Energy resilience to climate change of the school building stock in the Mediterranean area: the case of Apulia Region

D.R.S.A.T.E.

POLITECNICO DI BARI

06

2024

Doctor in Risk And Environmental, Territorial And Building Development

Coordinator: Prof. Vito Iacobellis

XXXVI CYCLE
Curriculum: ICAR/10

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Department of Civil, Environmental, Building Engineering and Chemistry

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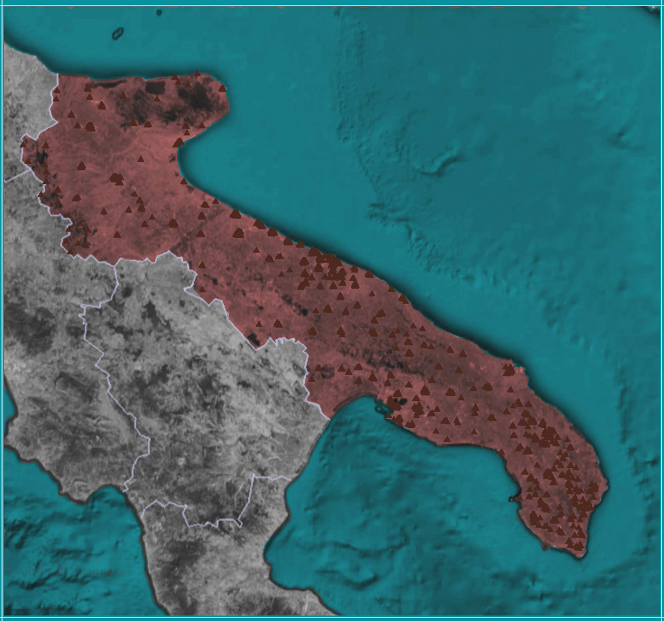

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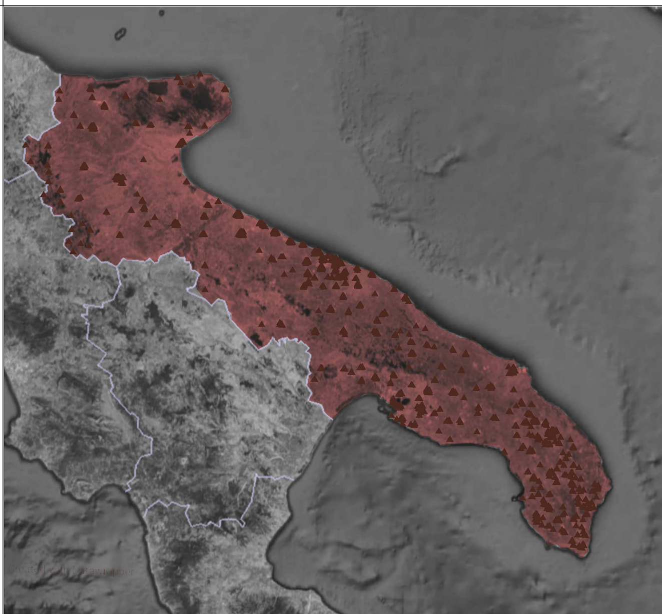

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06

2024

Dottorato in Rischio e Sviluppo Ambientale, Territoriale ed Edilizio

Coordinatore: Prof. Vito Iacobellis

XXXVI CICLO
Curriculum: ICAR/10

DICATECh
Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica

Ludovica Maria Campagna

Resilienza energetica al cambiamento climatico del patrimonio edilizio scolastico in area mediterranea: il caso della Regione Puglia

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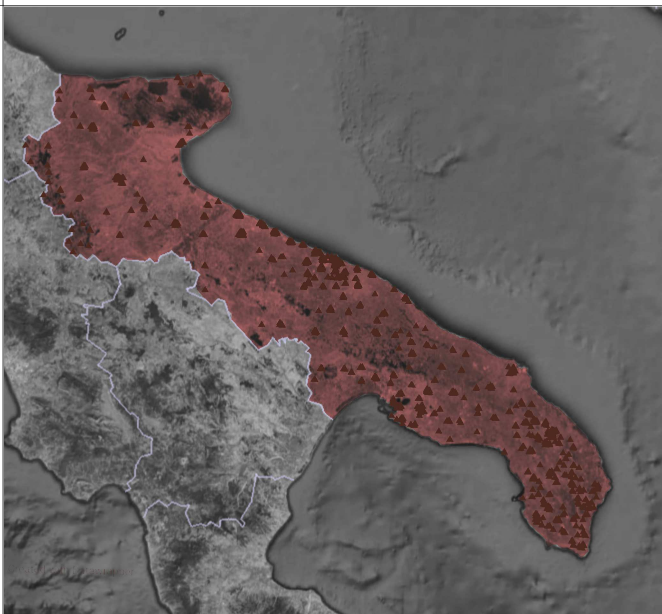

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– Avviso pubblico n. 2/FSE/2020 "Dottorati di ricerca in Puglia XXXVI Ciclo".

LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al magnifico Rettore
del Politecnico di Bari

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Bari, 12/04/2024 Firma

“L’ultima cosa che ho imparato
consiste nell’avere necessariamente un’idea,
chiamala pure ideale,
e a essa attenersi fermamente ma senza nessuna faziosità,
ascoltando sempre le idee degli altri diverse dalle proprie,
sostenendo le proprie ragioni con fermezza,
spiegandole e rispiegandole,
e magari perché no, cambiando la propria idea.
Ricordati che, sconfitta o vittoriosa,
non c’è bandiera che non stinga al sole.”

Andrea Camilleri

EXTENDED ABSTRACT *(eng)*

Over time, the growing awareness of the responsibilities of the construction sector in the emission of greenhouse gases has prompted the international scientific community to investigate the relationship between climate change and the built environment. The complexity of this relationship has been definitively clarified by the recent IPCC Sixth Assessment Report (AR6), which identified this sector among the most impactful anthropogenic activities, while recognizing its high vulnerability to the effects of climate change. In this light, research in the construction sector is called upon to play a crucial role, as policymakers' choices concerning mitigation and adaptation policies are significantly influenced by the research advancements of the scientific community. However, although the body of literature on the topic has been growing exponentially in recent years, it still seems limited compared to the breadth of the problem, remaining associated to specific building types, such as residential and office buildings, but neglecting others. Undoubtedly, the focus on these buildings was comprehensible in the early years of the studies on the topic - since they constitute the most widespread building types - but today it is no longer accountable, so much so that it has been recognized to be an important research gap even by the IPCC. Indeed, many building types, mainly the non-residential ones - have peculiarities that do not allow them to be assimilated with others, thus requiring specific research. In detail, the increasingly ambitious development of climate policies requires adequate knowledge of the features of the whole existing building stock, in order for them to be properly applied. For instance, with the goal of reducing Greenhouse Gases emissions by 55% by 2030, a regulatory update is underway in the European Union that will include new energy measures involving not only new buildings, but also existing buildings - residential and not - which

will be required to meet minimum energy performance standards. Accordingly, further studies involving different building types are as necessary as ever.

Among the building types that are potentially highly vulnerable to climate change are certainly educational buildings, for multiple reasons. First, they should ensure high levels of energy performance and indoor comfort, as they significantly affect the performance, productivity, attendance and health of both teachers and students, who spend the majority of their day in school spaces (excluding homes). Second, schools are particularly vulnerable to overheating risk, as they are characterised by high occupancy rates – which can reach up to four times the occupancy rate of offices - especially during the hottest hours of the day. Moreover, it is now recognised that schools lie in an inadequate state, hosted in outdated buildings with poor energy performance and comfort features, especially in the Italian context. Fortunately, good opportunities for renovation come from the ongoing climate policies, which encourage the energy renovation of existing buildings to contain CO_2 emissions. However, for them to be properly applied, two issues need to be considered. On the one hand, an adequate knowledge of the characteristics of the whole school building stock is required to identify its main features and thus select sample-buildings to be studied. On the other hand, there is a need to conduct specific investigations at the building level, assessing its performance under both current and future climate scenarios, to identify potential retrofit solutions that will improve its resilience to climate change. However, such studies concerning school buildings still appear to be sorely lacking in the literature.

The present thesis fits within this research context, aiming to explore the energy resilience of school building stock located in the Mediterranean area, focusing on the Apulia region. Two main macro-objectives led the entire work. First, to provide an overview of the current condition of Apulian school building stock, especially from an energy perspective, based on the analysis of actual data. Second, to conduct a predictive assessment of the impact of climate change on existing schools, based on energy simulations of representative buildings - properly validated - exploring potential solutions. For this purpose, a literature review on the impact of climate change on buildings was preliminarily conducted to identify the adopted methodologies and results obtained.

Then, based on information collected in the regional school database, a series of data were collected, processed, and analysed to provide an overview of the characteristics of this heritage, analysing its typological and technological features. Based on this data, a cluster analysis was conducted involving more than 1000 schools, which allowed to identify not only homogeneous groups of buildings, but also representative buildings. A large-scale survey of the energy performance of schools was then conducted, involving a sample of nearly 50 buildings, showing the evolution of billed consumption over a five-year period. In addition, representative buildings were modelled on dynamic simulation software and, once validated, were used to assess the impact of climate change on schools energy performance. Finally, the effectiveness of different retrofit solutions - both in the current and future climate scenarios - was evaluated through a life cycle cost assessment.
The results of the present work - which covered a variety of research topics and involved multiple methodologies - could be a useful reference for public administrations, helping to increase awareness of the current state of this building stock of such importance. In detail, the results related to the first macro-objective - which focuses on the current conditions of schools – could provide a useful reference in the assumption of carrying out intervention planning and identifying priorities. In addition, benchmarking energy consumption based on actual data can be a useful reference for assessing the conditions of a specific school against the overall data for the region. Instead, results related to the second macro-objective - which focuses on schools future performance - contribute to increasing public administration awareness of climate change by highlighting critical issues specific to schools, as well as providing insight into potential solutions.

keywords
climate change, schools, energy performance, cluster analysis, field study, building simulation, life cycle cost analysis, architectural engineering, built environment management.

EXTENDED ABSTRACT *(ita)*

Nel corso del tempo, la consapevolezza crescente delle responsabilità del settore delle costruzioni nell'emissione di gas climalteranti ha spinto la comunità scientifica internazionale ad approfondire la relazione tra il cambiamento climatico e l'ambiente costruito. La complessità di tale relazione è stata definitivamente chiarita dal recente Sesto Rapporto di Valutazione (AR6) dell'IPCC, il quale ha identificato questo settore come una delle attività antropiche di maggiore impatto, riconoscendone al contempo l'elevata vulnerabilità agli effetti del cambiamento climatico. In quest'ottica, la ricerca nel settore delle costruzioni è chiamata a svolgere un ruolo cruciale, in quanto le scelte dei decisori politici riguardanti le politiche di mitigazione e adattamento vengono largamente influenzate dai progressi compiuti dalla comunità scientifica. Tuttavia, sebbene il corpo della letteratura sul tema sia cresciuto esponenzialmente negli ultimi anni, essa sembra ancora limitata rispetto all'ampiezza del problema, restando legata a specifiche tipologie edilizie, come quella residenziale e quella per uffici, ma trascurando le altre. Indubbiamente, il focus su questi edifici era comprensibile agli albori degli studi sul tema - costituendo quelli maggiormente diffusi – ma oggi non è più giustificabile, tanto da essere stato riconosciuto essere un importante gap di ricerca anche da parte dell'IPCC. Infatti, molte tipologie edilizie – in particolare quelle non residenziali - presentano peculiarità che non consentono di assimilarle alle altre, richiedendo pertanto ricerche specifiche. In particolare, lo sviluppo sempre più ambizioso delle politiche climatiche, richiede un'adeguata conoscenza delle caratteristiche dell'intero patrimonio edilizio esistente, affinché esse siano applicate correttamente. Ad esempio, con l'obiettivo di ridurre le emissioni di gas climalteranti del 55% entro il 2030, nell'Unione Europea è in corso un aggiornamento normativo che prevederà nuove misure che coinvolgeranno non solo gli edifici di nuova costruzione, ma anche quelli esistenti – residenziali e non -, ai quali sarà richiesto di rispettare degli standard minimi di prestazione energetica. Di conseguenza, ulteriori studi che coinvolgano diverse

tipologie edilizie sono quanto mai necessari. Tra le tipologie edilizie potenzialmente vulnerabili al cambiamento climatico sono sicuramente da annoverare gli edifici scolastici, per molteplici motivi. In primo luogo, essi devono garantire elevati livelli di performance energetiche e comfort indoor, poiché influenzano in modo significativo il rendimento, la produttività, la frequenza e la salute sia degli insegnanti che degli studenti, che trascorrono la maggior parte della loro giornata negli spazi scolastici (escludendo le abitazioni). In secondo luogo, le scuole sono particolarmente soggette al rischio di surriscaldamento, poiché caratterizzate da elevati tassi di occupazione – che superano anche di quattro volte quelli degli uffici – che si concentrano nelle ore più calde della giornata. Inoltre, è ormai riconosciuto che le scuole versino in uno stato inadeguato, ospitate in edifici ormai datati, dalle povere performance energetiche e caratteristiche di comfort, soprattutto nel contesto italiano. Fortunatamente, delle buone opportunità di rinnovamento provengono dalle stesse politiche climatiche, che incentivano la riqualificazione degli edifici esistenti, al fine di contenere le emissioni di CO_2. Tuttavia, affinché esse siano applicate correttamente, è necessario considerare due aspetti. Da un lato è necessaria una conoscenza adeguata delle caratteristiche dell'intero patrimonio edilizio scolastico, al fine di identificarne i caratteri peculiari e quindi selezionare degli edifici-campione da studiare. Dall'altro lato, è necessario lo svolgimento di indagini specifiche a livello di edificio, che ne valutino le performance tanto nello scenario climatico attuale che in quello futuro, in modo da individuare delle potenziali soluzioni di retrofit che ne migliorino la resilienza al cambiamento climatico. Tuttavia, studi di questo tipo appaiono ancora molto carenti in letteratura. La presente tesi si inserisce all'interno di questo contesto di ricerca, con lo scopo di esplorare la resilienza energetica del patrimonio edilizio scolastico sito in area mediterranea, focalizzandosi sulla regione Puglia. Due obiettivi principali hanno guidato l'intero lavoro. In primo luogo, fornire una panoramica delle attuali condizioni del patrimonio edilizio scolastico pugliese, soprattutto dal punto di vista energetico, basata sull'analisi di dati reali. In secondo luogo, condurre una valutazione predittiva dell'impatto dei cambiamenti climatici sulle scuole esistenti, sulla base di simulazioni energetiche di edifici rappresentativi - opportunamente validati - ipotizzando potenziali soluzioni. A tal fine, è stata condotta

preliminarmente un’indagine di letteratura sull’impatto dei cambiamenti climatici sugli edifici, allo scopo di identificare le metodologie di indagine e i risultati ottenuti. Successivamente, sulla base dei dati raccolti nel portale dell’Edilizia Scolastica della Regione, sono stati raccolti, elaborati ed analizzati una serie di dati che hanno consentito di fornire una panoramica delle caratteristiche di tale patrimonio, analizzandone i caratteri tipologici e tecnologici. Sulla base di questi, è stata realizzata una analisi dei cluster coinvolgendo oltre mille edifici scolastici, che ha consentito di identificare non solo dei gruppi omogenei di edifici, ma anche degli edifici rappresentativi. È stata poi realizzata una indagine a larga scala delle performance energetiche delle scuole, coinvolgendo un campione di quasi 50 edifici, mostrando l’evoluzione dei consumi misurati per un periodo di cinque anni. Inoltre, gli edifici rappresentativi sono stati modellati su un software di simulazione dinamica e, una volta validati, sono stati utilizzati per valutare l’impatto dei cambiamenti climatici sulle performance energetiche. Infine, l’efficacia di diverse soluzioni di retrofit – sia nel clima attuale che in quello futuro – è stata valutata attraverso un life cycle cost assessment. I risultati del presente lavoro – che ha toccato diversi temi di ricerca e coinvolto molteplici metodologie – possono rappresentare un utile riferimento per le pubbliche amministrazioni, contribuendo ad incrementare la consapevolezza dello stato attuale di questo patrimonio edilizio di così grande importanza. In particolare, i risultati legati al primo macro-obiettivo - che si focalizza sulle condizioni attuali delle scuole - contribuiscono a fornire un utile riferimento nell’ipotesi di effettuare una programmazione degli interventi, individuandone delle priorità. Inoltre, la definizione di benchmark dei consumi energetici basata su dati reali, può costituire un utile riferimento per valutare le condizioni di una determinata scuola rispetto ai dati globali della regione. Al contrario, i risultati legati al secondo macro-obiettivo - che si focalizza sulle performance future - contribuiscono ad incrementare la consapevolezza delle pubbliche amministrazioni sul tema del cambiamento climatico, evidenziandone le criticità specifiche delle scuole, nonché fornendo un’idea delle potenziali soluzioni.

Keywords

cambiamento climatico, scuole, prestazioni energetiche, analisi dei cluster, indagine sul campo, simulazioni dell'edificio, analisi dei costi del ciclo di vita, architettura tecnica, gestione dell'ambiente costruito

INDEX

CHAPTER 1

1. INTRODUCTION

1.1. Background and rationale of the research

Increase in temperatures, rise in frequency and intensity of precipitation, increase in magnitude of heat waves, melting of glaciers, rise in sea level: the adverse effects of climate change are now undeniable and noticeable for all to see. In fact, such impacts are becoming increasingly pervasive, affecting every area of our planet, and making vulnerable not only natural systems, but also the built environment and human lives. Although identified since the First Assessment Report (FAR) of the Intergovernmental Panel of Climate Change (IPCC) published in 1990 [1], the latest IPCC Sixth Assessment Report (AR6) released in 2022 sheds light on the extent and magnitude of these impacts, which are beyond any expectation, making them increasingly difficult to handle [2].

Indeed, the Earth's Climate System is suffering a rapid and unusual variation that is without precedent in thousands of years. Natural drivers that have always caused natural variations in the Climate System are not sufficient to explain such rapid and extensive changes: the source is unequivocally to be blamed on human activities. Scientific evidence has proven that human activities can result in a change in the composition of the atmosphere, due to an increase in the concentration of greenhouse gases (GHGs), which can alter the natural greenhouse effect. For instance, in 2019, the concentration of CO_2 - which represents one of the most impactful GHGs - reached 410 ppm, which is a frightening finding when we consider that, during the past 800 thousand years, such concentration has never exceeded 300 ppm. Theoretically, the greenhouse effect is a beneficial phenomenon that allows a temperature compatible with life to be maintained. However, a growth in the concentration of GHGs in the atmosphere can increase this effect, trapping infrared radiation near the earth surface and thus leading to warming temperatures, along with many other effects. Without any doubt, the most evident consequence of climate change on the planet is the increase in temperatures, not only atmospheric, but also oceanic and land temperatures. For instance, an average surface temperature 1.1°C higher than pre-industrial levels (1850-1900) has been recorded for the period 2011-2020, with larger increases over land (1.59°C) than over the ocean (0.88°C) [2]. Currently, the best estimation predicts that 1.5°C will be reached in the short-term, intensifying multiple and concomitant risks as well as the interaction between climate and non-climate risks, which will create compound and cascading risks that are more complex and difficult to manage. In fact, along with increasing temperature, climate change results in many other consequences which affect all the ecosystems: increased global precipitation on land, changes in near-surface ocean salinity, global retreat of glaciers, ocean warming and acidification, increased global mean sea level, and changes in the terrestrial biosphere. In addition, climate change exacerbates extreme weather events, such as heat waves, heavy precipitation, droughts, and tropical cyclones. Even the human system is not excepted from the adverse effects of climate change, which could involve water scarcity and food production; human health, and well-being; cities, settlements, and infrastructure.

However, scholars agree that both the effects on natural and human ecosystems do not occur across the planet evenly, differing not only between regions, but also within regions. The difference in climate risk depends on various climatic hazards, different exposure of systems, as well as their different vulnerability. Consequently, the adoption of adaptation measures - which allows for reducing both exposure and vulnerability - becomes vital. Evidently, to prevent the disastrous effects of climate change, the increase of the adaptive capacity of human and natural systems is not sufficient, but mitigation strategies that act directly on the causes of climate variations are needed. Therefore, the sectors that most contribute to the emission of GHGs must be identified to become the focus of mitigation actions. Five main economic sectors have been recognised to be responsible for anthropogenic GHG emissions (both direct and indirect): industry (34%), Agriculture, Forestry and Other Land Uses (22%), transport (15%), buildings (16%), and the energy sector not including electricity and heat generation (12%) [2]. The latest AR6 has definitively clarified the complex involvement of the built environment among the anthropogenic drivers of climate change, along with its significant vulnerability to the inevitable effects of future climate fluctuations. In light of this, the research in the construction field is called upon to play a critical role, as the mitigation and adaptation policies pursued are closely linked to the progress achieved by the research community.

Regarding the role of buildings in climate change, it is worth noting that they accounted for 21% of the global GHG emissions recorded in 2019 [3]. The majority of these emissions are related to CO_2 - while the other GHGs are negligible – which has reached 33% of all global CO_2 emissions in 2022 [4,5]. These emissions result from three main components: indirect emissions (18%), direct emissions (8%) and embodied emissions (7%). Overall, building operations – which affect both direct and indirect emissions – account for 30% of final global energy consumption [4]. Consequently, mitigation measures become essential, which mainly involve the construction of new high-performance buildings, as well as the renovation of existing buildings. Likewise, during their life cycle, buildings suffer from climate change, because it leads to significant variations in external conditions in which the buildings operate. These impacts may concern building structures, building material properties, as well as building indoor conditions or building energy use; the latter represent the most widely studied in the literature [3]. In fact, the changing climate results in worsening of both energy performance [6] and thermal comfort [7], affecting also high-performance buildings [8]. Therefore, proper adaptation measures become a crucial factor in addressing climate change [9], as the impacts of the climate crisis will continue for centuries, regardless of the efforts to reduce anthropogenic GHG emissions [3]. However, the existing literature on building adaptation strategies to climate change is still limited compared to the breadth of the topic [10]. Certainly, evaluating the behaviour of buildings in a changing climate is not an easy task, because it adds to the typical difficulties of building behaviour simulations those related to the use of future climate projections, which are typically the domain of climate science and not of research in the built environment. Consequently, although research in the field of climate modelling has achieved remarkable results in recent years, the transfer of knowledge to the field of building engineering is found to be slow and, hence, the application to buildings remains limited [11]. Furthermore, the literature still seems to refer to limited building types, such as residential [12,13] and office [14,15], while neglecting others.

Nevertheless, each building type has specific features that do not allow it to be compared with others, so it needs to be specifically investigated [16], especially considering the increasingly more ambitious development of climate policies, whose proper application requires adequate knowledge of the characteristics of the existing building stock. For instance, the European Union (EU) is discussing a proposal to revise the current Energy Performance of Buildings Directive (EPBD) [17], involved in the new “fit for 55” package, which aims to achieve a reduction of minimum 55% GHG emissions by 2030. Specifically, all new buildings will be required to be zero-emission by 2028 (public buildings) or 2030 (all others) [18]. In addition, ambitious prospects affect existing buildings, both residential and non-residential. On the one hand, for non-residential buildings, member states will have to set minimum energy performance standards, that is, the maximum amount of energy that buildings can use per m^2/year, establishing thresholds by 2030 and 2034. On the other hand, residential buildings will have to meet specific energy performance levels, achieving zero emissions by 2050. Therefore, properly knowing the behaviour of different building types than residential ones becomes more crucial than ever, for proper application of the climate regulations, so much that the lack of studies involving non-residential buildings has been clearly identified as a knowledge gap in the latest IPCC AR6. In fact, the IPCC Working Group III (WGIII) underlines that the analysis of energy demand trends in non-residential buildings is limited due to the number of building types included in this category, but mainly to the lack of data referred to these building types [3].

The present thesis fits within this research context, focusing on a building type that is potentially highly vulnerable to climate change: educational buildings. Indeed, schools cannot be assimilated with other types of non-residential buildings due to their peculiarities and, hence, they require specific evaluations that have yet to be explored in the literature. Firstly, school buildings show discontinuous occupancy, both throughout the day and throughout the year, which can affect their overall behaviour. In addition, they are characterised by users' activities, clothing, and ages significantly different from other building types [19], as well as an occupancy level that can reach up to four times the occupancy rate of offices [20]. These aspects, together with the fact that classrooms operate at full capacity during the hottest hours of the day [19], lead to an increased risk of overheating [21]. In addition, school buildings need to ensure high levels of indoor comfort for their occupants due to several reasons. In fact, indoor environmental conditions play a crucial role in the terms of performance, productivity, attendance and health of both students and teachers [22]. Compared to adults, children are more vulnerable to poor thermal comfort conditions due to their age, bodies, and differences in metabolism [23].

