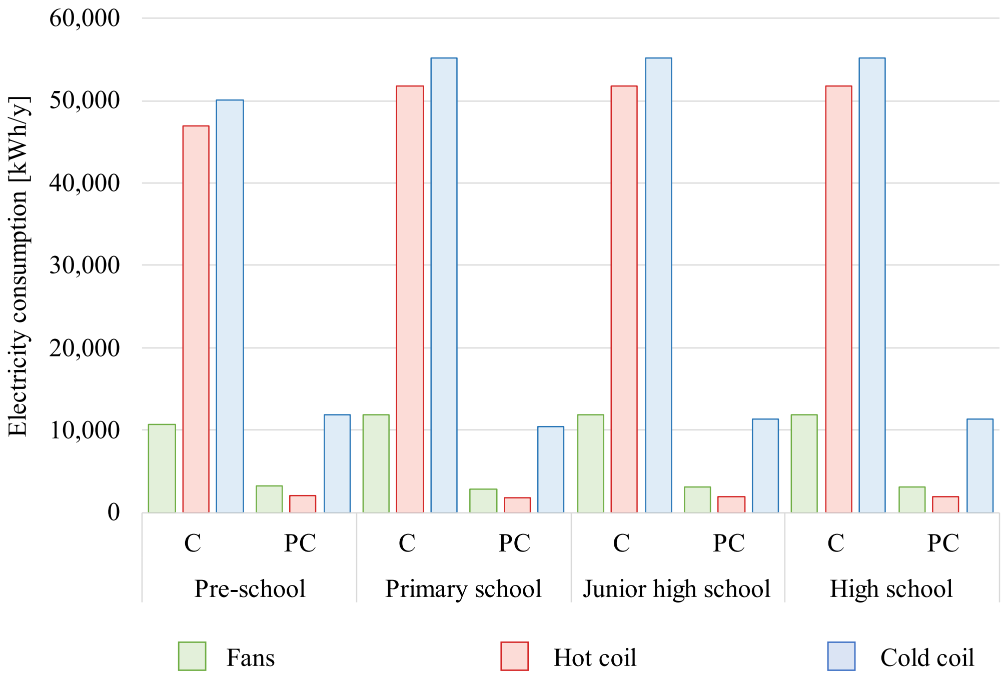


Figure 24: Electricity consumption referred to the operational of the different school typologies. From [220].

Therefore, the overall energy consumption for the C and PC configurations is evaluated by adding the energy consumption of fans and coils. Then, the total energy consumption for each case study is converted into an energy cost by multiplying it by the unit price of the energy source (0.20 €/kWh [248]). The results reveal that the energy cost associated with the C configuration is 22,450 €/y in pre-school and 24,750 €/y in primary, junior-high and high school. While the energy cost related to the PC configuration accounts for 3,550 €/y in pre-school, 3,120 €/y in primary school and 3,400 €/y in junior high and high school. As mentioned in section 4.3.1, the ΔBCR can lead to financial impacts that are either costs (if higher than the reference scenario) or benefits (if lower than the reference scenario). In this application, as the C configuration is set as reference scenario and the energy costs are lower in the PC configuration, the difference between the resulting energy costs of the C and PC configurations represents the energy benefits for the PC configuration.

Figure 25 shows the results in terms of energy-, occupants health- and students' performance-related benefits associated with both C and PC configurations, comparing all case studies.

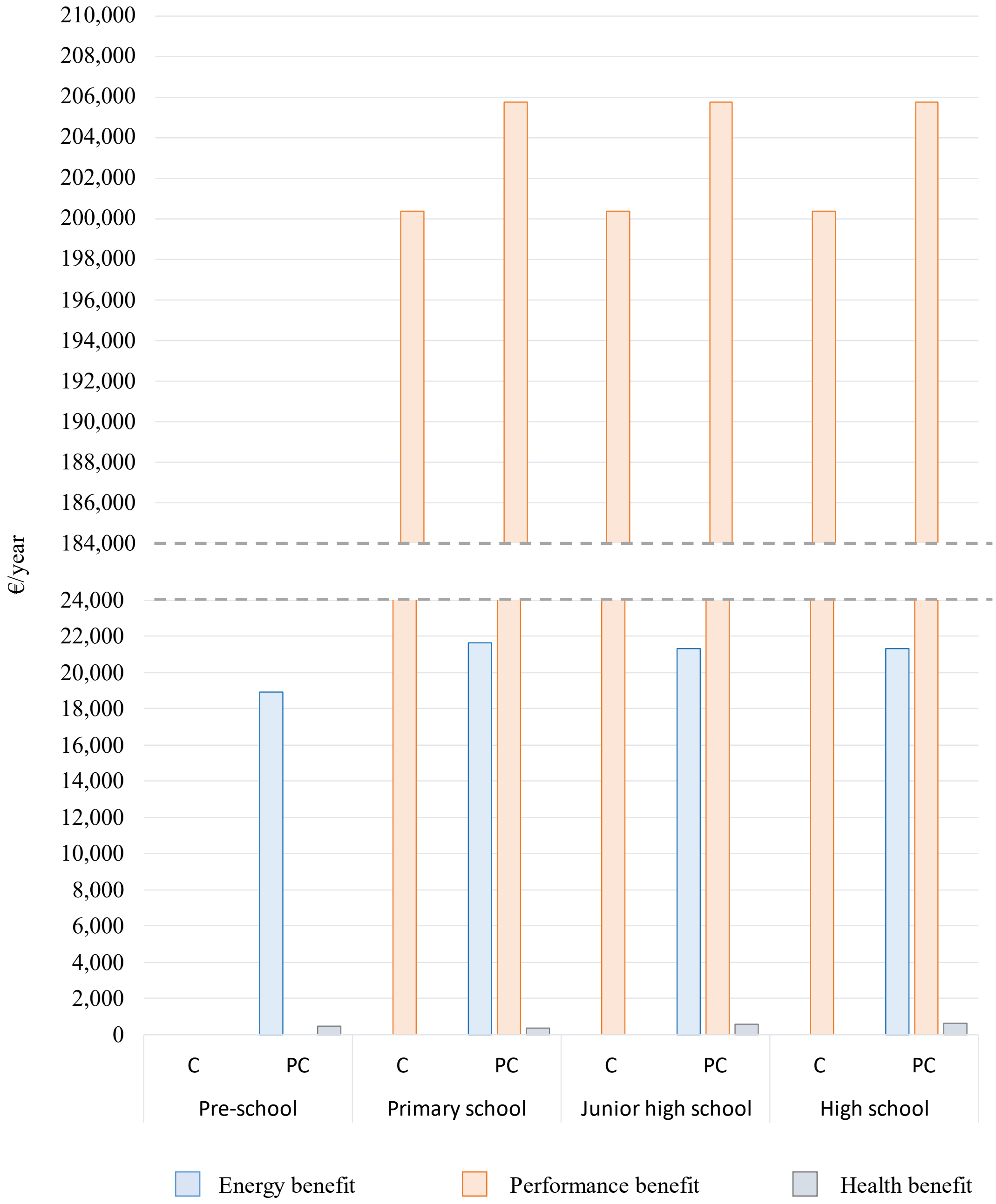


Figure 25: Energy-, health- and performance-related benefits referred to the operational of the different school typologies. From [220].

In the light of the above, there are no energy and health benefits for the C configuration. Therefore, the energy costs are calculated as a benefit for the PC configuration, resulting in a total of 18,898 €/y in pre-school, 21,620 €/y in primary school and 21,330 €/y in junior high and high school.

Similarly, the health benefits are calculated using the COI method in terms of cost savings associated with the use of the PC configuration, which amount to 483 €/y in pre-school, 325 €/y in primary school, 561 €/y in junior high school and 600 €/y in high school. The results differ for each type of school, as they depend on variations in the parameters associated with the children's age groups. These parameters include the incidence rate of Covid-19, the distribution percentage of patients, as well as the duration of the school year and the amount of time spent in the classroom.

With regard to the benefits in terms of student performance, they were calculated for both the C and PC configurations, resulting in values of 200,357 €/y and 205,735 €/y, respectively, for all case studies. For pre-schools, where children aged 3-5 years do not perform typical school tasks, the value of the performance benefit is zero and is therefore not considered.

The final step is to calculate the ΔBCR between the C and PC configurations once the costs and benefits of each configuration are established. Setting the C configuration as the reference scenario, the comparison between the C and PC configurations shows that the PC configuration incurs higher costs in terms of investment, maintenance, replacement, and disposal (due to the presence of innovative filtering solutions). However, it offers significant benefits in terms of energy efficiency, health and performance compared to the C configuration. Subsequently, the difference in total costs (Δ total costs) and total benefits (Δ total benefits) between the two scenarios (C and PC configurations) are assessed. Specifically, costs include those associated with the lifecycle of system components, while benefits are the sum of energy-, health- and performance-related benefits. Finally, the Δ total costs and Δ total benefits are actualized for a 10-years period using a 3% annual discount rate, obtaining the ΔBCR (according to Equation 6) for the four case studies, as shown in Table 8.

Table 8: Incremental BCR outputs: C vs. PC configuration. From [220].

	Δ benefits	Δ costs	Δ BCR
Pre-school	165,329.1 €	5,524.9 €	29.92
Primary school	233,079.3 €	5,524.9 €	42.19
Junior high school	232,612.4 €	5,524.9 €	42.10
High school	232,949.6 €	5,524.9 €	42.16

As shown in the table above, the ΔBCR exceeds 1 in all case studies, indicating that despite the higher cost of the PC configuration, its greater advantages in terms of energy efficiency, occupant health and student learning performance make it a more favourable scenario. Furthermore, Table 5 demonstrates that the Δ benefits associated with pre-school are lower due to the exclusion of student performance benefits. As shown by the results, the majority of the Δ benefits are related to energy, highlighting the unsustainability of implementing energy-intensive HVAC systems as a pandemic emergency measure, as well as emphasising the importance of identifying solutions that provide healthy indoor environments with minimal energy impact on buildings. To conclude, the CBA allowed the consideration of additional externalities beyond costs. Specifically, the innovative biocidal and photocatalysis-based filtration technologies implemented in PC AHU configurations were assessed not only financially, but also from a socio-economic perspective, considering advantages such as energy efficiency, improved occupant health and well-being, and improved student performance.

All cost and benefit data used to develop the CBA for both C and PC configurations are presented in Appendix B, organised by case study typology.

4.6 Conclusions and future developments

The Covid-19 pandemic highlighted the inadequacies of AHU's technologies and system management, raising attention on the ability of HVAC systems to provide safe and healthy buildings for occupants. Specifically, the management of mechanical ventilation systems in school buildings is critical for reducing SARS-CoV-2 transmission, as they are considered critical hotspots due to high population densities and extended school hours. In fact, mechanical ventilation not only reduces the spread of the disease, but also contributes to the creation of a healthy environment for student health and performance. This study aims to identify proper methodological approaches able to quantify the benefits of advanced biocidal and photocatalytic filtration technologies installed in AHUs of non-residential buildings, not only to improve indoor air quality control, but also to enable energy savings through the use of conventional HVAC operating strategies. In fact, while the adoption of such technologies has potential energy and socio-economic benefits, the high investment costs may deter consumers from investing in them. For this reason, in order to support energy investment decision making processes, this study identifies and applies the CBA methodology to estimate the effects of two AHU configurations that accurately reflect Covid-19 and post-Covid-19 conditions. These configurations are installed in four typologies that are representative of Italian schools (pre-school, primary, junior high and high school) facing urgent intervention needs due to critical air quality conditions. The results show that the introduction of advanced filtering technologies in AHU configurations can significantly contribute to energy savings, as well as to improve health and performance of teachers and students, despite the high investment costs. Specifically, the CBA shows that the PC configuration, featuring both biocidal and photocatalytic air filters, can ensure a significant ΔBCR (approximately 30 for pre-school and over 40 for the other case studies) when compared to the C configuration. Furthermore, the majority of the Δ benefits are linked to the energy benefits achieved by the PC configuration. The purpose of the study was to verify the methodology chosen to understand the criticality of data collection. In fact, the study is not intended to provide comprehensive results, but rather to suggest a methodology that can be applied to other emerging technologies.

Future work will focus on the extension of the developed CBA methodology to other public areas, such as offices, hotels, and commercial buildings. In addition, statistical analyses (such as the coefficient of determination, R^2) will be developed to test the accuracy of the hypothesis. The investigation and application of other evaluation methods, such as the MCDA might be an interesting focus to explore. The MCDA is a tool for evaluating multiple qualitative and quantitative criteria simultaneously, considering the various perspectives of decision makers involved in the process [271]. Specifically, this approach could be incorporated into the analysis to evaluate additional benefits that are difficult to monetise. Furthermore, it would be interesting to extend the present analysis performed in typical school buildings located in Italy, to other countries and climatic zones.

Chapter 5

Energy efficiency and electrification in buildings

5.1 Overview

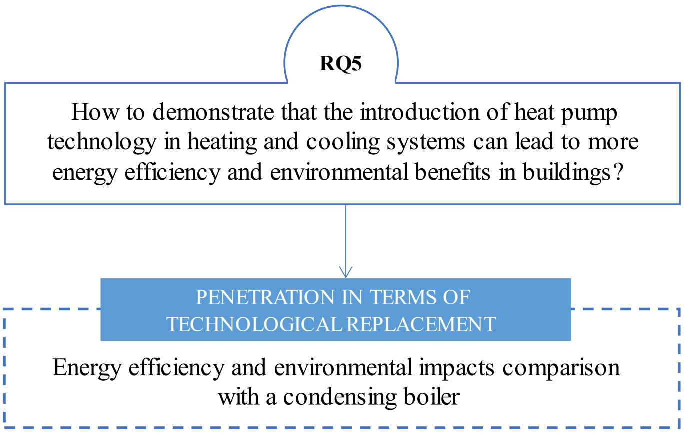


Figure 26: Structure of Chapter 5.

The following chapter aims to demonstrate the effectiveness of air-to-water heat pumps as an alternative to the traditional condensing boilers in residential buildings. Chapter 5 provides a detailed response to RQ 5: "*How to demonstrate that the introduction of heat pump technology in heating and cooling systems can lead to more energy efficiency and environmental benefits in buildings?*".

The following structure is presented: section 5.2 aims to explore the current and forthcoming legislations and standards relating to reversible heat pump technology. Section 5.3 provides an overview of the main context and goal of the case study, while section 5.4 outlines the methodology used to answer RQ 5. Section 5.5 defines the characteristics of the case study, followed by the presentation of the main findings, conclusions and future developments in sections 5.6 and 5.7, respectively.

Keywords: heat pump, condensing boiler, residential, single-family house.

Declaration: the topics described in this chapter were previously published in the following publications:

- **Lingua C.**; Abbà I.; Becchio, C.; Viazzo, S.; Corgnati, S.P. (2021). Legislation and Standards for the implementation of reversable heat pump technologies in Mediterranean climate. In: CLIMAMED 2020, 10th Mediterranean Congress of Climatization Towards Climate Neutral Mediterranean Buildings and Cities, Lisbon, Spain, 11-12 May 2021 [272].
- **Lingua, C.**; Viazzo, S.; Corgnati, S.P.; Lena, S.; Prendin, L. Air/water heat pumps: energy and environmental assessment in Mediterranean residential building sector. In: Proceedings CLIMA 2022, 14th REHVA HVAC World Congress, Rotterdam, The Netherlands, 22-25 May 2022, pp. 1555-1562 [273].

5.2 Regulations and standards for implementing reversible heat pump technology

In recent years, the focus on energy efficiency and environmental sustainability had a major impact on the building heating market. The search for more environmentally friendly and energy efficient products has led to the emergence of technological solutions that do not use fossil fuels. According to section 2.4.2, the demand for efficient and sustainable technologies was driving the European air-conditioning market towards a greater use of heat pumps. Specifically, heat pump systems are becoming more and more widespread as they represent the preferred choice for renovation projects and the mandatory choice for new buildings. In fact, the development of the market in this direction was encouraged by incentives and tax deductions available to those who choose new generation equipments to improve the energy efficiency of their homes. As emphasised by [274], HVAC systems will play a crucial role in addressing the current energy challenge, in particular the heat pump technology, which offers numerous benefits, including (i) reduced the CO_2 emissions through the use of RES; (ii) reduced energy consumption and costs; (iii) possibility of integration with other green technologies; (iv) increased energy performance and property value; (v) possibility of benefiting from the tax deductions.

Heat pump technologies are already competitive in the current building energy market, but the regulations are constantly changing. Therefore, it is essential for producers and consumers to have a clear understanding of the regulatory context in which they operate. For this purpose, to provide guidance to producers wishing to keep abreast of recent regulatory developments and to meet the minimum requirements for introducing high performance technologies to the market, a literature review was performed to examine the current and forthcoming regulations and standards relating to reversible heat pump technology. Specifically, this review analysed the main European directives, the Italian national legislation, and the Piedmont regulations with the aim of providing producers with a map of the rules and constraints they have to comply with.

Figure 27 provides an overview of the key findings, emphasising the range of geographical competencies explored. The research began with an analysis of current and forthcoming European directives relating to energy efficiency and renewable energy, before subsequently narrowing the geographical scope to national and regional levels.

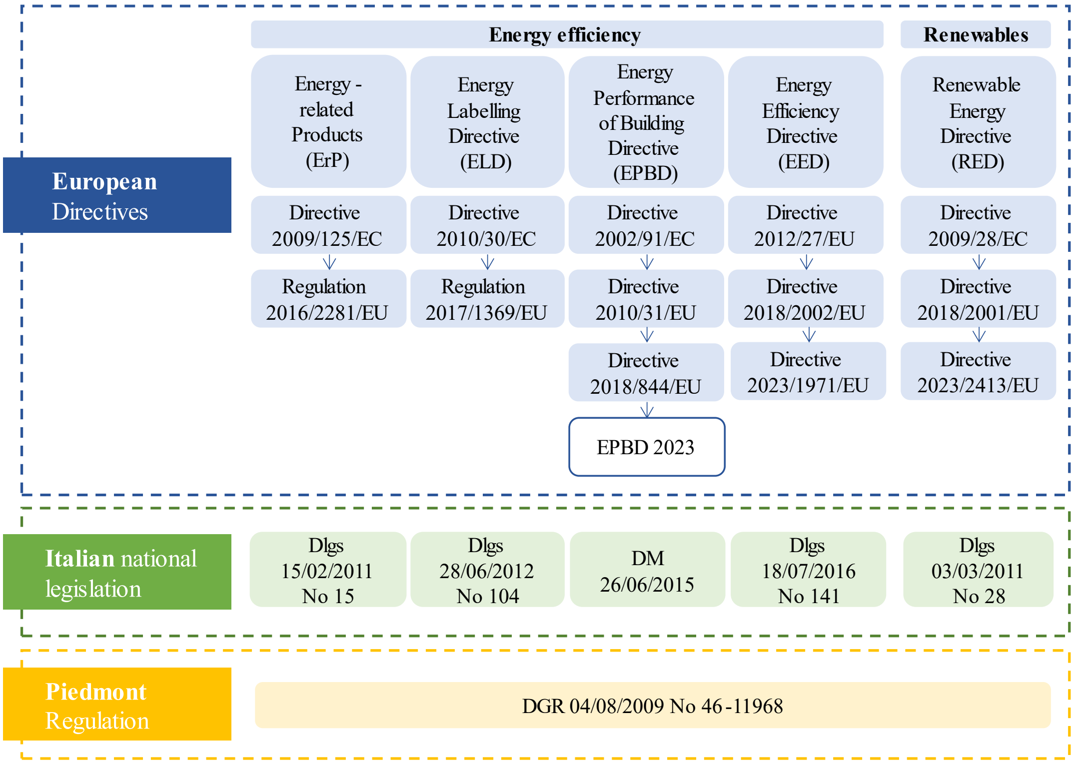


Figure 27: Overview of the European Directives, Italian national legislation and Piedmont Regulations relating to energy efficiency and renewable sources. Elaboration from [272].

Figure 27 provides an overview of the main regulatory context related to reversible heat pump technology. At the European level, the Energy-Related Products (ErP) (Directive 2009/125/EC [275]), the Energy Labelling Directive (ELD) (Directive 2010/30/EC [276]), the Energy Performance of Buildings Directives (Directive 2002/91/EC [37], Directive 2010/31/EU [38], Directive 2018/844/EU [6]), the Energy Efficiency Directives (Directive 2012/27/EU [43], Directive 2018/2022/EU [44]) and the Renewable Energy Directives (Directive 2009/28/EC [49], Directive 2018/2001/EU [51]) were detected, highlighting the most recent regulations and directives [277],[278], [47],[46],[55].

Then, to illustrate the typical Mediterranean context, Italian legislation was thoroughly examined. The wide latitude of the peninsula results in a variety of climatic conditions, with the central and southern regions having a distinct

Mediterranean climate, while some northern regions have an Alpine climate. In this regard, Figure 27 shows the main legislative decrees [279],[280],[281],[282] as well as the Ministerial Decree of 26 June 2015 [84], which act as the implementation of the European Directives mentioned above. Specifically, in Annex B of the Ministerial Decree, the specific requirements for existing buildings that are subject to energy upgrading, as well as the main requirements (COP and EER) for heat pumps and chillers were established [84]. In addition, at the Italian level, the reference standard for calculating and analysing the seasonal performance of heat pumps was the UNI EN 14825:2019 [283]. This standard defined the method for determining the Seasonal Energy Efficiency Ratio (SEER) for cooling and the Seasonal Coefficient of Performance (SCOP) for heating [283]. Furthermore, a key role was also played by the UNI/TS 11300-4:2016 Standard [284]. It was used to verify the performance parameters of reversible heat pumps with electrical resistance, which were provided by manufacturers for the calculation of energy demand at national level [284].

Finally, the main focus concerns the legislation of the Piedmont region [285], emphasising the disparity in the minimum requirements compared to the national level. It was examined not only as an example of a regional framework, but also as one of the first Italian regions to legislate independently in the field of energy.

After analysing the requirements outlined in [84] and [285] for electric reversible heat pumps in Italy and Piedmont, respectively, Table 9 presents the necessary test conditions needed for heating services. The values for cooling services are not analysed as they are identical to those required at national level.

Table 9: Minimum requirements and reference conditions for electric reversible heat pump for heating service. From [272].

			Italy DM 26/06/2015	Piedmont DGR 04/08/2009
Type of heat pump	Outdoor environment temperature conditions	Indoor environment temperature conditions	COP	
Air/Air	Dry bulb = 7°C Wet bulb = 6°C	Dry bulb = 20 °C	**3.5**	**3.2**
	Dry bulb = -7°C Wet bulb = 6°C	Wet bulb = 15°C		**2.7**
Water/Water Ph ≤ 35 kW	Dry bulb = 7°C Wet bulb = 6°C	T_{inlet} = 30°C T_{outlet} = 35°C	**3.8**	**3.2**
Water/Water Ph > 35 kW	Dry bulb = -7°C Wet bulb = 6°C	T_{inlet} = 30°C T_{outlet} = 35°C	**3.5**	**2.7**
Brine/Air	T_{inlet} = 0°C	Dry bulb = 20°C Wet bulb = 15°C	**4**	**4**

Brine/Water	T_{inlet} = 0°C	T_{inlet} = 30°C T_{outlet} = 35°C	**4**	**4**
Water/Air	T_{inlet} = 15°C T_{outlet} = 12°C	Dry bulb = 20°C Wet bulb = 15°C	**4.2**	**4**
Water/Water	T_{inlet} = 10°C	T_{inlet} = 30°C T_{outlet} = 35°C	**4.2**	**4**

The main results of this analysis are a detailed guide for producers in the field of reversible heat pumps and an illustration of the difficulty of providing a clear regulatory framework. Contrary to expectations, a comparison of the minimum performance requirements outlined in Italian legislation and those set by the Piedmont region reveals that the latter are actually less restrictive. This discrepancy may be due to the fact that the national regulation is more recent than the regional one. However, as each region can legislate independently on energy issues, the Piedmont region now has to comply with both regulations, which can lead to confusion in identifying the minimum performance requirements for effective reversible heat pumps.