Despite the recognised importance of such heritage in the human society, as children spend most of their time in school spaces (except for home) [24], scholars agree that it is often an outdated and inadequate heritage, especially in the Italian context [25]. In fact, school buildings are characterized by poor energy performance and inadequate indoor comfort levels. Taking action to improve them is as urgent as ever, especially since these troubles will be exacerbated by climate change. Large opportunities for renovating the school building stock arise precisely from emerging climate policies, since - as mentioned - one of the main ongoing policies concerns the renovation of the existing building stock, with the aim of reducing its high levels of energy consumption [26]. Despite good proposals, the annual renovation rate of buildings is still inadequate [27], therefore a new EU directive has been enacted in 2020 with the aim of doubling the annual energy renovation rate over the next 10 years, considering the possibility to extend both renovation and energy audit requirements to all public buildings, including schools [28]. Similarly, an investment program focusing on the renovation of school buildings has been planned in Italy to improve energy classes with a consequent reduction in energy consumption [29].

To adequately capture these renovation opportunities, a twofold awareness is required: a comprehensive knowledge of the building stock to understand its current state and thus establish priorities for actions, as well as detailed knowledge at the building level to identify how energy is actually being used and to identify opportunities for energy savings. In addition, since the climate is unavoidably expected to change, savings opportunities should be evaluated not only in the current climate but also considering the expected future climate conditions. The whole process is as tricky as ever because it faces problems at different levels.

Firstly, an in-depth knowledge of the entire building stock is not feasible [30], so it is necessary to identify appropriate typical buildings (i.e., reference buildings [31]) as representative of homogeneous classes of buildings [32]. Within this framework, the identification of appropriate characteristics to classify buildings represents the main challenge [30], which is often further complicated by the unavailability of such data. In fact, collecting field data from a large sample of schools seems complex and time-consuming, as it requires the involvement of several stakeholders who are required to make data available [33,34]. Consequently, research often identifies representative buildings based on samples consisting of a small number of schools, the only ones for which exhaustive data are available.

Secondly, to explore the renovation potential of the building sample, a large-scale analysis of actual consumption needs to be performed both to understand its status and identify energy benchmarks which allows for assessing energy performance and retrofit effectiveness [35]. In this framework, a significant gap in the literature has been found to be the lack of energy benchmarks that denote actual energy consumption [36], because the commonly methodological approach to assess the energy performance of a sample of buildings is based on software simulations [37,38], while studies that rely on analysis of field data still seem limited [39]. Once again, the lack of empirical studies can be attributed to the unavailability of actual data [33]. In fact, in contrast to other countries [40], Italy lacks a national electronic database that systematically collects and reports information concerning efficiency and energy consumption of school buildings. Consequently, the state of public schools is only surveyed by sporadic reports published by national research centres [41] or private associations [25].

Third, once representative buildings have been selected, it is required to identify the appropriate methodology to reliable evaluate their performance not only under current climate scenarios but also under future climate scenarios. In this regard, correctly analysing the behaviours of buildings becomes the fundamental basis for assessing performance variations due to changing climatic conditions. For this purpose, the literature currently adopts the so-called white-box models, which are physics-based models that require detailed knowledge of the characteristics of the physical system, since they analyse energy behaviour by solving heat and mass balance equations [42]. However, although software like Energy Plus or TRNSYS potentially yields detailed outcomes, there are often discrepancies between simulated and actual behaviour because software requires many input parameters that can be biased by both epistemic and aleatory uncertainties [43]. In detail, the gap between actual and simulated building energy performance is known as the "performance gap" problem, addressed in CIBSE TM54 [44], and requires a calibration process to be solved [45], although still not always performed in the literature. Clearly, to assess the impacts of climate change on buildings, appropriate methodology to generate future climate files should be adopted [6,46], which represent the boundary conditions needed to carry out simulations. In this regard, the literature still seems to lack studies using the new Shared Socioeconomic Pathways (SSPs) scenarios [16].

Fourth, approaches based on evaluating not only energy performance but also costs should be adopted to assess the effectiveness of retrofit measures, to encourage stakeholders to implement the interventions. Nevertheless, examples of life cycle cost analysis in the literature are based on the evaluation of a few intervention measures, often manually combined a priori, lacking a consistent method for identifying optimal solutions [47]. In detail, examples applied to school buildings are very limited and lack any consideration of effects due to changing environmental conditions.

1.2. Literature gaps

The previous section has provided an overview of the research background in which the present dissertation falls. As evident, multiple research topics are approached, starting with future climate modelling in the context of built environment research, moving from the characterization of an existing building stock and the field investigation of its performance, and ending with predictive simulation at the building scale of representative schools in current and future weather conditions. Clearly, each of these topics suffers from literature gaps, which represent the basis on which the present study is built.

With reference to the climate change macro area:

- The literature on the impacts of climate change still appears to be related to specific building types, mainly residential and office buildings, lacking other building typologies. However, since the inevitable effects of climate change will require the adoption of adaptation measures, understanding the behaviour of different building types is as essential as ever, as clarified by the IPCC.
- Literature lacks studies based on the latest IPCC SSPs scenarios, which represents an issue because impact assessments are strongly influenced by the emission scenario selected to generate future weather files.

Referring purely to the research area concerning school buildings:

- The samples selected to identify school buildings as representative for in-depth analyses consist of a small number of buildings, the only ones for which exhaustive data are available. Moreover, literature is completely lacking in such studies involving schools in southern Italy, for which representative buildings to study are missing.
- Empirical evidence on energy performance of school samples appears limited due to the difficulty in retrieving data, although field data analysis is crucial in the built environment management. The only Italian studies found in the literature concern schools located in northern Italy and are now outdated.
- Studies looking at the impact of climate change on school buildings are very limited and based on outdated climate scenarios.
- Literature lacks studies regarding schools that analyse different retrofit options by evaluating their cost-benefit effectiveness while considering the effects of changing environmental conditions due to climate change.

1.3. Thesis aim and research questions

The main purpose of this thesis is to explore the energy resilience to climate change of the school building stock in the Mediterranean area. In detail, since the doctoral program of the writer was funded by a grant from the Apulia Region, the research adopts the Apulia Region as a case study, focusing on the municipally owned schools (pre-schools, primary and lower secondary schools). Two macro-objectives have driven the work:

- Providing a comprehensive overview of the current condition of Apulian school building stock, performing a large-scale field assessment of the energy status of existing schools, which could provide a useful reference for policy makers in planning intervention programs, identifying priorities.
- Conducting a predictive assessment of the impact of climate change on existing schools at the building scale, based on representative validated buildings, to increase stakeholder awareness of the issue, highlighting critical challenges specific to schools, and providing guidance on potential solutions.

The above macro-objectives have been developed into the following research questions, based on the literature gaps previously explained.

- **RQ1.** What are the main implications of climate change on building energy consumptions according to the existing literature?
  This research question is related to the following sub-questions:
  RQ1.1. To what extent do these implications differ between the studies?
  RQ1.2. Since several research methodologies can be pointed out, are there any correlations between methodological inputs and research outcomes?
- **RQ2.** What are the main features of Apulian school buildings and how can they be split into homogeneous clusters to identify representative buildings for energy analyses?
- **RQ3.** What is the current energy performance status of Apulian school buildings and what have been the trends in billed consumption in recent years?
- **RQ4.** What will be the impact of climate change on the energy performance of school buildings?
- **RQ5.** If we were obliged to renovate our schools by meeting the normative values, would it be sufficient to achieve them or would it be appropriate to exceed them, also considering how the climate context will evolve?

1.4. Structure of the thesis

Given the multitude of research topics addressed and the variety of methodologies employed, the present dissertation is divided into eight Chapters, each one seeking to answer a research question (**Figure 1**). For each chapter, a brief introduction that contextualises the research question is provided, outlining its related research objectives; then the methodology adopted, and the results obtained are reported.

This chapter has provided the background of the research, highlighting gaps in the literature, and clarifying the research questions which underly the work.

Since the research involves two main topics - climate change and school buildings - **Chapter 2** provides a brief review of the state of knowledge related to these issues. Firstly, subsection 2.1 explores the topic of climate change, presenting the theoretical background behind climate change theory, discussing the complex relationship between climate change and built environment, and deepening existing methodologies for considering climate change in building research. Then, subsection 2.2 provides an overview of research concerning the school building stock from different perspectives, covering all topics addressed in the thesis. First, the Italian school building stock - the subject of the study - is briefly presented. Then, methods for characterizing the school building stock are discussed and existing studies on field schools energy assessments are reviewed. Finally, a review of existing literature concerning school buildings in a changing climate is presented.

Given the state of the art, **Chapter 3** delves deeper into the topic of climate change related to building energy performance, attempting to answer **RQ1** through a meta-analysis. The objective is to highlight the main implications of climate change on building consumption through an extensive literature review, conducted both from a qualitative and a quantitative perspective, to identify potential relationships between energy variation and a series of variables that depend on the methodology adopted.

Chapter 4 moves into the field of school buildings, aiming to answer **RQ2**, first showing an overview of the main features of the Apulian school building stock, and then detailing how the stock is split in homogeneous clusters to identify representative buildings for further energy analyses. Indeed, starting from an overview of the typological and technological features of the school building stock, the goal is to find suitable predictors to divide the large number of schools into homogeneous clusters, to identify representative buildings for each cluster.

Provided the comprehensive overview of Apulian schools**, Chapter 5** deals with **RQ3**, presenting an insight into the actual energy performance of school buildings, through a large-scale field study, based on gas and electricity consumption data billed over a five-year period (2017–2021) in almost 50 schools. The main objective is to explore energy use in schools, assessing the trend in consumption in recent years, as well as identifying energy benchmarks.

Completed the investigation at the regional level, **Chapter 6** moves down to the building scale, aiming to answer **RQ4,** exploring the impact of climate change on the energy performance of school buildings. For this purpose, based on the cluster analysis carried out in Chapter 4, four representative schools are identified to be used for energy analysis. These buildings are modelled in a dynamic simulation software and calibrated against measured data adopting an automatic optimisation-based calibration approach, thus providing a reliable reference for these and future analyses. In addition, to evaluate the impact of climate change, future climate files are generated, based on the latest SSPs Socioeconomic Pathways scenarios.

After analysing the impact of climate change on energy needs, **Chapter 7** discusses potential solutions, dealing with **RQ5**. The objective is to compare retrofit intervention in compliance with the reference building required by the Italian regulation with improved retrofitted options, performing a life cycle cost analysis with an optimisation approach.

Chapter 8 provides the overall conclusions and suggestions for future works.

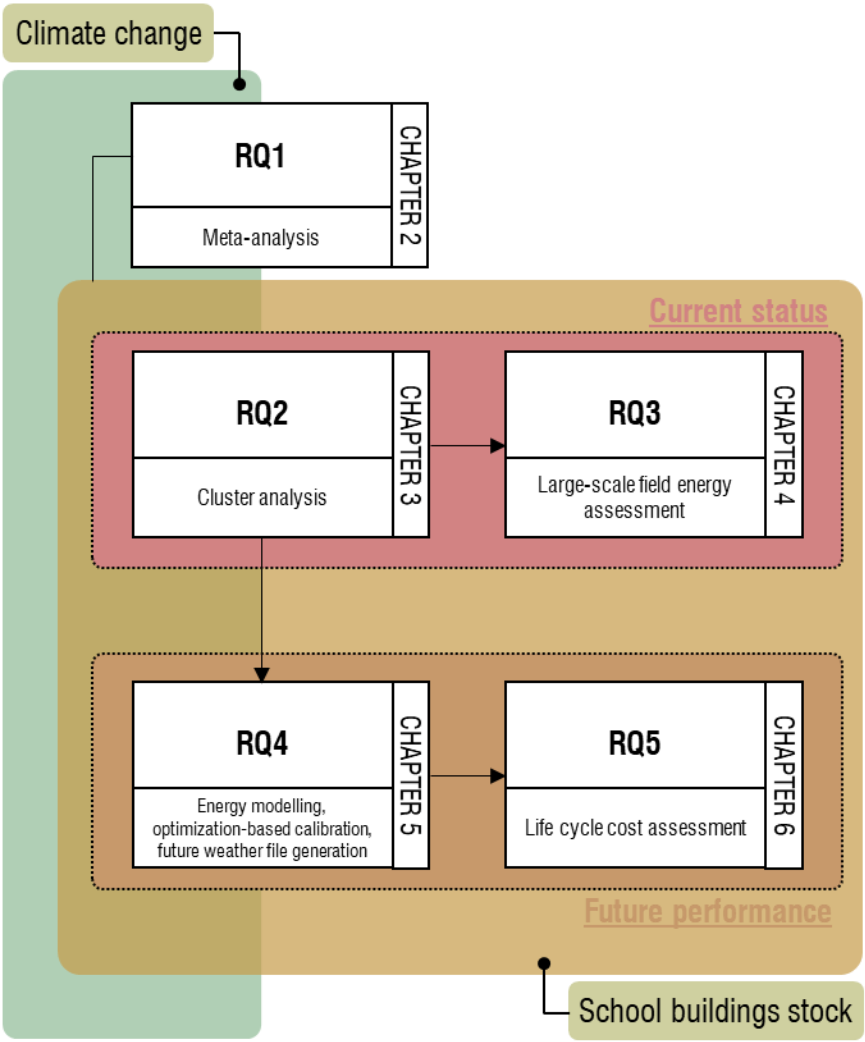


Figure 1. Structure of the thesis, outlining the research questions addressed in each chapter and the methodologies involved.

CHAPTER 2

2. STATE OF THE ART

The present chapter aims to set the research context, presenting a brief overview of the state of the art concerning the two main themes that provide the background for the research. In detail, the issues related to climate change are discussed in **section 2.1**, while an overview of research concerning the school building stock is provided in **section 2.2**. Both subsections are drawn starting from some of the previous works of the writer: the main references are [16] for the subsection related to climate change and [48] for the subsection related to school buildings.

2.1. The climate emergency

The struggle against climate change is undoubtedly the major challenge of our century, involving the whole international community on several fronts. Indeed, the complexity of the issue unavoidably requires a joint effort by the entire community, involving political forces, research communities and the citizens themselves. In detail, advances in the construction research field have an important responsibility in this process, as buildings significantly contribute to CO_2 emissions while suffering the negative impacts of climate change.
The present section aims to provide a brief overview of the topic of climate change, starting with the theoretical background supporting the subject, then outlining the close relationship with the built environment, and finally providing an overview of the methods for taking climate change into account in building research activities.

2.1.1. Theoretical background

The topic of climate change is not something new, as discussed since as early as the 1990s, with the publication of the First IPCC Assessment Report (FAR) [1]. Although it has often been underestimated throughout the recent years, the increasingly evident effects of climate change no longer allow us to overlook it, as it now represents a worldwide emergency. The two main references in defining climate change are given by the United Nations Framework Convention on Climate Change (UNFCCC) and the IPCC, which, however, differ in one main factor. In fact, the UNFCCC defines climate change as "*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*" [49]. Otherwise, the IPCC defines climate change as "*a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer*" [50]. Accordingly, the UNFCCC associates the term climate change specifically with anthropogenic causes, while the IPCC adopts the term more broadly, regardless of whether it depends on natural or human causes. Indeed, for a long time the causes of climate change have been debated, often denying the responsibility of human actions in this regard, as climate variations have always existed. However, natural drivers are not enough to justify the rapidity and magnitude of changes in the Climate System, making clear the responsibility of human activities in such processes. The Global Climate System is undoubtedly a complex system, regulated by a multitude of relationships, which are studied by climate science. However, understanding how it works is critical to understanding the phenomenon of climate change, the factors that drive it and the implications it entails. The Global Climate System is made up of five major interacting components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere. In particular, the atmosphere is made up of nitrogen (78.1%), oxygen (20.9%), and argon (0.93%), as well as the so-called Greenhouse Gases (GHGs), which include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). Although they occur in limited amounts – accounting for only 0.1% - the GHGs play a crucial role in climate change. Indeed, the GHGs are responsible for the greenhouse effect, a natural process that allows the Earth to maintain an average temperature suitable for life. Briefly, the main energy source driving the Climate System is the solar radiation, which reaches our planet in the form of electromagnetic radiation [51]. About one-third of the incoming solar radiation is immediately reflected back into the space, one-fifth is absorbed by the atmosphere, while a further one-half is absorbed by the Earth's surface (oceans and lands), which warms up. Part of such heat is returned from the Earth's surface in the form of infrared radiation, being partly released into the space and mostly absorbed by GHGs in the atmosphere (70%). The GHGs allow infrared radiation to be absorbed and re-emitted in all directions, including towards the Earth's surface, leading to an increase of temperature near the Earth's surface, and thus ensuring temperature values compatible with life. Overall, a balance between the incoming solar radiation and the outgoing solar radiation is required. Otherwise, if the energy balance is perturbed, variations in the Climate System may occur. For instance, due to the reasons previous explained, the concentration of GHGs in the atmosphere can significantly alter the Climate System.

Actually, the Climate System has always been characterized by its own variability, due to changes in the internal dynamics of the System (internal variability) or due to changes in the external forcings of the System (forced variability), including both natural and anthropogenic causes. Natural forcings involve solar variations, volcanic eruptions, as well as orbital forcings and plate tectonics, whereas anthropogenic forcings mainly involve changes in atmospheric composition and in land use (**Figure 2**).

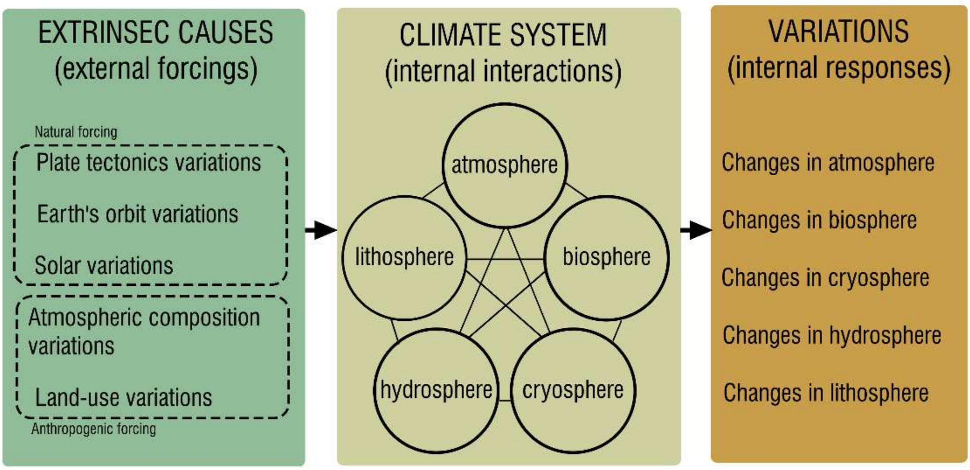


Figure 2. Climate system variability: external forcings and internal responses.

Undoubtedly, the most noticeable periods of changes in the Climate System were the eight glacial-interglacial cycles over the past 800 thousand years. During these cycles, atmospheric CO_2 concentrations, global mean surface temperature and global mean sea level – considered as the key indicators of climate change – experienced natural variations recurring in dominant cycles of about 100 thousand years. In that case, the main cause was natural and relied upon the oscillations in the Earth's orbit and consequent feedbacks on multi-millennial time scales [50]. The existence of periods such as glacial areas, has led many people to consider the climate change we are experiencing also as natural. Instead, scientific evidence shows that there is a great difference. In fact, over the past 800 thousand years, atmospheric CO_2 concentrations always ranged between 174 ppm and 300 ppm, which can be considered as a "natural" global-scale range of variation. However, starting from 1750, the growth in CO_2 concentrations has far exceeded such natural variations, reaching 410 ppm in 2019. Likewise, other GHGs like CH_4 and N_2O follow the same pattern of increase, dramatically affecting our Climate System. In fact, as already explained, the GHGs concentration in the atmosphere can alter the natural greenhouse effect, trap infrared radiation near the surface and thus leading to temperatures increase, as well as many other effects. Such rapid and extensive change cannot be explained by natural drivers, but must be unequivocally attributed to human activity, resulting in an increase in GHGs emissions. Such evidence led to the definitive awareness that "*human influence has warmed the atmosphere, the ocean and the land*", leading to atmosphere, ocean, cryosphere, and biosphere changes (**Figure 3**).

As clarified, such significant variations are undoubtedly caused by anthropogenic activities, which however assumed great potential in terms of climate change mitigation actions. Among the most impactful activities, burning of fossil fuels and changes in land use appear to be the major drivers. For instance, the increase in CO_2 concentrations is related to the burning of coal, oil and gas, but also to transportation, building heating and cooling and the manufacture of products (mainly cement), as well as deforestation. The growth of N_2O concerns the burning of fossil fuels, but also the agricultural activities, due to the widespread use of fertilizers. The rise of CH_4 is mainly related to the livestock farming, since animals like cows and sheep produce a significant amount of methane when they digest food.

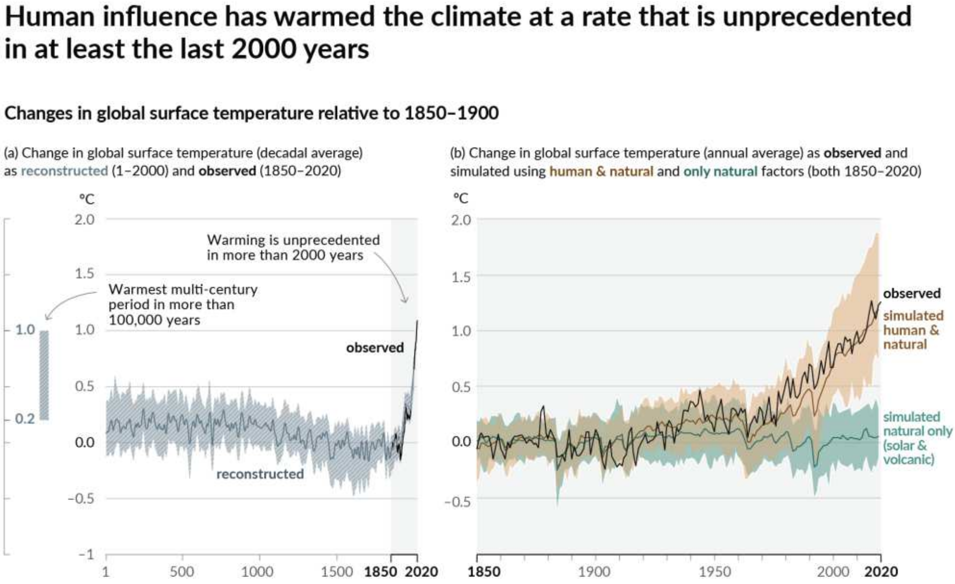


Figure 3. Changes in global surface temperature relative to 1850-1900. From ref. [52]

Even though the negative consequences of climate change have been clear since the FAR [1], their extent and magnitude have appeared beyond expectations in the latest report, making it clear how they are increasingly difficult to manage [2]. Climate change affects both ecosystem and human systems, but its impacts do not homogeneously affect the regions of our planet. Indeed, significant differences can be observed, related to climate hazards, exposure, and vulnerability of the systems, which constitute the so-called climate risks. To reduce such risks, adaptation strategies are a crucial point since they limit both exposure and vulnerability of the systems. Clearly, all the systems (natural or human) have a certain adaptive capability, but climate hazards often exceed their ability to adapt, causing damage or losses. Different strategies are available to increase the systems adaptability, whose implementation depends on the government policies but is crucial to support a climate resilient development. Nevertheless, to limit the adverse effects of climate change, increasing in adaptation capacity of human and natural system is not enough, but the adoption of mitigation strategies is also required. Overall, mitigation strategies involve both strategies to reduce GHGs emissions from energy production/use and land use, as well as strategies to remove emissions already emitted in the atmosphere through land use or other mechanisms, included artificial ones. Of course, such strategies can be applied to all sectors responsible for GHGs emissions, with different potential and costs [3].

2.1.1. The role of the built environment

The built environment consists of three main components: buildings, infrastructure, and human-made landscape. Complex and interrelated relationships occur among these components, affected by social, environmental, and economical aspects. Nowadays, the built environment is facing problems like overpopulation, poverty, excessive energy consumption, and pollution, exacerbated by the growing issue of global and local climate changes. Indeed, the built environment shows a high vulnerability to climate risk, that directly produces adverse impacts or worsens impacts that would occur anyway because of the problems mentioned above [53]. Moreover, given the complex relationships that govern the built environment, impacts usually extend beyond the area directly affected by climate risk [3]. Three main hazards have been identified to affect the built environment, briefly described below [2].

- Temperature extreme, since climate change leads not only to an increase in global average temperatures, but also in an increase in frequency and magnitude of regional heat wave events, which strongly impact urban systems. In particular, large cities suffer from higher temperatures than suburbs and rural areas due to the urban heat island phenomenon, which can be exacerbated by the increasing heat waves. The adverse effects of urban overheating are manifold and well-documented, involving energy demand and supply, environmental quality, heat-related mortality, and survivability [54].
- Urban flooding and sea level rise, mainly relevant to cities located on low elevation coastal zone [55]. Overall, the reduction of the permeable surface area of the soil due to urban expansion as well as the changes in the frequency and intensity of rainfall concur to increase the flooding risk [56].
- Urban water scarcity, due to the growing gap between water demand and supply, related to land use changes, migration to cities, together with rising temperatures and drought [57].

Evidently, urgent adaptation measures are required to increase the built environment resilience to the irreversible impacts of climate change, even because cities are often exposed to multiple climate hazards [58]. At the same time, urban settlements strongly influence climate change as they are recognized to be large emitters of CO_2, accounting for 70% of global CO_2-eq emissions [3].

The IPCC Working Group III definitively sheds light on the responsibilities of the construction sector in GHGs emissions. In fact, among the five main economic sectors responsible for anthropogenic GHGs emissions, there are industry (34%), buildings (16%), Agriculture, Forestry and Other Land Uses (22%), transportation (15%) and other energy uses [2]. In 2019 the construction sector has been responsible of 21% of global GHGs emissions [3], resulting from: direct emissions related to building operations (i.e., heating, cooling, ventilation, or air conditioning); indirect emissions, associated with fuel combustion for the off-site generation of electricity and heat, then consumed in the buildings as energy end-use; embodied emissions associated with the production of building materials. Such emissions are mainly related to CO2, for which buildings reaches the 31% of global emissions [3]. Referring to more recent data, in 2022, the construction sector accounted for about one-third of total energy system emissions: the 26% was related to building operations (8% representing direct emissions and 18% indirect emissions), while the 7% was related to building materials.

Given the significance of the construction sector in increasing CO2 concentrations, it also shows high potential in terms of mitigation strategies. In particular, the main measures involve the construction of new high-performance buildings as well as the renovation of the existing building stock, which thus represent the main building policies promoted by the international community. The construction of new high-performance buildings requires an appropriate building shape and orientation, an efficient envelope to reduce thermal losses between indoor and outdoor environment, as well as advanced HVAC technologies to meet the thermal needs. Such buildings are now compulsory in many countries due to the existence of specific regulations and allow for reductions in emissions related to the building operation phase. However, their cost-effectiveness is often debated, as well as their effectiveness in terms of embodied emissions, which could grow compared to a traditional building. Otherwise, the renovation of existing buildings requires an improvement of both efficiency and utilisation. To improve the building efficiency, energy retrofits can be carried out, which could involve envelope retrofit and/or systems replacement. Also, the replacement of lights, appliances, and equipment is considered as an efficient solution. In addition, for both existing and new buildings the integration of renewable energy technologies is required to further reduce the building direct emissions, which is now mandatory in many countries. In this context, the technological advances achieved by the scientific community in the construction research field are crucial to the identification of effective and environmentally low-impact technologies. In addition, it is worth noting that the effectiveness of both new high-performance buildings and retrofitted buildings should be evaluated not only considering the actual climate scenarios, but also the future weather scenarios. In fact, besides contributing to climate change, the construction sector suffers its adverse consequences as it alters the typical environmental conditions in which buildings operate, and this will happen regardless of efforts to tackle the climate crisis. Four main categories summarise the potential impacts of climate change on buildings: impacts on building structures, impacts on building construction, impacts on building material properties, impacts on building indoor conditions or building energy use [59]. Among them, impacts on building energy use and indoor conditions undoubtedly represent the most investigated category in the literature, since the focus is on the rising temperatures [10]. Scientific evidence shows that global warming affects thermal needs, leading to a decrease in heating needs and an increase in cooling needs, which result in an overall growth in total energy consumption. Clearly, the impacts of climate change are not homogeneous across the planet, but the magnitude of these variations depends on the location investigated [16]. It is worth noting that the increase in cooling needs not only influences energy consumption (and thus direct emission of GHGs), but also affects the peaks in energy demand. For instance, the rise in both frequency and magnitude of extreme phenomena such as heatwaves during summer increases the risk of grid failures and supply interruptions [60]. Furthermore, indoor comfort conditions suffer from global warming, which leads to a growth in the risk of overheating

[61], also in high-performance buildings [8]. Clearly, buildings located in large cities particularly experience this risk due to urban overheating [54]. Accordingly, adaptation measures are vital to address the unavoidable consequences of the climate crisis. Strategies for adapting buildings to climate change are manifold and extensively discussed by the IPCC Working Group II in the AR6, in which a whole section is dedicated to buildings [2]. Unavoidably, adaptation strategies are intertwined with mitigation strategies, making often difficult to distinguish between them, since some mitigation strategies lead to beneficial effects on adaptation and vice versa [62]. For instance, due to global warming, keeping comfortable temperatures inside buildings will be much harder, increasing the risk of discomfort. To meet the thermal needs (mainly cooling) and ensure adequate indoor comfort conditions, greater energy demand will be required, leading to a growth of energy consumption and thus CO_2 emissions [63]. Consequently, implementing adaptation strategies that improve indoor comfort under new climate scenarios also leads to a reduction in energy consumption as well as CO_2 emissions, even acting as a mitigation strategy. Overall, adaptation is achieved by increasing the adaptive capacity of buildings to climate variations, ensuring user comfort, also during climate extremes. The main strategies include reducing both heating and cooling demand, but also improving appliance efficiency and using renewable energy systems [64]. Clearly, the strategies selection depends on several factors, like the building type and the building location as well [16]. Among adaptation strategies, passive measures that improve the building envelope seem to be the most frequently implemented, enhancing its thermal performance. They involve the implementation of green roofs or green facades [65], changes in the thermal mass of opaque envelope [66], as well as the increase of insulation levels [67,68]. Thanks to the latter, the heat exchange between outdoor and indoor environment can be limited, contributing to reduce both heating and cooling needs and ensuring adequate indoor comfort conditions. However, to be effective, adaptation measures must be carefully selected considering the environmental context in which they will be installed. For instance, especially in warmer climates, the increase of insulation level could lead to negative impacts by increasing cooling needs [69], if not combined with further strategies [70]. As an example, adding

solar shadings (i.e., overhangs, louvres) can significantly contribute to reduce cooling heat loads by shielding the building from solar radiation thus reducing internal heat loads [71]. Likewise, the reduction of internal loads can be achieved by increasing natural ventilation, especially in the night-time [72]. Nevertheless, the effectiveness of natural ventilation can be limited in the long term due to the average increase in outdoor temperatures [73]. Although these constitute the adaptation strategies proven to be most effective, many other options are available. The aforementioned strategies are called hard adaptation measured, because they alter the buildings structure. In addition, there are the so-called soft adaptation strategies, which require a change in users' behaviour (for instance new strategies for windows opening). Also new patterns in building use can be considered among the soft adaptation measures, which include new working hours, different schools hours, different setpoint temperatures for heating and cooling systems. However, such strategies present some limitations, firstly related to the difficulty of assessing their robustness in terms of likelihood of implementation, thus - while potentially effective - they cannot replace hard measures [74,75].

2.1.3. Climate change modelling in building research

The complex relationship between climate change, buildings and GHGs emissions has been explored since the publication of the FAR in 1990 [76,77]. Nevertheless, a significant growth in the body of literature on this topic has occurred after the release of the IPCC Third Assessment Report (TAR) in 2001. Overall, research studies involving climate change and buildings pursue five main targets [78], briefly described below.

- Assessment of climate change impacts on building energy consumption.
- Evaluation of building adaptation and mitigation measures against adverse effects of climate change.
- Assessment of building retrofit strategies to cope with climate change.
- New tools and methods for future climate projection.
- Uncertainty of climate projection models and their impact on building simulation results.

Regardless of the end goal, the methodologies adopted in assessing the impact of climate change on buildings include three main steps [16], summarised in **Table 1**.

They cover the identification of the study context (geographical context and building typology), the prediction of future weather data (based on the selection of emission scenarios, General Circulation Models, downscaling technique, weather file types, study period), and the evaluation of building performance (mainly with dynamical simulation models). Each phase is characterized by a range of uncertainties, making the assessment of the relationship between the built environment and the outdoor climate even more complex.

Table 1. Methodological phases to evaluate climate change impacts on building performance, adapted from the writer's work [16].

Methodological phase	Ref.	Input variable	Variation
1. Study context	[79]	Geographical context	Difference climate resulting in different Heating Degree Days (HDDs) and Cooling Degree Days (CDDs)
	[80]	Building type	Residential, Office, Commercial etc.
	[81]	Reference period	Different baseline period depending on the recorded data availability (TMY2, TMY3, IWEC)
2. Future weather files prediction	[52,82,83]	Storyline/Representative Concentration Pathways	Emissions Scenarios (SRES), Representative Concentration Pathways (RCPs), Shared Socioeconomic Pathways (SSPs)
	[15]	Global Circulation Model (GCMs)	Single or combined GCMs
	[84]	Downscaling technique	Statistical (imposed offset method - i.e., morphing - or stochastic weather method)

			Dynamical (using Regional Climate Models, RCMs). Hybrid
	[85]	Weather file type	Typical Meteorological Year (TMY), Extreme Cold Year (ECY), Extreme Warm Year (EWY)
	[86]	Study period	Near term, middle term, long term
3. Building performance assessment	[87]	Building models	Dynamical energy simulation model, regression model (degree-days method)

The first step deals with the definition of the context of study, which requires the selection of the location and the building typology to be investigated. The second step deals with the prediction of future weather files, which represents a crucial point in the reliability of building performance forecasts in a changing climate. The third step concerns the prediction of energy consumption, which can be conducted by two main approaches: the degree-day method and building performance simulations (BPS), briefly reviewed in [87].

Referring to the second step, the science involved in predicting future climate is climate science, which has achieved to simulate the Earth's climate system through climate modelling. In detail, General Circulation Models (also known as Global Climate Models, both abbreviated as GCMs) allow for simulating the Earth's climate through mathematical equations, which represent fundamental physical and chemical processes [88]. Such processes refer to the major climate system components: atmospheric, oceanic, land surface, and the sea ice component. Typically, IPCC assessments are not based on the output of a single GCM but adopts an ensemble of GCMs involved in the so-called Coupled Model Intercomparison Project (CMIP), currently in its Sixth Update

(CMIP6). In the GCMs, the planet is divided into a three-dimensional cells grid, representing the Earth's surface, based on geographic locations and elevations (**Figure 4**).

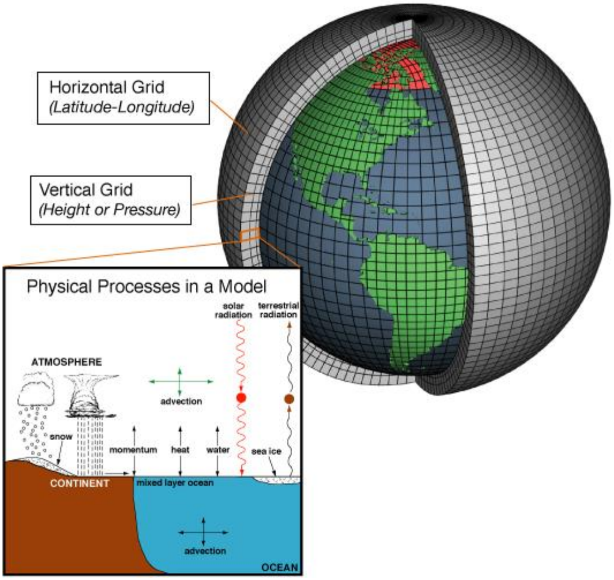


Figure 4. Structure of a GCM, from ref. [89]

For each cell, mathematical equations - concerning the fundamental laws of physics, fluid motion and chemistry - are solved for a given number of time steps, to then evaluate the interactions with neighbouring cells. The horizontal size of cells (measured in degrees of latitude/longitude or in km/miles) defines the spatial resolution of the model, while the time-steps used in models defines the temporal resolution [90]. As a result, both different spatial and temporal resolutions can characterise the GCMs, thus affecting the computational demand. Thanks to the progress of computational technologies, the complexity of models has significantly grown, not only in terms of spatial resolution but also in terms of physical phenomena involved in the simulations. On the one hand, the complexity in modelling the individual process has increased over time, along with the number of processes. On the other hand, the spatial resolution has also been improved, both in horizontal resolution and vertical levels. The reliability of a GMC is evaluated by simulating it in the past and comparing the outputs with observed historical climate data [91]. Undoubtedly, the reliability of GCMs has improved over time, but they are still characterized by significantly uncertainties. Consequently, to generate future projections, multi-model ensembles of General Circulation Models (GCMs) are adopted, which allow to define both the uncertainty in projections and uncertainties in variations of initial conditions or parameterizations [92]. Once being validated against past weather observations, the GCMs can be forced by future emissions scenarios - associated with different potential world developments - to generate climate projections. Overall, three main sources of uncertainty affected climate projections, including emission scenarios uncertainty, models uncertainty, and internal climate variability. Over the years, the emission scenarios adopted by the IPCC have been modified, moving from the AS90 to the current SSPs scenarios (**Figure 5**).

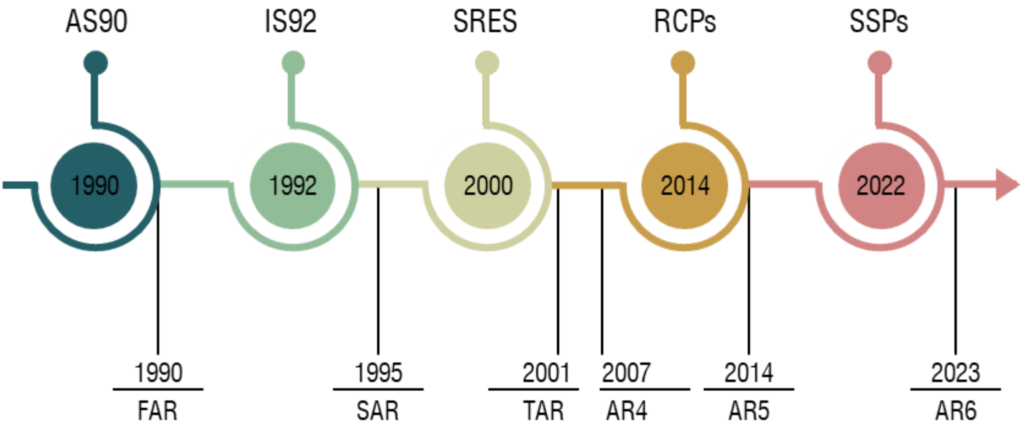


Figure 5. Timeline of the development of the IPCC emission scenarios, as well as the year of publication of the six IPCC reports in which the scenarios are adopted.

The first set of long-term emissions scenario was released in 1990 (SA90 scenario), and thus replaced in 1992 with the scenarios IS92. They involved an extensively range of assumptions on GHGs trends in the absence of climate policies, resulting in an order of magnitude range of potential GHG values [93]. The IS92 were replaced in 2000, when the IPCC Working Group III released the Special Report of Emission Scenarios [82], adopted in the Third Assessment Report (TAR) in 2001. Such scenarios – known as SRES scenarios - were further refined in the IPCC Fourth Assessment Report (AR4) published in 2007. To generate the scenarios, four qualitative storylines were considered based on the relationship between the emission driving forces and their evolution over the 21st century, not considering any climate policy-induced mitigation plan. Consequently, four set of scenarios called "scenario family" were generated (A1, A2, B1, B2), which share the same demographic, politico-societal, economic, and technological storyline. From the four families, six group of scenarios were derived: three group belong to the A1 family (A1F1, A1T, A1B), while the others belong to one family each (A2, B1, B2). The above scenarios have been replaced in 2014 by the Representative Concentration Pathways (RCPs), adopted in the IPCC Fifth Assessment Report (AR5) [86]. These scenarios conceptually differ from the previous ones: while the SRES started from the socioeconomic context to project emission trends, the RCPs set the emission trends and the resulting radiative forcing a priori. As a result, each emission trend may result from different socioeconomic scenarios, thus the RCP provides only one of the possible assumptions that lead to a specific radiative forcing (hence the name "representative"). These scenarios involve four concentrations pathways, based on four radiative forcing values up to 2100 [94], defined as "*the change in the net, downward minus upward, radiative flux at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide (CO_2) or the output of the Sun*" [86]. Four radiative forcings are considered, resulting in four emission scenarios, namely RCP2.6, RCP4.5, RCP6.0, RCP8.5. Finally, the latest set of scenarios – knows as Shared Socio-Economic Pathways (SSPs) – were released in 2022 and thus adopted in the last IPCC Sixth Assessment Report of the IPCC (AR6) [50]. The SSPs are based on five narratives referred to socioeconomic assumptions (from SSP1 to SSP5 [95]), including socioeconomic challenges for both mitigation and adaptation [96]. The scenarios do not consider new climate policies further than those in place today, therefore they need to be combined with emission mitigation targets. Consequently, SSPs are coupled with the RCP projections, resulting in a SSPx-y scenario, where x refers to the SSP and y refers to the RCP (for instance SSP2-4.5). Therefore, each SSP scenario evaluates how the radiative forcings at 2100 set by the RCPs can be achieved based on their socioeconomic assumptions. Overall, climate projections adopted in the IPCC AR6 are generated based on five scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

Thanks to these scenarios, the Global Climate Models - validated based on past climate observations - can be forced to obtain future climate projections [91]. Nevertheless, the direct application of the outputs of GCMs in the building research field is not feasible, as they show both spatial and temporal inadequate resolution, along with bias in the data. In fact, the Building Performance Simulation (BPS) software require as boundary conditions hourly weather files (namely epw files), thus not consistent with the outputs of GCMs, which are characterized by a spatial resolution of about 100 - 300 km^2 and a monthly temporal resolution. Consequently, both spatial and temporal downscaling is needed to make the projections suitable for direct application in BPS tools. It is worth noting that scaling the results of a GCM to a finer spatial and temporal resolution presumes the assumption that the local climate is a combination of large-scale climate features and local conditions (topography, water bodies, land surface properties), which are beyond the modelling capabilities of GCMs [97]. Over time, several methodologies have been developed to downscaled GCMs, which can be classified into three major approaches [84]: statistical downscaling (imposed offset method and stochastic weather approach), dynamical downscaling, and hybrid downscaling (**Figure 6**). Clearly, the downscaling process involves different steps each one based on approximations and assumptions, resulting in an increase of the level of uncertainty in climate projections [97]. For instance, the *imposed offset method* imposes the predicted future climate information from the more complex climate models on the recorded current reference year weather data and it is most notable in the form of morphing [98], whilst the *stochastic weather model,* developed by Luo [99] and Adelard et al. [100], is based on an artificial meteorological database. On the contrary, the *dynamical approach* derives local or regional climate information using a Regional Climate Models (RCMs). A further methodology is hybrid downscaling, in which the outputs of RCMs are scaled using statistical approaches.

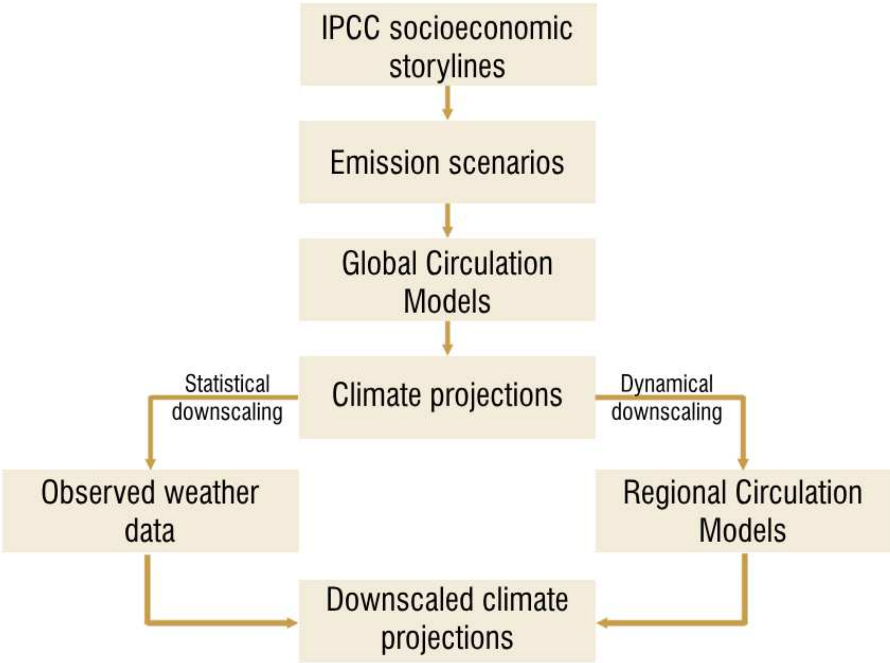


Figure 6. Flowchart for generating future climate projections with spatial and temporal resolution suitable for use in BPS.

With the aim of generating future weather files readable to be used in Building Performance Simulation (BPS) software, researchers could self-apply downscaling techniques to scalarize the future weather prediction provided by GCMs (or RCMs). However, such activity appears to be challenging and time-consuming, being more related to climatic science than to construction research field. Consequently, several tools have been developed over time to allow researchers to easily generate future weather files, which can be directly used in BPS tools. Although these tools certainly lead to a benefit by facilitating studies concerning the built environment in a changing climate, their adoption also brings disadvantages. Indeed, their use implies that the methodologies adopted in the studies - in terms of climate scenarios, time horizons of analysis, and downscaling techniques - are strongly correlated with the tools' capabilities. Interestingly, the available tools are all based on statistical downscaling techniques. In detail, four tools are based on the use of the morphing method, which is the easiest downscaling technique to be implemented. They are the CCWorldWeatherGen [101], the WeatherShift [102], and the Future Weather Generator [103]. Furthermore, one tool – Meteonorm [104] - is based on the stochastic weather method.

2.2. The school building stock

Although often neglected in our society, educational buildings constitute the focus of an interesting and extensive field of research. In this section, an overview of research activities concerning the school building stock from different perspectives is provided, addressing the different topics covered in this thesis. Firstly, the Italian school building stock - the subject of the study - is briefly presented. Then, methods for characterizing the school building stock are discussed and existing studies on field schools energy assessments are reviewed. Finally, a review of existing literature concerning school buildings in a changing climate is presented.

2.2.1. The Italian school building stock

Italy shows more than one million public buildings, among which schools rank fifth in terms of units (with 48101 surveyed schools), but first in terms of total occupied area occupied (98 million m^2) [105]. According to the Italian educational system [106], they are divided in:

- Early Childhood Education and Care (ECEC), divided in childcare centres (0-3 years old) and pre-schools (3-6 years old).
- Primary schools (6-10 years old).
- Lower secondary schools (11-13 years old).
- Upper secondary schools.
- Tertiary education.

Primary and lower secondary schools represent the “first cycle of education”, and along with ECECs are city-owned buildings, while upper secondary schools constitute the “second cycle of education”, owned by provinces [34].

Given the multitude of building ownerships, for a long time, information about schools remained disaggregated and uncertain. An attempt to collect them into a comprehensive reference was made in 1996, with the introduction of the “National Register of School Buildings" (Anagrafe Nazionale dell'Edilizia Scolastica, SNAES), an official public database which aimed to assess the consistency, status and functionality of the school buildings stock [107]. Unfortunately, the development of the database was not started until 2017, after the publication of the "Buona Scuola" reform [108]. Currently, the database consists of two parts: a national one (SNAES) and a series of regional nodes (ARES), which ensure monitoring at the regional level. The regional nodes employ an online information system, in which each school building is associated with an information form, filled out partly by the owner (who is required to enter a set of data characterizing the building) and partly by the school principal [109]. Accordingly, the reliability of the collected data is strongly related to the users who fill the database. So far, regional databases are still under construction, lacking a large number of data, which results in one of the main barriers in conducting extensive studies in regional territories.