To conclude, at the end of October 2023, the European Parliament's Committee on Environment, Public Health and Food Safety (ENVI) approved the text of the new regulation on fluorinated greenhouse gases [286], which will replace the current regulation EU 517/2014 [287]. According to [288], F-gases, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3), are GHGs with a global warming potential up to 25,000 times greater than that of CO_2. These refrigerant gases are used in air source heat pumps for summer cooling. The use and spread of these gases has environmental consequences, as their release into the atmosphere contributes significantly to global warming [288]. For this reason, the need to reduce GHG emissions has led the European community to adopt the aforementioned regulation on the use, recovery and destruction of fluorinated greenhouse gases. Specifically, according to the new regulation [286], a 48% reduction in the EU's F-gas market share is confirmed for the two-year period 2025-2026 compared to 2023 level. While for the year 2024, the reduction will be 31%, as already foreseen in the previous regulation [287].

Among the main changes introduced, the provisional agreement establishes a ban on the use of refrigerant gases with a GWP>150 in packaged heat pumps and small air conditioners (<12 kW) from 2027 and a complete phase-out from 2032. Finally, for air conditioners and split heat pumps containing F-gases, a total ban has been agreed from 2035, with shorter deadlines for certain types of higher GWP split systems.

This new regulation has proved to be crucial for industrial heat pump manufacturers, who have had to adapt their technologies to these new restrictions.

5.3 Background

Energy efficiency improvement in buildings are crucial to achieve the energy system transformation. As stated in Chapter 1, it represents one of the main objectives of the current European policy actions to achieve climate neutrality and to move Europe towards a post-carbon society by 2050. In this context, heat pump technologies are regarded as the most promising heating solution for application in both new buildings and refurbished ones, in order to reduce the carbon footprint of the building sector [289],[290]. In fact, these systems are at the centre of the main interventions supported by various financial mechanisms introduced to promote energy investments in buildings, by supporting the transition of the building sector. Focusing on the Italian national context, the Decree-Law 34/2020 introduced in May 2020 an incentive mechanism, the so-called Superbonus, which increased the tax rebate for building interventions from 50-65% to 110% for expenses incurred from July 1, 2020 to December 31, 2021 [64]. The Superbonus 110% covers specific energy efficiency measures, interventions to reduce the risk of earthquakes, the installation of photovoltaic systems as well as infrastructures for recharging electric vehicles in buildings. Specifically, according to Article 119 of the D.L. 34/2020, the highest deductions are allowed for the following types of interventions, the so-called "*driving interventions*" [64]: (1) thermal insulation of vertical, horizontal and inclined opaque surfaces of the building envelope, including single-family houses, with an incidence of more than 25% of the building's gross dispersion area; (2) replacement of existing air-conditioning systems with centralised systems for heating and/or cooling and/or DHW supply in the common parts of buildings; (3) anti-seismic interventions. In addition, the Superbonus 110% also applies to the following measures, the so-called "*towed interventions*", provided that they are carried out in conjunction with at least one of the listed thermal insulation interventions or replacement of winter air-conditioning systems: (1) energy efficiency interventions covered by the Ecobonus; (2) installation of grid-connected solar PV systems on buildings; (3) integration of storage systems in solar PV systems; (4) installation of infrastructure for recharging electric vehicles in buildings. Subsequently in 2021, with the introduction of the Law 178/2020 [291] (known as Budget Law 2021), the Superbonus 110% was extended until June 30, 2022. In certain circumstances, it could be extended until December 31, 2022 or June 30, 2023. Finally, in January 2022, with the entered into force of the Law 234/2021 [292], the majority of building tax deductions, including the Superbonus, were extended until 2024.

Among the considerable amount of actions involved by the Superbonus 110%, the study focuses on the intervention related to the replacement of existing air-conditioning systems with centralised systems for heating and/or cooling and/or DHW supply. In this context, the installation of heat pump technologies is encouraged in new construction or as replacement of existing fossil-fuelled heating systems in the renovation of existing buildings.

In line with the above, the study aims to examine the efficiency of air-to-water heat pump technologies as an alternative to conventional condensing boilers in typical Mediterranean residential buildings. Specifically, the research focuses on the following two main objectives:

1. the first analysis focuses on demonstrating the energy and environmental benefits of replacing a condensing boiler with a heat pump system solution for space heating and DHW in **new dwellings with high envelope performances**;
2. the second application focuses on **existing buildings with low envelope performances**. The aim is to verify whether a system upgrading intervention, which involves replacing a condensing boiler with a heat pump technology without modifying the building envelope, can guarantee the improvement of two energy classes as required by the D.L. 34/2020 to obtain the Superbonus 110%.

For both applications, quasi-steady-state simulations are performed on single-family houses (SFHs) of different sizes and building envelope performances, located in various Italian climatic zones.

The study is structured as follows: the methodology employed for the analysis is shown in section 5.4. Section 5.5 describes all the main parameters considered for the development of the simulation models. Section 5.6 outlines the key findings of the research, with a distinction between the two case study objectives. Lastly, section 5.7 provides the concluding remarks and future outlooks.

5.4 Methodology

In this section the methodology applied to demonstrate the energy and environmental benefits of implementing heat pump systems for space heating and DHW in new residential buildings and renovation of existing ones is provided.

In detail, the energy assessment is conducted in six steps: i) characterising the building models to be analysed (e.g., building size, building envelope performances, climate zones, etc.) ; ii) choosing the KPIs; iii) energy modelling of the selected buildings; iv) selecting retrofit scenarios; v) running the energy models in pre- and post-retrofit conditions; vi) computation of the selected KPIs. Starting from the selection of the relevant KPIs, the following two KPIs are measured:

- non-renewable global energy performance index ($EP_{g,nren}$) expressed in $kWh/(m^2y)$;
- CO_2 emissions expressed in kg CO_2/y.

Specifically, the non-renewable global energy performance index is used to assess the energy impact. This index represents the overall energy performance of the building, indicating the total non-renewable primary energy requirement per unit area for services. According to [84], the $EP_{g,nren}$ index is used to define the energy class of a building before and after retrofit interventions. The KPI is calculated using Equation 16:

$$EP_{g,nren} = EP_{H,nren} + EP_{W,nren} + EP_{V,nren} \text{ [kWh/(m}^2\text{y)]} \tag{16}$$

where $EP_{H,nren}$, $EP_{W,nren}$, $EP_{V,nren}$ represent the amount of primary non-renewable energy consumed for heating, DHW, and ventilation respectively. In the present study the share of cooling was not included.

Specifically, for the purpose of the first application, the non-renewable global energy performance index is calculated considering both pre- and post-retrofit conditions in order to assess the energy impact. While, for the second application on existing buildings with low envelope performances, the index is used to identify the energy classes for both the pre- and post-retrofit conditions with the aim of verifying whether a system upgrading intervention can guarantee the improvement of almost two energy classes. In fact, the non-renewable global energy performance indicator is used to determine the energy class of a building. In detail, as shown in Table 10, the energy class scale is determined based on the global non-renewable energy performance index of the reference building ($EP_{g,nren,ref,standard\ (2019/21)}$), as defined in [84]. It is assumed that the reference building's standard elements and systems are installed in the building, meeting the minimum legal requirements for public buildings as of January 2019, and for all other buildings as of January 2021 [84]. According to [84], the energy efficiency classes range from class G ($EP_{g,nren} > 3.50$) to class A4 ($EP_{g,nren} < 0.40$).

Table 10: Building classification scale based on the overall non-renewable global energy performance index.

	$EP_{g,nren,rif,standard\ (2019\text{-}21)}$
Class A4	≤ 0.40
Class A3	0.41 - 0.60
Class A2	0.61 - 0.80
Class A1	0.81 - 1.00
Class B	1.01 - 1.20
Class C	1.21 - 1.50
Class D	1.51 - 2.00
Class E	2.01 - 2.60
Class F	2.61 - 3.50
Class G	> 3.51

The environmental impact is assessed using the CO_2 emission index. According to [293], it is calculated as a function of the CO_2 emission factor of the fuel used for the heating and/or hot water system as shown in Equation 17:

$$M_{del,i\,CO2} = Q_{del,i} \times k_{em,i} \text{ [kg CO}_2\text{/y]} \tag{17}$$

where $Q_{del,i}$ is the energy delivered by energy carriers [kWh/y]; $k_{em,i}$ represents the CO_2 emission factor of the fuel [kg CO_2/kWh].

The emission factor is 0.21 kg CO_2/kWh for methane fuel (natural gas) and 0.46 kg CO_2/kWh for electricity. In the case of natural gas, the energy delivered need to be converted into kWh/y by multiplying it by the calorific value of the gas (equal to 9.940 kWh/Nm^3 for methane).

Concerning the energy simulation of the buildings' portfolio, it was carried out using the EdilClima commercial software certified by the Italian Committee for Thermal Engineering (CTI). It is based on the Italian technical specification UNI/TS 11300 and covers all the energy services defined in the technical specification UNI/TS 1300-5:2016 [294], such as heating, cooling, DHW and ventilation. The tool relies on a quasi-steady-state calculation approach, including monthly heat balance and utilisation factors according to national and EU standards [295],[296]. Specifically, the interface used for the study is EC700 [297] which supports the following calculations: (1) the dynamic hourly calculation of the building energy performance, which follows the European standard UNI EN ISO 52016-1:2018 [298]; (2) the heat load is used for the sizing of the heating systems, according to UNI EN 12831-1:2018 [299]; (3) the heating and cooling requirements to assess the energy performance of the building envelope according to UNI/TS 11300-1:2014 [300]; (4) the contributions from renewable sources, including thermal solar, photovoltaic, and biomass, are evaluated in line with UNI/TS 11300-4:2016 [293]; (5) the primary energy required for cooling, according to UNI/TS 11300-3:2010 [301].

5.5 Case study

To assess the energy and environmental impacts associated with the use of heat pump technologies in different building scenarios, including both new constructions and renovation of existing buildings, the study established specific building models and, subsequently, performed simulations using the EdilClima EC700 thermo-technical software.

This section provides an overview of the basic assumptions made during the characterisation of the models, covering aspects such as geometric features, building envelope, climate zones, and reference building systems. After establishing the reference conditions for the building models, different HVAC solutions, with a focus on heat pump technologies, are presented for potential installation in both new and existing buildings.

Building size characterisation

The research focuses on single-family houses falling under the Italian category E1(1), which includes dwellings used for permanent residential purposes, such as civil and rural dwellings. Two SFH models were defined, each with different building size: model S (small) and model L (large). Table 11 provides the main geometric characteristics of each model, including the net and gross floor area, as well as the net and gross volume.

Table 11: Geometric characteristics of models S and L.

Building type	Net floor area (m^2)	Gross floor area (m^2)	Net volume (m^3)	Gross volume (m^3)	S/V *
Model S	150	560	400	635	0.88
Model L	220	755	585	900	0.83

* The ratio S/V expresses the compactness of a building, and it is calculated by dividing the dispersing surface (e.g., external walls, roofing, floor slabs) by the air-conditioned volume.

Both models had one floor above ground and a net floor height of 2.7 m. In addition, the south-facing façade of both SFHs had a larger glazed area than the north-facing façade to maximise solar gain and minimise heat loss.

Figures 28 and 29 represent the floor plans of the two SFHs, model S and model L respectively. As shown, the geometry of the defined buildings was the same.

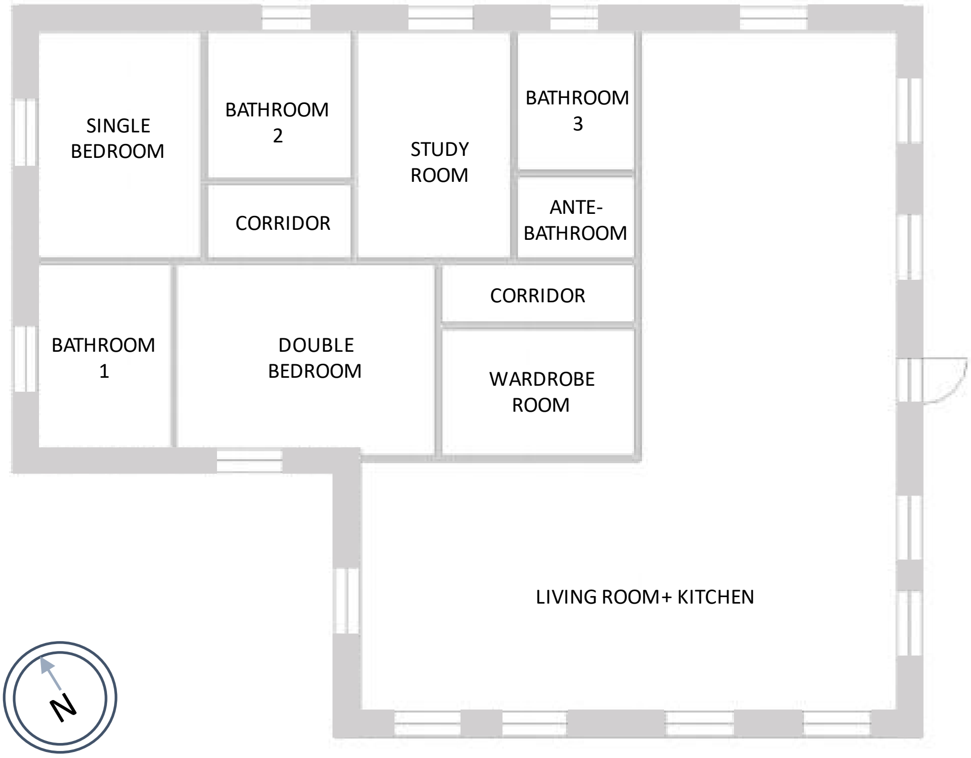


Figure 28: Floor plant of model S (out of scale).

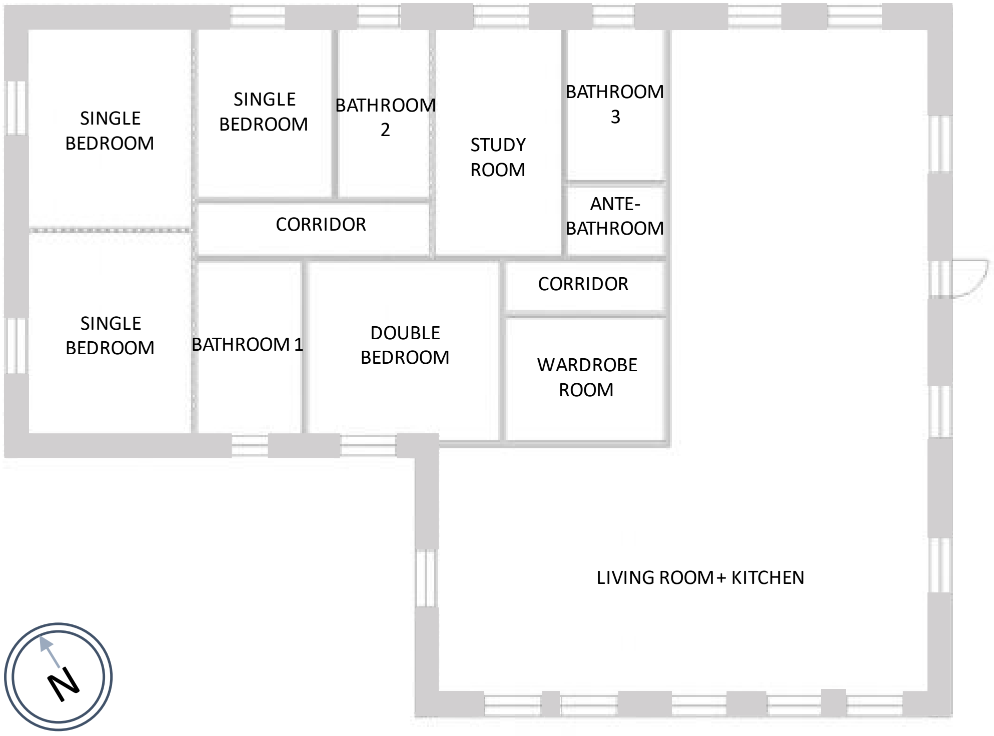


Figure 29: Floor plant of model L (out of scale).

Building envelope performances

Both new and existing building applications were represented by the SFHs defined above. To account for the differences in envelope performance between the two case study objectives, the four levels of envelope performance, each characterised by the specific thermal transmittance of opaque and transparent envelopes, were considered. In the simulations, the envelopes followed the traditional characteristics of Italian single-family houses. Specifically, the external walls were typically made of brick and external thermal insulation, while the floors and ceilings were made of concrete and masonry. Windows were equipped with Polyvinyl chloride (PVC) frames and triple low-emissivity glass. Although the envelope elements were similar in construction, the energy performance levels vary according to the thickness of the insulation, ranging from low to very high performance. Specifically, it was assumed that very high (envelope A) and high (envelope B) performance envelopes would be used for new construction purposes, while low (envelope C) and very low (envelope D) performance envelopes would be used for the verification of the energy class improvements. Tables 12, 13, 14 and 15 show the thermophysical properties of the building envelopes A, B, C, and D respectively.

More details on the layers of the opaque envelope (external wall, floor, and roof) of each different envelope typology are described in Appendix C.

Table 12: Thermophysical properties of building envelope A components.

Envelope component	Thickness [mm]	U-value [W/m^{2}K]
External wall	426	0.154
Windows	/	1.200
Floor	460	0.117
Roof	435	0.175

Table 13: Thermophysical properties of building envelope B components.

Envelope component	Thickness [mm]	U-value [W/m^{2}K]
External wall	420	0.279
Windows	/	1.400
Floor	280	0.212
Roof	435	0.175

Table 14: Thermophysical properties of building envelope C components.

Envelope component	Thickness [mm]	U-value [W/m^{2}K]
External wall	330	0.853
Windows	/	2.200
Floor	240	0.496
Roof	275	1.167

Table 15: Thermophysical properties of building envelope D components.

Envelope component	Thickness [mm]	U-value [W/m^{2}K]
External wall	330	0.853
Windows	/	4.500
Floor	240	0.496
Roof	275	1.167

Climate zones

The study simulated eight models (models S and L, each with four levels of envelope performance A, B, C, and D) in three different climatic zones of Italy. Specifically, the climate zone E in northern Italy was characterised by the climate of Turin, while the central region, representing climate zone D, was characterised by the climatic conditions of Rome. Lastly, for the warmer climate of southern Italy, the climate zone B was represented using data from Palermo. Table 16 shows the main input data, including the coordinates, the heating degree days, the design winter outdoor temperature, the climate zone and the heating period related to each of the three different climate zone considered for the simulation.

Table 16: Input data related to the three different climate zones.

	Coordinates	Heating Degree Days	Design winter outdoor temperature [°C]	Climate zone	Heating season
Turin	45.7° N 7.43° E	2617	-8°C	E	15th October- 15th April
Rome	41.53° N 12.28° E	1415	0°C	D	1st November- 15th April
Palermo	38.7° N 12.28° E	751	+5°C	B	1st December- 31st March

Table 17 shows the average monthly temperature for each of the three climate zones in Italy. The temperatures shown in the table were used by the simulation software. They affected both the demand side (i.e., the heat balance of the building) and the air-to-water heat pump side (i.e.; the performance of the machine).

Table 17: Monthly average outdoor temperatures for Turin, Rome and Palermo respectively. From [273].

	Turin [°C]	Rome [°C]	Palermo [°C]
January	1.20	8.10	11.9
February	3.10	9.10	11.5
March	8.30	11.5	13.6
April	11.9	15.9	16.8
May	18.0	19.2	20.3
June	22.1	22.6	24.1
July	23.6	26.4	27.1
August	22.6	26.6	27.2
September	19.1	21.7	24.1
October	12.3	17.8	20.8
November	6.80	12.7	16.8
December	2.60	8.70	13.1

Reference system

After defining the main geometric and envelope characteristics of the analysed SFHs, a reference system was identified. The aim was to compare its energy and environmental performance with those of heat pumps that could potentially be installed in the different simulated building models. Assuming a common reference system for all eight models - comprising four models for new construction purpose (SA, SB, LA, LB) and four models for the application to the renovation of existing buildings (SC, SD, LC, LD) - each was assumed to equip an independent heating system responsible for both DHW production and space heating. The system incorporated a modulating regulation and uses a class A condensing boiler generator with a nominal power of 22 kW.

In addition, for each simulated model, two categories of emission terminals were considered: (1) fan coil operating at a hot water temperature of 45°C and (2) radiant floor operating at a hot water temperature of 35°C. All models included radiators in the bathrooms.

Finally, the new and existing building applications differed only in terms of the ventilation system used. Specifically, the new buildings application featured a mechanical ventilation system with heat recovery, while the existing building application presented only a natural ventilation system through window openings. As mentioned before, the present research focuses exclusively on heating requirements, excluding any consideration on the space cooling needs.

Proposed heat pump solutions

In line with the aim of the study to examine the efficiency of air-to-water heat pump technologies as an alternative to conventional condensing boilers in the simulated SFHs, different system solutions were proposed. Specifically, focusing on all-electric solutions, the study included the assessment of the following two air-to-water heat pump technologies:

1. one-section air-to-water heat pump space heater, HP (1), ideal for new buildings with medium-low energy requirements and for renovation. Table 18 provides the nominal power and the COP of each one-section air-to-water heat pump used to simulate the models.

Table 18: Nominal thermal power and COP of one-section air-to-water heat pumps considered in the simulated models.

		Nominal thermal power [kW]	COP
HP (1)	Fan coil *1	6	3.80
6	Radiant floor *2		5.00
HP (1)	Fan coil	7.5	3.75
7.5	Radiant floor		4.60
HP (1)	Fan coil	10	3.7
10	Radiant floor		4.61
HP (1)	Fan coil	14	3.35
14	Radiant floor		4.35

*1 Air: 7°C B.S. – 6°C B.U.; Water: 45°C
*2 Air: 7°C B.S. – 6°C B.U.; Water: 35°C

2. two-section air-to-water heat pump space heater, HP (2), ideal for new buildings with medium-low energy requirements, for renovation or for the replacement of existing generators. Table 19 provides the nominal power and the COP of each two-section air-to-water heat pump used to simulate the models.

Table 19: Nominal thermal power and COP of two-section air-to-water heat pumps considered in the simulated models.

		Nominal thermal power [kW]	COP
HP (2) 4	Fan coil [*1]	4	3.92
	Radiant floor [*2]		5.13
HP (2) 6	Fan coil	6	3.91
	Radiant floor		5.00
HP (2) 8	Fan coil	8	3.74
	Radiant floor		4.71
HP (2) 9.5	Fan coil	9.5	3.60
	Radiant floor		4.59

[*1] Air: 7°C B.S. – 6°C B.U.; Water: 45°C
[*2] Air: 7°C B.S. – 6°C B.U.; Water: 35°C

In all simulations, the assessment of heat pumps was limited to the heating mode, and any analysis related to cooling was beyond the scope of this study. In addition, the performance data provided in the tables above were extracted from the technical documentation of real commercial units.

Case studies definition

Considering the two different building sizes (S and L), the four envelopes (A, B, C, and D) and the three climatic zones of Italy (Turin, Rome and Palermo), a total of 24 simulations were carried out. Table 20 summarises the results of the thermal energy demand for heating ($Q_{h,nd}$) and the design thermal load (P_u), calculated according to UNI/TS 11300-1:2014 [300] and UNI EN ISO 12831-1:2018 [299].

Table 20: Characterisation of the building envelope energy performance of the simulated models. Elaboration from [273].

	Turin		Rome		Palermo	
	P_u [kW]	$Q_{h,nd}$ [kWh/(m^{2}y)]	P_u [kW]	$Q_{h,nd}$ [kWh/(m^{2}y)]	P_u [kW]	$Q_{h,nd}$ [kWh/(m^{2}y)]
Model SA	7.15	31.26	5.07	6.55	3.80	2.44
Model LA	9.38	33.39	6.65	8.81	4.98	4.03
Model SB	8.42	47.75	5.98	14.34	4.48	6.81
Model LB	10.92	47.95	7.74	16.41	5.81	8.22
Model SC	16.61	163.8	11.82	82.35	8.87	46.59
Model LC	22.43	160.9	16.02	83.66	11.96	47.65

Model SD	19.01	183.2	13.54	87.84	10.16	50.42
Model LD	25.3	176.9	18.06	87.46	13.51	50.52

In addition, for each simulated model, Table 21 provides an overview of the heat pump typologies (described previously in Tables 18 and 19) used for the comparison with the condensing boiler installed in the reference building system.

Table 21: Heat pump typologies for each simulated model.

	One-section air-to-water heat pump			Two-section air-to-water heat pump		
	Turin	Rome	Palermo	Turin	Rome	Palermo
Model SA	HP (1) 10	HP (1) 6	HP (1) 6	HP (2) 9.5	HP (2) 6	HP (2) 4
Model LA	HP (1) 14	HP (1) 7.5	HP (1) 7.5	-	HP (2) 8	HP (2) 6
Model SB	HP (1) 10	HP (1) 6	HP (1) 6	HP (2) 9.5	HP (2) 6	HP (2) 4
Model LB	HP (1) 14	HP (1) 7.5	HP (1) 7.5	-	HP (2) 8	HP (2) 6
Model SC	-	HP (1) 14	HP (1) 10	-	-	HP (2) 9.5
Model LC	-	-	HP (1) 14	-	-	-
Model SD	-	HP (1) 14	HP (1) 14	-	-	-
Model LD	-	-	HP (1) 14	-	-	-

5.6 Results and discussion

The analysis aims to demonstrate the energy and environmental benefits of replacing a condensing boiler with a heat pump system for space heating and DHW in new residential buildings with high envelope performances, as well as to verify whether a system upgrade intervention, without modifying the building envelope, can guarantee an improvement of two energy classes in existing buildings characterised by low envelope performances.

The total non-renewable global primary energy and CO_2 emissions resulting from heating, DHW, and ventilation are calculated for all models based on the simulation of the SFHs, considering both the reference system and the two proposed heat pump solutions.

Specifically, the replacement of condensing boilers with heat pumps in new buildings is explored, as well as their deployment for the renovation of existing buildings heating systems (assuming no intervention in the building envelope).

The following graphs show the results for three different climate zones: Turin, Rome, and Palermo. The results are presented for two different emission systems, radiant floors and fan coils, represented by blue and red colours respectively. The graphs compare the three building system solutions (including the reference system) for the three climate zones. The x-axis displays the solutions, while the y-axes shows the total non-renewable primary energy [kWh/(m^{2}y)] on the left and the CO_2 emissions [kg CO_2/y] on the right.

Finally, the detailed results of the non-renewable primary energy for each energy service offered ($EP_{H,nren}$, $EP_{W,nren}$, $EP_{V,nren}$) for new buildings case study and renovation of existing buildings one are provided by Tables 41 and 42 in Appendix C, respectively. In addition, Tables 43 and 44 in Appendix C show the energy delivered by energy carriers ($Q_{del,i}$) used to assess the CO_2 emission index in all the simulated models.

New buildings with high envelope performances

This section presents the simulation results for four models of new residential buildings (SA, SB, LA and LB). These models share common features, including controlled mechanical ventilation and envelopes that vary from very high (envelope A in Table 12) to high (envelope B in Table 13) performance. All the four models are simulated with three different types of heating systems for the three different climatic zones of Italy, as provided in the previous section:

(1) reference building equipped with a traditional condensing boiler;
(2) retrofit scenario 1 with a one-section air-to-water heat pump space heater [HP (1)];
(3) retrofit scenario 2 with a two-section air-to-water heat pump space heater [HP (2)].

The main results shown in the following figures (from Figure 30 to Figure 33) demonstrate the benefits associated with the use of both HP (1) and HP (2). These advantages extend both to energy savings and to a reduction in the environmental footprint, showing a significant decrease in non-renewable primary energy consumption and CO_2 emission indicators when compared to the application of a condensing boiler, both in the presence of radiant floors and fan coils. It is evident that the heat pump system solutions proposed in the two retrofit scenarios provide comparable global non-renewable energy indicators within a country, with evident variations across different climate zones. Furthermore, as shown in the graphs below, the performances of the heat pumps mentioned above are consistent with the minimum requirements performance standards required by regulations.

Table 45 in Appendix C provides a detailed description of the $EP_{g,nren}$ and CO_2 indicators for each simulated model.

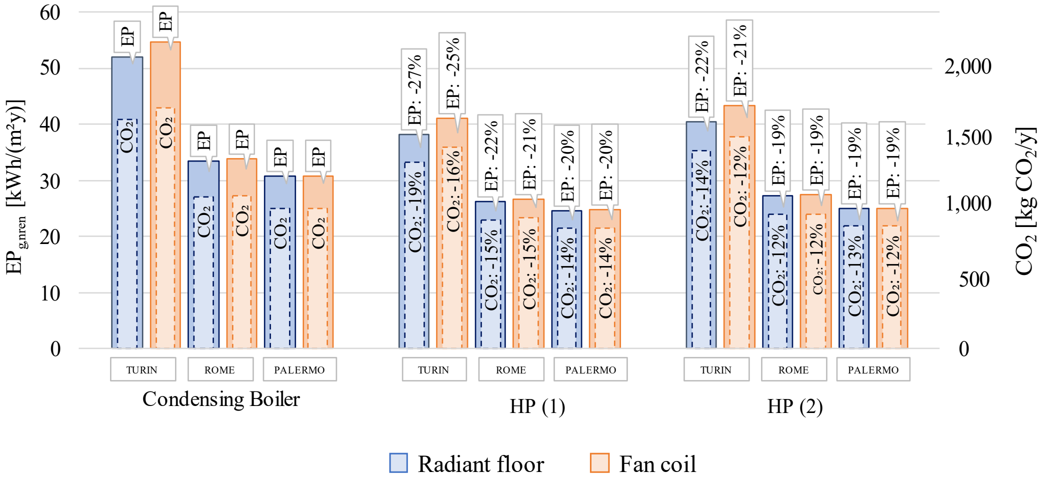


Figure 30: Energy- and environmental-related benefits for SA models. From [273].

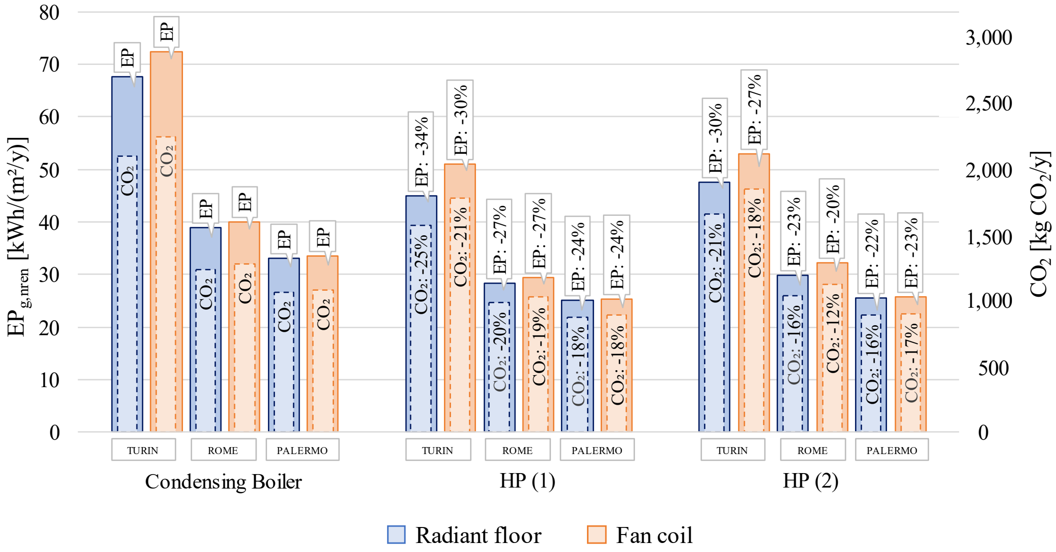


Figure 31: Energy- and environmental-related benefits for SB models. From [273].

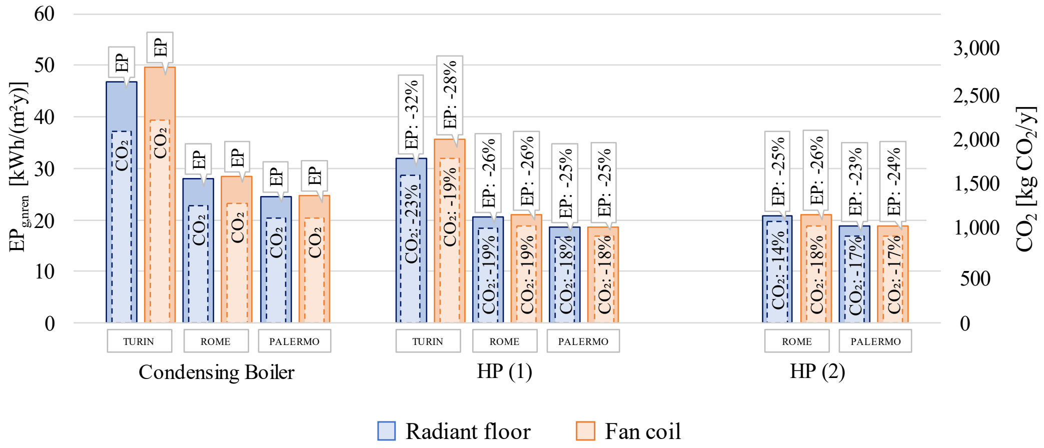


Figure 32: Energy- and environmental-related benefits for LA models. From [273].

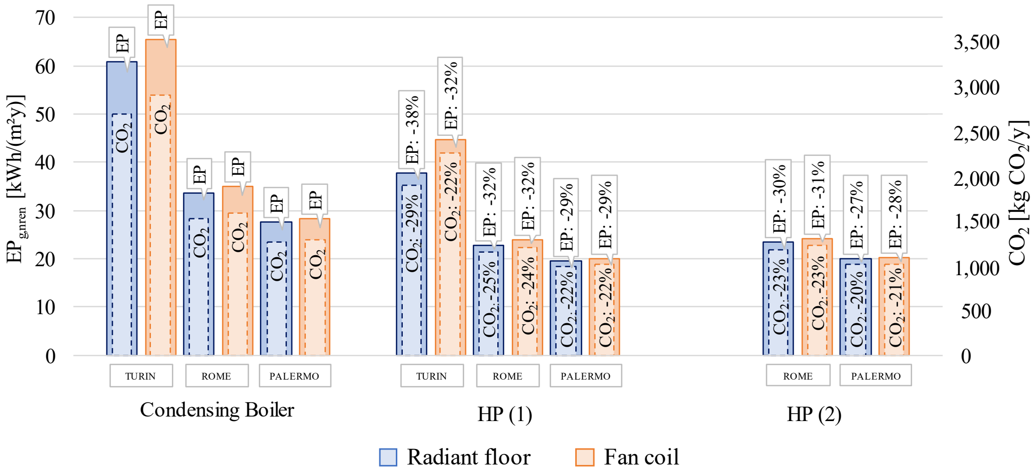


Figure 33: Energy- and environmental-related benefits for LB models. From [273].

In Turin, energy savings, ranging from 27% for the SA model to 38% for the LB model, are consistently achieved with one-section heat pump combined with the use of radiant floor. Even when fan coils are used, energy saved range from 25% to 32% for the SA and LB models respectively. Analysis of the results for the two-section heat pump system shows that the use of radiant floor saves between 22% and 30% of energy for the SA and LB models respectively, while the use of fan coil units does not differ significantly (21% for the SA and 27% for the SB). It is also interesting to note the environmental benefits of replacing condensing boilers with the heat pump technologies. Specifically, for small models, CO_2 emission savings reach 25% when combined with radiant floor, and up to 21% with fan coils. Similarly, the CO_2 savings for large models are 29% and 22% respectively. As mentioned above, in the case of Turin, the study focused only on the small model, as the heat pumps considered were not able to provide the required thermal output for the larger model.

In the context of Rome, the percentages recorded for energy savings and CO_2 emission reduction are slightly lower compared to the outcomes observed in northern Italy. Energy savings for the one-section heat pump combined with the use of radiant floor range from 22% to 32% for the SA and LB models respectively. When considering the two-section heat pump, the energy savings are similar to those achieved with the HP (1), ranging from 19% to 30%. Considering the environmental benefits of replacing condensing boilers with the heat pump technologies, CO_2 emission savings reach 20% when combined with radiant floor in small models, and up to 25% in large models. In addition, when both HP (1) and HP (2) are combined with fan coils, there is no significant difference in energy savings and CO_2 emission reduction is observed.

Finally, focusing on the south of Italy climate zone, the percentages are very similar to those obtained for Rome. In fact, energy savings of between 20% and 29% are achieved with the one-section heat pump combined with the use of radiant floor, as well as between 19% and 27% in the scenario characterised by the replacement with two-section heat pump. As in the case of Rome, no significant difference in energy savings and CO_2 emission reduction is observed when heat pumps are combined with the use of fan coils.

Existing buildings with low envelope performances

This section presents the simulation results for four models of existing residential buildings (SC, SD, LC and LD). These models share common characteristics, including natural ventilation and envelopes that vary from low (envelope C in Table 14) to very low (envelope D in Table 15) performance. All the four models are simulated with three different types of heating systems for the three different climatic zones of Italy, as provided in the previous section:

(1) reference building equipped with a traditional condensing boiler;
(2) retrofit scenario 1 with a one-section air-to-water heat pump space heater (HP (1));
(3) retrofit scenario 2 with a two-section air-to-water heat pump space heater (HP (2)).

As previously mentioned, this section aims to determine whether an intervention of sole system upgrading - the replacement of a condensing boiler with an air-to-water heat pump solution - without any measures on the building envelope, can guarantee an improvement of two energy efficiency classes.

The main results shown in the following figures (from Figure 34 to Figure 37) demonstrate how the replacement of a condensing boiler with an air-to-water heat pump solution, including both HP (1) and HP (2), allows an improvement of at least two energy efficiency classes. Notably, these improvements are achieved without any changes to the building envelope. This double energy class shift is always verified in the presence of both radiant floors and fan coils (blue and red respectively).

In terms of the environmental analysis, the results shown in the figures below show a significant reduction in CO_2 emissions achieved through the use of heat pump technologies.

It is important to note that the analysis is not available for Turin because the heat pumps considered do not meet the useful thermal power requirements for both the S and L models. Furthermore, the simulations for large SFHs (LC and LD models, depicted in Figures 36 and 37, respectively) are exclusively conducted for Palermo. This was due to the fact that the heat pump sizes did not meet the criteria required for simulations in Rome.

Table 46 in Appendix C provides a detailed description of the $EP_{g,nren}$ and CO_2 indicators for each simulated model.

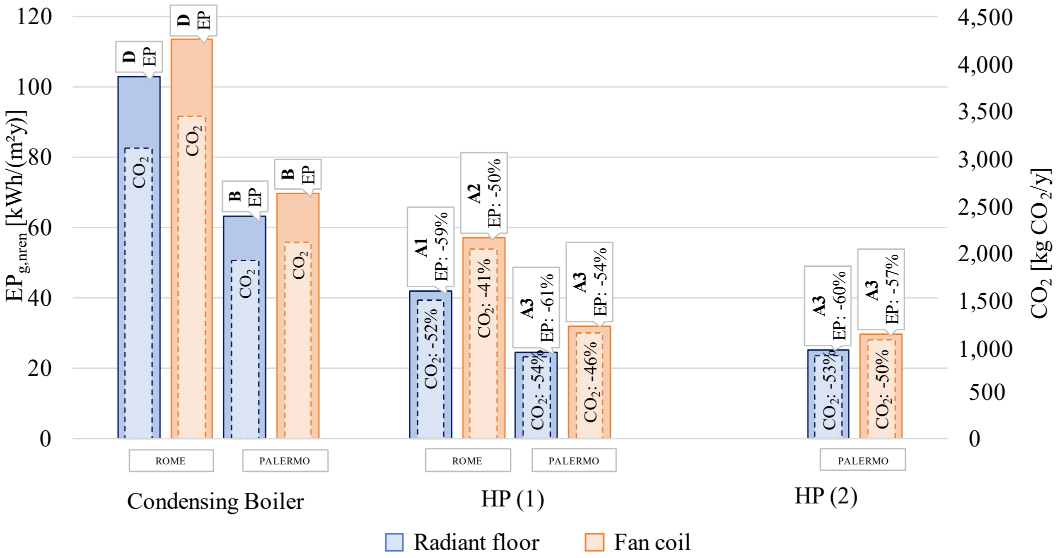


Figure 34: Energy- and environmental-related benefits for SC models. From [273].

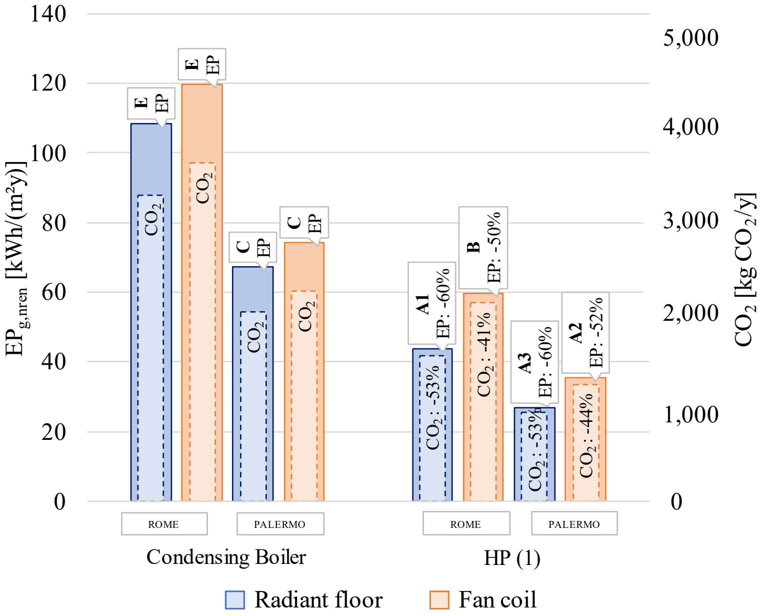


Figure 35: Energy- and environmental-related benefits for SD models. From [273].

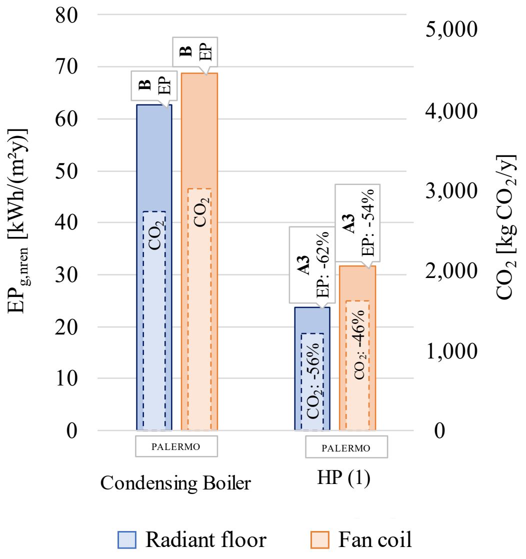


Figure 36: Energy- and environmental-related benefits for LC models. From [273].

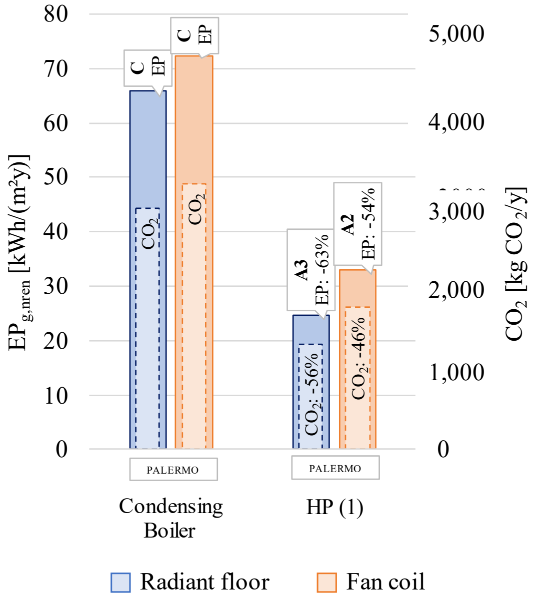


Figure 37: Energy- and environmental-related benefits for LD models. From [273].

In Rome, the one-section heat pump leads to a significant energy savings when combined with both radiant floor and fan coil. Specifically, the energy savings are 60% for both SC and SD models in the presence of radiant floor, and about 50% with the use of fan coils. The graphs show that the obtained energy savings lead from 3 to 4 energy classes changes. Specifically, from class D with the presence of condensing boiler to class A1 or A2 when replaced by a heat pump system (for the SC model in Figure 34) and from class E to class B or A1 (for the SD model in Figure 35).

In Palermo, the percentages of energy savings are quite similar. The one-section heat pump, associated with the use of radiant floor, leads to energy savings of around 60% for all the S and L models. The graphs show that the energy savings obtained lead to changes from 2 to 3 energy classes. Specifically, from class B with the presence of a condensing boiler to class A3 when replaced by a heat pump system (for the SC and LC models in Figures 34 and 36 respectively) and from class C to class A2 or A3 (for the SD and LD models in Figures 35 and 37 respectively). In the same way, considering the two-section heat pump available only for the SC model the amount of energy saved is equal to 60%, leading to a change of energy class from class B in the reference scenario to class A3 in the retrofit scenario 2. There is no significant difference for the combination of heat pumps and fan coils.

5.7 Conclusions and future developments

Improving the energy efficiency is a key objective within the prevailing European policy initiatives aimed at achieving climate neutrality and moving Europe towards a post-carbon society by 2050. Within this framework, heat pumps are emerging as a key technology. Due to their reliance on low-emission electricity, heat pumps are recognised as a promising technology for improving the overall energy efficiency of the system and reducing the environmental impact of the building sector. Despite their potential for long-term savings, the substantial initial investment required for heat pumps can act as a deterrent to consumers. Nevertheless, the heat pump market has experienced significant growth in recent years, due to the introduction of financial incentives such as the Superbonus 110% to encourage their integration into buildings. Specifically, the study focuses on the energy efficiency measures promoted by the Superbonus 110%, emphasising the interventions related to the replacement of existing air-conditioning systems with centralised systems for heating, cooling and/or DHW supply. Consequently, the promotion of reversible heat pump technologies in new buildings or as a replacement for existing fossil fuel heating systems in building renovations is highlighted.

Chapter 5 provides a detailed response to the following research question: "*How to demonstrate that the introduction of heat pump technology in heating and cooling systems can lead to more energy efficiency and environmental benefits in buildings?*". To answer to RQ5, the study aims to examine the efficiency of air-to-water heat pump technologies as an alternative to conventional condensing boilers in typical Mediterranean residential buildings. Specifically, the research focuses on the following two applications: (1) to demonstrate the energy and environmental advantages associated with replacing a condensing boiler with a heat pump system solution designed for both space heating and DHW in new buildings characterised by high envelope performance; (2) to verify whether a system retrofit intervention, which involves replacing a condensing boiler with a heat pump technology without modifying the building envelope, can guarantee an improvement of two energy classes in existing buildings with low envelope performances. For both applications, quasi-steady-state simulations are performed on single-family houses of different sizes and building envelope performances, located in various Italian climatic zones representative of the North (Turin), the Centre (Rome) and the South (Palermo) of the region.

The results of the first analysis indicate that the use of a one or two-section air-to-water heat pump space heater is advantageous in terms of both energy savings and reduced environmental impact for all the simulated models. This is evidenced by a significant reduction in non-renewable global energy performance indicator and CO_2 emissions when a heat pump solution is installed instead of a traditional condensing boiler. Specifically, the greatest energy savings are achieved in Turin with the installation of one-section heat pump combined with the use of radiant floor. (accounting for 38% of the energy savings).

Furthermore, for the second application, the study shows that a single system upgrade, replacing a condensing boiler with an air-to-water heat pump technology, can result in an improvement of more than two energy efficiency classes, even without any changes to the building envelope. This double energy class shift is always verified for the models simulated in the presence of both radiant floors and fan coils.

The current analysis focused on single-family houses, with all simulations assessing the performance of heat pumps exclusively in heating mode. As a perspective for future exploration, extending the study to include apartment buildings as well as to encompass the summer season, including the cooling mode, could prove insightful. In addition, beyond the focus on energy and environmental savings, examining the potential impact on the economic value of buildings after energy retrofitting could be an interesting dimension for further investigation.

Chapter 6

Concluding remarks

The setting of this Ph.D. dissertation is marked by a specific historical period characterised by the spread of the Covid-19 pandemic emergency in 2020 and the Russian-Ukrainian war in 2022. This scenario has led to an increased focus on two main pillars related to the building sector: (1) the role of indoor environmental quality in ensuring the health and well-being of people who spend most of their time in enclosed environments, and (2) the role of energy efficiency and electrification of final energy consumption in achieving the climate-neutrality target by 2050. These two pillars represent the main trajectories of the entire Ph.D. dissertation.