Overall, the national SNAES database includes 58236 educational buildings, apart from the self-governing provinces of Trento e Bolzano [110]. ECEC schools represent the largest part of the sample (38%), followed by primary (29%), upper secondary (18%) and lower secondary schools (15%). Hence, the majority of public Italian schools are municipally owned, reaching 82%. From a geographical perspective, northern regions host the largest number of educational buildings (40.1%), followed by southern (27.6%), central (19%) and island regions (13.3%). Looking at the data related to the year of construction, the ageing of the buildings is clearly revealed: 42% of the schools was built before 1976 - hence in the absence of any energy regulation -, 20% was built between 1976 and 1992, and only 12% was built after 1992. Accordingly, more than 60% of Italian educational buildings age more than 30 years old.

From the perspective of building patterns, Italian schools share some common features. Firstly, they are hosted in naturally ventilated buildings, in which gas and electricity represent the main energy sources. In detail, on the one hand, electricity supplies the energy needs for lighting, appliances, and auxiliaries of heating systems. On the other hand, energy needs for heating are supplied by fossil fuels, such as natural gas (which appears to be the most widespread accounting for 67.3% of schools), oil

(11.7%) or liquefied petroleum gas (LPG). Depending on the schools, domestic hot water (DHW) can be provided either by gas or electric boilers, but its consumption is considered negligible [111]. Moreover, since schools are almost unoccupied during the summer period (July and August), they are not equipped by cooling systems, which are limited to individual split A/C units located in staff offices at most [111,112].

With reference to school maintenance work, the implementation of energy efficiency measures is still not sufficient [25]. The renovated schools accounted for 17.1% in 2022, exceeding that of 2021 by only 1.6% [113]. Schools most subject to retrofit interventions are in the north regions (21.2%), while lowest values are reached in southern regions (14.7%) and in the island regions (5.8%) [25]. Evidently, further efforts are needed to address these issues, considering the exemplary role that Public Administration is required to play.

2.2.2. The characterisation of a school building stock

The scientific community has always faced the issue of finding proper methodologies that allow the overall exploration and characterization of existing building heritages. In detail, with the implementation of climate policies concerning the renovation of existing buildings [28], it became clear that a comprehensive knowledge of building stocks features was a crucial part of the renovation process, required to understand the current status of the assets and thus set priorities for intervention. Clearly, a detailed knowledge of a whole building stock is not feasible [30], so the methodology typically adopted consists of identifying typical buildings to be studied, representative of homogeneous classes into which the entire heritage is divided [32], as suggested by the European regulations that introduced the concept of a reference building [31].

In the literature, various approaches have been proposed to solve the issue of grouping existing buildings in homogeneous classes and identifying representative buildings of a building stock, highlighting that the main problem is related to the selection of appropriate features to group buildings, which obviously depends on the objectives of the analysis. Considerable work has undoubtedly been done in this research field, but it mainly focuses on residential buildings [32], which exhibit very different characteristics than school buildings. Regarding the latter, limited examples have been retrieved in the literature.

Early work exploring clustering techniques applied to educational building stocks includes the work by Santamouris et al., who used the fuzzy clustering approach to group 320 Greek schools, with the aim of developing a new method for energy classification and schools rating [114]. Greek schools are also the focus of a further work by Gaitani et al., who explored a method to identify representative buildings and an energy classification tool [115]. Based on a sample of 1100 buildings, data concerning: i) annual consumption for space heating and lighting, ii) building area, number of students and professors, iii) boiler power, iv) manufacturing year of the building, v) schedule of operation, were collected and a k-means clustering technique was applied, allowing 5 clusters to be found out. The k-means was also adopted by Raatikainen et al., who explored electricity use and district heating consumption trends of six Finnish schools built in different periods [116].

Referring to the Italian context, limited examples were retrieved in the literature. For instance, sixty schools located in North-East Italy (province of Treviso) have been clustered by Arambula Lara et al., adopting the k-means approach [35]. Firstly, they performed statistical analyses to correlate the actual energy consumption of the schools collected over a five-years period and their geometrical and technical features. Then, energy predictors affecting heating consumption were selected and adopted to perform the cluster analysis, identifying reference buildings to evaluate energy retrofit strategies. Otherwise, thirty-eight schools located in North-West Italy (municipality of Lecco) have been clustered in the work of Salvalai et al., with the aim of identifying reference schools to evaluated different renovation strategies [117]. In that case, three benchmark variables were used to group the buildings: i) building type (linear block, merged block at C or at L, internal court block, stepped block), ii) number of floors (1-2 floors, 3-4 floors), iii) percentage of transparent vertical surface on the vertical surface total (13-23%, 24-34%). In Central Italy (municipality of Perugia), eighty refurbished school buildings have been clustered based on five predictors: i) shape factor, ii) heating primary energy use, iii) declared jumps in energy classes, iv) gross heated volume, v) normalized primary

saved energy for heating per year [118]. Accordingly, two statistically significant clusters were retrieved, allowing two reference buildings to be selected.
As far as we know, no studies involving areas of southern Italy were found. In addition, the brief overview performed highlights that the predictors of cluster analyses can significantly differ among studies, as they are influenced by data availability, which is one of the main obstacles to defining clusters. As a result, relying on a large number of parameters for the clustering procedure often results in the analysis of a small sample of buildings - as many buildings have missing data - which may not be representative of the entire stock.

2.2.3. School buildings energy performance

The assessment of building energy consumptions represents one of the key issues currently addressed in the literature, as many efforts occurs to reduce such consumptions. In the schools field, a comprehensive review on this topic was published by Dias Pereira et al. [119], who aimed to achieve a functional benchmarking based on actual operation of schools. They made a cross-country comparison, showing a great variability in actual consumptions and highlighting the trouble in comparing energy performance due to the different indicators adopted. Overall, such a great variability is revealed by several research studies, which emphasize the heterogeneity of schools in terms of building characteristics, level of education, school management, and climatic conditions of the site [119–122]. The work carried out by Dias Pereira et al. [119] involved manuscripts published between 1997 and 2013, therefore a review of more recent literature on the topic has been conducted, involving the main studies from the last decade dealing with the analysis of actual consumption of school building samples. The main findings of these studies are summarised in **Table 2**, as presented in the work by the author [48].

Table 2. Comparison between energy consumptions of school buildings, from the writer's work [48]. Abbreviations: TC (total consumption), GC (gas consumption), OC (oil consumption), EC (electricity consumption), HC (heating consumption), EUI (energy intensity use). Values with * refer to median and not to mean values.

Ref.	Loca-tion	Sam ple	School type	Target	Units	Mean value [range]
[120]	Portugal	23	Lower secondary	TC costs	€/m^2	6.05 [3.86-9.39]
		23	Lower secondary	EC costs	€/m^2	3.89 [2.29-5.30]
		23	Lower secondary	GC costs	€/m^2	0.66 [3.86-9.39]
[123]	Brazil	42	Middle	TC	kWh/stud/mth	5.30
		11	High	TC	kWh/stud/mth	7.15
		47	Middle&High	TC	kWh/stud/mth	6.57
[121]	Hong Kong	121	Secondary	EUI	kWh/m^2	105.61[49.22-182.73]
[124]	Australia	3701	Primary	TC	kWh/m^2	38.00
[122]	Los Angeles	562	Primary	EC	kWh/m^3	11.9268
		496	Primary	GC	Therms/m^3	0.13188
		111	Middle	EC	kWh/m^3	8.898
		91	Middle	GC	Therms/m^3	0.107772
		111	High	EC	kWh/m^3	18.972
		92	High	GC	Therms/m^3	1.2096
[39]	Canada	5	K-12	EUI	kWh/m^2	127
		11	Elementary	EUI	kWh/m^2	270
		14	Secondary	EUI	kWh/m^2	264
[125]	South Korea	10	Elementary	GC	MJ/m^2	- [78-81]
		10	Elementary	OC	MJ/m^2	- [13-22]
		10	Elementary	EC	MJ/m^2	- [163-262]
[126]	Korea	10	Various	GC	Nm^3	- [8769-756411]
		10	Various	EC	kWh	-[20920-522561]
[127]	Korea	9	Middle	TC	kWh/m^2	133
[128]	Finland	80	Day-care	TC	kWh/m^2	251*
		80	Day-care	HC	kWh/m^2	- [61-551]
		80	Day-care	EC	kWh/m^2	- [37-372]
		74	Various	TC	kWh/m^2	214 *
		74	Various	HC	kWh/m^2	- [45-383]
		74	Various	EC	kWh/m^2	- [10-125]
[129]	Greece	77	Primary&Secondary	TC	kWh/m^2	84
[40]	Greece	17	Primary&Secondary	HC	kWh/m^2	97.8*[12.7-450.3]
		22	Primary&Secondary	EC	kWh/m^2	13.6* [3.8-34.3]
		25	Primary&Secondary	TC	kWh/m^2	88.9*

As illustrated in the table, the manuscripts focused on school buildings present different characteristics, including samples composed of a different number of buildings as well as different school grades. In fact, samples range from those involving only five buildings [39], to those consisting of more than 3000 buildings [124], although they are usually much smaller than 100. Overall, all types of schools appear studied in the literature, from day-care centres [128] to primary [125] and secondary [121] schools, including several nations. As already been pointed out [119], making a comparison of research findings is very tricky, since consumption are evaluated based on different benchmarks, going from consumption in terms of energy costs [120], to consumption normalized by students [123] or m^2 [121].

Referring to the Italian context, a limited number of studies exploring the existing conditions of school building samples was retrieved. These studies include 29 high schools located in Perugia (central Italy) [130], 120 high schools in the province of Turin (north-west Italy) [131], 60 schools in the province of Treviso (north-east Italy) [35], and 49 schools of different grades in Lombardy (northern Italy) [132]. Only one study is focused on southern Italy, involving 9 high schools in Matera [133]. Three main aspects can be outlined from the reviewed manuscripts, summarised below.

- The reviewed studies are not recent, ranging from 2002 to 2017. Consequently, consumption cannot be considered as representative of the current school conditions.
- Studies mainly focused on school in central and northern Italy, while southern Italy is under investigated.
- Studies mainly focused on high school since they belong to a single owner (the province) and thus it is easier to retrieve energy data.

2.2.4. School buildings in a changing climate

The previous sections focused on the characteristics of existing school buildings, including the methodologies useful for their overall analyses, as well as the current status in terms of energy performance based on field studies. In contrast, the present section focuses on the existing literature dealing with school buildings and climate change. Surprisingly, although the topics of “climate change” and “educational buildings" both constitute two extensive fields of research, their combination lacks significant attention from the research community. The literature review reveals that the extent of this topic is still limited, showing few results related to the combination of the theme "climate change" and "school buildings". In detail, only 30 manuscripts consistent with the subject have been found by querying the Scopus database.

The first dedicated paper on the topic has been published in the year 2009. Thereafter, the number of publications remains steadily limited until 2020, when the trend starts to increase. In fact, it is interesting to note how the number of publications doubles in 2021 compared to 2020, becoming five times larger in 2023, in which ten papers on the topic were released (**Figure 7**).

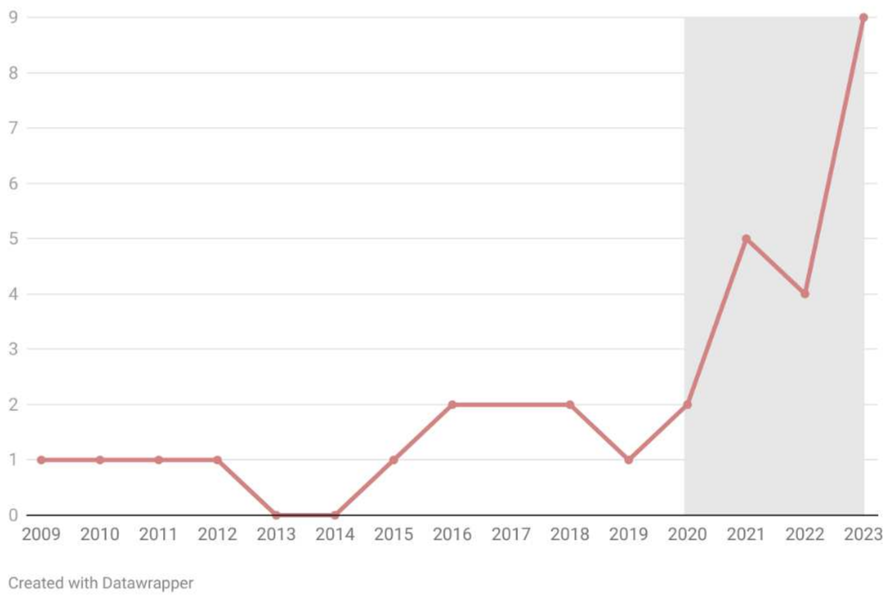


Figure 7. Publications trend from 2009 to 2023

Referring to the geographical perspective, the UK appears to be the most investigated country, accounting for 6 out of 30 papers. The remaining manuscripts are distributed over several nations (i.e., Italy, Canada, Turkey), with no specific trend being identified.

The research papers focused on school buildings evaluations in a changing climate appears to be related to three main topics: energy performance assessment, indoor comfort assessment or both. Of course, within these main topics, several issues can be addressed, as summarized in **Figure 8**.

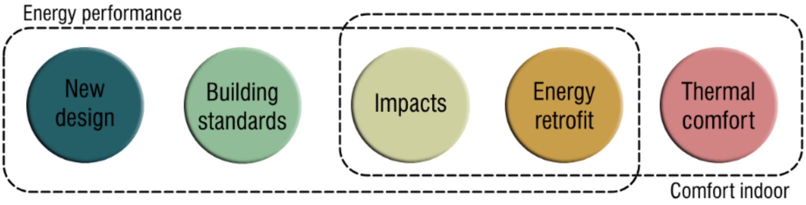


Figure 8. Main topics addressed in research studies involving educational buildings in a changing climate.

Energy performance assessments of school buildings in future climate scenarios seems to be an interesting topic, as it involves 20 of the 30 manuscripts analysed. In detail, papers can be divided into 4 categories, each one addressing a specific theme of research.

The first category concerns the design phase of school buildings, carried out in the light of future temperature increases. For instance, different configurations of schools' windows were assessed by Epa et al. [134], who modified orientation, glazing type and window size, assessing the implications in future climate in three Turkey cities.

The second category focuses on the impacts of climate change on existing schools in terms of energy consumption variations. Studies evaluating the impact of global warming have been found as early as 2011, both in term of consumption and indoor temperatures [135]. Typically, a decrease in heating consumptions was found, ranging from 16%-26% in Toronto [136], 20%-39% in Los Angeles [137], 15%-81% in Florida [138], 23%-87% in Greece [139]. Otherwise, an increase in cooling consumptions was revealed, ranging from 40%-57% in Toronto [136], 38%-68% in Los Angeles, 10%-50% in Florida [138], and 91%-284% in Greece [139]. Since the reduction in heating consumption is smaller than the increase in cooling consumption, an overall increase in total consumption was shown due to climate change, except for the city of

Toronto where a slight decrease was found [136]. An innovative approach in schools future performance was tested by Luo et al. [140], who developed a methodology based on a hybrid genetic algorithm and long-short term memory neural network model to predict future energy consumption, and then tested it on two educational buildings.

The third category – the largest one - evaluates the effectiveness of different retrofit strategies in future climate scenarios. Such strategies involve passive measures affecting the building envelope [19,141–143], active measures affecting the schools' systems [144], or both [145–147]. Typically, the studies methodology requires simulating retrofit actions in the current climate scenario, and thus comparing them with those simulated in a future climate scenario, to capture any differences. Of course, the effectiveness of retrofit actions is often evaluated not only in relation to energy consumption, but also in relation to indoor comfort, mainly in terms of overheating [19,141–143,146] or comfort models based on PMV and PPD [147]. Interestingly, among the papers dealing with retrofit strategies, most of them assesses their effectiveness in terms of thermal or energy performance, but a few consider the retrofit costs [145,147,148]. A different approach was adopted to evaluate the reduction of future cooling needs of three representative buildings (including a school), by combining mitigation strategies applied at the urban scale and adaptation measures applied to those buildings. Interestingly, the combination of such measured would reduce future cooling needs of the school by 59.4% [149].

A fourth category concerns a potential evolution of future energy benchmarks or building standards. For instance, potential energy benchmarks were evaluated by Geraldi et al., who assessed the impacts of the implementation of air-conditioning systems in Brazilian schools, without adopting other intervention strategies [150]. Two studies involved school buildings meeting the Passivhaus standard, both located in the Mediterranean area, analysing their performance in future climate [68,151]. Both studies showed that - due to rising temperatures - buildings experience a significant increase in cooling consumption in the future climate. However, by taking adaptation measures, the EnerPHit standard can be reached in all scenarios [68].

Referring to the school indoor conditions, scholars concur that provide adequate indoor comfort conditions in school buildings is essential, because they affect both students' performance and students' health [152]. Unfortunately, the schools' indoor environment is often poorly comfortable today [24], and it is expected to get worse with climate change. Indeed, rising temperatures result in an increased risk of overheating, which is found to be the most investigated parameter within the reviewed studies [153]. In fact, all studies focus on the analysis of comfort from the thermal point of view. Some studies analyse different strategies to reduce the risk of overheating in the future climate by reducing solar gain [154], adopting windcatcher [155], improving envelope performance [156], but mainly by investigating different ventilation strategies as passive mitigation measures [154,157]. Together with natural ventilation, indirect evaporative cooling also appears an effective strategy [158]. However, the comprehensive effectiveness of passive cooling strategies appears to be declining in the future, making cooling systems unavoidable to preserve indoor thermal comfort [157]. Just linked to this topic, an assessment of passive mitigation strategies to reduce the overheating risks without increasing cooling energy needs in future climate has shown that the combination of night cooling and the reduction of solar gain allows to guarantee acceptable thermal conditions [159]. A remarkably study on schools' resilience to overheating was carried out by Sengupta et al., who analysed the impact of different shock types, involving both heatwaves and three system shocks: i) failure of indirect evaporative cooling, ii) natural night ventilation, iii) solar shading failure [160]. Obviously, such evaluations are strictly related to the location investigated. For instance, the Mediterranean area experiences a larger risk of overheating, which can occur even in the intermediate seasons due to climate change [157]. Interestingly, in discussing indoor comfort conditions in future climate scenarios, researchers appear concerned about the behaviour of NZEB schools, wondering whether such target will remain adequate in the future [141,160].

This brief literature review shows that - despite climate change is undoubtedly recognised as a critical problem - studies involving schools are still limited. Overall, studies focus mainly on specific case studies, investigating specific schools in specific locations, while totally lacking investigations of representative buildings. In addition, the effects of climate change often appear to be inadequately considered, relying on outdated emission scenarios, and neglecting the effects of climate change at the local scale.

CHAPTER 3

3. CLIMATE CHANGE IMPACTS ON BUILDING ENERGY CONSUMPTION

3.1. Introduction

The literature review dealing with climate change modelling in the context of building research (**section 2.1.3**) revealed that the existing literature is still inadequate to the magnitude of the topic, so much so that the IPCC itself suggested that research should be expanded to a broader breadth of building types. In addition, the multitude of existing methodologies that emerged from the literature review - as well as the many associated uncertainties - suggested the need to map the impacts of climate change on building energy consumption. Consequently, the present section aims to fill this literature gap, with the aim of exploring from a quantitative perspective the main implications of climate change on building energy consumption, according to the existing literature, thus answering the first research question of this thesis (**RQ1**). More in detail, this chapter aims to achieve two key objectives. The first aim is to understand - based on data available from existing research - the effects of climate change on building consumption, highlighting the extent to which they differ among studies. The second aim is to explore whether correlations exist between methodological inputs (such as heating degree-days, cooling degree-days, reference period, future time slices and emission scenarios summarized by CO_2 concentrations) and research outcomes. The methodology used to pursue these objectives is described in **Section 3.2** and involved the collection of literature data, according to the PRISMA guidelines, the extraction of data from studies and finally a meta-analysis, followed by a correlation analysis to explore the sources of heterogeneity. The results obtained, presented and discussed in **Section 3.3**, have as their main reference a work published by the present writer in a dedicated journal paper [16], which can be referred to for more details. The novelty of the study lies in the fact that so far quantitative evaluations based on the results of existing studies in terms of energy consumption variation due to climate change have not been ever presented, although different methodological approaches have been already overviewed in previous studies [81,161], along with the main impacts of global warming on energy consumption [162–164].

3.2. Methodology

The methodology adopted to conduct the study consists of two main steps. First, a review of the existing literature to collect articles on the research topic has been conducted, selecting suitable manuscripts to carry out the quantitative analysis. Second, useful data associated with the problem statement have been extracted to prepare the data sheet to perform the meta-analysis.

3.2.1. Study selection

To proper conduct the literature review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and statements [165] have been followed, which require performing a five-step procedure: (1) identifying the research question, (2) identifying the keywords, (3) identifying the eligibility criteria, (4) selecting studies for the qualitative analysis based on the eligibility criteria, (5) selecting studies for the quantitative analysis. The whole process is summarised in **Figure 9** in the so-called PRISMA flow diagram.

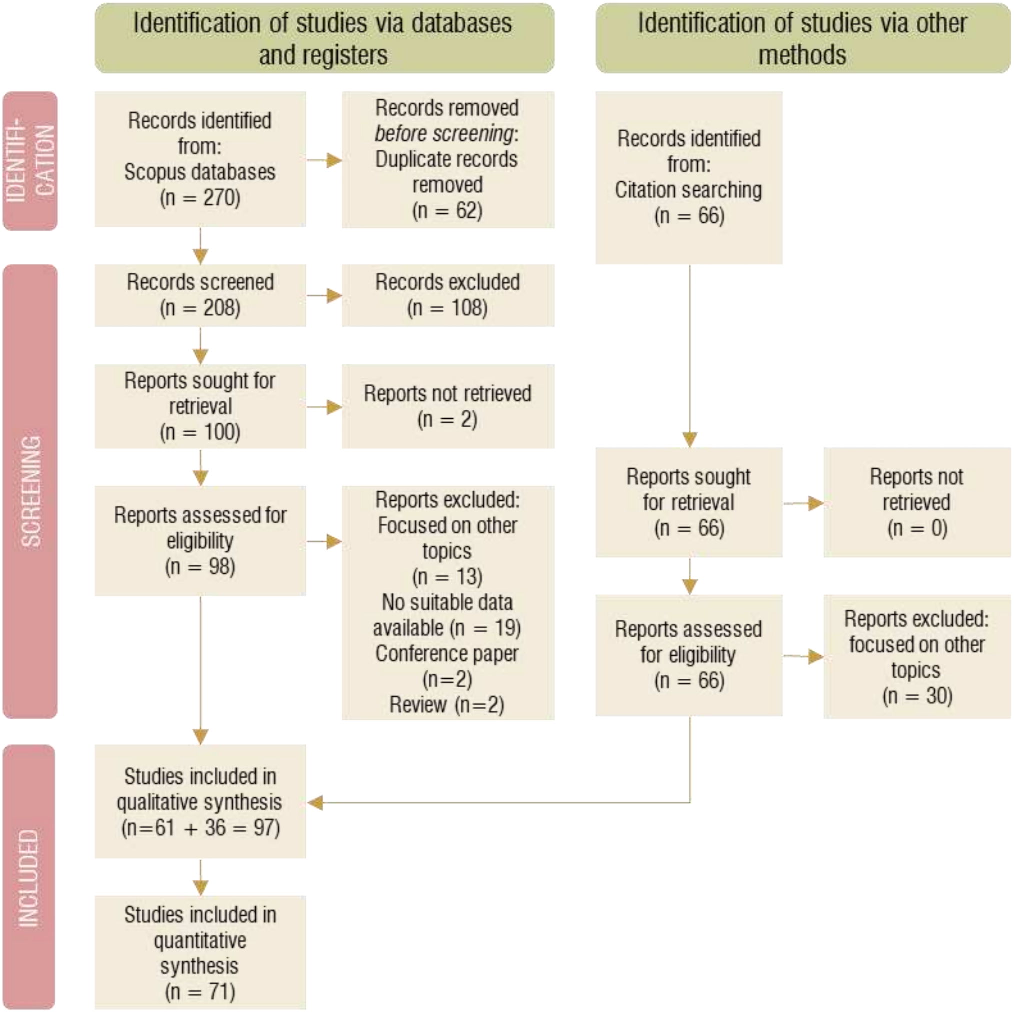


Figure 9. PRISMA flow diagram, adapted from [165]

Based on the research questions, the following keywords have been selected to conduct the search, properly combined to create the Boolean search queries needed by the search database.