In particular, the year 2020 marked a paradigm shift due to the spread of Covid-19 pandemic, which was declared a Public Health Emergency of International Concern by the World Health Organization. In fact, the EU's mission has shifted from tackling climate change to ensuring human health and well-being in indoor environments. Specifically, since the SARS-CoV-2 was identified as the cause of the infectious disease, as well as it is mainly transmitted airborne, ensuring a good indoor air quality, and promoting human health-related status is becoming the priority in the design of healthy and resilient buildings and in the renovation of existing ones. In addition, many of the standards and guidelines introduced in 2020 to support the pandemic response include ensuring the health and well-being of building users as a fundamental requirement. In this context, among various long-term strategies, the installation of innovative air filtration technologies in HVAC systems has been identified as a key measure to reduce the transmission of the SARS-CoV-2 virus or other indoor contaminants.

As far as the year 2022 is concerned, the severe impact of the war between Russia and Ukraine on the energy market has led to a sharp increase in energy prices, which requires strategic changes in EU policies. Thus, the EU needs to reduce energy consumption, improve energy efficiency, accelerate the deployment of RES, increase gas supply diversification, and strengthen its strategic energy autonomy in order to face the challenge of ensuring long-term energy security in

2023 and achieving a clean energy transition. Among the EU strategies adopted to respond to the energy crisis, the REPowerEU plan sets out a series of measures to rapidly reduce dependence on Russian fossil fuels in buildings. Specifically, the key driver for accelerating the energy transition and the decarbonisation of buildings is the electrification of end-use consumption through the deployment of RES. Therefore, the adoption of heating and cooling systems based on a carrier that is no longer gas has led to heat pumps being considered as a key technology for increasing the overall energy efficiency of the system and reducing the environmental impact of the building sector.

In the light of the above, it is clear that technologies are fundamental to achieve the two pillars resulting from the historical period under consideration. For this reason, this Ph.D. research dissertation stems from the strong demand from industrial companies to enhance their technologies in order to make them competitive in the current building energy market. The main problem faced by industrial companies concerns their high investment costs, which may prevent consumers from investing on them. Therefore, the Ph.D. dissertation aims to guide and support industrial companies in the launch of advanced technological solutions, which play a key role in the design and operation of the building of the future, in the current building energy market. The following overarching research questions characterised the whole thesis:

- RQ1: Which are the key targets to be included in the design and operation of the building of the future?
- RQ2: Which advanced technological solutions being driven by the current context to achieve the targets of the building of the future?
- RQ3: Which instrument can be used to launch an advance technological solution, making it competitive in the current building energy market?
- RQ4: How to demonstrate that the introduction of innovative air filtration technology in HVAC systems can lead to multiple benefits in term of occupant health and performance?
- RQ5: How to demonstrate that the introduction of heat pump technology in heating and cooling systems can lead to more energy efficiency in buildings?

The dissertation is structured according to the research questions presented. Specifically, Chapter 2 focuses on an in-depth examination of the main targets and technological solutions, driven by the current European and Italian national context, to be implemented in the design and operation of the building of the future (RQ 1 and RQ 2). Then, in order to answer to RQ 3, Chapter 3 highlights the need for research on new decision-support tools in the energy field. In addition, Chapters 4 and 5 deal with the case study applications, providing to answer RQ 4 and RQ 5, respectively. Finally, this chapter aims to summarise the key findings of the research in terms of their relevance to the research questions.

The originality of this Ph.D. dissertation lies in its pioneering use of a commonly used assessment methodology, the CBA methodology, within a rarely studied field, the energy sector. Additionally, another interesting aspect relates to the adaptability of the proposed approach to address potential future emergencies.

RQ1: Which are the key targets to be included in the design and operation of the building of the future?

The first research question is investigated in Chapter 2 of this dissertation. Specifically, with the aim to provide the key targets to be included in the design and operation of the building of the future, the discussion begins with a preliminary introduction to the pre-Covid-19 building targets (section 2.2). Then, section 2.3 deals with the identification of the emerging targets for future building construction, which are dictated by the historical context of this Ph.D. dissertation.

As described in section 2.2, before the spread of the Covid-19 pandemic emergency, the main focus of European and national strategies to achieve future climate and energy policy targets was to improve energy efficiency and to achieve high energy performance levels in both new and existing buildings. In this context, the Directive 2010/31/EU [38] introduced the nZEB concept as a key measure to reduce energy consumption in buildings. This section deals with showing various nZEB definitions according to the context and climate of each EU Member State. From this literature review, a variety of terms are used to characterise very low energy buildings with the overall aim of achieving zero energy. Among these, the terms net zero, zero energy, zero energy ready, and energy positive were analysed in detail. The conclusions of this preliminary analysis led to a general definition of the nZEB as a building that effectively sets energy efficiency requirements, reflecting the pre-covid building targets, but these requirements are no longer sufficient to meet the current needs.

In the light of the above, the current European and national context, characterised by the spread of the Covid-19 pandemic emergency and the war between Russia and Ukraine (Chapter 1), has driven towards two fundamental pillars to be integrated into the nZEB. Specifically, on the one hand, the Covid-19 and its aftermath have focused attention on the increasing need to ensure adequate IAQ for occupants' health and well-being in the built environment. On the other hand, the Russia-Ukraine conflict with the consequent increase in energy prices has led attention on the importance of electricity, leading to a shift towards heating and cooling systems that do not rely on gas as a fuel. To answer RQ 1 regarding the main targets to be incorporated in the design and operation of the building of the future, a definition of IAQ-resilient buildings and the pathway to the decarbonisation of the building sector were provided.

Specifically, to investigate the implications of an IAQ-resilient building for future transitions, a state-of-the-art literature review was conducted. As a notable lack of knowledge in the previous literature, the review focuses on resilient responses to the Covid-19 pandemic in the built environment. The research questions guiding the review are: i) what does the resilience of the built environment mean? (ii) how can the existing resilience definitions and features be extended to IAQ?. The results of the analysis shown in section 2.3.1 suggest that the primary goal of designing IAQ-resilient buildings should be the creation of an IAQ management plan for the built environment. In order to protect occupants from the risk of airborne infections, this plan should place a high priority on passive measures, ventilation and filtration requirements, and the control and regulation of indoor humidity and temperature. Finally, as improving IAQ can lead to increased energy consumption in buildings, it is crucial to align new IAQ-resilient strategies with sustainability goals and climate change mitigation efforts.

Furthermore, as mentioned above, it is essential to also consider the key role that electrification will play in the decarbonisation of the building sector when designing and operating the building of the future. This second pillar is explored in section 2.3.2 of this dissertation by showing the recent upgrading of the EU building targets. Specifically, contrary to the pre-Covid-19 building target (section 2.2), attention needs to shift towards the ZEB as the future building target by 2030 to achieve the global climate neutrality goal. This section presents different definitions of ZEB according to the context and climate of each EU Member State. From this literature review, a variety of terms are used to characterise zero or very low emission buildings. Among these, the terms zero/net zero emission, zero/net zero carbon, and zero carbon-ready were analysed in detail. The conclusions of this analysis led to consider electrification as a key strategy for reducing energy-related CO_2 emissions.

RQ2: Which advanced technological solutions being driven by the current context to achieve the targets of the building of the future?

After defining the main characteristics of the building of the future (section 2.3), which include high-energy performance, fully electric and autonomous features, low CO_2 emissions, and IAQ-resilience for the health and well-being of the occupants, the second research question focuses on investigating the main technologies that can support the design of such a building to achieve the new targets.

The answer to RQ 2 can be found in section 2.4. Specifically, to increase the IAQ resilience of indoor environments, with the aim of designing and operating buildings to be healthier and more IAQ-resilient for the future, different long-term strategies able to mitigate the spread of contaminants were investigated in section 2.4.1. The main findings of this analysis enabled the identification of cleaning and purification technologies as the key measures to control and limit the transmission of SARS-CoV-2. Among these technologies, the key role of air filtration systems and other air purification techniques properly installed in the HVAC system were emerged with the aim of ensuring a healthy IAQ in buildings. In particular, this section aims to present innovative antimicrobial filtration technologies able to the eliminate harmful agents, including the SARS-CoV-2 virus. These technologies were developed and launched on the building energy market in response to the spread of Covid-19.

On the other hand, electrification of space heating is considered to be one of the main contributors to reducing CO_2 emissions, as follows from RQ 1. Therefore, transitioning towards electric and renewable heating technologies is necessary to align with the NZE scenario by 2050. In this context, section 2.4.2 provides a detailed discussion on the replacement of fossil-fuel-based boilers with heat pumps, which are recognised as the key technology for achieving sustainable heating in buildings, as well as meeting decarbonisation in the current energy transition process. Specifically, this section shows a surge in the number of heat pump sales in each EU country, leading to a significant reduction in natural gas demand in 2022 (Figure 13).

RQ3: Which instrument can be used to launch an advance technological solution, making it competitive in the current building energy market?

Once the targets for the design and operation of the building of the future, as well as the main supporting technological solutions driven by the historical context were identified (Chapter 2), this Ph.D. dissertation examines the main instrument available to launch and make competitive these technologies in the current building energy market. In fact, as mentioned in Chapter 1, industrial companies have faced a major problem in introducing their technologies to the energy market due to the high investment costs, which may prevent potential consumers from investing in them. Therefore, Chapter 3 addresses the third research question by emphasising the need for research into new decision-support tools in the energy field. For this purpose, section 3.2 provides an overview of the most used tools in the energy investment decision-making process (i.e., Cost-Benefit Analysis and Multi-criteria Decision Analysis), with the aim of identifying among them the optimal one in response to RQ 3. Specifically, starting from the definition of the cost-optimal methodology based on financial analysis (section 3.3), this chapter provides an in-depth analysis of the CBA, including its objectives and methodological steps. Therefore, as a financial analysis is not suitable alone, an economic analysis was found to be necessary to consider the socio-economic impacts, including both positive and negative externalities. In particular, CBA was found to be the most suitable tool among the other decision-making methods shown in section 3.2, as it provides outcomes on a scale that is compatible with the market, and the resulted economic indicator can be easily understood by decision-makers who are not experts in the energy field.

As part of the detailed presentation of the CBA, the chapter also examines the main valuation approaches used to measure and monetise non-market impacts (section 3.4). Finally, the main performance indicators used in the CBA are presented, with a detailed description of the NPV, IRR and BCR indicators (section 3.6).

RQ4: How to demonstrate that the introduction of innovative air filtration technology in HVAC systems can lead to multiple benefits in term of occupant health and performance?

The above research question was dealt with in Chapter 4 of this Ph.D. thesis according to the first target identified in Chapter 2. The application presented in this chapter concerned the comparison of two different AHU configurations installed in four types of Italian school buildings, including pre-school, primary school, junior-high and high school. These configurations are representative of both Covid-19 (AHU management during the pandemic emergency: rotary heat recovery system deactivated, with a 100% outdoor air rate) and post-Covid-19 (AHU management during normal operation: rotary heat recovery system in operation, with a 50% recirculation rate) conditions. Specifically, the Covid-19 configuration consists of two standard ISO Coarse 55% pre-filters, and a standard ISO ePM1 50% filter on the supply air (Figure 19). In contrast, the post-Covid-19 configuration consists of two standard ISO Coarse 55% pre-filters, a biocidal ISO ePM1 50% filter for supply air, and a photocatalytic filter for recirculated air (Figure 20).

In this context, the aim of this study was to explore the advantages offered by the innovative biocidal and photocatalytic filtration technologies implemented in the PC configuration. The goal is not only to improve IAQ management, but also to allow energy savings by employing conventional HVAC operating strategies. This application demonstrated that the CBA methodology is an effective tool for supporting energy investment decisions, monetising the benefits of the AHU configuration equipped with innovative technological solutions and showing that their higher investment costs can be fully repaid through energy and socio-economic benefits in the long-term (Figure 25). Specifically, the study presents its fundings through the application of the BCR indicator, which allows the comparison between an alternative option (PC configuration) and a reference scenario (C configuration) in order to determine the most advantageous solution. Thus, the evaluation of the ΔBCR between the PC and C configurations answered RQ 4, demonstrating that the installation of advanced filtering technologies in the AHU configuration can significantly reduce energy consumption while improving the health and performance of teachers and students (Table 8).

RQ5: How to demonstrate that the introduction of heat pump technology in heating and cooling systems can lead to more energy efficiency in buildings?

Chapter 5 of this dissertation investigates the last research question by means of two applications related to the installation of heat pump technology in typical Mediterranean residential buildings. As in the case study presented in the previous chapter, the high initial investment cost of heat pumps can be a deterrent to consumers, despite their potential to save money in the long term. Nevertheless, the heat pump sector has significantly expanded in recent years, mainly due to the introduction of financial incentives such as the Superbonus 110%, aimed at promoting their installation into buildings. For this reason, the research involved energy efficiency measures promoted by the Superbonus 100%, specifically the implementation of reversible heat pump technologies in new constructions or as a substitute for current fossil-fuel-based heating systems during the renovation of existing buildings. The main objective of the study was to demonstrate the efficiency of air-to-water heat pump technologies as an alternative to conventional condensing boilers in residential buildings. Specifically, the research focuses on two analysis characterised by the following two distinct goals: (1) to demonstrate the energy and environmental benefits of replacing a condensing boiler with a heat pump system solution for space heating and DHW in new dwellings with high envelope performances; (2) focusing on existing buildings with low envelope performances, the aim is to verify whether a system upgrading intervention, which involves replacing a condensing boiler with a heat pump technology without modifying the building envelope, can guarantee the improvement of two energy classes as required by the Superbonus 110%.

For both scenarios, quasi-steady-state simulations were conducted using the EdilClima EC700 commercial software. The simulations involved single-family homes of varying sizes and diverse building envelope characteristics, situated in distinct Italian climatic zones representing the North, the Centre, and the South regions. Following the characterisation of the building models, the non-renewable global energy performance and the CO_2 emission indicators were identified as the KPIs for assessing the energy and environmental impacts, respectively. Once the selected buildings had been modelled in the software, 24 simulations were run to compare pre-retrofit (reference building system with a traditional condensing boiler) and post-retrofit (alternative scenarios with the installation of one- or two-section air-to-water heat pumps) conditions. The resulting KPIs were then calculated.

The main results of the first analysis suggest that using a one or two-section air-to-water heat pump space heater is beneficial in terms of energy savings and reduced environmental impact for all simulated models (form Figure 30 to Figure 33). This is supported by a significant decrease in non-renewable global energy performance indicator and CO_2 emissions when a heat pump solution is installed instead of a traditional condensing boiler in residential buildings. In addition, the analysis performed according to the second objectives demonstrates that a single system upgrade, which involves replacing a condensing boiler with an air-to-water heat pump technology, can improve energy efficiency by more than two classes, even without any changes to the building envelope.

Nomenclature

AHU: Air Handling Unit

AHP: Analytical Hierarchy Process

BCR: Benefit-Cost ratio

BT: Benefit Transfer

CAP: Community-Acquired Pneumonia

CBA: Cost-Benefit Analysis

CH_4: Methane

CM: Choice Modelling

CO_2: Carbon Dioxide

CO_2-eq: CO_2 equivalent

COI: Cost of Illness

COP: Coefficient of Performance

CTI: Italian Thermo-Technical Committee

CVM: Contingent Valuation Method

dB: decibel

DHW: Domestic Hot Water

DRSA: Dominance-based Rough Set Approach

EC: European Commission

EEAP: Energy Efficiency Action Plan

EED: Energy Efficiency Directive

EEM: Energy Efficiency Measure

EER: Energy Efficiency Ratio

EJ: Exajoule

ELD: Energy Labelling Directive

ELECTRE: ELimination Et Choix TRaduisant la REalité

ENVI: Environment, Public Health and Food Safety

EP: European Parliament

EPA: Environmental Protection Agency

EPBD: Energy Performance of Building Directive

EPC: Energy Performance Certificate

ErP: Energy-Related Product

EU: European Union

EU LTS: European Union Long-term Strategy

F-gas: Fluorinated gas

FM: Friction Method

GHG: Greenhouse Gas

$GtCO_2$: Gigatons of Carbon Dioxide

GWP: Global Warming Potential

HAP: Hospital-Acquired Pneumonia

HCA: Human Capital Approach

HEPA: High Efficiency Particulate Air

HFC: Hydrofluorocarbon

HP: Hedonic Pricing

HVAC: Heating Ventilation and Air-Conditioning

IAQ: Indoor Air Quality

ICU: Intensive Care Unit

IEA: International Energy Agency

IEQ: Indoor Environmental Quality

IPCC: Intergovernmental Panel on Climate Change

IRR: Internal Rate of Return

KPI: Key Performance Indicator

kWh: kilowatt-hour

LCA: Life Cycle Assessment

LCC: Life Cycle Cost

LCSA: Life Cycle Sustainable Assessment

LTRS: Long-Term Renovation Strategy

LED: Light Emitting Diodes

MAUT: Multi Attribute Utility Theory

MCA: Multi-Criteria Analysis

MCDA: Multi-Criteria Decision Analysis

MCDM: Multi-Criteria Decision-making

MS: Member State

Mtoe: Million Tonnes of Oil Equivalent

NECP: National Energy and Climate Plan

NF_3: Nitrogen trifluoride

NGEU: Next Generation EU

NIH: National Institute of Health

NLTS: National Long-term Strategy

N_2O: Nitrous Oxide

NPV: Net Present Value

NSAID: Non-Steroidal Anti-Inflammatory Drug

NZE: Net Zero Emission

nZEB: Nearly Zero Energy Building

NZED: Net Zero-Energy District

PEB: Positive Energy Building

PFC: Perfluorocarbon

PHEIC: Public Health Emergency of International Concern

PNIEC: Piano Nazionale Integrato Energia e Clima

PNRR: Piano Nazionale di Ripresa e Resilienza

ppm: parts per million

PROMETHEE: Preference Ranking Organization METHod for Enrichment of Evaluations

PV: Photovoltaic

PVC: Polyvinyl Chloride

RED: Renewable Energy Directive

RES: Renewable Energy Source

RP: Revealed Preference

SARS-CoV-2: Severe Acute Respiratory Syndrome Coronavirus 2

SCOP: Seasonal Coefficient of Performance

SEER: Seasonal Energy Efficiency Ratio

SF_6: Sulphur hexafluoride

SFH: Single-Family House

SLCA: Social Life Cycle Assessment

SP: Stated Preference

SRI: Smart Readiness Indicator

STREPIN: Strategia italiana per la riqualificazione energetica del parco immobiliare nazionale

UV: Ultraviolet

UV-C: Type C ultraviolet

UVGI: Ultraviolet Germicidal Irradiation

VAP: Ventilator-Associated Pneumonia

WHO: World Health Organization

WO_3: Tungsten Trioxide

WTA: Willingness To Accept

WTP: Willingness To Pay

References

Chapter 1

[1] European Commission. Energy performance of building directive. [Accessed: 2023]. URL: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en.

[2] European Commission. Kyoto 1st commitment period (2008-2012). [Accessed: 2023]. URL: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/progress-made-cutting-emissions/kyoto-1st-commitment-period-2008-12_en#:~:text=In%20the%20first%20period%20of,of%205%25%20below%201990%20levels.

[3] United Nations Framework Convention on Climate Change (UNFCCC). The Paris Agreement. Phoenix Design Aid, Denmark, 2016. [Accessed: 2023]. URL: https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf.

[4] European Commission. Clean Energy for All Europeans package. [Accessed: 2023]. URL: https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en.

[5] Worl Health Organization. COVID 19 Public Health Emergency of International Concern (PHEIC) Global research and innovation forum: towards a research roadmap. 11-12 February 2020. [Accessed: 2023]. URL: https://www.who.int/publications/m/item/covid-19-public-health-emergency-of-international-concern-(pheic)-global-research-and-innovation-forum.

[6] European Parliament. *DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*. 2018.

[7] International WELL Building Institute. The WELL Building Standard Version 2 Pilot; International WELL Building Institute: New York, NY, USA, 2020.

[8] Osicka, J.; Cernoch, F. European energy politics after Ukraine: The road ahead. *Energy Research & Social Science 91*, 2022, p. 102757. DOI: N10.1016/j.erss.2022.102757.

[9] European Commission. State of the Energy Union 2023: EU responds effectively to crisis, looks to the future, and accelerates the green transition. 24 October 2023, Brussels. [Accessed: 2023]. URL: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_5188.

[10] Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Review 24*, 2019, pp. 38-50. DOI: 10.1016/j.esr.2019.01.006.

[11] European Commission. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the regions REPowerEU Plan. COM/2022/230 final. Brussels, 18.05.2022.* 2022.

[12] United Nations Environment Programme. 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi, 2022.

[13] United Nations Environment Programme. 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi, 2021.

[14] International Energy Agency. Tracking Buildings 2022. Paris: International Energy Agency. [Accessed: 2023]. URL: https://www.iea.org/energy-system/buildings.

[15] Buildings Performance Institute Europe (BPIE). On the Way to a climate-neutral Europe: contributions from the building sector to a strengthened 2030 climate target. [Accessed: 2023]. URL: https://www.bpie.eu/wp-content/uploads/2020/12/On-the-way-to-a-climate-neutral-Europe-_Final.pdf.

[16] European Commission. Energy efficiency in buildings. 17 February 2020, Brussels. [Accessed: 2023]. URL: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en.

[17] Council of the European Union. *Directive 93/76/EEC of 13 September 1993 to limit carbon dioxide emissions by improving energy efficiency (SAVE). COM/92/182 COM/93/*279. Official *Journal L 237*, 1993.

[18] European Parliament. Energy Efficiency Action Plan. [Accessed: 2023]. URL: https://www.greens-efa.eu/en/article/document/energy-efficiency-action-plan.

[19] European Commission, 2000. Action Plan to Improve Energy Efficiency in the European Community. COM (2000) 247 final. Brussels, 2000.

[20] European Commission, 2006. Communication from the Commission - Action Plan for Energy Efficiency: Realising the Potential. COM (2006)545 final. Brussels, 2006.

[21] European Commission. 2020 Climate and Energy Package. [Accessed: 2023]. URL: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2020-climate-energy-package_en.

[22] European Commission, 2011. Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions: A Roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112 final. Brussels, 8.03.2011.

[23] da Graca Carvalho, M. EU energy and climate change strategy. *Energy 40*, 2012, pp. 19-22. DOI: 101016/j.energy.2012.01.012.

[24] European Commission, 2011. Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions: Energy Efficiency Plan 2011. COM(2011) 109 final. Brussels, 8.03.2011.

[25] Economidou, M.; Todeschi, V.; Bertoldi, P.; D'Agostino, D.; Zangheri, P.; Castellazzi, L. Review of 50 years of EU energy policies for buildings. *Energy & Buildings 224*, 2020, p. 110322. DOI: 10.1016/j.enbuild.2020.110332.

[26] European Commission. Kyoto 2nd commitment period (2013-20). [Accessed: 2023]. URL: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/progress-made-cutting-emissions/kyoto-2nd-commitment-period-2013-20_en#:~:text=In%20this%20period%2C%20the%20EU,2020EN%E2%80%A2%E2%80%A2%E2%80%A2.

[27] European Commission. 2030 Climate & Energy framework. [Accessed: 2023]. URL: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-energy-framework_en.

[28] European Commission, 2015. Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions and the European investment bank: A framework strategy for a resilient Energy

Union with a forward-looking climate change policy. COM(2015) 080 final.

[29] European Commission. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM (2019) 640 final. Brussels, 11.12.2019.* 2019.

[30] European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. COM(2020) 662 final. Brussels, 14.10.2020.* 2020.

[31] European Commission. Renovation Wave. [Accessed: 2023]. URL: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en.

[32] European Commission. Renovation Wave: doubling the renovation rate to cut emissions, boost recovery and reduce energy poverty. 14 October 2020, Brussels. [Accessed: 2023]. URL: https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1835.

[33] Filippidou, F.; Jimenez Navarro, J.P. Achieving the cost-effective energy transformation of Europe's buildings, EUR 29906 EN, Publications Office of the European Union, Luxembourg, 2019. DOI:10.2760/278207, JRC117739.

[34] European Council. Fir for 55. [Accessed: 2023]. URL: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/#:~:text=Fit%20for%2055%20refers%20to,line%20with%20the%202030%20goal.

[35] European Commission. REPowerEU: A plan to rapidly reduce the dependence on Russian fossil fuels and fast forward the green transition. 18 May 2022, Brussels. [Accessed: 2023]. URL: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131.

[36] International Energy Agency (IEA). RePowerEU Plan : Joint European action on renewable energy and energy efficiency. 2022. [Accessed: 2023]. URL: https://www.iea.org/policies/15691-repowereu-plan-joint-european-action-on-renewable-energy-and-energy-efficiency.

[37] European Parliament. DIRECTIVE 2002/91/EC *OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings.* 2022.

[38] European Parliament. *DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast)*. 2010.

[39] European Commission. *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast). COM/2021/802 final, Brussels, 15.12.2021*. 2021.

[40] European Commission. Energy efficiency directive. [Accessed: 2023]. URL: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en.

[41] Council of the European Union. *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast) – Analysis of the final compromise text with a view to agreement. Brussels, 14.12.2023.* 2023.

[42] EU Policy news. ITRE committee endorses EPBD Recast. REHVA Journal. [Accessed: 2024]. URL: https://www.rehva.eu/news/article/itre-committee-endorses-epbd-recast.

[43] European Parliament. *DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.* 2012.

[44] European Parliament. *DIRECTIVE 2018/2002/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 amending Directive 2012/27/EU on energy efficiency.* 2018.

[45] European Parliament. Energy efficiency. [Accessed: 2023]. URL: https://www.europarl.europa.eu/factsheets/en/sheet/69/energy-efficiency.

[46] European Parliament. *DIRECTIVE (EU) 2023/1791 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast).* Official Journal of the European Union. 20.09.2023. 2023.

[47] European Commission. *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on energy efficiency (recast). COM (2021) 558 final, Brussels, 14.7.2021*. 2021.

[48] European Commission. Fit for 55 Package: Energy Efficiency Directive. [Accessed: 2023]. URL: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698045/EPRS_BRI(2021)698045_EN.pdf.

[49] European Parliament. *DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending*

and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union. 2009.

[50] European Commission. Renewable Energy Directive. [Accessed: 2023]. URL: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en.

[51] European Parliament. *DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of renewable sources (recast). Official Journal of the European Union.* 2018.

[52] European Commission. *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources and repealing Council Directive (EU) 2015/652. COM (2021) 557 final, Brussels, 14.7.2021.* 2021.

[53] European Parliament. Revision of the Renewable Energy Directive: Fit-for-55 package. [Accessed: 2023]. URL: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698781/EPRS_BRI(2021)698781_EN.pdf.

[54] European Parliament. *European Parliament legislative resolution of 12 September 2023 on the proposal for a directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. COM(2021)0557.* 2023.

[55] European Parliament. *DIRECTIVE (EU) 2023/2413 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL OF 18 OCTOBER 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources and repealing Council Directive (EU) 2015/652. Brussels, 31.10.2023.* 2023.

[56] European Parliament. *REGULATION (EU) 2018/1999 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of*

the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council. Official Journal of the European Union. 2018.

[57] European Commission. National Energy and Climate plan. [Accessed: 2023]. URL: https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en.

[58] European Commission. National long-term strategies. [Accessed: 2023]. URL: https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-long-term-strategies_en.

[59] European Commission. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. COM (2018) 773 final, Brussels, 28.11.2018.

[60] European Parliament. *REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')*. Official Journal of the European Union. 9.07.2021.

[61] Italia Domani. Piano Nazionale di Ripresa e Resilienza. [Accessed: 2023]. URL: https://www.governo.it/sites/governo.it/files/PNRR.pdf.

[62] Ministero dello Sviluppo Economico, Ministero dell'Ambiente e della tutale del Territorio e del Mare, Ministero delle Infrastrutture e dei Trasporti. Piano Nazionale integrato per l'Energia e il Clima. Dicembre 2019. [Accessed: 2023]. URL: https://www.mimit.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf.

[63] Ministero dello Sviluppo Economico, Ministero dell'Ambiente e della tutale del Territorio e del Mare, Ministero delle Infrastrutture e dei Trasporti. Strategia per la riqualificazione energetica del parco immobiliare nazionale. 25 Novembre 2020. [Accessed: 2023]. URL: https://energy.ec.europa.eu/system/files/2021-12/2020_ltrs_italy_-_en.pdf.

[64] Presidente della Repubblica. *Decreto-legge 19 maggio 2020, n. 34 recante Misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonché di politiche sociali connesse all'emergenza*

epidemiologica da Covid-19. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n.128 del 19-05-2020 - Suppl. Ordinario n. 21.

[65] Ministero dello Sviluppo Economico. *Decreto 19 febbraio 2007 recante Criteri e modalità per incentivare la produzione di energia elettrica mediante conversione fotovoltaica della fonte solare, in attuazione dell'articolo 7 del decreto legislativo 29 dicembre 2003, n. 387*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 45 del 23.02.2007.

[66] Ministero dello Sviluppo Economico. *Decreto 11 marzo 2008, Attuazione dell'articolo 1, comma 24, lettera a), della legge 24 dicembre 2007, n. 244, per la definizione dei valori limite di fabbisogno di energia primaria annuo e di trasmittanza termica ai fini dell'applicazione dei commi 344 e 345 dell'articolo 1 della legge 27 dicembre 2006, n. 296.* Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 66 del 18.03.2008.

[67] Presidente della Repubblica. *Legge 17 luglio 2020 no.77. Conversione in legge, con modificazioni, del decreto-legge 19 maggio 2020 no.34, recante Misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonché di politiche sociali connesse all'emergenza epidemiologica da Covid-19*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n.180 del 18-07-2020 - Suppl. Ordinario n. 25.

[68] Presidente della Repubblica. *Legge 30 dicembre 2021 no. 234. Bilancio di previsione dello Stato per l'anno finanziario 2022 e bilancio pluriennale per il triennio 2022-2024*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale no. 310 del 31.12.2021 – Suppl. Ordinario n.49.

[69] Presidente della Repubblica. *Legge 29 dicembre 2022 no. 197. Bilancio di previsione dello Stato per l'anno finanziario 2023 e bilancio pluriennale per il triennio 2023-2025*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale no. 303 del 29.12.2022 – Suppl. Ordinario n.43.

[70] Abouleish, M.Y.Z. Indoor air quality and COVID-19. *Public Health* 191, 2021, pp. 1-2. DOI: 10.1016/j.puhe.2020.04.047.

[71] American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). In: *Handbook of Fundamentals*, 1st ed.; American Society of Heating, Refrigerating and Air Conditioning Engineers: Atlanta, GA, USA, 2005.

[72] Awada, M.; Becerik-Gerber, B.; Hoque, S.; O'Neill, Z.; Pedrielli, G.; Wen, J.; Wu, T. Ten questions concerning occupant health in buildings during normal operations and extreme events including the COVID-19 pandemic. *Build. Environ.* 188, 2021, p. 107480. DOI: 10.1016/j.buildenv.2020.107480.

[73] Harvard T.H. Chan School of Public Health. The 9 Foundations of a Healthy Building. [Accessed: 2022]. URL: https://forhealth.org/9_Foundations_of_a_Healthy_Building.February_2017.pdf.

[74] U.S. Environmental Protection Agency (EPA). *Report to Congress on Indoor Air Quality: Volume 2*; U.S. Environmental Protection Agency: Washington, DC, USA, 1989.

[75] European Parliament. Energy performance of buildings: climate neutrality by 2050. [Accessed: 2023]. URL: https://www.europarl.europa.eu/news/it/press-room/20230206IPR72112/energy-performance-of-buildings-climate-neutrality-by-2050#:~:text=Ban%20on%20fossil%20fuels%20heating,of%20transposition%20of%20this%20Directive.

Chapter 2

[76] Lingua, C.; Crespi, G.; Becchio, C.; Corgnati, S.P. Designing IAQ-Resilient Post-Pandemic Buildings. *Sustainability 15*, 2023, p. 2187. DOI: 10.3390/su15032187.

[77] Erhorn, H.; Erhorn-Kluttig, H. New buildings & NZEBs. Concerted action – energy performance of building, (CT1). [Accessed: 2023]. URL: https://www.epbd-ca.eu/ca-outcomes/outcomes-2015-2018/book-2018/ct/new-buildings-nzebs.

[78] D'Agostino, D. and Mazzarella, L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *Journal of Building Engineering* 21, 2019, pp. 200-212. DOI: 10.1016/j.jobe.2018.10.019.

[79] International Partnership for Energy Efficiency Cooperation (IPEEC). Zero Energy Building definitions and policy actions, an international review, 2018. [Accessed: 2023]. URL: https://globalabc.org/sites/default/files/2020-04/%5BIPEEC%5D%20Zero%20Energy%20Building%20Definitions%20and%20Policy%20Activity.pdf.

[80] Ala-Juusela, M.; Rehman, H.U.; Hukkalainen, M.; Reda, F. Positive Energy Building Definition with the Framework. *Elements and Challenges of the Concept Energies 14 (19)*, 2021, p. 6260. DOI: 10.3390/en14196260.

[81] Rehman, H.; Hasan, A.; Reda, F. Challenges in reaching positive energy building level in apartment buildings in the Nordic climate: A techno-economic analysis, *Energy and Buildings 262*, 2022, p. 111991. DOI: 10.1016/j.enbuild.2022.111991.

[82] Fayyad, M.; John, J. Defining Nearly Zero Energy Buildings in the UAE. Emirates Green Building Council, 2017. [Accessed: 2023]. URL: https://emiratesgbc.org/wp-content/uploads/2020/05/Defining-nZEBs-in-the-UAE-2017-1.pdf.

[83] Presidente della Repubblica. *Legge 3 agosto 2013, n. 90: Conversione in legge, con modificazioni, del decreto-legge 4 giugno 2013, n. 63, recante disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissione europea, nonché' altre disposizioni in materia di coesione sociale*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 181 del 03.08.2013.

[84] Ministro dello Sviluppo Economico, Ministro dell'Ambiente e della Tutela del Territorio e del Mare, Ministro delle Infrastrutture e dei Trasporti. *Decreto 26 giugno 2015: Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 162 del 15.07.2015, Suppl. Ordinario n. 39.

[85] Presidente della Repubblica. *Decreto Legislativo 3 marzo 2011, n. 28: Attuazione della direttiva 2009/28/CE sulla promozione dell'uso dell'energia da fonti rinnovabili, recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 71 del 28.03.2011, Suppl. Ordinario n. 81.

[86] Settimo, G.; Avino, P. The Dichotomy between Indoor Air Quality and Energy Efficiency in Light of the Onset of the COVID-19 Pandemic. *Atmosphere 12*, 2021, p. 791. DOI: 10.3390/atmos12060791.

[87] Bahnfleth, W. IAQ Control for Healthy, Resilient, Low Energy Buildings. [Accessed: 2022] . URL: https://blog.belimo.com/blog/iaqcontrol-for-healthy-resilient-low-energy-buildings.

[88] Coleman, K.K.; Nguyen, T.T.; Yadana, S.; Hansen-Estruch, C.; Lindsley, W.G.; Gray, G.C. Bioaerosol Sampling for Respiratory Viruses in Singapore's Mass Rapid Transit Network. *Sci. Rep. 8*, 2018, p. 17476. DOI: 10.1038/s41598-018-35896-1.

[89] Nishiura, H.; Oshitani, H.; Kobayashi, T.; Saito, T.; Sunagawa, T.; Matsui, T.; Wakita, T.; Suzuki. M. Closed environments Facilitate Secondary Transmission of Coronavirus Disease 2019 (COVID-19). medRxiv 2020. DOI: 10.1101/2020.02.28.20029272.

[90] Megahed, N.A.; Ghoneim, E.M. Indoor air quality: Rethinking rules of building design strategies in post-pandemic architecture. *Environ. Res.* 193, 2021, p. 110471. DOI: 10.1016/j.envres.2020.110471.

[91] Folke, C. Resilience (Republished). *Ecol. Soc.21(4)*, 2016. DOI: 10.5751/es-09088-210444.

[92] Cerè, G.; Rexgui, Y.; Zhao, W. Critical review of existing built environment resilience frameworks: Directions for future research. *Int. J. Disaster Risk Reduct.* 25, 2017, pp. 173–189. DOI: 10.1016/j.ijdrr.2017.09.018.

[93] Roege, P.E.; Collier, Z.A.; Mancillas, J.; McDonagh, J.A.; Linkov, I. Metrics for energy resilience. *Energy Policy 72*, 2014, pp. 249–256. DOI:10.1016/j.enpol.2014.04.012.

[94] International Energy Agency, OECD/IEA. Making the Energy Sector more Resilient to Climate Change (2015). [Accessed: 2023]. URL: https://static1.squarespace.com/static/570b03987c65e49ce6174883/t/5be2e7cdc2241b9d4d539f18/1541597137574/COP21_Resilience_Brochure-Making+the+Energy+Sector+more+Resilient+to+Climate+Change.pdf

[95] Bosher, L. The need for built in resilience. In Hazards and the Built Environment-Attaining Built-in Resilience; Bosher, L., Ed.; Routledge: London, UK; New York, NY, USA, 2008; pp. 3–19.

[96] Faller, G. The resilience of timber buildings. In Research and Applications in Structural Engineering, Mechanics, and Computation, 1st ed.; Zingoni, A., Ed.; Balkema: Rotterdam, The Netherlands, 2013.

[97] Champagne, C.L.; Aktas, C. Assessing the Resilience of LEED Certified Green Buildings. *Procedia Eng. 145*, 2016, pp. 380–387. DOI: 10.1016/j.proeng.2016.04.095.

[98] Pearson, L.J.; Flanery, T.H. Designing, planning, and managing resilient cities: A conceptual framework. *Cities 35*, 2013, pp. 89–99. DOI: 10.1016/j.cities.2013.06.003.

[99] Lupíšek, A.; Růžička, J.; Tywoniak, J.; Hájek, P.; Volf, M. Criteria for evaluation of resilience of residential buildings in central Europe. *Int. Rev. Appl. Sci. Eng. 9*, 2018, pp. 89–93. DOI: 10.1556/1848.2018.9.2.2.

[100] Homaei, S.; Hamdy, M. Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric. *Build. Environ. 201*, 2021, p. 108022. DOI: 10.1016/j.buildenv.2021.108022.

[101] Moazami, A.; Carlucci, S.; Geving, S. Robust and resilient buildings: A framework for defining the protection against climate uncertainty. *IOP Conf. Series Mater. Sci. Eng. 609*, 2019, p. 072068. DOI: 10.1088/1757-899x/609/7/072068.

[102] Haigh, R.; Amaratunga, D. Introduction: Resilience in the built environment. In Post Disaster Reconstruction of the Built Environment: Rebuilding for Resilience; Amaratunga, D., Haigh, R., Eds.; Willey-Blackwell: Oxford, UK, 2011; pp. 1–11.

[103] Hewitt, E.; Oberg, A.; Coronado, C.; Andrews, C. Assessing “green” and “resilient” building features using a purposeful systems approach. *Sustain. Cities Soc. 48*, 2019, pp. 1–20. DOI: 10.1016/j.scs.2019.101546.

[104] Sun, K.; Specian, M.; Hong, T. Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home. *Build. Environ. 177*, 2020, p. 106842. DOI: 10.1016/j.buildenv.2020.106842.

[105] UN-Habitat Annual Report 2021. [Accessed: 2023]. URL: https://unhabitat.org/annual-report-2021

[106] Casta˜no-Rosa, R.; Pelsmakers, S.; Jarventausta, H.; Poutanen, J.; Tahtinen, L.; Rashidfarokhi, A.; Toivonen, S. Resilience in the built environment: Key characteristics for solutions to multiple crises. *Sustainable Cities and Society 87*, 2022, p. 104259. DOI: 10.1016/j.scs.2022.104259.

[107] Lizarralde, G.; Chmutina, K.; Bosher, L.; Dainty, A. Sustainability and resilience in the built environment: The challenges of establishing a turquoise agenda in the UK. *Sustain. Cities Soc. 15*, 2015, pp. 96–104. DOI: 10.1016/j.scs.2014.12.004.

[108] Roostaie, S.; Nawari, N.; Kibert, C. Sustainability and resilience: A review of definitions, relationships, and their integration into a combined building assessment framework. *Build. Environ.* 154, 2019, pp. 132–144. DOI: 10.1016/j.buildenv.2019.02.042.

[109] Tokazhanov, G.; Tleuken, A.; Guney, M.; Turkyilmaz, A.; Karaca, F. How is COVID-19 Experience Transforming Sustainability Requirements of Residential Buildings? A Review. *Sustainability 12* , 2020, p. 8732. DOI: 10.3390/su12208732.

[110] Tleuken, A.; Tokazhanov, G.; Guney, M.; Turkyilmaz, A.; Karaca, F. Readiness Assessment of Green Building Certification Systems for Residential Buildings during Pandemics. *Sustainability 13*, 2021, p. 460. DOI: 10.3390/su13020460.

[111] Tokazhanov, G.; Tleuken, A.; Durdyev, S.; Otesh, N.; Guney, M.; Turkyilmaz, A.; Karaca, F. Stakeholder based weights of new sustainability indicators providing pandemic resilience for residential buildings. *Sustain. Cities Soc. 75*, 2021, p. 103300. DOI: 10.1016/j.scs.2021.103300.

[112] Hassler, U.; Kohler, K. Resilience in the built environment. *Building Research and Information 42(2)*, 2014, pp. 119-129. DOI: 10.1080/09613218.2014.873593.

[113] Attia, S.; Levinson, R.; Ndongo, E.; Holzer, P.; Kazanci, O.B.; Homaei, S.; Zhang, C.; Olesen, B.W.; Qi, D.; Hamdy, M.; et al. Resilient cooling of buildings to protect against heat waves and power outages: Key

concepts and definition. *Energy Build. 239*, 2021, p. 110869. DOI: 10.1016/j.enbuild.2021.110869.

[114] Folke, C.; Carpenter, S.; Elmqvist, T.; Gunderson, L.; Holling, C.S.; Walker, B. Resilience and sustainable development: Building adaptive capacity in a world of transformations. *AMBIO J. Hum. Environ. 31*, 2002, pp. 437–440. DOI: 10.1579/0044-7447-31.5.437.

[115] Megahed, N.A.; Ghoneim, E.M. Antivirus-built environment: Lessons learned from Covid-19 pandemic. *Sustain. Cities Soc. 61*, 2020, p. 102350. DOI: 10.1016/j.scs.2020.102350.

[116] Al Assaad, D.; Sengupta, A.; Breesch, H. A novel quantitative assessment framework of the IAQ resilience performance of buildings: The resilience score metric. *Building and Environment 243*, 2023, p. 110669. DOI: 10.1016/j.buildenv.2023.110669.

[117] Royal Academy of Engineering; National Engineering Policy Centre; CIBSE. Infection Resilient Environments: Time for a Major Upgrade. [Accessed: 2023]. URL: https://www.raeng.org.uk/infection-resilient-environments-2.

[118] Widuto, A. Energy Transition in the EU, 2023. [Accessed: 2023]. URL: https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/754623/EPRS_BRI(2023)754623_EN.pdf.

[119] European Commission. European Green Deal: Commission proposes to boost renovation and decarbonisation of buildings. 15 December 2021, Brussels. [Accessed: 2023]. URL: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683

[120] European Parliament. EU Progress towards its 2020 climate change goals (infographic). [Accessed: 2023]. URL: https://www.europarl.europa.eu/news/en/headlines/society/20180706STO07407/eu-progress-towards-2020-climate-change-goals-infographic

[121] Skaar, C.; Labonnote, N.; Gradeci, K. From zero emission buildings (ZEB) to zero emission neighbourhoods (zen): a mapping review of algorithm-based lca, *Sustainability 10*, 2018, p. 2405. DOI: 10.3390/su10072405.

[122] Moum, A.; Hauge, A.L.; Thomsen, J. ZEB Definitions. The Research Centre on Zero Emission Buildings, Project report no. 30, Four Norwegian Zero Emission Pilot Buildings – Building Process and User Evaluation, 2017.

[123] Fufa, S.M.; Schlanbusch, R.D.; Sørnes, K.; Inman, M.; Andresen, I. A Norwegian ZEB Definition Guideline. ZEB Project Report 29. SINTEF Academic Press: Trondheim, 2016. DOI: 10.13140/RG.2.2.26443.80162.

[124] Good, C.; Georges, L.; Kristjansdottir, T.; Wiberg, A.H.; Hestnes, A.G. A comparative study of different PV installations for a Norwegian NZEB concept, in: Proceedings of the EuroSun 2014 Conference. Presented at the EuroSun 2014, International Solar Energy Society, Aix-les-Bains, France, 2015, pp. 1–10. DOI: 10.18086/eurosun.2014.20.03.

[125] Riedy, C.; Lederwasch, A.; Ison, N. Defining Zero Emission Buildings - Review and Recommendations: Final Paper, 2011. DOI:10.13140/ RG.2.1.4470.5520.

[126] Government Property Agency. Sustainability and Net Zero. Design Guide - Sustainability Annex. [Accessed: 2023]. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1080617/Sustainability___Net_Zero_Annex_-_March_2022.pdf_Document_uploaded_via_email._A_Accepted_as_Stage_Complete_1.pdf.

[127] International Energy Agency, 2021. Net zero by 2050: a roadmap for the global energy sector. URL: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

[128] Maduta, C., Melica, G., D'agostino, D., Bertoldi, P., Defining Zero-Emission Buildings. Support for the revision of the Energy Performance of Buildings Directive, Publications Office of the European Union, Luxembourg, 2023. DOI:10.2760/107493, JRC129612.

[129] International Energy Agency. Perspectives for the Clean Energy Transition. The Critical Role of Buildings. IEA, 2019. [Accessed: 2023]. URL: https://iea.blob.core.windows.net/assets/026bff1b-821d-48bc-8a0e-7c10280c62bc/Perspectives_for_the_Clean_Energy_Transition_2019.pdf.

[130] Enel Group. Electricity's strategic role in leading Europe's decarbonization. [Accessed: 2023]. URL: https://www.enel.com/company/our-commitment/electricity-role-europe-decarbonization/electrification.

[131] International Energy Agency. Electrification. [Accessed: 2023]. URL: https://www.iea.org/energy-system/electricity/electrification#tracking.

[132] International Energy Agency. Heating. [Accessed: 2023]. URL: https://www.iea.org/energy-system/buildings/heating.

[133] International Energy Agency. Heat Pumps. [Accessed: 2023]. URL: https://www.iea.org/energy-system/buildings/heat-pumps.

[134] Agarwal, N.; Meena, C.S.; Raj, B.P.; Saini, L.; Kumar, A.; Gopalakrishnan, N.; Kumar, A.; Balam, N.B.; Alam, T.; Kapoor, N.R.; et

al. Indoor air quality improvement in COVID-19 pandemic: Review. *Sustain. Cities Soc. 70*, 2021, p. 102942. DOI: 10.1016/j.scs.2021.102942.

[135] Navaratnam, S.; Nguyen, K.; Selvaranjan, K.; Zhang, G.; Mendis, P.; Aye, L. Designing Post COVID-19 Buildings: Approaches for Achieving Healthy Buildings. *Buildings 12*, 2022, p. 10074. DOI: 10.3390/buildings12010074.

[136] United States Environmental Protection Agency (EPA). Indoor Air and Coronavirus (COVID-19). [Accessed: 2023]. URL: https://www.epa.gov/coronavirus/indoor-air-and-coronavirus-covid-19

[137] Morawska, L.; Tang, J.; Bahnfleth, W.; Bluyssen, P.; Boerstra, A.; Buonanno, G. How can airborne transmission of COVID-19 indoors be minimized? *Environ. Int. 142*, 2020, p. 105832. DOI: 10.1016/j.envint.2020.105832.

[138] Gao, X.; Li, Y.; Leung, G. Ventilation control of indoor transmission of airborne diseases in an urban community. *Indoor Built Environ. 18,* 2009, pp. 205–218. DOI: 10.1177/1420326X09104141.

[139] Goyal, S.M.; Anantharaman, S.; Ramakrishnan, M.; Sajja, S.; Kim, S.W.; Stanley, N.J.; Farnsworth, J.E.; Kuehn, T.H.; Raynor, P.C. Detection of viruses in used ventilation filters from two large public buildings. *Am. J. Infect. Control. 39*, 2011, pp. e30–e38. DOI: 10.1016/j.ajic.2010.10.036.

[140] Cao, Q.; Li, F.; Zhang, T.; Wang, S. A ventilator that responds to outdoor conditions for ventilation and air filtration. Energy and Buildings 229, 2020, p. 110498. DOI: 10.1016/j.enbuild.2020.110498.

[141] UNI EN 1822-1: 2019. Filtri per l’aria (EPA, HEPA and ULPA) - Part 1: Classificazione, prove di prestazione, marcatura. Brussels, Belgium, 2019.

[142] Prussin, A.J.; Marr, L.C. Sources of airborne microorganisms in the built environment. *Microbiome 3*, 2015, pp. 1–10. DOI: 10.1186/s40168-015-0144-z.