- To capture articles related to climate change: future weather data; future climate data; climate variables; weather files; weather data; future projections; weather forecasting; climate change impact; climate change; changing climate; future climate condition; future scenarios.

- To capture articles related to buildings: buildings.
- To capture articles related to energy consumption: energy demand, energy consumption, energy performance, performance assessment.

The analysis has been conducted in the Scopus bibliographic database, considered the most reliable database along with Web of Science [166]. The two databases have been extensively compared in several studies, revealing that not only Scopus has a broader coverage of journals and scientific production than Web of Science [167,168], but it relies on a faster indexing process, allowing more recent publications to be found and thus enriching the data collection with updated manuscripts [169]. Hence, using only Scopus does not affect the validity of the sample. The first search results (557 manuscripts) have been reduced based on the inclusion criteria: language (English), year of publication (from 1990 - when the First IPCC Assessment Report was released – to June 2021 – when the review was conducted), no grey literature. Furthermore, both references cited in manuscripts included in the review and references cited in reviews on similar topics have been screened to identify additional studies. Overall, nearly 300 articles have been retrieved and submitted for a two-step screening: titles and abstracts have been surveyed and excluded if not related to the research topic; if titles and abstracts were found to be relevant, the full text has been assessed for eligibility in detail. After the screening process, nearly 100 manuscripts have been selected and then evaluated to perform the quantitative analysis, as the results of a meta-analysis are closely related to the proper selection of studies. In the process of selecting relevant studies, the evaluation criterion was based on the presence of quantitative data on energy consumption changes under future climate scenarios, either in numerical or graphical form, thus excluding qualitative outcomes. As a result, the number of manuscripts was eventually reduced to 71.

3.2.2. Data extraction

Once the manuscripts were selected, a manual data extraction has been performed, collecting data on parameters identified as relevant (**Table 3**). Since appropriate data selection is a crucial aspect of meta-analysis, the present author collected data while the supervisor checked them, debating contradictions together.

Table 3. List of extrapolated data. ([1]Calculated data)

	Variable	Brief description
P1.	Building typology	Type of building in accordance with usage
P2.	Location	Reference city/region. When a study was referred to a region, the most representative city was selected.
P3.	Climate zone[1]	Climatic zones in accordance with Köppen-Geiger climate classification system [170]
P4.	Heating Degree Days[1]	Calculated based on reference period and location (T=18°C)
P5.	Cooling Degree Days[1]	Calculated based on reference period and location (T=18°C)
P6.	Reference period	Baseline weather file for simulation in current climate conditions
P7.	Emission scenario	Emission scenario adopted for future climate projections
P8.	Downscaling technique	Technique used for generating the future weather files
P9.	Future time slices	Future weather file for simulation in future climate conditions
P10.	CO_2 concentration (ppm)[1]	Selected in accordance with the emission scenario and the future time slice
P11.	Target	Outcome measured
P12.	Heating consumption variation[1]	Percentage variation between heating consumption in the reference period and in the future weather scenario considered
P13.	Cooling consumption variation[1]	Percentage variation between heating consumption in the reference period and in the future weather scenario considered

A total of 14 parameters have been extracted, either directly collected from papers (P1, P2, P7, P8, P11) or calculated (P3, P4, P5, P10). For instance, based on the reference period and location investigated [170], heating and cooling degree-days have been calculated on a baseline temperature of 18°C, by downloading the corresponding weather file from Energy Plus [171] or Meteonorm [104]. In addition, in accordance with the emission scenario and the future time slice, CO_2 concentration has been selected from [83,172,173]. Instead, other variables (P6, P9, P12, P13, P14) required to be standardised and unified to make the evaluations feasible. Both reference periods and future time slices have been reduced to three groups: namely 1990, 2000, 2010 for the reference periods, according to last recorded year of the climate series used to generate the reference weather file; 2020 (near-term), 2050 (mid-term), 2080 (long-term) for the future time periods.

To standardize the outcomes of research, often based on different energy targets, the percentage change in consumption has been calculated for all studies. In addition, if the manuscripts presented the results in graphical form, the software Origin has been used to extrapolate numerical data [174].

3.2.3. Meta-analysis

The meta-analysis aims to summarise the results – i.e., effect sizes - of different studies answering the same research question. It also allows for exploring the heterogeneity of outcomes, quantifying the magnitude of variance, and thus providing insights into the factors influencing the variability of results. In this study, the meta-analysis has been conducted according to the well-established methodology given by Borenstein et al. [175], following a three-step procedure explained below: i) data preparation; ii) studies combination; iii) exploration of heterogeneity. Since not all the manuscripts included all the parameters described in the previous paragraph, the sample narrowed down from 71 to 19 articles.

Data preparation

The correlation coefficient r (with p-value) has been selected as the effect size, and thus calculated for each study. Although mainly employed in the clinical field, the effect size can represent any relationship between two variables [175]: thus, in our study it represents the relationship between climate change (measured as the increase in CO_2 concentration) and the energy consumption variation. Three distinct effect sizes have been calculated for each study ($r_{HEATING}$, $r_{COOLING}$, r_{TOTAL}), defining the 95% confidence interval. Hence, all computations are carried out using the Fisher's z transformed values [175].

Studies combination

The meta-analysis aims to summarise the results of individual studies into a single effect (known as combined effect). To this end, the individual outcomes need to be weighted based on their reliability, since high reliability studies should affect the combined effect more than the low-reliability ones. Two approaches can be adopted to weight the outcomes: a fixed effect model - which assumes that the true outcome (unknown) is the same for all studies – and a random effect model [175]. In the research field focused on the impact of climate change on building energy performance, findings are not expected to be identical, since different methodological approaches can be adopted. Hence, the random-effect model has been selected to carry out the meta-analysis, although it results in a greater variance, standard error, and confidence interval for the summary effect. According to this approach, the process of weighted involves two steps, based on the two source of error that can occur (within-study V_y and between-study variations τ^2). The former results in a fixed-effect weighting (w_i), expressed as the inverse of the total variance. The latter results in a random-effect weighting (w^*_i), expressed as the inverse of the sum of the within-study and between-study variance, estimated with the method of moments [175]. Once the random-effect weights were computed for each study, the combined outcome has been calculated as the weighted mean, while its standard error has been calculated as the square root of the variance, that is the inverse of the weights. Finally, the combined effect size and their confidence intervals have been converted into correlations by the Fisher's z metric [175], and thus depicted in three Forest plots (respectively for heating outcomes, cooling outcomes and total variation outcomes).

Exploration of heterogeneity

The meta-analysis enables the exploration of the heterogeneity of individual studies, quantifying the magnitude of variance and thus providing insights into the potential sources of variation. Heterogeneity is detected when the variation between different studies is above the variation expected by chance and can be evaluate with several approaches [175]. In this thesis, heterogeneity has been assessed through the index of inconsistency I^2 proposed by Higgins et al. [176], which can assume values ranging from 0 to 100%, indicating low (25%), moderate (50%) or high (75%) heterogeneity respectively. If evidence of heterogeneity is found, further analysis should be conducted to explore the reasons behind the variability. For instance, since a high level of heterogeneity has been found in this study, a correlation analysis has been performed in an effort to identify potential relationships between energy variations and input methodological parameters that might influence them.

3.3. Results

3.3.1. Qualitative overview

This section provides a brief qualitative overview of the reviewed studies, exploring locations and building types investigated, as well as the methodologies adopted.

Geographical overview

From a geographical point of view, the surveyed studies cover 46 different countries around the world, for a total of 146 cities investigated (**Figure 10**). The United States of America represent the most investigated country (with 9 studies involving U.S. cities), followed by the Honk Kong Special Administrative Region-China (8 studies). Other significant contributions come from Japan, China and Spain, with 6 studies, respectively. Finally, further analyses were conducted in the United Kingdom (5 studies), Australia, Canada and Italy (4 studies each). From a climatological point of view, most of the literature concerns cities that are in a temperate climate (type C, 65%), with a focus on the Csa zone (hot -summer Mediterranean climate). Continental climate (type D) appears to be the second most targeted climate zone (16%), followed by tropical climate (type B, 10%), dry climate (type A, 9%) and polar climate (type E, 1%). Only one research paper exploring different climate zones was found, which includes 102 case studies providing results as an average. Interestingly, most of the manuscripts are "city level" based (42 out of 71), that is, they focus their analysis on a specific city. A further 24 manuscripts are "regionally based", analysing different cities located in the same country or region, regardless of the climate zone they belong to. Finally, only five papers are "climate zone" based, selecting cities belonging to the same climate zone (regardless of country).

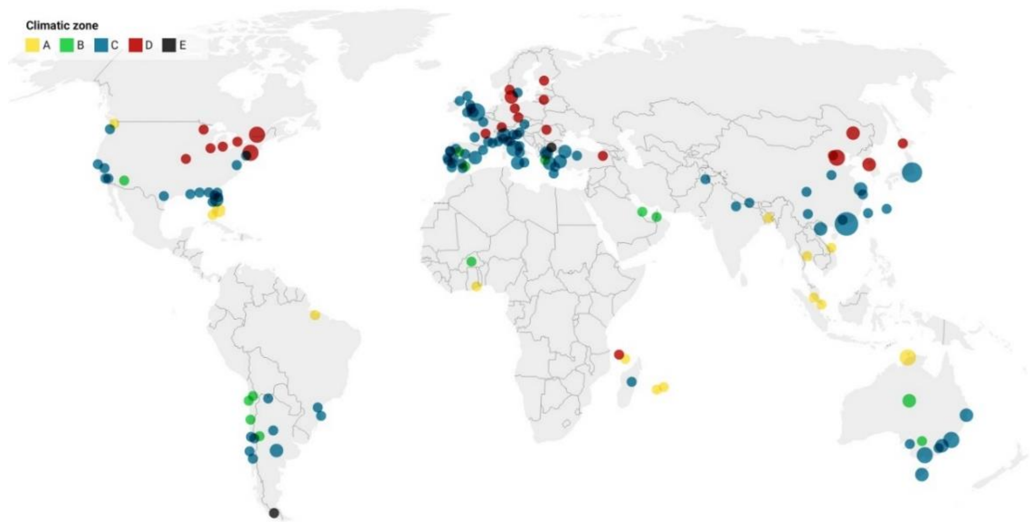


Figure 10. Locations investigated in the reviewed manuscripts, sorted by the climate zone [170]. Markers size indicates the number of studies performed in the location. From the writer's work [16]

Building typologies overview

From the building type perspective, although it can significantly affect heating and cooling energy consumption [177], most of the manuscripts explores future energy performance based on one/two building types. In fact, 86% of the surveyed papers (61 out of 71) concerns evaluations on a single building type, while 7% investigates two building types, and the other 7% compare more than two building typologies. A significative exception to the so-called "individual building level" was found in the work of

Zheng et al. [178], who explored the relationship between global warming and energy consumption at different spatio-temporal scales based on estimates at 925 U.S. locations, highlighting the importance of assessing impacts at local scales, and the need for adaptation/mitigation strategies tailored to different building typologies. A further contribution was given in [137], where a GIS-based approach to combine climate modelling, building energy simulation, and inventory of building characteristics is presented, aiming at quantifying climate change implications on building energy demand in Los Angeles. Undoubtedly, residential buildings represent the building typology most investigated (40% of the studies), followed by office buildings (26%). Less attention is given to other building types, namely commercial buildings (9%), schools (6%), hospitals (6%), hotels (4%), warehouses (4%), restaurants (3%) and universities (3%). Referring to the building models adopted for the analyses, they can be categorized in four main groups. The first group - the numerous one - focuses on the energy evaluations based on real case studies, which could be validated against measured data. The second and the third groups involve manuscripts which concern typical buildings assumed as representative of the building stock, and building prototypes developed by different standards (i.e., DOE), respectively. Finally, the last group deals with reference buildings in compliance of local standards.

Methods overview

From the methodological perspective, to provide an overview of the methodologies adopted, information related to the reference period (P6), the emission scenario (P7), the downscaling technique (P8), and the future time slice (P9) have been presented and discussed below (**Table 4**). The first column represents the variable, (i.e., the input parameter chosen in the methodological framework), the second column represents the possible parameters of choices, the third column represents the frequency related to the number of papers in which that parameter is chosen. In addition, since several evaluations can be performed in each study, the 71 papers result in 1676 data. Thus, a fourth column was added to indicate the number of available items referred to that parameter.

Table 4. List of extracted parameters related to the methodological framework. n.g. stands for not-given. From the writer's work [16].

	Input variable	Variation	Frequency (%)	Number of items
P6	Emission scenario	A2	22	841
		RCP8.5	12	148
		A1B	12	156
		RCP4.5	10	91
		B1	9	89
		No scenario (recorded data)	8	56
		n.g.	7	53
		Other scenarios	19	233
P7	Downscaling technique	Morphing	45	1083
		Offset method	10	145
		Dynamical	7	57
		Stochastic	7	147
		Hybrid	2	10
		Recorded data	13	56
		PCA	5	34
		Other methods	9	141
		n.g.	1	3
P8	Reference period	1990	39	581
		2000	20	580
		2010	37	485
		n.g.	4	30
P9	Future time slice	2020	25	485
		2050	34	659
		2080	31	454
		Recorded data	9	56
		n.g.	1	22

The reviewed studies encompass the four main downscaling techniques explained in [84]. The “extrapolated statistical method” is the less frequently method adopted, appearing in only 4 studies. Such approach extrapolates statistical historical weather data to predict future weather conditions and is commonly applied in the prediction of building energy consumption trends using degree-day theory, rather than building simulation techniques. Nevertheless, given its limitations [15,76,87,179] and thanks to the development of simulation software (BPS), the degree-day method has been rapidly substituted by building simulation techniques, adopted in 60 studies. The literature review shows that there is a heterogeneous use of the others downscaling approaches. The imposed offset method is the most adopted approach (adopted in 43 papers), mainly through the morphing method (39 papers). A limited number of manuscripts adopts the stochastic weather models and dynamical downscaling, which account for 6 and 8 studies respectively, while the hybrid method is adopted in only one study. An attempt to directly correlate building energy consumption with daily/monthly climate data has been carried out by means of principal component analyses (PCA) and regression analyses in [180–183]. Referring to the emission scenarios, the SRES still represent the most adopted (54% of the studies), followed by the RCPs (24%). More in detail, the A2 scenario appears in 39% of manuscripts while RCP8.5 in 21% of studies, as they are adopted in two widely used software, namely CCWorldWeatherGenerator [184] and WeatherShiftTM [185]. By contrast, the last SSP scenarios are adopted in a single study [186]. To analyse the impact of future climate conditions on building energy consumptions, two different types of weather data are required: current weather files to be used as a baseline for assessing actual consumptions, and future weather data files as representative of future scenarios to evaluate future consumption, thus allowing the variation to be calculated. The literature review shows that a considerable number of studies is still related to the reference period “1990” (39%), derived from weather data observed before 1990 and representative of TMY2 weather files [187], or similar. Hence, these studies assume obsolete climate files as a baseline and do not consider climate changes that have already occurred in recent years. However, more recent climate files are used as a basis in a great number of studies (37%), based on the "2010" reference period, representative of climate files that include data beyond 2000 (i.e. TMY3 [188]). The remaining papers (20%) are based on the "2000" reference period, which is representative of climate files involving data up to 2000 (i.e. IWEC [189]). With regard to future climate scenarios, the reviewed studies carry out assessments on the basis of three-time horizons: 2020 (25%), 2050 (34%), 2080 (31%), whilst a reduced group of manuscripts (8%) bases assessments not only on predicted data, but also on measured data. These observations allow to create measured weather files, representative of climate trends of recent years, as an average between a range of years [190,191] or as a typical meteorological year [192,193].

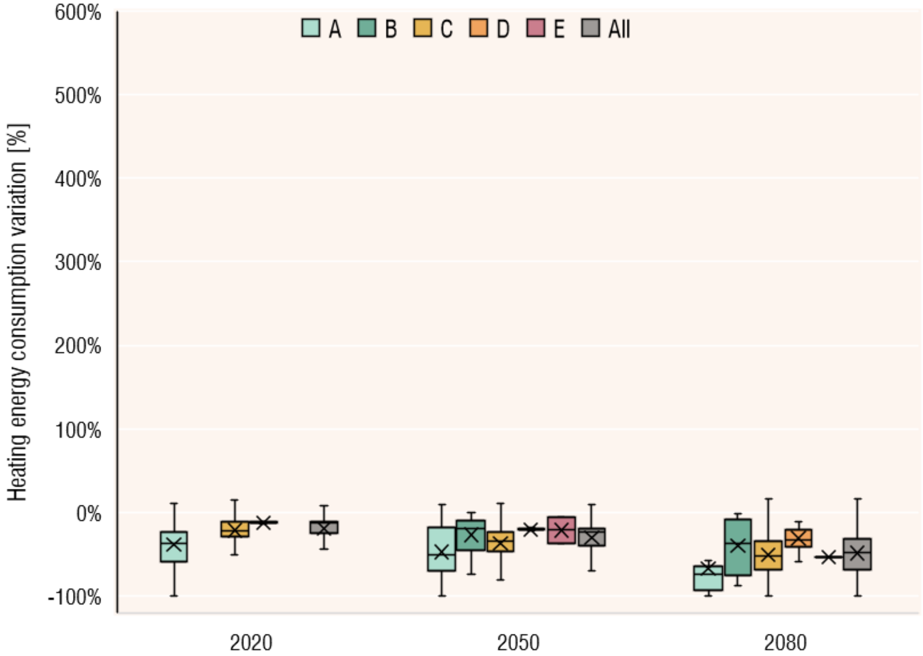
3.3.1. Findings overview

Based on the reviewed research studies, the main findings on the energy consumption variation due to climate change are presented and discussed below.

Interestingly, most of the manuscripts explore the impacts of climate change on heating, cooling and thus total energy consumption. However, some studies provide information only on total consumption, neglecting individual contributions or instead provide information only on heating (or cooling) consumption while neglecting total consumption.

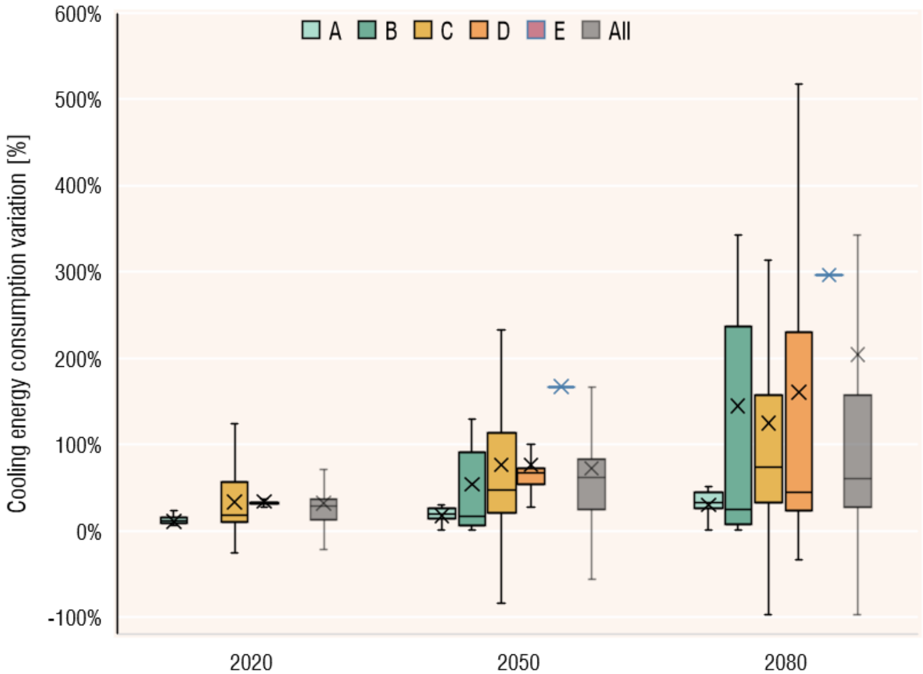
The above manuscripts deal with annual consumption changes (often being expressed in percentage terms), although a minority of studies provide results in terms of rates of increase/decrease in cooling loads per year [179], or changes in energy performance in representative months [194–196].

Given the considerable number of collected data, they have been analysed through descriptive statistics. In detail, the distribution of data on heating, cooling and total consumption variations has been depicted with three boxplots (**Figure 11**), and the corresponding synthetic indices have been calculated (**Table 5**). Each boxplot includes five subgroups representative of the main climate zones (subgroups A, B, C, D, E represent climate zones A, B, C, D, E, respectively), along with an additional group (All) that captures the totality of data. In addition, data are displayed according to the three future time frames (2020, 2050, 2080), as well as data referring to the recorded years.



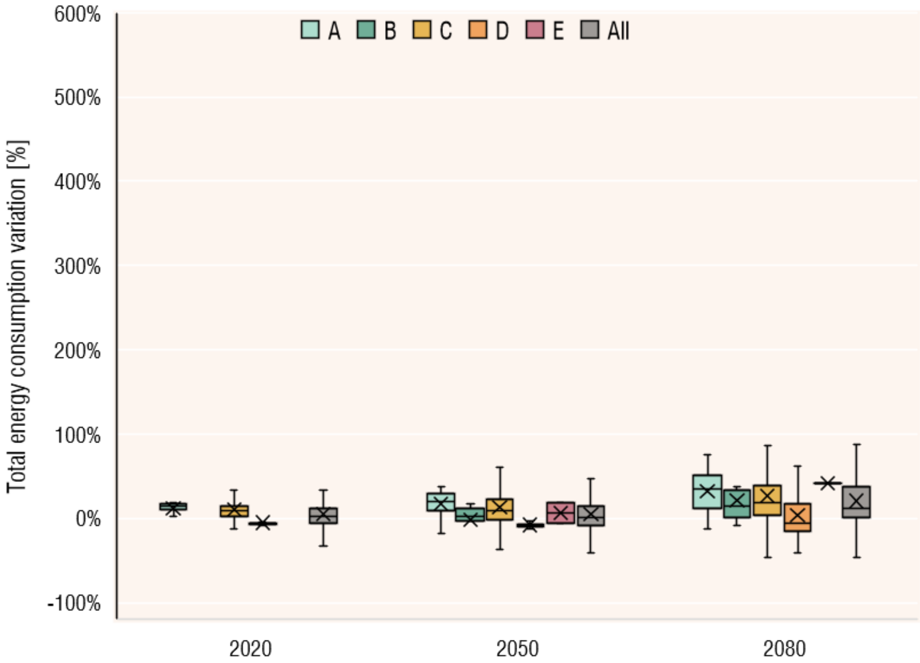
A
B
C
D
E
All
Heating energy consumption variation [%]
600%
500%
400%
300%
200%
100%
0%
-100%
2020
2050
2080

(a)



A
B
C
D
E
All
Cooling energy consumption variation [%]
600%
500%
400%
300%
200%
100%
0%
-100%
2020
2050
2080

(b)



(c)

Figure 11. Data distribution of consumption variation divided by climate zones (zones A, B, C, D, E, and overall zones) and by future time slices, referred to: **(a)** heating consumption variation, **(b)** cooling consumption variation, **(c)** total consumption variation. The marker "x" indicates the mean values, whilst the marker "-" indicates the median values. Adapted from the writer's work [16].

Table 5. Summary of synthetic descriptive indices related to the overall dataset. From the writer's work [16].

	Overall data	**2020**	**2050**	**2080**
Heating variation	Median	-12.6%	-23.3%	-47.5%
	Mean	-18.83%	-30.28%	-48.72%
	Standard deviation	0.176	0.218	0.272
Cooling variation	Median	28.8%	61.5%	60.9%
	Mean	32.1%	72.3%	204.1%
	Standard deviation	0.366	1.060	11.096
Total variation	Median	2.6%	0.3%	12.0%
	Mean	5.23%	4.73%	20.36%
	Standard deviation	0.345	0.478	0.659

Looking at the overall dataset (group All), climate change impacts consumption trends at two levels. On the one hand, it leads to a progressive decrease in heating consumption, whose median value ranges from -18.6% (2020) to -48.5% (2080). On the other hand, it leads to positive variation in cooling demand since median value rises from 28.8% (2020) to 60.9% (2080). Consequently, the overall energy consumption steadily increases from 2.6% (2020) to 12% (2080).