[143] Batterman, S.A.; Burge, H. HVAC Systems as Emission Sources Affecting Indoor Air Quality: A Critical Review. *HVAC&R Res. 1*, 1995, pp. 61–78. DOI: 10.1080/10789669.1995.10391309.

[144] Pejtersen, J.; Bluyssen, P.; Kondo, H.; Clausen, G.; Fanger, P.O. Air pollution sources in ventilation systems. In Proceedings of Clima 2000 World Congress on Heating, Ventilating, Refrigerating and Air Conditioning, Sarajevo, Yugoslavia, 27 August–1 September 1989.

[145] Ghezzi, S.; Pagani, I.; Poli, G.; Perboni, S.; Vicenzi, E. Rapid inactivation of severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2) by Tungsten Trioxide-based (WO_3) Photocatalysis. bioRxiv 2020. DOI: 10.1101/2020.08.01.232199.

[146] Bono, N.; Ponti, F.; Punta, C.; Candiani, G. Effect of UV Irradiation and TiO2-Photocatalysis on Airborne Bacteria and Viruses: An Overview. *Materials 14*, 2021, p. 1075. DOI: 10.3390/ma14051075.

[147] Prakash, J.; Cho, J.; Mishra, Y.K. Photocatalytic TiO_2 nanomaterials as potential antimicrobial and antiviral agents: Scope against blocking the SARS-CoV-2 spread. *Micro and Nano Engineering 14,* 2022, p. 100100. DOI: 10.1016/j.mne.2021.100100.

[148] Biloria, N.; Thakkar, Y. Integrating algae building technology in the built environment: A cost and benefit perspective. *Front. Arch. Res. 9*, 2020, pp. 370–384. DOI: 10.1016/j.foar.2019.12.004.

[149] Berry, G.; Parsons, A.; Morgan, M.; Rickert, J.; Cho, H. A review of methods to reduce the probability of the airborne spread of COVID-19 in ventilation systems and enclosed spaces. *Environmental Research 203*, 2022, p. 111765. DOI: 10.1016/j.envres.2021.111765.

[150] Regency Lighting. Using UV Light to Kill Viruses like COVID-19. [Accessed: 2023]. URL: https://insights.regencylighting.com/canuv-light-kill-viruses-like-covid-19.

[151] Biasin, M.; Bianco, A.; Pareschi, G.; Cavalleri, A.; Cavatorta, C.; Fenizia, C.; Galli, P.; Lessio, L.; Lualdi, M.; Tombetti, E.; et al. UV-C irradiation is highly effective in inactivating SARS-CoV-2 replication. *Sci Rep. 11*, 2021, p. 6260. DOI: 10.1038/s41598-021-85425-w.

[152] Vranay, F.; Pirsel, L.; Kacik, R.; Vranayova, Z. Adaptation of HVAC Systems to Reduce the Spread of COVID-19 in Buildings. *Sustainability 12*, 2020, p. 9992. DOI: 10.3390/su12239992.

[153] Zeng, Y.; Manwatkar, P.; Laguerre, A.; Beke, M.; Kang, I.; Ali, A.S.; Farmer, D.K.; Gall, E.T.; Heidarinejad, M.; Stephens, B. Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation. *Build. Environ. 195*, 2021, p. 107750. DOI: 10.1016/j.buildenv.2021.107750.

[154] International Energy Agency. The Future of Heat Pumps. 2022. [Accessed: 2023]. URL: https://iea.blob.core.windows.net/assets/4713780d-c0ae-4686-8c9b-29e782452695/TheFutureofHeatPumps.pdf.

[155] Thomaßen, G.; Kavvadias, K.; Jiménez Navarro, J.P. The decarbonisation of the EU heating sector through electrification: A parametric analysis. *Energy Policy 148*, 2021, p. 111929. DOI: 10.1016/j.enpol.2020.111929.

[156] International Energy Agency (2023), Global heat pump sales continue double-digit growth. [Accessed: 2023]. URL: https://www.iea.org/commentaries/global-heat-pump-sales-continue-double-digit-growth.

[157] European Heat Pump Association. European Heat Pump Market and Statistics Report (2023). [Accessed: 2023]. URL: https://www.ehpa.org/market-data/.

[158] Toleikyte, A.; Roca Reina, J. C.; Volt, J.; Carlsson, J.; Lyons, L.; Gasparella, A.; Koolen, D.; De Felice, M.; Tarvydas, D.; Czako, V.; Koukoufikis, G.; Kuokkanen, A.; Letout, S. The Heat Pump Wave: Opportunities and Challenges, Publications Office of the European Union, Luxembourg, 2023. DOI:10.2760/27877.

[159] Agenzia territoriale energia sostenibilità (ATES). Le pompe di calore per decarbonizzare il riscaldamento domestico, 2023. [Accessed: 2023]. URL: https://www.atesparma.it/2023/02/21/le-pompe-di-calore-per-decarbonizzare-il-riscaldamento-domestico/.

Chapter 3

[160] Cakan, M.; Becchio, C.; Corgnati, S.P.; Mazzarella, L.; Quiles, P.; Ekren, O.; Yay, T.; Dell'Anna, F.; Bottero, M.; Lingua, C.; Toksoy, M.; Aktakka, S.; Karadeniz, Z.H.; Saglam, S.; Arisoy, A. Design Strategies for Residential Buildings in Mediterranean Regions - Part 2. European Guidebook 31. Federation of European Heating, Ventilation and Air Conditioning associations (REHVA), 2021.

[161] Strantzali, E.; Aravossis, K. Decision making in renewable energy investments: A review. *Renewable and Sustainable Energy Reviews 55*, 2016, pp. 885–898. DOI: 10.1016/j.rser.2015.11.021.

[162] Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F. Decision making for sustainable urban energy planning: an integrated evaluation framework of alternative solutions for a NZED (Net Zero-Energy District) in Turin. *Land Use Policy 78*, 2018, pp. 803-817. DOI: 10.1016/j.landusepol.2018.06.048.

[163] Bottero, M.C.; Dell'Anna, F.; Morgese, V. Evaluating the transition towards Post-Carbon Cities: A literature review. *Sustainability 13(2)*, 2021, p. 567. DOI: 10.3390/su13020567.

[164] Becchio, C.; Bottero, M.C.; Bravi, M.; Corgnati, S.P.; Dell'Anna, F.; Mondini, G.; Vergerio, G. Integrated assessments and energy retrofit: The contribution of the energy centre lab of the Politecnico di Torino. *Green Energy and Technology*, 2020, pp. 365–384. DOI: 10.1007/978-3-030-23786-8_21.

[165] Diakoulaki, D.; Karangelis, F. Multi-criteria analysis and cost-benefit analysis of alternative scenarios for the power generation sector in Greece. *Renewable and Sustainable Energy Reviews 11*, 2007, pp. 716-727. DOI: 10.1016/j.rser.2005.06.007.

[166] Becchio, C.; D’Agostino, D.; Zangheri, P. Evaluation tools: cost-optimal and cost-benefit analysis. *Rehva Journal 2*, 2022, pp. 5–9.

[167] Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell’Anna, F.; Fabi, V.; Lingua, C.; Prendin, L.; Ranieri, M. Effects on energy savings and occupant health of an antibacterial filter. In Proceedings of E3S Web of Conference, Bucharest, Romania, 26–29 May 2019.

[168] Montgomery, J.F.; Reynolds, C.C.; Rogak, S.N.; Green, S.I. Financial implications of modifications to building filtration systems. *Build Environ 85*, 2015, pp.17–28. DOI: 10.1016/j.buildenv.2014.11.005.

[169] Vergerio, G.; Becchio, C. Pursuing occupants’ health and well-being in building management: Definition of new metrics based on indoor air parameters. *Build Environ 223*, 2022, p. 109447. DOI: 10.1016/j.buildenv.2022.109447.

[170] Liu, Y.; Liu, T.; Ye, S.; Liu, Y. Cost-benefit analysis for Energy Efficiency Retrofit of existing buildings: A case study in China. *Journal of Cleaner Production 177*, 2018, pp. 493– 506. DOI: 10.1016/j.jclepro.2017.12.225.

[171] Tureckova, K.; Nevima, J. The Cost-Benefit Analysis for the concept of a smart city: How to measure the efficiency of smart solutions? *Sustainability 12(7)*, 2020, p. 2663. DOI: 10.3390/su12072663.

[172] Zeleny, M. The Decision Process and its Stages, in: Multiple Criteria Decision Making, 1982.

[173] Kluczek, A.; Zeglen, P.; Matusikova, D. The use of prospect theory for energy sustainable industry 4.0. *Energies 14*, 2021, p. 7694. DOI: 10.3390/en14227694.

[174] Assumma, V.; Bottero, M.; De Angelis, E.; Lourenco, J.M.; Monaco, R.; Soares, A.J. A decision support system for territorial resilience assessment and planning: an application to the Douro Valley (Portugal). *Science of the Total Environment 756*, 2021, p. 143806. DOI: 10.1016/j.scitotenv.2020.143806.

[175] Taherdoost, H.; Madanchian, M. Multi-Criteria Decision Making (MCDM) methods and concepts. *Encyclopedia 3(1)*, 2023, pp. 77-87. DOI: 10.3390/encyclopedia3010006.

[176] Cinelli, M.; Coles, S.R.; Kirwan, K. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators 46*, 2014, pp. 138-148. DOI: 10.1016/j.ecolind.2014.06.011.

[177] Greco, S.; Matarazzo, B.; Slowinski, R. Axiomatic characterization of a general utility function and its particular cases in terms of conjoint measurement and rough-set decision rules. *European Journal of*

Operational Research 158, 2004, pp. 271–292. DOI: 10.1016/j.ejor.2003.06.004.

[178] Slowinski, R.; Greco, S.; Matarazzo, B. Axiomatization of utility, outranking and decision rule preference models for multiple-criteria classification problems under partial inconsistency with the dominance principle. *Control Cybernetics 31*, 2002, pp. 1005-1035.

[179] Keeney, R.L.; Raiffa, H. Decisions with multiple objectives: preferences and value trade-offs. Cambridge University Press, 1993. ISBN 0521438827.

[180] Yilan, G.; Kadirgan, M.A.N.; Çiftçioğlu, G.A. Analysis of electricity generation options for sustainable energy decision making: The case of Turkey. *Renewable Energy 146*, 2020, pp. 519–529. DOI:10.1016/j.renene.2019.06.164.

[181] Ghimire, L.P.; Kim, Y. An analysis on barriers to renewable energy development in the context of Nepal using AHP. *Renewable Energy 129*, 2018, pp. 446–456. DOI: 10.1016/j.renene.2018.06.011.

[182] März, S. Assessing the fuel poverty vulnerability of urban neighbourhoods using a spatial multi-criteria decision analysis for the German city of Oberhausen. *Renewable and Sustainable Energy Reviews 82*, 2018, pp. 1701–1711. DOI: 10.1016/j.rser.2017.07.006.

[183] Roy, B. Aide multicritére à la décision: méthodes et cas, Economica, Paris, 1993.

[184] Becchio, C.; Bottero, M.; Corgnati, S.P.; Dell'Anna, F. A MCDA-Based Approach for Evaluating Alternative Requalification Strategies for a Net-Zero Energy District (NZED), in: C. Zopounidis, M. Doumpos (Eds.), Multiple Criteria Decision Making, Springer, Cham, 2017, pp. 189–211. DOI:10.1007/978-3-319-39292-9_10.

[185] Catalina, T.; Virgone, J.; Blanco, E. Multi-source energy systems analysis using a multi-criteria decision aid methodology. *Renewable Energy 36*, 2011, pp. 2245–2252. DOI: 10.1016/j.renene.2011.01.011.

[186] Haydt, V.; Leal, L.; Dias. A multi-objective approach for developing national energy efficiency plans, *Energy Policy*, 2014. DOI: 10.1016/j.enpol.2013.06.133.

[187] Theodorou, S.; Florides, G.; Tassou, S. The use of multiple criteria decision-making methodologies for the promotion of RES through funding schemes in Cyprus: A review. *Energy Policy 38*, 2010, pp. 7783–7792. DOI:10.1016/j.enpol.2010.08.038.

[188] Greco, S.; Matarazzo, B.; Slowinski, R. Rough sets theory for multicriteria decision analysis, *European Journal of Operational Research 129*, 2001, pp. 1–47. DOI: 10.1016/S0377- 2217(00)00167.

[189] EN 15459:2007; *Energy Performance of Buildings—Economic Evaluation Procedure for Energy Systems in Buildings*. CEN: 2007; CEN: Tallinn, Estonia, 2007.

[190] Becchio, C., Corgnati, S.P., Delmastro, C., Fabi, V., Lombardi, P. The role of nearly-zero energy buildings in the transition towards Post-Carbon Cities. *Sustainable Cities and Society 27*, 2016, pp. 324-337. DOI: 10.1016/j.scs.2016.08.005.

[191] European Commission. *Guide to Cost-Benefit Analysis of Investment Projects: Structural Funds, Cohesion Fund and Instrument for Pre-Accession, Directorate-General for Regional Policy*; European Commission: Brussels, Belgium, 2014.

[192] European Commission. *Guide to Cost-Benefit Analysis of Major Projects. In the context of EC Regional Policy*. European Commission: Brussels, Belgium, 1997.

[193] Schwartz, B. The Limits of Cost-Benefit Calculation: Commentary on Bennis, Medin, & Bartels, *Perspectives on Psychological Science 5*, 2010, pp. 203–205. DOI:10.1177/1745691610362355.

[194] European Commission. *Guide to Cost-Benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014-2020*; European Commission: Brussels, Belgium, 2014. URL: https://wayback.archive-it.org/12090/20221203224508/https://ec.europa.eu/inea/sites/default/files/cba_guide_cohesion_policy.pdf.

[195] EN 15686-5. *Buildings and constructed assets, Service Life planning. Part 5: Life-cycle costing* (2008).

[196] Fregonara, E.; Giordano, R.; Ferrando, D.G.; Pattono, S. Economic-Environmental Indicators to Support Investment Decisions: A Focus on the Buildings' End-of-Life Stage. *Buildings 7(3)*, 2017, p. 65. DOI: 10.3390/buildings7030065.

[197] Department of Education & Early Development. Life Cycle Cost Analysis Handbook. 2nd Edition Finance & Support Services / Facilities. 2018. [Accessed: 2023]. URL: https://education.alaska.gov/facilities/publications/LCCAHandbook.pdf.

[198] Mitchell, R.C.; Carson, R.T. Using Surveys to Value Public Goods: The Contingent Valuation Method, 1st ed.; Resources for the Future: New York, NY, USA; Washington, DC, USA, 1989; pp. 1–484. DOI: 10.4324/9781315060569.

[199] Haaijer, M.E. Modeling Conjoint Choice Experiments with the Probit Model; Labyrint Publications: Amsterdam, The Netherlands, 1999; pp. 1–177. ISBN: 90-72591-66-6.

[200] Louviere, J. Conjoint analysis modelling of stated preferences: A review of theory, methods, recent developments and external validity. *J. Transp. Econ. Policy 22*, 1988, pp. 93–119.

[201] Rosen, S. Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. *J. Politi- Econ. 82*, 1974, pp. 34–55. DOI: 10.1086/260169.

[202] Jefferson, T.; Mugford, M.; Demicheli, V. Elementary Economic Evaluation in Health care, 2nd ed.; BMJ Book: England, UK, 2000; pp. 1–148. ISBN: 0727914782.

[203] Broome, J. The economic value of life. In Economica; New Series: England, University of Bristol, 52, 1985 pp. 281–294.

[204] Koopmanschap, M.A.; Rutten, F.F.; van Ineveld, B.M.; van Roijen, L. The friction cost method for measuring indirect costs of disease. *J. Health Econ. 14*, 1995, pp. 171–189. DOI: 10.1016/0167-6296(94)00044-5.

[205] Richardson, L.; Loomis, J.; Kroeger, T.; Casey, F. The role of benefit transfer in ecosystem service valuation. *Ecol. Econ. 115*, 2015, pp. 51–58. DOI: 10.1016/j.ecolecon.2014.02.018.

[206] IPCC, 2015. 7.10 Co-benefits of industrial GHG mitigation, in: Climate Change 2007 - Mitigation of Climate Change: Working Group III, 2015: p. 484. [Accessed: 2023]. URL: https://archive.ipcc.ch/publications_and_data/ar4/wg3/en/ch7s7-10.html.

[207] IEA, 2019. Perspectives for the Clean Energy Transition: the critical role of buildings. International Energy Agency. [Accessed: 2023]. URL: https://iea.blob.core.windows.net/assets/026bff1b-821d-48bc-8a0e-7c10280c62bc/Perspectives_for_the_Clean_Energy_Transition_2019.pdf.

[208] IPCC, 1994: Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios. Houghton, J.T., L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, E.F. Haites, N. Harris, and K. Maskell (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. ISBN: 0521 559626.

[209] IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.).

Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-562. DOI:10.1017/9781009157940.008.

[210] Copiello, S.; Bonifaci, P. Green Housing: toward a new energy efficiency paradox? *Cities 49*, 2015, pp. 76-87. DOI: 10.1016/j.cities.2015.07.006.

[211] Bottero, M.C.; Bravi, M.; Dell'Anna, F.; Mondini, G. Valuating building energy efficient through Hedonic Prices Method: are spatial effects relevant? *Valori e Valutazioni 21*, 2018, pp. 27-40.

[212] Eichholtz, P.; Kok, N.; Quigley, J.M. The Economics of green building. *Review of Economics and Statistics*, 2011. DOI: 10.1162/REST_a_00291.

[213] Bottero, M.; Bravi, M. Valutazione dei benefici connessi al risparmio energetico degli edifici: un approccio econometrico. In: *GEAM. GEOINGEGNERIA AMBIENTALE E MINERARIA 3*, 2014, pp. 15-24. ISSN 1121-9041.

[214] Bjørner, T.B. Combining socio-acoustic and contingent valuation surveys to value noise reduction. *Transportation research 9(5)*, 2004, pp. 341-356. DOI: 10.1016/j.trd.2004.05.002.

[215] Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F. Evaluating health benefits of urban energy retrofitting: an application for the city of Turin. In: *Smart and Sustainable Planning for Cities and Regions*, 2018, pp. 281-304. DOI: 10.1007/978-3-319-75774-2_20.

[216] Liddell, C.; Morris, C. Fuel poverty and human health: a review of recent evidence. *Energy Policy 38(6)*, 2010, pp. 2987-2997. DOI: 10.1016/j.enpol.2010.01.037.

[217] IPCC, 2007: Climate change 2014: Mitigation of climate change, Edenhofer, O., Pichs-Madruga, R., Sokona, Y. (eds.). Contribution of Working Group III to the Fifth Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK, and New York.

[218] Threlfall, A. Understanding the cost and benefits of fuel poverty interventions: a pragmatic economic evaluation from greater Manchester. Greater Manchester Public Health Practice Unit, Manchester, 2011.

[219] Bonner, S. Social Cost Benefit Analysis and economic evaluation. Brisbane, Australia: The University of Queensland, 2022. DOI: 10.14264/2c7588c

Chapter 4

[220] Becchio, C.; Corgnati, S.P.; Crespi, G.; Lingua, C. Impacts of different AHU configurations on health and students' performance in

Italian schools in post-pandemic era. *Sustainable Energy Technologies and Assessments 60*, 2023, p. 103479. DOI: 10.1016/j.seta.2023.103479.

[221] Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F.; Fabi, V.; Lingua, C.; Prendin, L.; Ranieri, M. The effects of indoor and outdoor air pollutants on workers productivity in office building. In: *Proceedings of CLIMA 2019, REHVA 13rd HVAC World Congress*, Bucharest, Romania, 26 May 2019. DOI: 10.1051/e3sconf/201911102057.

[222] Becchio, C.; Corgnati, S.P.; Fabi, V.; Lingua, C., Prendin, L.; Ranieri, M. Costs and benefits of antibacterial filter and its effects on energy saving, human health and worker productivity. In: *Proceedings of 51st AiCARR International Conference*, the human dimension of building energy performance, Venice, Italy, 20 February 2019. DOI: 10.1051/e3sconf/201911102056.

[223] World Health Organization. Air quality guidelines for Europe. WHO Regional Publications, European Series, No. 23. Copenhagen, Denmark, 1987.

[224] Fanger, P.O.; Lauridse, P.; Bluyssen, P.; Clausen, G. Air pollution sources in offices and assembly halls, quantified by the olf unit. *Energy and Buildings 12*, 1988, pp. 7-19. DOI: 10.1016/0378-7788(88)90052-7.

[225] Thorstensen, E.; Hansen, C.; Pejtersen, J.; Clausen, G.; Fanger, P.P. Air pollution sources and indoor air quality in schools. In: *Proceedings of Indoor Air 1990*, 1, pp. 531-536.

[226] Pejtersen, J.; Clausen, G.; Sorensen, J.; Quistgaard, D.; Iwashita, G.; Zhang, Y.; Onishi, T.; Fanger, P.O. Air pollution sources in kindergartens. In: *Proceedings of Healthy Buildings - IAQ 91*, Washington D.C., ASHRAE, pp. 221-224.

[227] Pan, Y.; Du, C.; Fu, Z.; Fu, M. Re-thinking of engineering operation solutions to HVAC systems under the emerging COVID-19 pandemic. *J Build Eng 43*, 2021, p. 102889. DOI: 10.1016/j.jobe.2021.102889.

[228] Xu, Y.; Cai, J.; Li, S.; He, Q.; Zhu, S. Airborne infection risks of SARS-CoV-2 in U.S. schools and impacts of different intervention strategies. *Sustain Cities Soc 74*, 2021, p. 103188. DOI: 10.1016/j.scs.2021.103188.

[229] Zheng, W.; Hu, J.; Wang, Z.; Li, J.; Fu, Z.; Li, H. COVID-19 impact on operation and energy consumption of Heating, Ventilation and Air-Conditioning (HVAC) systems. *Advance Appl Energy 3*, 2021, p. 100040. DOI: 10.1016/j. adapen.2021.100040.

[230] Santos, H.; Leal, V. Energy vs. ventilation rate in buildings: A comprehensive scenario-based assessment in the European context. *Energ Buildings 54*, 2012, pp. 111–21. DOI: 10.1016/j.enbuild.2012.07.040.

[231] United States Environmental Protection Agency. Energy cost and IAQ performance of ventilation systems and controls. Washington D.C.: Indoor Environments Division Office of Radiation and Indoor Air; 2000.

[232] Addae-Dapaah, K.; Wai, T.K.; Bin Dollah, M.J.; Foo, Y. Indoor air quality and office property value, *Journal of Sustainable Real Estate 2(1)*, 2020, pp. 91-115. DOI: 10.1080/10835547.2010.12091799.

[233] Alsmo, T.; Holmberg, S. Sick buildings or not: indoor air quality and health problems in schools. *Indoor Built Environ 16(6)*, 2007, pp. 548–55. DOI: 10.1177/ 1420326X0708441.

[234] Al-Awadi, L. Assessment of indoor levels of volatile organic compounds and carbon dioxide in schools in Kuwait. *J Air Waste Manag Assoc 68*, 2018, pp. 54–72. DOI: 10.1080/10962247.2017.1365781.

[235] Bako-Biro, Z.; Clements-Croome, D.J.; Kochhar, N.; Awbi, H.B.; Williams, M.J. Ventilation rates in schools and pupils' performance. *Build Environ 48*, 2012, pp. 215–23. DOI: 10.1016/j.buildenv.2011.08.018.

[236] Simoni, M.; Annesi-Maesano, I.; Sigsgaard. T.; Norback, D.; Wieslander, G.; Nystad, W.; Canciani, M.; Sestini, P.; Viegi, G. School air quality related to dry cough, rhinitis and nasal patency in children. *Eur Respir J 35(4)*, 2010, pp. 742–9. DOI: 10.1183/09031936.00016309.

[237] Sadrizadeh, S.; Yao, R.; Yuan, F.; Awbi, H.; Bahnfleth, W.; Bi, Y.; Guangyu, C.; Croitoru, C.; de Dear, R.; Haghighat, F.; Kumar, P.; Malayeri, M.; Nasiri, F.; Ruud, M.; Sadeghian, P.; Wargocki, P.; Xiong, J.; Yu, W.; Li, B. Indoor air quality and health in schools: a critical review for developing the roadmap for the future school environment. *J Build Eng 57*, 2022, p. 104908. DOI: 10.1016/j.jobe.2022.104908.

[238] Jo, C. Cost-of-illness studies: concepts, scopes, and methods. *Clin Mol Hepatol 20(4)*, 2014, pp. 327–37. DOI: 10.3350/cmh.2014.20.4.327.

[239] Jefferson, T.; Mugford, M.; Demicheli, V. Elementary economic evaluation in health care. 2nd edition. London: BMJ Books; 2000.

[240] Fautrel, B.; Boonen, A.; de Wit, M.; Grimm, S.; Joore, M.; Guillemin, F. Cost assessment of health interventions and diseases. *RMD Open 6*, 2020. DOI: 10.1136/rmdopen-2020-001287.

[241] Lucioni, C.; Costa, B.; Sessa, A. I costi dell'influenza in Italia. *Farmeconomia e percorsi terapeutici 2(1)*, 2001, pp. 11–8.

[242] Wargocki, P.; Porras-Salazar, J.A.; Contreras-Espinoza, S.; Bahnfleth, W. The relationship between classroom air quality and children's performance in school. *Build Environ 173*, 2020, p. 106749. DOI: 10.1016/j.buildenv.2020.106749.

[243] EN ISO 16890-1:2017. Filtri d'aria per ventilazione generale - Parte 1: Specifiche tecniche, requisiti e sistema di classificazione dell'efficienza basato sul particolato (ePM), 2017.

[244] Amalfitano, S.; Poletti, L.; Ascani, F.; Tonon, A.; Snidar, R.; Zoppini, A. Applicazione della citometria a flusso per valutare il potere battericida di filtri destinati all'impiego in impianti aeraulici, *Attività Scientifica 21(3)*, 2012, pp. 25-27.

[245] Ghezzi, S.; Pagani, I.; Poli, G.; Perboni, S.; Vicenzi, E. Rapid Inactivation of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) by Tungsten Trioxide-Based (WO3). *Photocatalysis bioRxiv*, 2020. DOI: 10.1101/ 2020.08.01.232199.

[246] UNI EN 16798-1:2019. Prestazione energetica degli edifici - Ventilazione per gli edifici - Parte 1: Parametri di ingresso dell'ambiente interno per la progettazione e la valutazione della prestazione energetica degli edifici in relazione alla qualit`a dell'aria interna, all'ambiente termico, all'illuminazione e all'acustica - Modulo M1-6, 2019.

[247] European Commission, *COMMISSION DELEGATED REGULATION (EU) No 480/2014 of 3 March 2014 supplementing Regulation (EU) No 1303/2013 of the European Parliament and of the Council laying down common provisions on the European Regional Development Fund, the European Social Fund, the Cohesion Fund, the European Agricultural Fund for Rural Development and the European Maritime and Fisheries Fund and laying down general provisions on the European Regional Development Fund, the European Social Fund, the Cohesion Fund and the European Maritime and Fisheries Fund*. Official Journal of the European Union, 15.05.2014.

[248] Autorità di Regolazione per Energia Reti e Ambiente (ARERA), 2021. [Accessed: 2023]. URL: https://www.arera.it/it/prezzi.htm.

[249] National Institutes of Health. COVID-19 Treatment Guidelines Panel. Coronavirus Disease 2019 (COVID-19) Treatment Guidelines. [Accessed: 2023], URL: https://www.covid19treatmentguidelines.nih.gov/.

[250] Agenzia Italiana del Farmaco (AIFA). Raccomandazione AIFA sui farmaci per la gestione domiciliare di COVID-19 [Accessed: 2023]. URL: https://www.aifa.gov.it/documents/20142/1269602/IT_Raccomandazioni_AIFA_gestione_domiciliare_COVID-19_Vers4_14.12.2021.pdf.

[251] Quotidiano Online di informazione sanitaria. Altems: ogni ricovero Covid in terapia intensiva costa in media 25 mila euro. Vaccinarsi fa anche bene alle casse della Sanità pubblica, 2021. [Accessed: 2023]. URL:https://www.quotidianosanita.it/studi-e-analisi/articolo.php?articolo_id=99902.

[252] URL: https://www.prezzifarmaco.it/. [Accessed: 2023].

[253] Sanità Informazione. Come sta andando la somministrazione di anticorpi monoclonali in pazienti Covid, 2021. [Accessed: 2023]. URL: https://www.sanitainformazione.it/salute/come-sta-andando-la-somministrazione-di-anticorpi-monoclonali-in-pazienti-covid/.

[254] Istituto Superiore di Sanità (ISS). Report Esteso ISS. COVID-19: sorveglianza, impatto delle infezioni ed efficacia vaccinale. Aggiornamento nazionale 19 gennaio 2022 – ore 12:00, 2022. [Accessed: 2023]. URL: https://www.epicentro.iss.it/coronavirus/bollettino/Bollettino-sorveglianza-integrata-COVID-19_19-gennaio-2022.pdf.

[255] Edscuola. Oltre 300mila docenti italiani hanno più di 54 anni. Ecco tutti i numeri per et`a e scuola, 2020. [Accessed: 2023]. URL: https://www.edscuola.eu/wordpress/?p=131807.

[256] Lab24 @ IlSole24Ore. Coronavirus in Italia, i dati e la mappa. [Accessed: 2023]. URL: https://lab24.ilsole24ore.com/coronavirus/.

[257] ISTAT statistics. [Accessed:2023]. URL: http://dati.istat.it/.

[258] National Institute of Health (NIH). What is Pneumonia?, 2022. [Accessed: 2023]. URL: https://www.nhlbi.nih.gov/health/pneumonia.

[259] Centro Diagnostico Italiano. Le polmoniti: come si classificano, le cause e le modalità di contagio, 2020. [Accessed: 2023]. URL: https://www.cdi.it/news/le-polmoniti-come-si-classificano-le-cause-e-le-modalita-di-contagio/.

[260] Loizzi, M.; Oliaro, A.; Bucca, C.; De Rose, V.; Foschino Barbaro, M.P.; Resta, O.; Ruffini, E.; Scagliotti, G.V.; Sollitto, F. Malattie dell'apparato respiratorio. Ed. Minerva Medica, 2015.

[261] Polmonite acquisita in comunità (CAP). [Accessed: 2023]. URL: https://infettive.com/index.php/malattie-infettive/polmonite/polmonite-acquisita-in-comunita-cap.

[262] Sethi, S. Polmonite acquisita in comunità. Manuale MSD, 2022. [Accessed: 2023]. URL: https://www.msdmanuals.com/it-it/professionale/malattie-polmonari/polmonite/polmonite-acquisita-in-comunit%C3%A0?query=Polmonite%20acquisita%20in%20comunit%C3%A0.

[263] Cartabellotta, A.; Potena, A. Linee guida per la diagnosi e il trattamento della polmonite acquisita in comunità negli adulti. *Evidence 7(4)*, 2015. DOI: e1000110.

[264] di Pietro, M.L.; Kheiraoui, F.; de Waure, C.; Specchia, M.L.; Cadeddu, C.; Capizzi, S.; Gualano, M.R.; Sferrazza, A.; Nicolotti, N.; Ferriero, A.M.; Veneziano, M.A.; di Nardo, F.; Gliubizzi, M.D.; La Torre,

G.; Saulle, R.; Zollo, A.; Reggio, P.; Mantonavi, L.; Furneri, G.; Cortesi, P. Il vaccino pneumococcico 13-valente per la prevenzione delle infezioni da S. pneumoniae in età adulta: una valutazione di HTA. *Italian Journal of Public Health 2(4)*, 2013.

[265] Grinta, R.; Bini, K.; Verri, F. Dalla polmonite comunitaria alla polmonite nosocomiale: quali costi nel processo? *Società Italiana di Medicina Generale*, 2013.

[266] Regione Piemonte, *Deliberazione della Giunta Regionale 2 luglio 2013, n. 11-6036 Decreto Ministero della Salute 18/10/2012: Remunerazione delle prestazioni di assistenza ospedaliera per acuti, assistenza ospedaliera di riabilitazione e lungodegenza post acuzie e di assistenza specialistica ambulatoriale. Recepimento ed aggiornamento del nomenclatore tariffario regionale delle prestazioni di assistenza specialistica ambulatoriale di cui alla D.G.R n. 73-13176 del 26.07.2004.* (Allegato 1).

[267] Regione Piemonte, *Deliberazione della Giunta Regionale 2 luglio 2013, n. 14-6039: determinazione delle tariffe per attivita' di ricovero erogate dagli istituti pubblici, dai Presidi classificati, dagli IRCCS e dalle case di cura accreditate ai sensi dell'art. 15 del D.L. 6.7.2012 n. 95 convertito nella Legge 135 del 7.8.2012. Revoca delle DDGR n. 34-251 del 19.6.2000 e n. 57-644 del 31.7.2000.*

[268] Casali, L. Le polmoniti. [Accessed: 2023]. URL: https://www.area-c54.it/public/le%20polmoniti.pdf.

[269] Carbonara, S.; Stano, F. Polmonite acquisita in comunità nell’adulto immunocompetente: principi di terapia antimicrobica. [Accessed: 2023]. URL: https://bibliotecamedica.ausl.re.it/allegati/Bibliogrpolmonite%20di%20comunita.pdf.

[270] Libanore, M.; Bicocchi, R.; Pantaleoni, M.; Antonioli, M.P.; Napoli, N.; Ghinelli, F. Le polmoniti acquisite in comunità: appropriatezza dei ricoveri, fattori di rischio e terapia adottata. *Le infezioni in Medicina 1*, 2004, pp. 34-43.

[271] Figueira, J.; Greco, S.; Ehrogott, M. Multiple Criteria Decision Analysis: State of the Art Surveys, Springer New York, New York, NY, 2005. DOI:10.1007/b100605.

Chapter 5

[272] Lingua C.; Abbà I.; Becchio, C.; Viazzo, S.; Corgnati, S.P. Legislation and Standards for the implementation of reversable heat pump technologies in Mediterranean climate. In: CLIMAMED 2020, 10th

Mediterranean Congress of Climatization Towards Climate Neutral Mediterranean Buildings and Cities, Lisbon, Spain, 11-12 May 2021.

[273] Lingua, C.; Viazzo, S.; Corgnati, S.P.; Lena, S.; Prendin, L. Air/water heat pumps: energy and environmental assessment in Mediterranean residential building sector. In: Proceedings CLIMA 2022, 14th REHVA HVAC World Congress, Rotterdam, The Netherlands, 22-25 May 2022, pp. 1555-1562. DOI: 10.34641/clima.2022.35.

[274] Martinopoulos, G.; Papakostas, K.T.; Papadopoulos, A.M. A comparative review of heating systema in EU countries, based on efficiency and fuel cost. *Revew. Sustain. Energy Rev. 90*, 2018, pp. 687-699. DOI: 10.1016/j.rser.2018.03.060.

[275] European Parliament, *DIRECTIVE 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 establishing a framework for the setting of eco-design requirements for energy-related products.*

[276] European Parliament, *DIRECTIVE 2010/30/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products.*

[277] European Commission, *Commission Regulation 2016/2281/EU of 30 November 2016 implementing Directive 2009/125/EC of the European Parliament and of the Council establishing a framework for the setting of eco-design requirements for energy-related products, with regard to eco-design requirements for air heating products, cooling products, high temperature process chillers and fan coil units.*

[278] European Commission, *Regulation 2017/1369/EU of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/30/EU.*

[279] Dlgs 15 febbraio 2011, n 15, *attuazione della direttiva 2009/125/CE relativa all'istituzione di un quadro per l'elaborazione di specifiche per progettazione ecocompatibile dei prodotti connessi all'energia.*

[280] Dlgs 28 giugno 2012, n 104, *attuazione della direttiva 2010/30/UE, relativa all'indicazione del consumo di energia e di altre risorse dei prodotti connessi all'energia, mediante l'etichettatura ed informazioni uniformi relativa ai prodotti.*

[281] Dlgs 28 luglio 2016, n 141, *disposizioni integrative al decreto legislativo 4 luglio 2014, n. 102, di attuazione della direttiva 2012/27/UE sull'efficienza energetica, che modifica le direttive 2009/125/CE e 2010/30/UE e abroga le direttive 2004/8/CE e 2006/32/CE.*

[282] Dlgs 3 marzo 2011, n 28, a*ttuazione della direttiva 2009/28/CE sulla promozione dell'uso dell'energia da fonti rinnovabili, recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE.*

[283] UNI EN 14825:2019, *Condizionatori d'aria, refrigeratori di liquido e pompe di calore, con compressore elettrico, per il riscaldamento e il raffrescamento degli ambienti - Metodi di prova e valutazione a carico parziale e calcolo del rendimento stagionale.*

[284] UNI/TS 11300-4:2016, *Prestazioni energetiche degli edifici - Parte 4: Utilizzo di energie rinnovabili e di altri metodi di generazione per la climatizzazione invernale e per la produzione di acqua calda sanitaria.*

[285] DPR 4 agosto 2009, n 46, *aggiornamento del Piano regionale per il risanamento e la tutela della qualità dell'aria.*

[286] European Parliament, Committee on the Environment , Public Health and Food Safety. Proposal for a regulation of the European Parliament and of the Council on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014 (COM(2022)0150 – C9-0142/2022 – 2022/0099(COD)). 18-10.2023

[287] European Parliament. *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006.* Official Journal of the European Union. 20.05.2014.

[288] European Parliament, Review of the regulation on fluorinated greenhouse gases, 2022. [Accessed: 2023]. URL: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/730323/EPRS_BRI(2022)730323_EN.pdf.

[289] Roccatello, E.; Prada, A.; Baggio, P.; Baratieri, M. Analysis of the influence of control strategy and heating loads on the performance of hybrid heat pump systems for residential buildings. *Energies 15(3)*, 2022, p. 732. DOI: 10.3390/en15030732.

[290] Ala, G.; Orioli, A.; Di Gangi, A. Energy and economic analysis of air-to-air heat pumps as an alternative to domestic gas boiler heating systems in the South of Italy. *Energy 173*, 2019, pp. 59-74. DOI: 10.1016/j.energy.2019.02.011.

[291] Presidente della Repubblica. *Legge 30 Dicembre 2020, No 178. Bilancio di previsione dello Stato per l'anno finanziario 2021 e bilancio pluriennale per il triennio 2021-2023*. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 322 del 30.12.2020. Suppl. Ordinario n. 46.

[292] Presidente della Repubblica. *Legge 30 Dicembre 2021, No 234. Bilancio di previsione dello Stato per l'anno finanziario 2022 e bilancio*

pluriennale per il triennio 2022-2024. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 310 del 31.12.2021. Suppl. Ordinario n. 49.

[293] Ente Nazionale Italiano di Unificazione. UNI/TS 11300-4:2016. *Prestazioni energetiche degli edifici. Parte 4: Utilizzo di energie rinnovabili e di altri metodi di generazione per la climatizzazione invernale e per la produzione di acqua calda sanitaria.* 31 marzo 2016.

[294] Ente Nazionale Italiano di Unificazione. UNI/TS 11300-5:2016. *Prestazioni energetiche degli edifici. Parte 5: Calcolo dell'energia primaria e della quota di energia da fonti rinnovabili*. 31 marzo 2016.

[295] Zinzi, M.; Mattoni, B.; Roda, R.; Ponzo, V. On the cost reduction of a nearly zero energy multifamily house in Italy: technical and economic assessment. *Energy Procedia 158*, 2019, pp. 3774-3781. DOI: 10.1016/j.egypro.2019.01.877.

[296] Zinzi, M.; Pagliaro, F.; Agnoli, S.; Bisegna, F.; Iatauro, D. On the Built-Environment Quality in Nearly Zero-Energy Renovated Schools: Assessment and Impact of Passive Strategies. *Energies 14*, 2021, p. 2799. DOI: 10.3390/ en14102799.

[297] Edilclima. Software termotecnica. EC 700: Calcolo prestazioni energetiche degli edifici. [Accessed: 2021]. URL: https://www.edilclima.it/software-termotecnica/prog-termotecnica-energetica/scheda/700.

[298] Comitato di Normazione Europeo, UNI EN ISO 52016-1:2018. Prestazione energetica degli edifici. Fabbisogni energetici per riscaldamento e raffrescamento, temperature interne e carichi sensibili e latenti. Parte 1: Procedure di calcolo. 1 marzo 2018.

[299] Ente Nazionale Italiano di Unificazione. UNI EN 12831-1:2018. Prestazione energetica degli edifici. Metodo per il calcolo del carico termico di progetto. Parte 1: Carico termico per il riscaldamento degli ambienti. 8 marzo 2018.

[300] Ente Nazionale Italiano di Unificazione. UNI/TS 11300-1:2014. *Prestazioni energetiche degli edifici. Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione invernale e estiva.* 2 ottobre 2014.

[301] Ente Nazionale Italiano di Unificazione. UNI/TS 11300-3:2010. *Prestazioni energetiche degli edifici. Parte 3: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione estiva.* 25 marzo 2010.

Appendix A

The present Appendix compiles the papers that were published during the Ph.D. programme.

- Becchio, C.; Crespi, G.; Corgnati, S.P.; **Lingua, C.** (2023). Impacts of different HVAC systems configurations on health and students' performance in Italian schools in post-pandemic era. *Sustainable Energy Technologies And Assessments 60*, p. 103479.

- **Lingua, C.;** Crespi, G.; Becchio, C.; Corgnati, S.P. (2023). Designing IAQ-Resilient Post-Pandemic Buildings. *Sustainability 15*, pp. 2187-2203.

- Andre, M.; Bandurski, K.; Bandyopadhyay, A.; Bavaresco, M.; Buonocore, C.; de Castro, Hahn, J.; Kane, M.; **Lingua, C.**; Pioppi, B.; Piselli, C.; Spigliantini, G.; Vergerio, G.; Lamberts, R. (2023). Practical differences in operating buildings across countries and climate zones: Perspectives of building managers/operators. *Energy and Buildings 278*, p. 112650.

- Chinazzo, G.; Andersen, R. K.; Azar, E.; Barthelmes, V. M.; Becchio, C.; Belussi, L.; Berger, C.; Carlucci, S.; Corgnati, S.P.; Crosby, S.; Danza, L.; de Castro, L.; Favero, M.; Gauthier, S.; Hellwig, R.T.; Jin, Q.; Kim, J.; Khanie, M.S.; Khovalyg, D.; **Lingua, C.**; Luna-Navarro, A.; Mahdavi, A.; Miller, C.; Mino-Rodriguez, I.; Pigliautile, I.; Pisello, A.L.; Rupp, R.F.; Sadick, A.; Salamone, F.; Schweiker, M.; Syndicus, M.; Spigliantini, G.; Vasquez, N.G.; Vakalis, D.; Vellei, M.; Wei, S. (2022). Quality criteria for multi-domain studies in the indoor environment: Critical review towards research guidelines and recommendations. *Building and Environment 226*, pp. 109719-109719.

- **Lingua, C.**; Viazzo, S.; Corgnati, S.P.; Lena, S.; Prendin, L. (2022). Air/water heat pumps: energy and environmental assessment in Mediterranean residential building sector. In: Proceedings CLIMA 2022, 14th REHVA HVAC World Congress, Rotterdam, The Netherlands, 22-25 May 2022, pp. 1555-1562.

- Cakan, M.; Becchio, C.; Corgnati, S.P.; Mazzarella, L.; Quiles, P.; Ekren, O.; Yay, T.; Dell'Anna, F.; Bottero, M.; **Lingua, C.**; Toksoy, M.; Aktakka, S.; Karadeniz, Z.H.; Saglam, S.; Arisoy, A. (2021). Design Strategies for Residential Buildings in Mediterranean Regions - Part 2. European Guidebook 31. Federation of European Heating, Ventilation and Air Conditioning associations (REHVA), Brussels, Belgium.

- Sarran, L.; Brackley, C.; Day, J.K.; Bandurski, K.; Andrè, M.; Spigliantini, G.; Roetzel, A.; Gauthier, S.; Stopps, H.; Agee, P.; Crosby, S.; **Lingua, C.** (2021). Untold stories from the field: a novel platform for collecting practical learnings on Human-Building Interactions. In: Proceedings IAQ 2020: Indoor Environmental Quality Performance Approaches. Transitioning from IAQ to IEQ., Athens, Greece, 4-6 May 2022, pp. 455-465.

- Becchio, C.; Crespi, G.; **Lingua, C.**; Corgnati, S.P. (2021). Coupling energy and numerical analyses for evaluating possible ventilation strategies in a NZEB. In: Proceedings ROOMVENT 2020, 15th Roomvent Conference on energy efficiency ventilation for healthy future buildings, Turin, Italy, 15 February 2021.

- **Lingua C.**; Abbà I.; Becchio, C.; Viazzo, S.; Corgnati, S.P. (2021). Legislation and Standards for the implementation of reversable heat pump technologies in Mediterranean climate. In: CLIMAMED 2020, 10th Mediterranean Congress of Climatization Towards Climate Neutral Mediterranean Buildings and Cities, Lisbon, Spain, 11-12 May 2021.

- Abbà, I.; Crespi, G.; **Lingua, C.**; Becchio, C.; Corgnati, S.P. (2020). Theoretical and actual energy behavior of a cost-optimal based Nearly-Zero Energy Building. In: AICARR JOURNAL.

- **Lingua, C.**; Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F.; Fabi, V. (2019). Energy and Economic Evaluation of Thermal Comfort. The Case Study of the Hotel Residence L'Orologio. In: Proceedings of Building Simulation 2019, 16th Conference of

International Building Performance Simulation Association (IBPSA), Rome, Italy, 2 September 2019.

- Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell’Anna, F.; Fabi, V.; **Lingua, C.**; Prendin, L.; Ranieri, M. (2019). Effects on energy savings and occupant health of an antibacterial filter. In: Proceedings of CLIMA 2019, REHVA 13rd HVAC World Congress, Bucharest, Romania, 26 May 2019.

- Becchio, C.; Corgnati, S.P.; Fabi, V.; **Lingua, C.**, Prendin, L.; Ranieri, M. (2019). Costs and benefits of antibacterial filter and its effects on energy saving, human health and worker productivity. In: Proceedings of 51st AiCARR International Conference, the human dimension of building energy performance, Venice, Italy, 20 February 2019.

- Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell’Anna, F.; Fabi, V.; **Lingua, C.**; Prendin, L.; Ranieri, M. (2019). The effects of indoor and outdoor air pollutants on workers productivity in office building. In: Proceedings of CLIMA 2019, REHVA 13rd HVAC World Congress, Bucharest, Romania, 26 May 2019.

- **Lingua, C.**; Becchio, C.; Corgnati, S.P. (2019). The effects of different ventilation types on IAQ and occupants' health in residential buildings. In: Proceedings of Efs 2019, 4th energy for sustainability International Conference: Designing a sustainable future, Turin, Italy, 24 June 2019.

Appendix B

The present Appendix compiles the Excel tables which included all cost and benefit data utilised in developing the CBA for both the C and PC configurations (Chapter 4).

Specifically, they are organised in three different tables for each case study: (i) the C configuration (Tables 22 and 25), (ii) the PC configuration (Tables 23, 26, 28 and 30), and (iii) the incremental BCR outputs: C vs. PC configuration (Tables 24, 27, 29 and 31). Only Table 25 shows the same C configuration for primary school, junior high, and high school typologies.

The investment, energy, maintenance, replacement, and disposal costs in the following tables are abbreviated with I_C, E_C, M_C, R_C, D_C, respectively.

Table 22: Total costs and benefits associated to the C configuration in pre-school typology.

Year		1	2	3	4	5	6	7	8	9	10
I_C		15,700 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
E_C		22,449 €	22,449 €	22,449 €	22,449 €	22,449 €	22,449 €	22,449 €	22,449 €	22,449 €	22,449 €
M_C	Standard pre-filter	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €
	Standard filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
R_C	Standard pre-filter	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €
	Standard filter	120 €	240 €	120 €	240 €	120 €	240 €	120 €	240 €	120 €	240 €
D_C	Standard pre-filter	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €
	Standard filter	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €
Total costs *		**16,244 €**	**664 €**	**544 €**	**664 €**	**544 €**	**664 €**	**544 €**	**664 €**	**544 €**	**664 €**

Health benefits	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
Energy benefits	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
Total benefits	**0 €**	**0 €**	**0 €**	**0 €**	**0 €**	**0 €**	**0 €**	**0 €**	**0 €**	**0 €**

* Total cost does not include energy costs.

Table 23: Total costs and benefits associated to the PC configuration in pre-school typology.