As is evident from the graphs, such results are strongly influenced by the impacts on different climate zones, which are affected by climate change to different extents. In fact, although the consumption trend in each zone complies with the global trend described above, differences between climate zones can be drawn. Overall, compared with the reference period, 50% of the results show a reduction in heating between 0 and 100%, with significant variability in data between zones. With the exception of zone B, considering the representative indices (mean, median), the change in heating consumption decreases from climate zone A to D. Although it may seem unexpected, since zone D has a colder climate, this observation can be explained by the fact that the change in consumption has been calculated as a percentage variation. Hence, in warmer zones (like zone A), since heating consumption is lower during the reference period, even a slight variation results in a large percentage increase. Concerning the change in total consumption, climate zone A seems to suffer from the largest increase in consumption, ranging from 14.1% (2020) to 35.1% (2080), while climate zone D experience a slight reduction in consumption, due to a high reduction in winter loads.

3.3.2. Statistical analysis

The results of the meta-analysis are drawn through a graph called Forest Plot, in which the effect size for each study (with its 95% confidence interval), as well as combined effect size for all the studies, are displayed. Since the effect size has been calculated separately for heating, cooling and total consumption, three Forest Plots are generated (**Figure 12**).

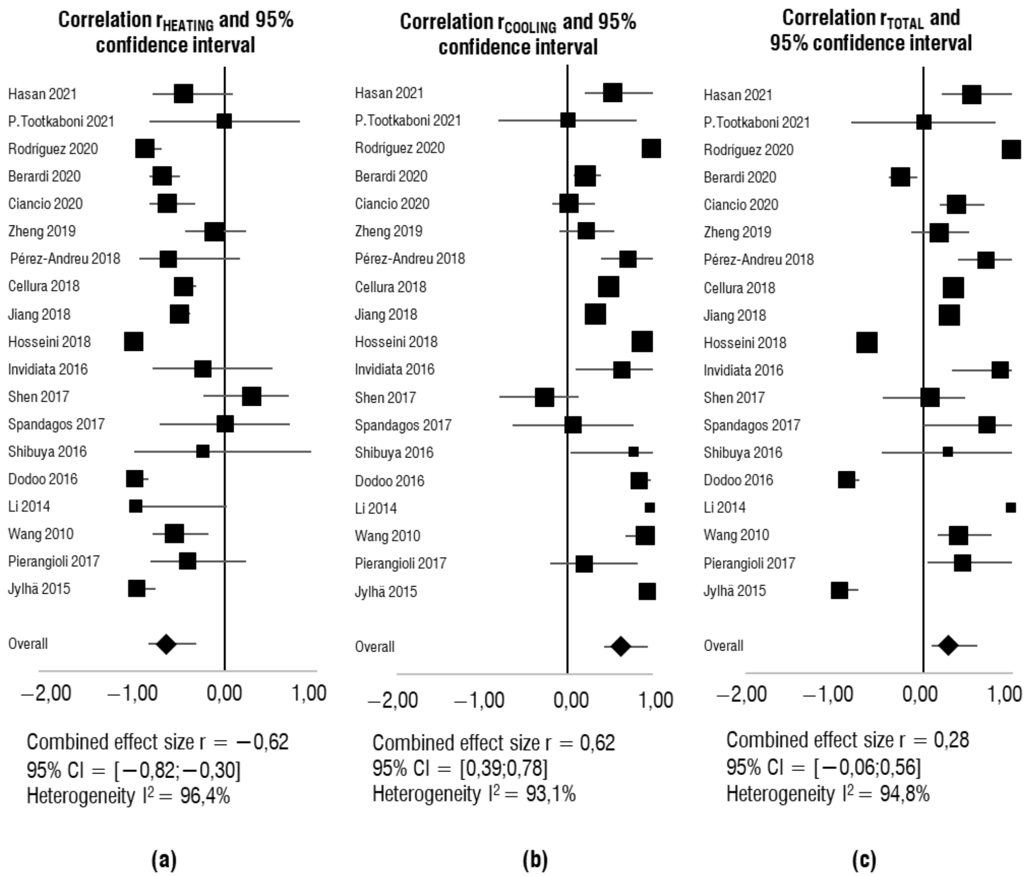


Figure 12. Forest plot obtained from the meta-analysis conducted on: **(a)** heating consumption variation, **(b)** cooling consumption variation, **(c)** total consumption variation. Author's elaboration based on references [15,67,79,136–138,180,197–208]

The effect sizes concerning the relationship between climate change and heating consumption variation is shown in **Figure 12a**. Accordingly, the combined effect size based on the random effect model is -0.62, with a 95% confidence interval ranging from -0.82 to -0.30 ($p<0.001$). Furthermore, the combined effect size referred to the relationship between climate change and cooling variation (**Figure 12b**) is equal to 0.62, with a 95% confidence interval ranging from 0.39 to 0.78 ($p<0.001$). Finally, the effect sizes referred to the relationship between climate change and total consumption variation (**Figure 12c**) are synthesized by a combined effect size of 0.28, with a 95% confidence interval ranging from -0.06 to 0.56 ($p<0.001$).

With the aim of evaluating the impact on the outcomes of the statistical methods employed, a sensitivity analysis has been performed: the analyses have been thus performed a second time, adopting the fixed effect model. In this case, the combined effect size is equal to -0.76 (95% confidence interval: [-0.79;-0.74]) for $r_{HEATING}$, 0.63 (95% confidence interval: [0.59; 0.67]) for $r_{COOLING,}$ and 0.001 (95% confidence interval: [0.066 to 0.068]) for r_{TOTAL}. In all the analyses, a high level of heterogeneity was found, with an inconsistency index of 96.4% for $r_{HEATING}$, 93.1 % for $r_{COOLING}$, and 94.8% for r_{TOTAL}. Although in the built environment research field there are no reference values for interpreting the consistency index, such values still denote a high level of heterogeneity, since close to the maximum value of 100%. However, the high deviation of studies outcomes should not be unexpected, as research can differ greatly in the adopted methodology, which can influence the obtained results. Therefore, heterogeneity has been explored by attempting to understand the sources of variation, investigating whether and to what extent methodological parameters might influence the results, through a correlation analysis. Four input variables have been included in the analysis: P4: Heating Degree Days (HDDs), P5: Cooling Degree Days (CDDs), P6: Reference Period (RP), and P10: CO_2 concentration measured in ppm (CO2); while percentage energy consumption variation has been evaluated as P12: heating (ΔH), P13: cooling (ΔC), and P14: total variation (ΔT).

Firstly, a normality test for the variables has been graphically performed, by means of q-q plots, which allows to compare the dataset with normal distribution values for quantiles determined from the dataset itself. Although most observations do not follow the reference normal line, according to the central limit theorem (CLT), the distribution of sample means approximates a normal distribution as the sample size gets larger, regardless of the population's distribution [209]. Hence, if the sample consists of hundreds of observations, the distribution of data can be ignored, and parametric procedures can still be adopted [210]. Secondly, data has been tested for outliers in XLSTAT software [211] and a limited number of outliers has been found, but still retained in the analysis as no data errors or measurement problems were found.

Then, to evaluate the correlation among the variables, Pearson correlation test has been performed in XLSTAT software [211]. It is a parametric test measuring the strength and direction of the linear association between two variables with no assumption of causality: a result equal to -1 indicates a strong negative correlation, +1 denotes a strong positive correlation, whilst a 0 means that there is no correlation. The calculated Pearson's r coefficients are presented in **Table 6**, with statistically significant results shown in bold type (p-value $p<0.05$).

Table 6. Pearson's r coefficients. From the author's work [16].

Variable	HDDs	CDDs	RP	CO_2	ΔH	ΔC	ΔT
HDDs	**1**	**-0.759**	**0.120**	**-0.239**	**0.458**	0.038	**-0.445**
CDDs	**-0.759**	**1**	**-0.212**	**0.161**	**-0.326**	**-0.198**	**0.280**
RP	**0.120**	**-0.212**	**1**	**-0.082**	0.050	**-0.129**	-0.012
CO_2	**-0.239**	**0.161**	**-0.082**	**1**	**-0.415**	**0.230**	**0.288**
ΔH	**0.458**	**-0.326**	0.050	**-0.415**	**1**	**-0.234**	**-0.273**
ΔC	0.038	**-0.198**	**-0.129**	**0.230**	**-0.234**	**1**	**0.239**
ΔT	**-0.445**	**0.280**	-0.012	**0.288**	**-0.273**	**0.239**	**1**

Abbr. HDDs = Heating Degree Days; CDDs = Cooling Degree Days; RP = reference period; CO_2 = CO2 concentration; ΔH = heating consumption variation; ΔC = cooling consumption variation; ΔT = total consumption variation.

Evidently, there is no strong linear correlation between energy consumption variations and the other input variables, even though moderate linear correlations emerge between heating variation and HDDs (0.458) and CO_2 (-0.415). By contrast, negative linear correlations can be pointed out between total energy consumption variation and HDDs (-0.445). Nevertheless, it is worth noting that Pearson's correlation coefficient is very sensitive to outliers, which can have a very large effect on the line of best fit. Since our datasets were characterized by a range of outliers, the bivariate correlation among all the variables has been assessed using a further test: the Spearman rank correlation coefficient (rho), which allows the presence of non-linear monotonic relations and non-normality in the datasets and is assumed to be robust to outliers [212]. This is a non-parametric test which measures the strength and direction of the association between two ranked variables. Once again, the rho coefficient can range from -1 (representing a perfect negative monotonic relationship) to 1 (representing a perfect negative monotonic relationship). The calculated rho coefficients are presented in **Table 7**, with statistically significant results shown in bold type (p-value $p<0.05$).

Table 7. Spearman rho coefficients. From the author's work [16].

Variable	HDDs	CDDs	RP	CO_2	ΔH	ΔC	ΔT
HDDs	**1**	**-0.766**	**0.237**	**-0.216**	**0.497**	**0.208**	**-0.588**
CDDs	**-0.766**	**1**	**-0.089**	0.034	**-0.408**	**-0.177**	**0.485**
RP	**0.237**	**-0.089**	**1**	**-0.140**	**0.074**	0.039	-0.002
CO_2	**-0.216**	0.034	**-0.140**	**1**	**-0.422**	**0.190**	**0.180**
ΔH	**0.497**	**-0.408**	**0.074**	**-0.422**	**1**	**-0.329**	**-0.337**
ΔC	**0.208**	**-0.177**	0.039	**0.190**	**-0.329**	**1**	**0.181**
ΔT	**-0.588**	**0.485**	-0.002	**0.180**	**-0.337**	**0.181**	**1**

Abbr. HDDs = Heating Degree Days; CDDs = Cooling Degree Days; RP = reference period; CO_2 = CO_2 concentration; ΔH = heating consumption variation; ΔC = cooling consumption variation; ΔT = total consumption variation.

Again, no very strong correlations have been found among the variables, although moderate positive correlations can be pointed out between ΔH and HDDs (0.497), as well as a negative correlation between ΔH and CDDs (-0.408). Surprisingly, no obvious correlations emerged between the cooling consumption variation and the other variables, nevertheless these results do not imply there is no relationship between the variables, rather that there is no monotonic one. In addition, significant negative associations can be observed between ΔT and HDDs (-0.588), and to a lesser extent between ΔT and CDDs (0.485).

To better understand the relationship between the considered variables, the most representative scatter plots are reported in **Figure 13**.

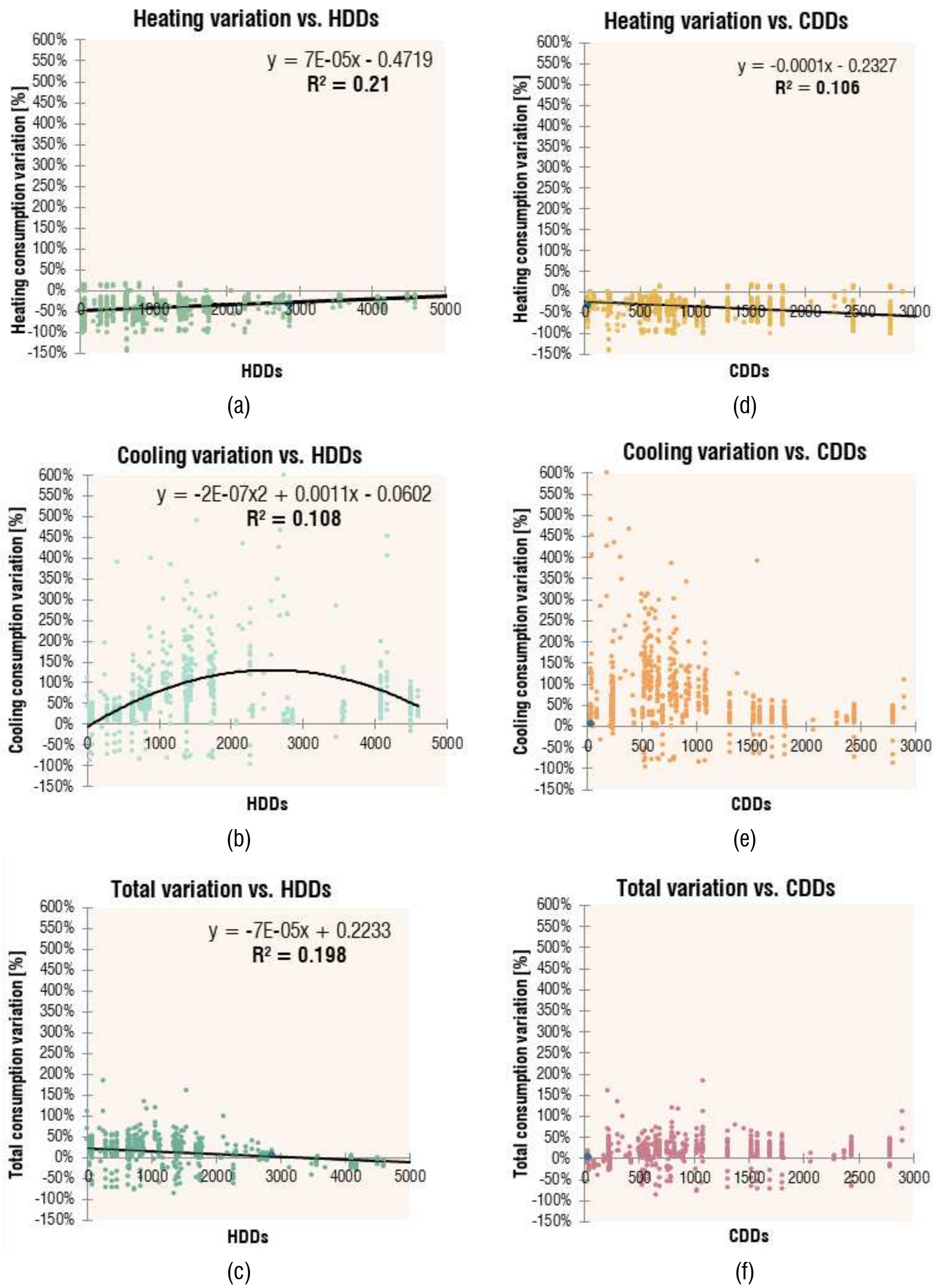


Figure 13. Relationship between HDDs and: **(a)** heating consumption variation; **(b)** cooling consumption variation; **(c)** total consumption variation. Relationship between CDDs and: **(d)** heating consumption variation; **(e)** cooling consumption variation; **(f)** total consumption variation. From the author's work [16].

The data distribution of energy consumption variation with respect to HDDs is illustrated in **Figure 13**, showing the correlation between HDDs and **(a)** heating variation, **(b)** cooling variation, **(c)** total variation. An upward trend characterizes the relationship between heating variation and HDDs, confirming the weak positive correlation suggested by the correlation coefficients. Although data appear evenly distributed, a higher concentrated spread of results can be recognized with HDDs values ranging from 0 to 2000. Overall, data appears to be distributed with a linear trend, hence a straight line seems to be the best fit ($R^2=0.21$). Given the positive gradient of the line, the greater the degree days, the greater the value of variation in heating consumption. However, since the variation is characterised by negative values, this results in a smaller reduction (in absolute value) in heating consumptions with the increase of HDDs. Since a weak value of a correlation coefficient does not imply the lack of correlation, but rather the absence of linear correlation (Pearson) and the absence of monotonic relationship (Spearman), the distribution of data concerning the variation of cooling consumptions with respect to HDDs has been plotted, to identify further suitable relationships. As depicted in **Figure 13b**, data do not appear to be randomly distributed, but higher variations of cooling consumptions seem to be concentrated in areas where HDDs range from 2000 to 4000. Therefore, a polynomial regression is found to be the best fit for the population of data, although with not a strong correlation ($R^2=0.108$). Finally, data concerning the variation of total consumptions with respect to HDDs are plotted in **Figure 13c**. Once again, the weak negative correlation suggested by the previously calculated Pearson and Spearman coefficients is confirmed by the points distribution. Indeed, the points follow a negative trend, which can be represented by a straight line with a negative slope ($R^2=0.198$). Thereby, the increase in total consumption is higher in areas characterized by smaller values of HDDs, decreasing progressively as the HDDs increase, until reaching negative values.

The data distribution of energy consumption variation with respect to CDDs is illustrated in **Figure 13**: showing the correlation between CDDs and **(d)** heating variation, **(e)** cooling variation, **(f)** total variation. A downward trend characterizes the relationship between heating consumptions variation and CDDs, already described by a low value of Pearson coefficient, but a medium value of Spearman coefficient (**Figure 13d**). Even in this case, although the data are well distributed, a higher concentration of results between 500 and 1000 CDDs can be found, whereas a considerable number of outliers characterized the whole chart. Despite that, the data distribution suggests a negative trend, with a reduction in heating consumption as CDDs increase. Assuming a linear relationship between the two variables, it would be characterised by an $R^2=0.106$, confirming the low value of the Pearson coefficient. Referring to **Figure 13e** and **Figure 13f**, the widespread distribution of the data does not allow a clear relationship between the variables to be identified. Nonetheless, the relationship between cooling consumption variation and CDDs appears to be on a downward trend (**Figure 13e**), with a high number of outliers for CDDs values ranging between 0 and 500. On the contrary, the variation of total consumption does not seem to follow any trend, as it is characterised by highly scattered values and thus not allowing to find any significant correlation.

3.4. Conclusions and limitations

The present chapter aimed to answer the first research question of the present thesis (RQ1), reviewing the state of the art on the impacts of climate change on building energy consumption. Once the papers were preliminarily analysed from a qualitatively perspective (exploring the most investigated locations and building types and the methodologies adopted), the problem was addressed from a quantitative point of view.

Concerning the qualitative analysis, the literature review showed that the studies are unevenly distributed, focusing predominantly on Europe, far-east Asia, and the eastern United States, involving mainly residential (40% of the studies) and office buildings (26% of the studies) located in climate zone C (65% of the studies). Consequently, further investigations involving different building types as well as different climate zones are certainly needed. In terms of methodology, the assessment of building energy performance often appeared to be based on inadequate climate files, both in terms of current climate and future climate. On the one hand, current climate files based on weather data measured before 1990 - thus no longer representative - are used as reference (37% of the studies); on the other hand, the generation of future climate files is based on outdated emission scenarios (mainly SRES). Moreover, among downscaling techniques, the imposed offset method (which includes morphing) undoubtedly prevails accounting for more than one half of the papers. However, the adoption of not a single approach would be desirable, considering the uncertainty in predictive analyses.

Referring to the quantitative analysis, the first objective dealt with the quantification of the effects of climate change on building consumption, exploring the extent to which they differ among studies. Accordingly, the analyses performed - based on a sample of 1671 data collected from the 71 manuscripts - confirmed that climate change will be responsible for a deep change in building energy consumption. In fact, rising temperatures will globally result in: i) a reduction in heating consumptions from -12.6% (2020) to -47.5% (2080); ii) an increase in cooling consumptions from +28.8% (2020) to +60.9% (2080); iii) a growth in total consumptions from +2.6% (2020) to +12% (2080). As expected, buildings falling in different climate zones are affected by climate change to different extents. For instance, zone D seems to be the least affected, while zone A seems to experience the largest increase in energy consumption.

The second objective concerned the investigation of potential relationships between research methodologies and research results. Statistical analysis of data extracted from the reviewed papers confirmed that impact analyses on building energy consumption led to highly heterogeneous results, with a significant level of heterogeneity that did not allow a synthetic combined effect to be identified through the meta-analysis. The variability could depend on climate zone, building type, and methodology adopted. The effort to identify a relationship between the variation in energy consumption and HDDs, CDDs, reference period, and CO_2 concentration did not lead to the identification of strong correlations between the parameters. However, two moderate linear correlations were found. The first one was found between the change in heating consumption and HDDs, which appeared to be related by a moderate positive linear correlation: the larger the HDDs, the lower the reduction in heating consumption. The second one was found between total consumption and HDDs. Indeed, the increase in total consumption is greater in areas characterized by lower values of HDDs, decreasing progressively as HDDs increase, until reaching negative values.

Beyond the result obtained, the work conducted is intended to highlight the high potential of the meta-analysis approach in conducting a literature review, constituting one of the limited examples in the construction research field. Indeed, systematic reviews and meta-analyses are a basic part of evidence-based medicine, in which strict protocols have already been established. In contrast, in the construction research field, meta-analyses and in general quantitative evaluations are still limited, as qualitative reviews prevail. As a new methodological approach in this area, specific methodologies have not yet been established, but rather attempts to adapt those used in the clinical practice are common, although several limitations make it difficult to comply with strict clinical protocols. Referring to this work, three main limitations can be outlined. The most significant one is the lack of a publication bias assessment, which may influence the results obtained. In addition, such results cannot be compared with other studies due to the lack of any other meta-analyses on the same topic. In addition, the low number of available manuscripts, as well as some missing data in the studies, significantly restricted the sample of manuscripts on which the meta-analysis was based.

CHAPTER 4

4. CHARACTERISATION OF APULIAN SCHOOL BUILDING STOCK

4.1. Introduction

The state-of-the-art investigation on existing educational buildings revealed that Italian schools suffer from poor energy performance and inadequate indoor comfort levels, resulting in an urgent need for renewal, which could be met through the renovation opportunities provided by climate policies. To this end, an adequate knowledge of the characteristics of the existing building stock is required to understand the current status of the assets and thus set priorities for intervention. Since detailed knowledge of a whole building stock is not feasible [30], suitable methodologies need to be applied to identify typical buildings to be studied, representative of homogeneous classes into which the entire heritage is divided [32], such as through cluster analysis. However, the literature review (**Section 2.2.2**) has shown that the application to the school building type is often difficult, as collecting field data on a large sample of schools is complex and time-consuming, since it requires different stakeholders to be involved to make data available [33,34]. As a result, research in this field is very limited (especially in the Italian context) and is based on small school samples, the only ones for which exhaustive data are available.

The present Chapter aims to fill this literature gap, providing an overview of the school building stock in the Apulia Region, and thus answering the second research question (**RQ2**) of this dissertation. In detail, two key objectives have been pursued. On the one hand, highlighting the main features of such school building stock, based on data collected and analysed from the regional database of schools (ARES database). On the other hand, splitting the large building sample in homogeneous classes for further energy analyses, by identifying proper factors to cluster all buildings based on both literature survey and available data. Indeed, for the first time, a cluster analysis has been performed encompassing a large number of school buildings, more than one thousand, to create clusters as representative as possible of the existing school heritage located in the Apulia Region. Accordingly, four representative buildings have been selected for further analyses. Methodology (**section 4.2**) and results (**section 4.3**) presented and discussed in this section summarise the main findings published in two dedicated articles by the present writer [48,213], which can be referred to for more details.

4.2. Methodology

The methodology adopted in this chapter is divided into three main steps, which include: i) defining the sample of school buildings to be explored, ii) the collection of associated data and its validation, (iii) cluster analysis to identify representative buildings in the sample. Each step is briefly explained below.

4.2.1. Building sample definition

The investigation carried out is entirely based on school buildings surveyed within the Apulian regional school register (ARES database) [109], implemented in an effort to ensure the proper planning of the school building stock at the regional level. The registry is based on an online information system, in which each school is associated with two forms: a form related to the school institution (compiled by the school director) and a form related to the building, filled in by the building owner (municipality or province). Hence, the reliability of the data is closely linked to the user who fills in the database. To date, the regional database is still under construction and shows many missing or incomplete data, resulting in one of the main obstacles to conducting in-depth studies at the regional level.

Among the 2451 schools surveyed in the ARES database, only those owned by municipalities have been selected, which account for a total of 1839 buildings to be investigated. According to the Italian educational system [34,106], such municipally owned schools involve childcares, preschools, primary and lower secondary schools. Otherwise, upper secondary schools - hosted in buildings managed by provinces – have not been included in the investigation, since they exhibit different features and utilization profiles that do not allow them to be assimilated with schools of lower grades. Likewise, the private schools have been excluded from the analyses since they are not officially surveyed.

Although the sample retrieved from the ARES database included 1839 educational buildings, a total of 616 schools have been excluded due to missing data on year of construction (536 schools) or building height (80 schools), allowing a sample of 1221 schools to undergo the data collection and validation process. Then, through the validation process, 131 schools have been discarded for two main reasons: i) the school area cannot be calculated since the school building hosted other non-school activities, ii) the building was built quite recently, so it is not yet shown in the Regional Technical Map. At the end of the validation process, a final sample of 1090 buildings has been obtained, thus maintaining the large scale of the database. Consequently, the list of the approved buildings has been extrapolated from the ARES database, together with further generic buildings data, involving i) building ID; ii) location, iii) geographical coordinates iv) school grade, v) year of construction.

4.2.2. Data detection and validation

Since the objective of this section was to identify a methodology to classify a large sample of schools for future energy analyses, it was essential to identify appropriate parameters that would allow buildings to be classified. From a literature review, the main parameters influencing heating consumption of schools have been identified, then sought in the ARES database, selecting those with the highest level of completeness, to group the large number of buildings as possible. Consequently, two benchmark variables have been chosen to group the sample, which - in accordance with the literature review - seem to strongly influence heating consumption:

- the construction year, since it reflects the building technological features and affects the energy use [41,116,214];
- the surface-to-volume ratio (S/V) [m^{-1}], which is correlated with the heat flows through the envelope and, therefore, affects building energy performance [215]. As such, this parameter is adopted by the Italian regulations as a criterion for setting regulatory thresholds for the containment of consumption [216].

While the year of construction have directly been extrapolated from the ARES database, an easy methodology to calculate the S/V ratio of all 1000 schools had to be created, as the database only provides data such as footprint area, total volume including basement spaces, and total height, or net interior height of floors. Consequently, the parameters required for S/V calculation were retrieved in a Geographic Information Systems (GIS) environment, widely adopted in the literature to collect geometric and typological data of buildings [217]. In this work, the Quantum GIS software (QGIS, version 3.22.0) has been used for data collection, while the Regional Technical Map (CTR, scale ratio 1:5000), developed by the Apulia Region – Department for Territorial Planning, has been adopted as cartographic basis to collect information [218]. The map is provided in ESRI-shapefile format, which enables the extraction of information about buildings as attributes of the polygons representing them. In detail, the data available from the map are related to the building footprint area and perimeter, which together with the height provided by the ARES database, allows the S/V ratio calculation. Nevertheless, since the map was generated in 2006 and updated in 2011, a process of data validation has been performed to appreciate potential variations in the built environment, drawn in **Figure 14**.

Based on the geographic coordinates extracted from the ARES database, a new vector of points has been created in QGIS and then used to "select by location" the school buildings in the CTR to generate a new polygonal shapefile that includes only the school buildings, each one characterized by footprint area and perimeter. To validate data, the footprints have been extracted in CSV format and compared with the footprints provided by the ARES database, setting an acceptance threshold of 20%. If the threshold was met, the geometric attributes were accepted. Otherwise, the buildings were searched on Google Maps and their footprint area was manually measured with the Google Maps area calculator. If this area met the threshold of 20% of the QGIS value, the QGIS geometric data was accepted. Otherwise, the value was definitely discarded, and the building was excluded from further analysis. Finally, the validated data were used to calculate the S/V ratio.

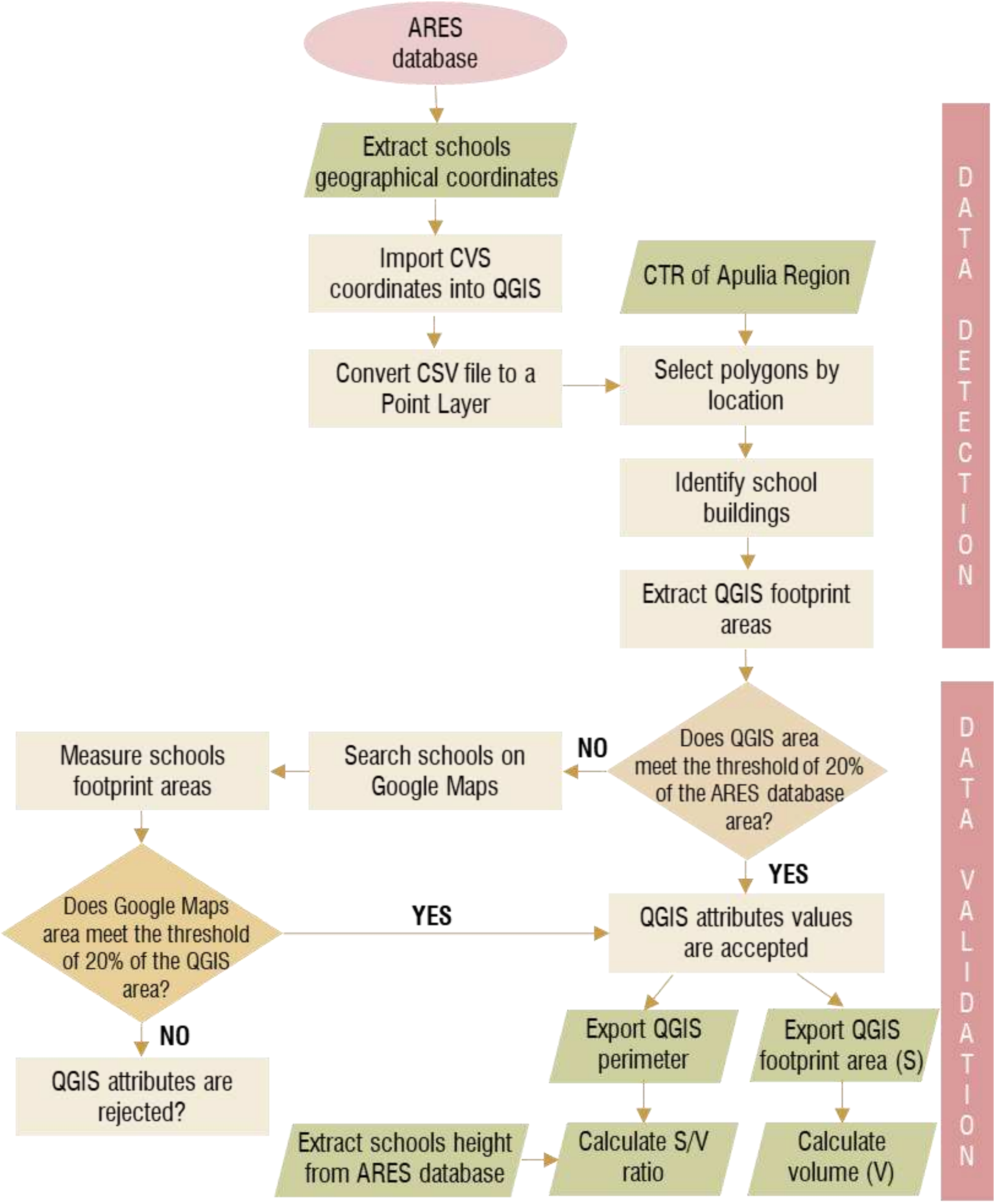


Figure 14. Methodological workflow for data detection and validation. Adapted from the author's work [213].

4.2.3. Cluster analysis

After collecting and validating the data on year of construction and S/V ratio, a further pre-processing has been required to effectively conduct the cluster analysis. Indeed, to avoid that attributes with larger variation ranges outweigh attributes with smaller ranges - thus dominating the clustering results [219] – data must be normalised. Consequently, a *z-scores* normalization has been performed, allowing each value to be normalized to the sample mean and standard deviation [219], according to the **Equation 1**:

$$v'_i = \frac{v_i - \bar{A}}{\sigma_A} \tag{1}$$

where v'_i represents the normalised value, v_i is the value belonging to the data sample A, $\bar{A}$ is the mean of the sample and σ_A is the standard deviation of the sample.
Once the pre-processing phase has been completed, cluster analysis has been performed. The cluster analysis is defined as "the organization of a collection of patterns (usually represented as a vector of measurements, or a point in a multidimensional space) into clusters based on similarity" [220]. Hence, each cluster is made up of objects with a higher degree of similarity than those in other clusters.
Among the different algorithms available in the literature to group objects – including hierarchical clustering, partitioning, density-based clustering, grid-based clustering, model-based clustering, and fuzzy clustering – a Agglomerative Hierarchical Clustering (AHC) has been adopted in this work, in XLSTAT software [211]. The AHC allows for a hierarchical decomposition of a given set of objects and does not require to establish the number of clusters a priori, but rather it provides a dendrogram as a result, which gives an idea of the suitable number of classes into which the data can be grouped [219]. The AHC works as an iterative approach, based on three phases: i) the dissimilarity between the N objects is calculated, ii) two objects which, when clustered together minimize a given agglomeration criterion, are clustered together thus creating a class comprising these two objects, iii) the dissimilarity between this class and the N-2 other objects is calculated using the agglomeration criterion. The two objects (or classes of objects) whose clustering together minimizes the agglomeration criterion are

then clustered together. This process continues until all the objects have been clustered [221]. In this work, the Squared Euclidean Distance was adopted as a dissimilarity measure and the Ward Method as the partition algorithm [222].

4.3. Results

The following paragraphs summarise the main findings of this investigation. First, an overview of the main characteristics of the selected schools is provided. Then, the results of the cluster analysis are presented and debated.

4.3.1. Apulian school buildings stock overview

A brief overview of the Apulian school building stock is provided below, in relation to geographical perspective and geometrical features.
From a geographical point of view, school buildings appear unevenly distributed throughout the region. In detail, the Metropolitan City of Bari hosts the highest percentage of municipally owned schools, with 31% of the buildings owned. The other buildings are distributed as follows: 24% in the Province of Lecce, 17% in the Province of Foggia, 13% in the Province of Taranto, 7% in the Province of Brindisi, and 7% in the Province of Barletta-Andria-Trani (BAT). Such distributions have been calculated based on the validated sample, but they still reflect the distribution of schools in the full dataset, thus remaining representative of the whole sample (**Table 8**).

Table 8. Distribution of educational buildings by provinces in the Apulia Region in the validated and in the full sample.

Province	Validated sample (%)	Full sample (%)
Bari	31	27
Lecce	24	24
Foggia	17	18
Taranto	13	13
Brindisi	7	12
BAT	7	6

As expected, the distribution of schools appears to be related to the distribution of the school-age population in the region (see **Figure 15**). In fact, according to the latest survey conducted by ISTAT, the 0–13-year-old population is distributed as follows: Metropolitan City of Bari (32%), Province of Lecce (18.6%), Province of Foggia (16%), Province of Taranto (14%), Province of BAT (10.3%), Province of Brindisi (9.3%) [223]. Except for the provinces of BAT and Brindisi, the distribution of educational buildings exactly follows the school-aged population distribution.

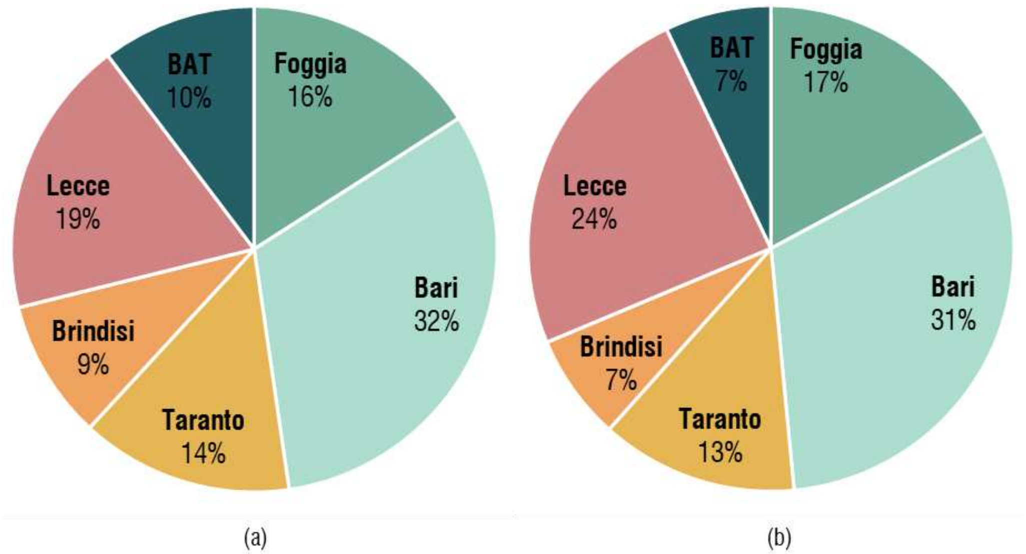


Figure 15. Distribution in the Apulian provinces of: **(a)** the population aged 0-13, **(b)** the municipally owned educational buildings (hosting students aged 0-13). Adapted from the author's work [48].

With a view to the educational institutions accommodated within the buildings, the most significant are the childcare centres and pre-schools (33%), since these buildings host a small number of students being spread throughout the whole territory. Accounting for 25%, buildings hosting multiple educational institutions rank second, involving building which host: i) pre-schools and primary schools, ii) pre-schools, primary and lower secondary schools, iii) primary and lower secondary schools. In fact, in recent years, the Italian government has introduced some legislative actions to reduce the number of small schools, and thus the number of buildings [224]. By contrast, the number of buildings housing exclusively primary or lower secondary schools appears to be similar, with 17% and 18% respectively. Finally, a 7% of the sample represents buildings occupied by school facilities, like administrative offices or school gyms.

As mentioned in the methodology section, the construction year and the S/V ratio have been selected as predictors to cluster the school sample, since they were found to strongly affect energy consumption. Referring to the construction year (**Figure 16**), the Apulian trend seems to reflect the national trend, with the majority of schools (46,2%) built before 1976, in the absence of any energy regulation. In fact, the first energy law in Italy was published in 1976 [225]. A further significant percentage of Apulian school building stock dates from 1976-1992, accounting for 44% of the buildings. Consequently, only 10% of the buildings were built after 1993. This distribution confirms the ageing of the school building stock and its high potential in terms of refurbishment. Disaggregating the results by school grade, schools built before 1949 host predominantly primary schools, while secondary schools constitute the majority of those built in the years 1950-1975. Pre-schools find widespread use since 1976, while childcare centres account for the majority of schools built after 2008. In fact, an increase in the spread of childcares across the whole Italian territory is strongly required today. Referring to the S/V ratio (**Figure 17**), the educational institution hosted by the school seems to affect this parameter. For instance, childcare centres and pre-schools are characterised by high shape ratios, mostly greater than 0.6. In fact, schools for younger children are tipically small single-storey buildings, as they are required to be spread across the whole municipally territory. Otherwise, buildings housing primary and lower secondary schools are characterised by a more compact shape, showing a shape ratio of about 0.5. Overall, larger areas characterized these buildings, since they accommodate a greater number of students, and predominantly consist of two levels (77%). The same trend can be recognised for buildings housing multiple educational institutions, also characterised by S/V ratios between 0.4 and 0.5. The present findings can be compared and debated with those found in other Italian studies. For example, Marrone et al. [118] analysed the S/V ratio of a sample of school buildings in the Lazio Region. On one hand, they found a percentage of only 6% of buildings with S/V ratios below 0.3, which was corroborated by the present study. On the other hand, they identified the highest percentage of S/V ratios above 0.5 (62%), while 32% ranges between 0.4-0.5. These results seem opposite to ours, but may be explained by the different sample size, as the study surveyed a sample of only 80 buildings. Another study conducted by Arambula et al. [35], found out a S/V ratio ranging from 0.3 to 0.5, based on a sample of 60 Italian schools. Thus, it is reasonable to conclude that the frequency distribution of the S/V ratio is influenced both by the selected sample and the educational institutions housed in the schools. However, shape ratios smaller than 0.3 seem to be unusual in all cases.

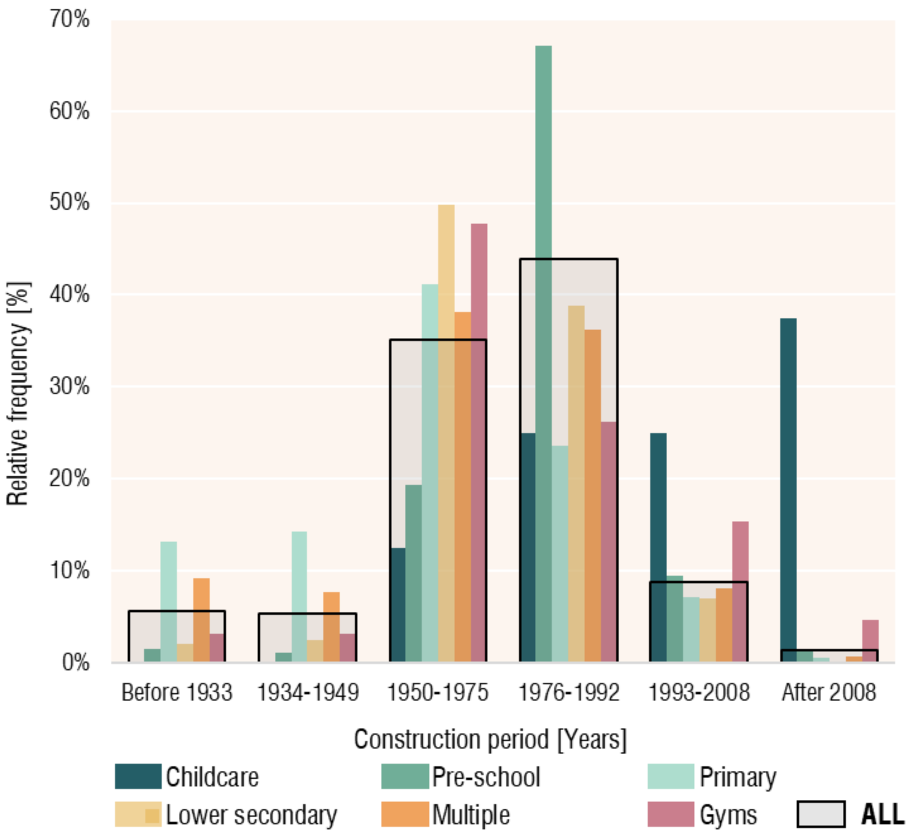


Figure 16. Frequency distribution of educational buildings - divided by educational institution - by the construction period. Adapted from the author's work [48].

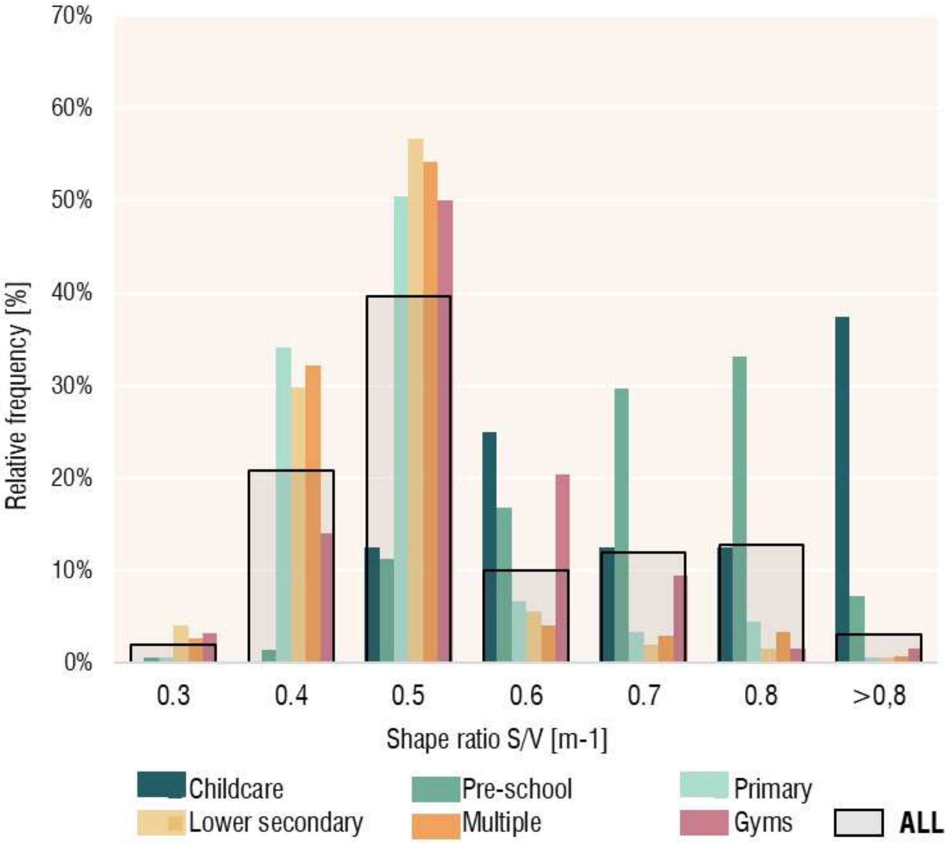


Figure 17. Frequency distribution of educational buildings - divided by educational institution - by the S/V ratio. Adapted from the author's work [48].

4.3.2. Cluster analysis

The results of the cluster analysis are presented and debated below. As explained in methodology, the AHC approach has been adopted to perform the cluster analysis, basing it on two predictors: year of construction and S/V ratio. Based on the results of the dendrogram, a number of 5 clusters has been identified as the most appropriate to subdivide the whole sample of schools. Since the benchmark parameters were limited to two, a two-dimensional scatter plot allows for a proper visualisation of the extent of each cluster (**Figure 18**). More in detail, the x-axis shows the construction year, the y-axis shows the S/V ratio, both presented in absolute value and not standardized scores. Each cluster is plotted by a different colour.

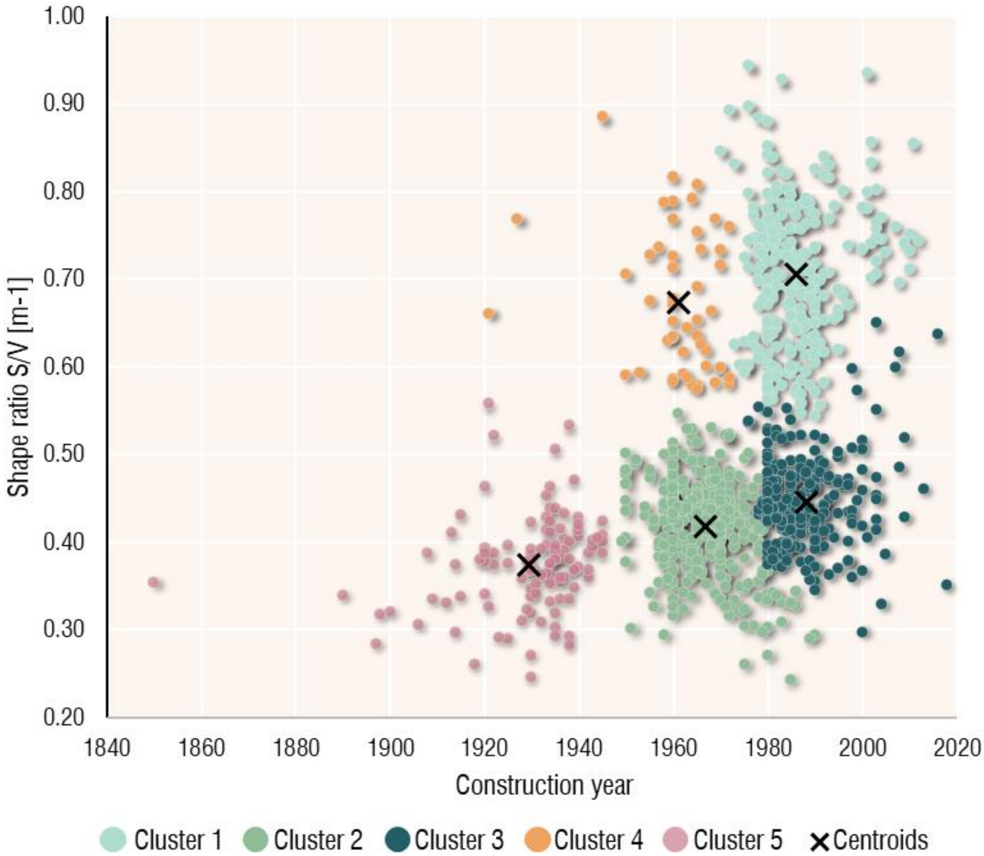


Figure 18. Scatter plot of educational buildings by shape ratio S/V and construction year. Adapted from the author's work [48].

As depicted in the Figure, the schools sample can be sorted according to three main construction periods and two S/V ratio ranges, allowing five clusters to be detected. Buildings clusters description is presented in **Table 9**, which summarises the number of buildings involved, their main features, as well as the centroids' features.