Year		1	2	3	4	5	6	7	8	9	10
I_C		16,670 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
E_C		3,551 €	3,551 €	3,551 €	3,551 €	3,551 €	3,551 €	3,551 €	3,551 €	3,551 €	3,551 €
M_C	Standard pre-filter	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €
	Biocidal filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
	Photocatalytic filter	150 €	150 €	150 €	150 €	100 €	150 €	150 €	150 €	150 €	100 €
R_C	Standard pre-filter	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €
	Biocidal filter	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
D_C	Standard pre-filter	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €
	Biocidal filter	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0.50 €	0 €	0 €	0 €	0 €	0.50 €
Total costs *		**17,554 €**	**1,194 €**	**884 €**	**1,194 €**	**1,434 €**	**1,194 €**	**884 €**	**1,194 €**	**884 €**	**1,745 €**

Health benefits	483 €	483 €	483 €	483 €	483 €	483 €	483 €	483 €	483 €	483 €
Energy benefits	18,898 €	18,898 €	18,898 €	18,898 €	18,898 €	18,898 €	18,898 €	18,898 €	18,898 €	18,898 €
Total benefits	**19,382 €**	**19,382 €**	**19,382 €**	**19,382 €**	**19,382 €**	**19,382 €**	**19,382 €**	**19,382 €**	**19,382 €**	**19,382 €**

Table 24: Incremental BCR outputs: C vs. PC configuration in pre-school typology.

Year	1	2	3	4	5	6	7	8	9	10
Δ total benefits	19,382 €	19,382 €	19,382 €	19,382 €	19,382 €	19,382 €	19,382 €	19,382 €	19,382 €	19,382 €
Δ total costs	1,310 €	530 €	340 €	530 €	891 €	530 €	340 €	530 €	340 €	1,081 €

Discounted benefits *	18,817 €	18,269 €	17,737 €	17,220 €	16,719 €	16,232 €	15,759 €	15,300 €	14,854 €	14,422 €	**165,329 €**
Discounted costs *	1,272 €	500 €	311 €	471 €	768 €	444 €	276 €	418 €	261 €	804 €	**5,525 €**

ΔB/ΔC	**29.92**

---

* Benefits and costs are actualised using an annual discount rate of 3% and considering a period of 10 years.

Table 25: Total costs and benefits associated to the C configuration in primary school, junior high, and high school typologies.

Year		1	2	3	4	5	6	7	8	9	10
I_C		15,700 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
E_C		24,742 €	24,742 €	24,742 €	24,742 €	24,742 €	24,742 €	24,742 €	24,742 €	24,742 €	24,742 €
M_C	Standard pre-filter	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €
	Standard filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
R_C	Standard pre-filter	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €
	Standard filter	120 €	240 €	120 €	240 €	120 €	240 €	120 €	240 €	120 €	240 €
D_C	Standard pre-filter	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €
	Standard filter	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €
Total costs *		**16,244 €**	**664 €**	**544 €**	**664 €**	**544 €**	**664 €**	**544 €**	**664 €**	**544 €**	**664 €**

Health benefits	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
Energy benefits	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
Performance benefits	200,357 €	200,357 €	200,357 €	200,357 €	200,357 €	200,357 €	200,357 €	200,357 €	200,357 €	200,357 €
Total benefits	**200,357 €**	**200,357 €**	**200,357 €**	**200,357 €**	**200,357 €**	**200,357 €**	**200,357 €**	**200,357 €**	**200,357 €**	**200,357 €**

* Total cost does not include energy costs.

Table 26: Total costs and benefits associated to the PC configuration in primary school typology.

Year		1	2	3	4	5	6	7	8	9	10
I_C		16,670 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
E_C		3,122 €	3,122 €	3,122 €	3,122 €	3,122 €	3,122 €	3,122 €	3,122 €	3,122 €	3,122 €
M_C	Standard pre-filter	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €
	Biocidal filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
	Photocatalytic filter	150 €	150 €	150 €	150 €	100 €	150 €	150 €	150 €	150 €	100 €
R_C	Standard pre-filter	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €
	Biocidal filter	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
D_C	Standard pre-filter	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €
	Biocidal filter	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0.50 €	0 €	0 €	0 €	0 €	0.50 €
Total costs *		**17,554 €**	**1,194 €**	**884 €**	**1,194 €**	**1,434 €**	**1,194 €**	**884 €**	**1,194 €**	**884 €**	**1,745 €**
Health benefits		325 €	325 €	325 €	325 €	325 €	325 €	325 €	325 €	325 €	325 €
Energy benefits		21,621 €	21,621 €	21,621 €	21,621 €	21,621 €	21,621 €	21,621 €	21,621 €	21,621 €	21,621 €
Performance benefits		205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €
Total benefits		**227,681 €**	**227,681 €**	**227,681 €**	**227,681 €**	**227,681 €**	**227,681 €**	**227,681 €**	**227,681 €**	**227,681 €**	**227,681 €**

Table 27: Incremental BCR outputs: C vs. PC configuration in primary school typology.

Year	1	2	3	4	5	6	7	8	9	10
Δ total benefits	27,324 €	27,324 €	27,324 €	27,324 €	27,324 €	27,324 €	27,324 €	27,324 €	27,324 €	27,324 €
Δ total costs	1,310 €	530 €	340 €	530 €	891 €	530 €	340 €	530 €	340 €	1,081 €

Discounted benefits [*]	26,528 €	25,756 €	25,005 €	24,277 €	23,570 €	22,883 €	22,217 €	21,570 €	20,942 €	20,332 €	**233,079 €**
Discounted costs [*]	1,272 €	500 €	311 €	471 €	768 €	444 €	276 €	418 €	261 €	804 €	**5,525 €**

ΔB/ΔC **42.19**

[*] Benefits and costs are actualised using an annual discount rate of 3% and considering a period of 10 years.

Table 28: Total costs and benefits associated to the PC configuration in junior high school typology.

Year		1	2	3	4	5	6	7	8	9	10
I_C		16,670 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
E_C		3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €
M_C	Standard pre-filter	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €
	Biocidal filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
	Photocatalytic filter	150 €	150 €	150 €	150 €	100 €	150 €	150 €	150 €	150 €	100 €
R_C	Standard pre-filter	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €
	Biocidal filter	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
D_C	Standard pre-filter	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €
	Biocidal filter	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0.50 €	0 €	0 €	0 €	0 €	0.50 €
Total costs *		**17,554 €**	**1,194 €**	**884 €**	**1,194 €**	**1,434 €**	**1,194 €**	**884 €**	**1,194 €**	**884 €**	**1,745 €**

Health benefits	561 €	561 €	561 €	561 €	561 €	561 €	561 €	561 €	561 €	561 €
Energy benefits	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €
Performance benefits	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €
Total benefits	**227,626 €**	**227,626 €**	**227,626 €**	**227,626 €**	**227,626 €**	**227,626 €**	**227,626 €**	**227,626 €**	**227,626 €**	**227,626 €**

Table 29: Incremental BCR outputs: C vs. PC configuration in junior high school typology.

Year	1	2	3	4	5	6	7	8	9	10
Δ total benefits	27,269 €	27,269 €	27,269 €	27,269 €	27,269 €	27,269 €	27,269 €	27,269 €	27,269 €	27,269 €
Δ total costs	1,310 €	530 €	340 €	530 €	891 €	530 €	340 €	530 €	340 €	1,081 €

Discounted benefits [*]	26,475 €	25,704 €	24,955 €	24,228 €	23,523 €	22,838 €	22,217 €	21,527 €	20,900 €	20,291 €	**232,612 €**
Discounted costs [*]	1,272 €	500 €	311 €	471 €	768 €	444 €	276 €	418 €	261 €	804 €	**5,525 €**

ΔB/ΔC	**42.10**

[*] Benefits and costs are actualised using an annual discount rate of 3% and considering a period of 10 years.

Table 30: Total costs and benefits associated to the PC configuration in high school typology.

Year		1	2	3	4	5	6	7	8	9	10
I_C		16,670 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
E_C		3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €	3,412 €
M_C	Standard pre-filter	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €	300 €
	Biocidal filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
	Photocatalytic filter	150 €	150 €	150 €	150 €	100 €	150 €	150 €	150 €	150 €	100 €
R_C	Standard pre-filter	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €	120 €
	Biocidal filter	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €	310 €	620 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €	0 €
D_C	Standard pre-filter	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €	3 €
	Biocidal filter	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €	0.50 €	1 €
	Photocatalytic filter	0 €	0 €	0 €	0 €	0.50 €	0 €	0 €	0 €	0 €	0.50 €
Total costs *		**17,554 €**	**1,194 €**	**884 €**	**1,194 €**	**1,434 €**	**1,194 €**	**884 €**	**1,194 €**	**884 €**	**1,745 €**

Health benefits	600 €	600 €	600 €	600 €	600 €	600 €	600 €	600 €	600 €	600 €
Energy benefits	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €	21,331 €
Performance benefits	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €	205,735 €
Total benefits	**227,666 €**	**227,666 €**	**227,666 €**	**227,666 €**	**227,666 €**	**227,626 €**	**227,666 €**	**227,666 €**	**227,666 €**	**227,666 €**

Table 31: Incremental BCR outputs: C vs. PC configuration in high school typology.

Year	1	2	3	4	5	6	7	8	9	10
Δ total benefits	27,309 €	27,309 €	27,309 €	27,309 €	27,309 €	27,309 €	27,309 €	27,309 €	27,309 €	27,309 €
Δ total costs	1,310 €	530 €	340 €	530 €	891 €	530 €	340 €	530 €	340 €	1,081 €

Discounted benefits [*]	26,513 €	25,741 €	24,991 €	24,264 €	23,557 €	22,871 €	22,205 €	21,558 €	20,930 €	20,320 €	**232,950 €**
Discounted costs [*]	1,272 €	500 €	311 €	471 €	768 €	444 €	276 €	418 €	261 €	804 €	**5,525 €**

ΔB/ΔC **42.16**

[*] Benefits and costs are actualised using an annual discount rate of 3% and considering a period of 10 years.

Appendix C

The present Appendix provides additional information on the case study presented in Chapter 5. Details of the stratifications of the opaque envelope (external wall, floor, and roof) of each different envelope typology (envelopes A, B, C, and D) considered in the simulated models are described from Table 32 to Table 40. Subsequently, Tables 41 and 42 provide the results of non-renewable primary energy for each energy service offered ($EP_{H,nren}$, $EP_{W,nren}$, $EP_{V,nren}$) for new buildings case study and renovation of existing buildings one, respectively. While Tables 43 and 44 show the energy delivered by energy carriers ($Q_{del,i}$) used to assess the CO_2 emission index in all the simulated models for new buildings case study and renovation of existing buildings one, respectively. Finally, a detail description of the main energy ($EP_{g,nren}$) and environmental-related (CO_2) results are provided for each simulated models in Tables 45 and 46.

Table 32: Characterisation of the external wall layer in envelope A.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Plasterboard	13	0.21	0.06
2	Rock wool panel	40	0.03	1.14
3	Semi-solid blocks in brick	200	0.43	0.47
4	Rock wool panel	160	0.03	4.57
5	Plasterboard	13	0.21	0.06

Table 33: Characterisation of the floor layer in envelope A.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Ceramic tile	20	1.30	0.01
2	Thin concrete subfloor	50	0.90	0.06
3	Extruded polystyrene foam panel	40	0.03	1.21
4	Lightweight substrate Perlideck	150	0.06	2.38
5	Extruded polystyrene foam panel	100	0.03	3.03
6	Sand and gravel concrete	100	1.61	0.06

Table 34: Characterisation of the roof layer in envelope A.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Extruded polystyrene foam panel	80	0.03	2.42
2	Extruded polystyrene foam panel	80	0.03	2.42
3	Concrete screed with metal mesh	40	1.49	0.03
4	Brick slab	220	0.36	0.61
5	Gypsum and sand plaster	15	0.80	0.02

Table 35: Characterisation of the external wall layer in envelope B.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Lime and gypsum plaster	10	0.70	0.01
2	Brick masonry	80	0.30	0.27
3	Rock wool panel	80	0.03	2.29
4	Brick masonry	240	0.30	0.80
5	Concrete and sand plaster	10	1.00	0.01

Table 36: Characterisation of the floor layer in envelope B.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Ceramic tile	10	1.30	0.00
2	Thin concrete subfloor	50	0.90	0.05
3	Extruded polystyrene foam panel	40	0.03	1.21
4	Lightweight substrate Perlideck	100	0.06	1.59
5	Sand and gravel concrete	80	1.61	0.05

Table 37: Characterisation of the roof layer in envelope B.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Extruded polystyrene foam panel	80	0.03	2.42
2	Extruded polystyrene foam panel	80	0.03	2.42
3	Concrete screed with metal mesh	40	1.49	0.03
4	Brick slab	220	0.36	0.61
5	Gypsum and sand plaster	15	0.80	0.02

Table 38: Characterisation of the external wall layer in envelopes C and D.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Lime and gypsum plaster	15	0.70	0.02
2	Brick masonry	120	0.30	0.40
3	Weakly ventilated cavity	60	-	-
4	Brick masonry	120	0.30	0.40
5	Concrete and sand plaster	15	1.00	0.02

Table 39: Characterisation of the floor layer in envelopes C and D.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Ceramic tile	10	1.30	0.008
2	Thin concrete subfloor	50	0.90	0.05
3	Thin concrete subfloor	100	0.90	0.11
4	Sand and gravel concrete	80	1.61	0.05

Table 40: Characterisation of the roof layer in envelopes C and D.

	Description	Thickness [mm]	Conductance [W/mK]	Resistance [m^{2}K/W]
1	Concrete screed with metal mesh	40	1.49	0.03
2	Brick slab	220	0.36	0.61
3	Gypsum and sand plaster	15	0.80	0.02

Table 41: Non-renewable primary energy indicator for each energy service offered in new building application.

			$EP_{H,nren}$ [kWh/(m^2y)]			**$EP_{W,nren}$ [kWh/(m^2y)]**			**$EP_{V,nren}$ [kWh/(m^2y)]**		
			Condensing Boiler	**HP (1)**	**HP (2)**	**Condensing Boiler**	**HP (1)**	**HP (2)**	**Condensing Boiler**	**HP (1)**	**HP (2)**
Model SA	Radiant Floor	**Turin**	18.23	9.10	10.36	17.71	12.83	13.88	16.13	16.13	16.13
	Fan coil		20.86	12.08	13.24	17.71	12.83	13.88	16.13	16.13	16.13
	Radiant Floor	**Rome**	2.29	0.74	0.99	15.08	9.40	10.14	16.13	16.13	16.13
	Fan coil		2.53	1.03	1.07	15.08	9.40	10.14	16.13	16.13	16.13
	Radiant Floor	**Palermo**	1.00	0.39	0.48	13.62	7.99	8.38	16.13	16.13	16.13
	Fan coil		1.00	0.54	0.53	13.62	7.99	8.38	16.13	16.13	16.13
Model SB	Radiant Floor	**Turin**	33.83	16.02	17.5	17.71	12.83	13.88	16.12	16.12	16.12
	Fan coil		38.69	21.99	22.9	17.71	12.83	13.88	16.12	16.12	16.12
	Radiant Floor	**Rome**	7.66	2.76	3.53	15.08	9.40	10.14	16.12	16.12	16.12
	Fan coil		8.89	3.87	4.96	15.08	9.40	11.07	16.12	16.12	16.12
	Radiant Floor	**Palermo**	3.29	0.91	1.11	13.62	7.98	8.38	16.12	16.12	16.12
	Fan coil		3.83	1.29	1.25	13.62	7.98	8.38	16.12	16.12	16.12

Model LA	Radiant Floor	**Turin**	20.04	9.92	-	15.63	10.84	-	11.09	11.09	-
	Fan coil		22.93	13.73	-	15.63	10.84	-	11.09	11.09	-
	Radiant Floor	**Rome**	3.57	1.35	1.58	13.31	8.12	8.20	11.09	11.09	11.09
	Fan coil		4.02	1.75	1.79	13.31	8.12	8.20	11.09	11.09	11.09
	Radiant Floor	**Palermo**	1.49	0.54	0.65	12.02	6.90	7.10	11.09	11.09	11.09
	Fan coil		1.71	0.69	0.68	12.02	6.90	7.10	11.09	11.09	11.09
Model LB	Radiant Floor	**Turin**	34.07	15.76	-	15.62	10.84	-	11.09	11.09	-
	Fan coil		38.84	22.74	-	15.62	10.84	-	11.09	11.09	-
	Radiant Floor	**Rome**	9.23	3.55	4.09	13.30	8.12	8.20	11.09	11.09	11.09
	Fan coil		10.65	4.72	4.93	13.30	8.12	8.20	11.09	11.09	11.09
	Radiant Floor	**Palermo**	4.45	1.57	1.86	12.02	6.89	7.10	11.09	11.09	11.09
	Fan coil		5.12	2.07	2.00	12.02	6.89	7.10	11.09	11.09	11.09

Table 42: Non-renewable primary energy indicator for each energy service offered in existing building application.

			$EP_{H,nren}$ [kWh/(m^{2}y)]			**$EP_{W,nren}$ [kWh/(m^{2}y)]**		
			Condensing Boiler	**HP (1)**	**HP (2)**	**Condensing Boiler**	**HP (1)**	**HP (2)**
Model SC	Radiant Floor	**Rome**	87.84	32.17	-	15.05	9.77	-
	Fan coil		98.51	47.35	-	15.05	9.77	-
	Radiant Floor	**Palermo**	49.48	16.42	16.55	13.60	8.16	8.61
	Fan coil		55.89	23.81	21.21	13.60	8.16	8.61
Model SD	Radiant Floor	**Rome**	93.49	34.04	-	15.05	9.77	-
	Fan coil		104.52	50.07	-	15.05	9.77	-
	Radiant Floor	**Palermo**	53.57	18.62	-	13.60	8.29	-
	Fan coil		60.57	27.05	-	13.60	8.29	-
Model LC	Radiant Floor	**Palermo**	50.77	16.88	-	11.93	6.80	-
	Fan coil		56.94	24.88	-	11.93	6.80	-
Model LD	Radiant Floor	**Palermo**	53.94	17.83	-	11.93	6.80	-
	Fan coil		60.30	26.24	-	11.93	6.80	-

Table 43: Energy delivered by energy carriers to assess the CO_2 emission indicator in new building application.

			$Q_{del.i}$			
			Condensing Boiler		**HP (1)**	**HP (2)**
			Natural gas [Nm^3/y]	**Electricity [kWh/y]**	**Electricity [kWh/y]**	**Electricity [kWh/y]**
Model SA	Radiant Floor	**Turin**	500	1,284	2,893	3,069
	Fan coil		532	1,312	3,120	3,288
	Radiant Floor	**Rome**	244	1,242	1,997	2,073
	Fan coil		247	1,243	2,019	2,079
	Radiant Floor	**Palermo**	206	1,238	1,863	1,900
	Fan coil		206	1,238	1,875	1,904
Model SB	Radiant Floor	**Turin**	714	1,325	3,421	3,613
	Fan coil		773	1,381	3,874	4,024
	Radiant Floor	**Rome**	318	1,256	2,151	2,266
	Fan coil		333	1,266	2,235	2,446
	Radiant Floor	**Palermo**	237	1,244	1,903	1,948

	Fan coil		244	1,248	1,932	1,959
Model LA	Radiant Floor	**Turin**	720	1,314	3,522	-
	Fan coil		770	1,366	3,942	-
	Radiant Floor	**Rome**	344	1,252	2,274	2,427
	Fan coil		352	1,256	2,318	2,331
	Radiant Floor	**Palermo**	276	1,244	2,048	2,084
	Fan coil		280	1,245	2,065	2,087
Model LB	Radiant Floor	**Turin**	1,000	1,367	4,168	-
	Fan coil		1,081	1,466	4,940	-
	Radiant Floor	**Rome**	457	1,273	2,517	2,585
	Fan coil		482	1,294	2,647	2,678
	Radiant Floor	**Palermo**	335	1,255	2,162	2,217
	Fan coil		347	1,264	2,218	2,233

Table 44: Energy delivered by energy carriers to assess the CO_2 emission indicator in existing building application.

			$Q_{del.i}$			
			Condensing Boiler		**HP (1)**	**HP (2)**
			Natural gas [Nm^3/y]	**Electricity [kWh/y]**	**Electricity [kWh/y]**	**Electricity [kWh/y]**
Model SC	Radiant Floor	**Rome**	1,431	241	3,221	-
	Fan coil		1,551	420	4,386	-
	Radiant Floor	**Palermo**	879	140	1,887	1,932
	Fan coil		955	223	2,455	2,290
Model SD	Radiant Floor	**Rome**	1,509	256	3,364	-
	Fan coil		1,631	449	4,595	-
	Radiant Floor	**Palermo**	935	151	2,066	-
	Fan coil		1,016	258	2,713	-
Model LC	Radiant Floor	**Palermo**	1,267	206	2,639	-
	Fan coil		1,364	372	3,531	-
Model LD	Radiant Floor	**Palermo**	1,331	218	2,744	-
	Fan coil		1,430	396	3,682	-

Table 45: Energy- and environmental-related benefits for all the simulated models in new building application.

			$EP_{g,nren}$ [kWh/(m^2y)]			**CO_2 [kg CO_2/y]**		
			Condensing Boiler	**HP (1)**	**HP (2)**	**Condensing Boiler**	**HP (1)**	**HP (2)**
Model SA	Radiant Floor	**Turin**	52.07	38.06	40.37	1,634	1,331	1,412
	Fan coil		54.7	41.04	43.25	1,714	1,435	1,513
	Radiant Floor	**Rome**	33.5	26.27	27.26	1,080	919	954
	Fan coil		33.74	26.56	27.34	1,088	929	956
	Radiant Floor	**Palermo**	30.75	24.51	24.99	999	857	874
	Fan coil		30.75	24.66	25.04	999	862	876
Model SB	Radiant Floor	**Turin**	67.66	44.97	47.5	2,099	1,574	1,662
	Fan coil		72.52	50.94	52.9	2,248	1,782	1,851
	Radiant Floor	**Rome**	38.86	28.28	29.79	1,241	990	1,042
	Fan coil		40.09	29.39	32.15	1,277	1,028	1,125
	Radiant Floor	**Palermo**	33.03	25.01	25.61	1,067	875	896

	Fan coil		33.57	25.39	25.75	1,083	889	901
Model LA	Radiant Floor	**Turin**	46.76	31.85	-	2,108	1,620	-
	Fan coil		49.65	35.66	-	2,236	1,814	-
	Radiant Floor	**Rome**	27.97	20.56	20.87	1,294	1,046	1,116
	Fan coil		28.42	20.96	21.08	1,313	1,066	1,072
	Radiant Floor	**Palermo**	24.6	18.53	18.84	1,148	942	958
	Fan coil		24.82	18.68	18.87	1,158	950	960
Model LB	Radiant Floor	**Turin**	60.78	37.69	-	2,717	1,917	-
	Fan coil		65.55	44.67	-	2,930	2,273	-
	Radiant Floor	**Rome**	33.62	22.76	23.38	1,539	1,158	1,189
	Fan coil		35.04	23.93	24.22	1,602	1,217	1,232
	Radiant Floor	**Palermo**	27.56	19.55	20.05	1,276	995	1,020
	Fan coil		28.23	20.05	20.19	1,305	1,020	1,027

Table 46: Energy- and environmental-related benefits for all the simulated models in existing building application.

			$EP_{g,nren}$ [kWh/(m^{2}y)]			**CO_2 [kg CO_2/y]**		
			Condensing Boiler	**HP (1)**	**HP (2)**	**Condensing Boiler**	**HP (1)**	**HP (2)**
Model SC	Radiant Floor	**Rome**	102.89	41.94	-	3,098	1,482	-
	Fan coil		113.56	57.12	-	3,430	2,018	-
	Radiant Floor	**Palermo**	63.08	24.58	25.16	1,899	868	889
	Fan coil		69.49	31.97	29.82	2,097	1,129	1,053
Model SD	Radiant Floor	**Rome**	108.54	43.81	-	3,269	1,547	-
	Fan coil		119.57	59.84	-	3,612	2,114	-
	Radiant Floor	**Palermo**	67.17	26.91	-	2,022	950	-
	Fan coil		74.17	35.34	-	2,239	1,248	-
Model LC	Radiant Floor	**Palermo**	62.7	23.68	-	2,739	1,214	-
	Fan coil		68.87	31.68	-	3,019	1,624	-
Model LD	Radiant Floor	**Palermo**	65.87	24.63	-	2,877	1,262	-
	Fan coil		72.23	33.04	-	3,166	1,694	-