The construction years involve three periods:

- the first construction period covers years up to 1945, involving all the schools built up to the end of the World War II;

- the second construction period covers predominantly the years from 1945 to the mid-1970s, including schools built from the post-World War II years to the 1970s;
- the third construction period covers years since the late 1970s.

Interestingly, the cluster analysis led to the definition of a clear limit in terms of construction year (the middle 1970s) that coincides with a turning point in Italian building legislation, due to the first publication of an energy legislation [225]. In addition, clusters can be related to the years of national regulation adoption regarding educational building construction. In fact, a key-role in the regulatory framework of school construction was played by the Ministerial Decree of 18 December 1975 [226], which introduced technical standards for schools, for the first time. Nevertheless, only two clusters (1 and 3) involve schools built after the adoption of this law, and thus in compliance with its guidelines. In contrast, clusters 2, 4 and 5, concern buildings constructed earlier and thus in the absence of any national directives.

Referring to the S/V ratio, two groups can be identified:

- the first group shows high values of the S/V ratio (higher than 0.55), thus including not very compact buildings, with high dispersion rate.
- the second group shows lower S/V ratio, involving compact buildings with limited dispersion rate.

Table 9. Clusters identified, with the number of schools, the main features of the cluster and of its centroid.

		Clusters features		**Centroids features**	
Clusters	Buildings n.	Construction year	S/V ratio	Construction year	S/V ratio
1	282	1970-2012	0.54-0.94	1986	0.71
2	332	1949-1990	0.24-0.55	1967	0.42
3	237	1976-2018	0.30-0.65	1988	0.45
4	50	1921-1972	0.57-0.89	1961	0.67
5	110	1850-1945	0.25-0.46	1929	0.37

Clusters 1, 2 and 3 involve the majority of buildings, while Clusters 4 and 5 encompass a smaller number of schools. A brief description of each cluster is given below, based on the two selected predictors. In addition, further information is provided, concerning the school grade (**Figure 19**) and the territorial and climatological distribution of schools in each cluster (**Figure 20** and **Figure 21**).

Cluster 1 involves schools built since the 1970s, characterised by a great S/V ratio. As expected, such buildings mainly host pre-schools, reaching the 70% of the total. Otherwise, Cluster 3 covers almost the same years but including schools with a lower S/V ratio. In that case, multiple and lower secondary schools appear to be the most involved. Likewise, Clusters 2 and 4 rely almost in the same construction years, including buildings with a high and a low S/V ratio respectively. Once again, Cluster 2 includes mainly multipurpose buildings and lower secondary schools, along with primary schools which are grouped larger in this cluster to a greater extent than the others. By contrast, Cluster 4 is predominantly made up by school hosting childcare centres and pre-schools. Schools built from the 1800s up to 1945 - characterized by low values of S/V ratio - are included in Cluster 5, which is dominated by primary and multiple schools. It should be noted that, unlike previous cases, there is no cluster corresponding to the same years with high S/V ratios, as the building technologies of that period required buildings to be constructed with compact shapes.

From a geographical perspective (**Figure 20**), schools located in the Metropolitan City of Bari belong equally to Cluster 1, 2 and 3, whereas those located in the Provinces of Brindisi, Taranto e Lecce predominantly lie in Clusters 1 and 2. By contrast, the Provinces of Foggia and BAT involves belonging to Cluster 2, with the Province of Foggia reaching almost 45% of its overall school buildings heritage.

From a climatological perspective (**Figure 21**), all clusters include the most buildings located in climate zone C, which is the most extended in the region, followed by schools falling in climate zone D. By contrast, schools lying in climate zone E are very limited - as its extent is extremely little in the region - and they appear almost all located in Cluster 2.

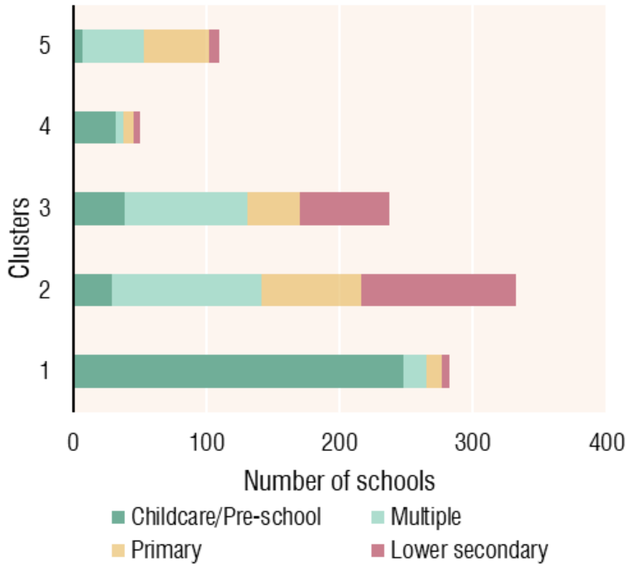


Figure 19. Bar chart of the school type distribution for each cluster. Adapted from the author's work [48].

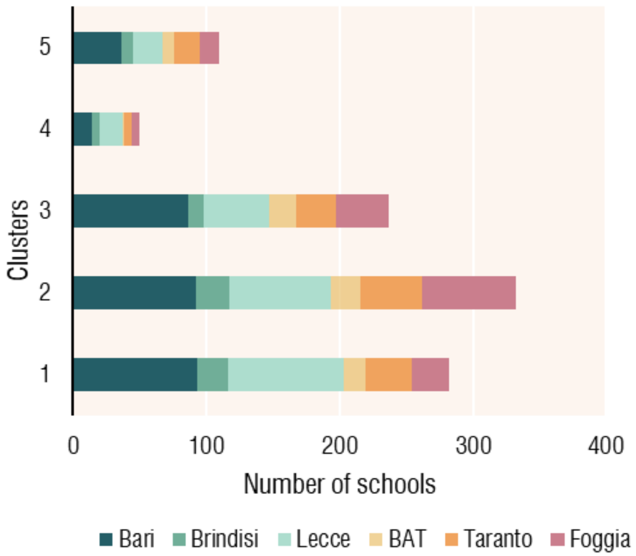


Figure 20. Bar chart of distribution of school in the Apulian Provinces for each cluster. Adapted from the author's work [48].

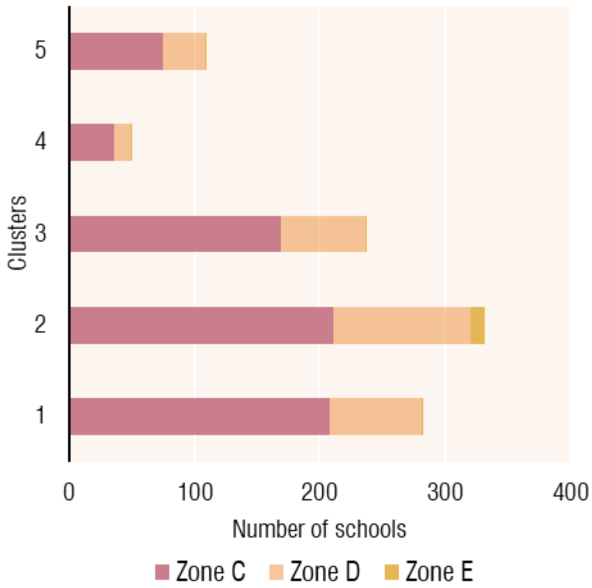


Figure 21. Bar chart of distribution of school in the Apulian climate zones (C, D, E) for each cluster.

4.3.3. Reference buildings

The cluster analysis has been performed with the main aim of identifying reference buildings, considered as representative of the whole Apulian school building stock, that could be useful for further energy analyses. Therefore, once the cluster analysis was carried out, the Euclidean distance of all schools from the corresponding centroids has been calculated, identifying the closest ones. With the aim of subjecting the representative buildings to a validation process based on the calibration carried out through a BPS, among the schools nearest to centroids, those for which data were available to implement the calibration process - based on the field investigation discussed in **Chapter 5** - have been identified. Accordingly, four schools have been identified, representative of Clusters 1,2,3,5. Indeed, Cluster 4 was found to consist of a very small number of schools (50 out of 1080), therefore discarded from the analyses as it was considered not representative. The position of the identified schools with respect to the theoretical centroids is shown in **Figure 22**, while their main features are presented in **Table 10**. In contrast, for an in-depth discussion regarding the description of the representative buildings, as well as their validation process, please refer to **Chapter 6**, where such representative schools – once validated against billed consumption data - are also adopted to evaluate climate change impacts on energy consumption.

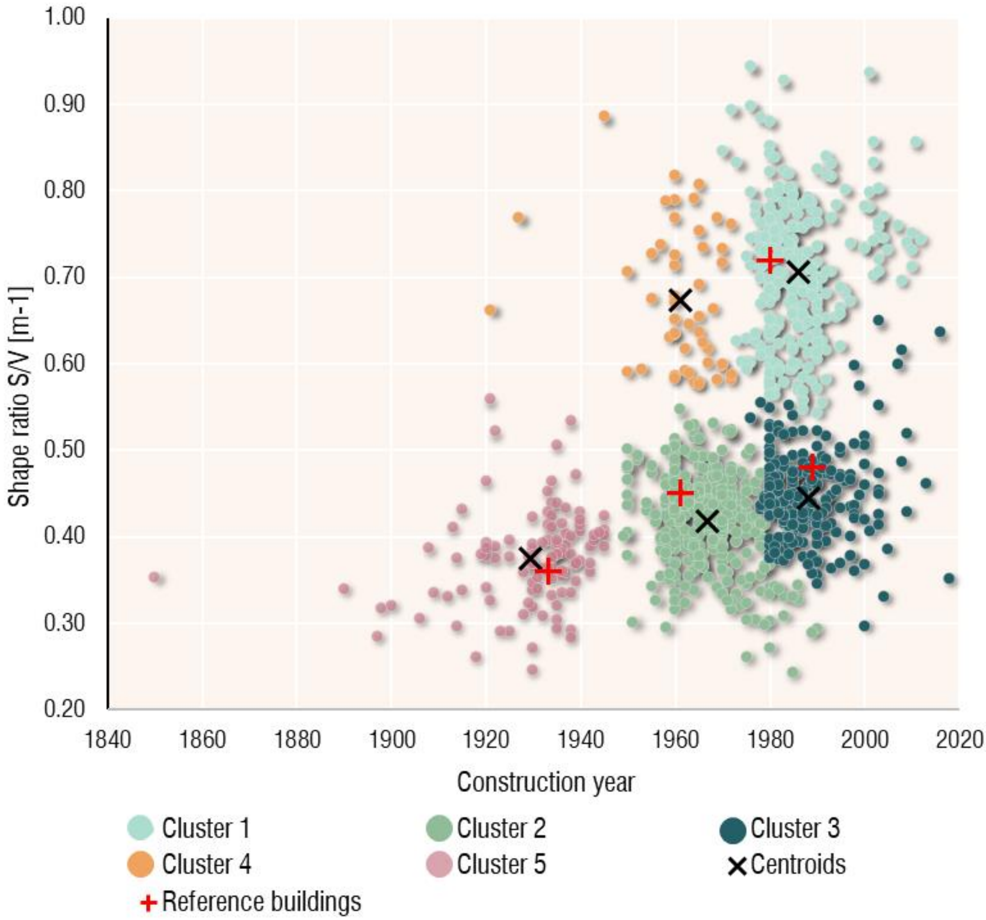


Figure 22. Identification of representative buildings within clusters (indicated by a red cross).

Table 10. Reference buildings for each cluster with their main features.

Clusters		Location	Construction year	S/V ratio
1		Barletta	1980	0.72
2		Barletta	1961	0.45
3		Barletta	1989	0.49
4	-	-	-	-
5		Barletta	1933	0.36

4.4. Conclusion and limitations

The present chapter aimed to answer the second research question of the present work (**RQ2**), providing documentation of the existing status of southern Italian educational buildings, from an energy perspective. Accordingly, a general overview of the status of schools has been performed based on data retrieved from the regional dataset ARES. Hence, more than 1000 buildings have been clustered according to two predictors (year of construction and surface-to-volume ratio), identifying five groups representing the majority of schools in Apulia.

With reference to the first objective, an overall assessment of Apulian school building stock, involving more than a thousand buildings (childcare, primary and lower secondary schools) has been provided for the first time in the literature. Briefly, according to the Italian trend, most of schools (46.2%) was built before 1976, thus without any energy regulations, while a significant percentage (44%) dates from 1976-1992. The S/V ratio appears to be affected by the educational institution hosted by the school, since childcare centres and pre-schools are characterised by high shape ratios (greater than 0.6), whereas primary and lower secondary schools show more compact shape.

With reference to the second objective, a hierarchical cluster analysis has been performed, identifying five clusters, based on two energy predictors (year of construction and S/V ratio). Cluster 1 involves schools built since the 1970s, characterised by great S/V ratio, while Cluster 3 covers almost the same years but includes schools with a lower S/V ratio. Likewise, Clusters 2 and 4 rely almost in the same construction years, including buildings with a high and a low S/V ratio respectively. Finally, Cluster 5 covers schools built from the 1800s up to 1945, always characterized by low values of S/V ratio. Accordingly, four representative buildings have been selected for further energy analyses.

Some research limitation can be outlined in this study. Firstly, the great number of schools involved (more than one thousand) have drastically reduced the possibility of obtaining comprehensive data characterizing all buildings, resulting in the selection of only two predictors to perform the cluster analysis. However, the potential of the analysis conducted should encourage public administrations to share more data. In addition, although based on the clusters identified, the selection of representative schools was opportunistic, as it was strongly affected by the availability of the data provided by local authorities, later used for validating the identified buildings.

CHAPTER 5

5. LARGE SCALE FIELD ENERGY ASSESSMENT

5.1. Introduction

Proper knowledge of the current condition of a building stock is a crucial starting point for planning an appropriate renovation process, as it allows to understand its current state - with its strengths and weaknesses - as well as to identify energy benchmarks for assessing energy performance and retrofit effectiveness. However, the literature review (**section 2.2.3**) clearly highlighted the lack of studies based on field data regarding schools, again due to the difficulty in finding data, especially in the Italian context. Indeed, in Italy, only not recent studies were found, mainly concerning high schools, and never located in southern Italy. The present chapter aims to make the effort to fill this gap in the literature, thus answering the third research question (**RQ3**) of this dissertation. Indeed, based on the cluster analysis findings, a more detailed study concerning actual energy consumption of educational buildings in the Apulia Region was conducted, including as numerous buildings as possible. The main objective was to provide a large-scale empirical analysis of the existing energy conditions of a sample of school buildings in southern Italy, through the collection of energy consumption data, involving pre-schools, primary and lower secondary schools. Gas and electricity consumption data were collected for a five-year period (2017-2021) for a sample of nearly 50 schools, allowing the evaluation of: i) energy consumption trends, both on annual and monthly basis; ii) impact that Covid-19 pandemic on school energy consumption; iii) energy consumption trends in relation to the school grade; iv) energy consumptions benchmarks based on billed data, comparable with data found in the international research. Methodology (**section 5.2**) and results (**section 5.3**) presented and discussed in this section summarise the main findings published in two dedicated articles by the present writer [48,227], which can be referred to for more details.

5.2. Methods

The methodology adopted in the present section consists of two parts: i) the collection of billed energy consumption data from a sample of school buildings, ii) the processing and statistical analysis of the collected data.

5.2.1. Data collection

To give an overview of the current energy status of the Apulian schools based on field data, municipalities were asked for gas (or oil) and electricity consumption over a five-year period (2017-2021), on a preferably monthly or at least annual basis. As already mentioned, in the Italian schools, gas (or oil) supplies the energy needs for heating, and potentially for domestic hot water (DHW), often provided by electric boilers. In any case, DHW consumption can be considered negligible, since Italian students typically do not use gym showers. Consequently, gas consumption can be allocated to heating demand only [111]. On the contrary, electricity consumption supplies energy needs for lighting, appliances, and auxiliaries of heating systems, or individual split A/C units if existing. Hence, energy consumption associated with heating can be directly retrieved from gas utility bills, while energy consumption associated with electricity can be directly retrieved from electric utility bills.

The six chief-town of Apulian provinces - where the greatest number of schools are located - have been asked for billed consumption data, eventually provided by only four of them: Bari, Barletta, Lecce, and Taranto. Hence, the investigated schools are all located in the same climatic zone (zone C), according to the national law [228]. Overall, heating consumption data has been obtained for a sample of 53 buildings, whereas electricity consumption were available for only 36 buildings (**Figure 23**). Energy data cover the required period (2017-2021), based on different time resolutions: unfortunately, only a limited group had data available on a monthly basis (11 buildings), while all others are based on annual periods, as summarized in

Table 11.

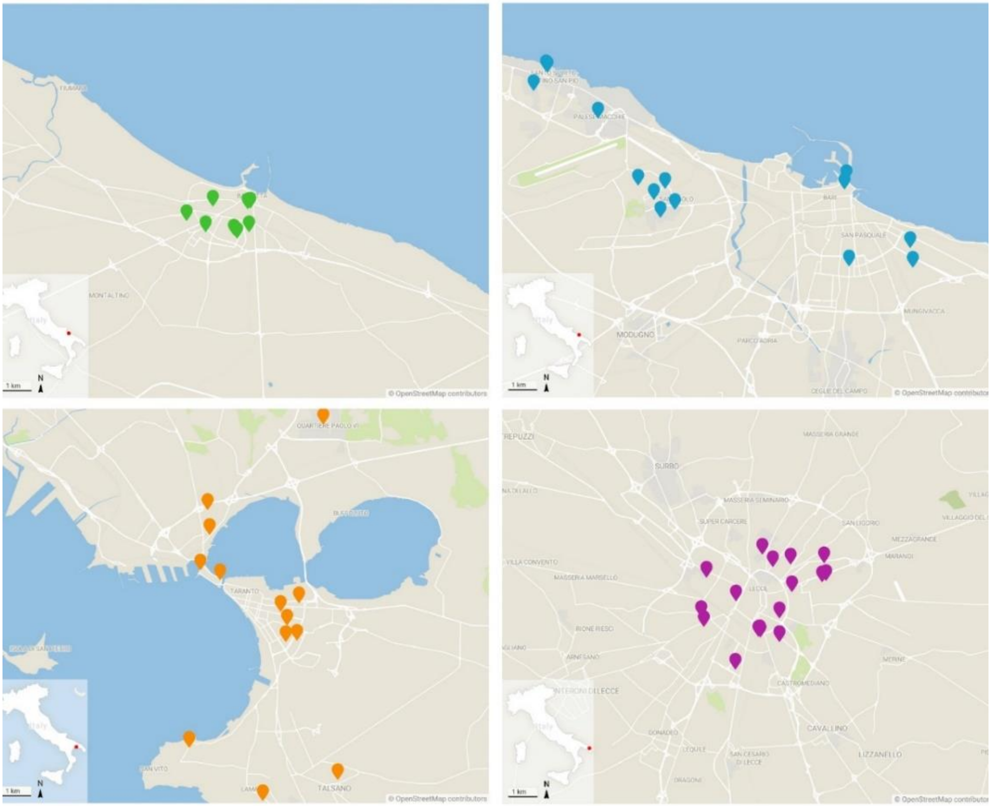


Figure 23. Educational buildings' location in the investigated cities: Barletta (top-left), Bari (top-right), Taranto (bottom-left), Lecce (bottom-right). From the writer's work [48].

Table 11. Distribution of educational buildings by provinces in the Apulia Region and distribution of school-aged population. NG stands for Not Given.

Location	Buildings	Gas consumption		Electricity consumption	
		Period	Time-base	Period	Time-base
Bari	15	2017-2021	Yearly	2017-2021	Yearly
Barletta	8	2017-2021	Monthly	2017-2021	Monthly
Brindisi	NG	NG	NG	NG	NG
Foggia	NG	NG	NG	NG	NG
Lecce	17	2017-2021	Yearly	NG	NG
Taranto	13	2017-2021	Yearly(9) Monthly(4)	2017-2021	Yearly(9) Monthly(4)

5.2.2. Data processing

With the aim of removing inconsistent data from the sample, a pre-processing analysis has been performed. Data has been removed if not related to municipally owned schools, or if missing values were identified in the survey period. Consequently, six schools have been excluded from the sample. Furthermore, an outlier detection has been performed for each year of survey, by means of the *z-score* [219] method. Referring to gas consumption, one outlier has been identified for a school in 2018 and thus removed. Referring to electricity consumption, four outliers have been identified: they were related to the same school in the years 2017, 2018, 2019, 2020. However, as the values were consistent for the school over four years of the survey, they were kept in the analyses.

Since in Italy electricity consumption are typically measured by kilowatt-hours (kWh) and gas consumption are measured by different units depending on the fuel type (standard cubic meter or litres), the overall energy billed data have been handled to obtain comparable values for analyses purposes. Hence, gas consumption has been turned into kWh, according to the conversion factors provided by Italian Regulatory Authority for Energy, Networks and Environment (ARERA) [229]. In addition, the energy use intensity both for heating consumption (HUI) and for electricity consumption (EUI) have been calculated, normalizing consumption by the building floor area. In detail, gas consumption has been normalized based on the gross heated floor area, as suggested by Dias Pereira et al. [119], and electricity consumption has been normalized by the total gross floor area of the building. Finally, to evaluate total energy consumptions, site energy values of both gas and electricity consumption have been converted to source energy values and then added together. In fact, while “site energy” refers to the energy used in a building as it is - recorded by utility meters and reported on utility bills - “source primary energy” represents the raw fuel burned to create heat and electricity.

Site energy values can be converted into source energy values by means of the primary energy conversion factor (PEF). In this study, the PEFs provided by the Italian legislation have been adopted, which are equal to 2.42 for electricity, 1.05 for natural gas and 1.07 for oil [230].

The data collected allowed for several analyses, thus providing an insight into the status of energy efficiency of schools in southern Italy, based on field data. The performed analyses allow for investigations concerning:

- annual consumption trends, in terms of heating and electricity consumption (site energies) and total consumption (source energy);
- annual consumption sorted by school type, to explore differences in energy use in relation to the school level hosted by the building;
- annual consumption sorted by clusters;
- monthly energy trends.

5.3. Results

The energy analyses findings are reported and discussed in the present section. Firstly, as suggested by Dias Pereira et al. [119], data on gas and electricity consumption have been analysed separately in terms of site energy. Secondly, total consumption has been calculated as the sum of gas and electricity available data and thus analysed in terms of source energy. After the validation process, the surveyed sample narrowed down to 46 educational buildings, including:

- 12 pre-schools (3-6 years old).
- 14 primary schools (6-10 years old).
- 3 lower secondary schools (11-13 years old).
- 17 building hosting multiple educational institutions (16 buildings hosting pre-schools and primary schools, 1 building hosting preschool, primary and lower secondary school).

Referring to the building locations, 15 schools are located in the metropolitan city of Bari, 17 schools in the city of Lecce, 13 in the city of Taranto and 8 in the city of Barletta.

5.3.1. Annual consumption trends

The main results of yearly energy consumption analyses are reported and discussed below, in terms of gas, electricity and then total energy consumption.

Referring to gas consumption, the surveyed schools experience annual consumption from 11.4 MWh (2019) to 343.6 MWh (2021). On average, a mean gas consumption of about 97.2 MWh has been registered over the five-year surveyed period, with great standard deviation (73.7 MWh). Gas consumption data are in line with those found by Rospi et al. [133], who investigated 9 schools in the city of Matera (located in southern Italy). Although the surveyed buildings accommodate upper secondary schools - typically characterised by greater size - the smallest school (1500 m^2) showed an average consumption of about 7654 standard meters cube, equal to 81.8 MWh, which falls within the range of values we found in the present study. Among the sampled school, electricity consumption appears to be significantly lower, varying from a minimum of 4.2 MWh recorded in 2020 to a maximum of 115.9 MWh measured in 2017. Indeed, mean electricity consumption of the sample is about one-third of mean gas consumption, accounting for 36.3 MWh (standard deviation=22.9). Overall, source total consumption account for 208.8 MWh (standard deviation=126.9), ranging from 30.6 MWh (registered in 2020) to 550.7 MWh (2017).

More in-depth analyses have been performed with reference to energy use intensity (kWh/m^2/yr). In detail, to explore consumption trends over time, the frequency distributions of EUIs for each energy source (gas, electricity and total consumption) have been calculated. Then, descriptive statistics have been used to explore the collected data, including distribution analyses, measures of central tendency and variability measures. Analyses have been carried out separately for each survey year, as well as for the whole five-year survey period.

The percentage of relative and cumulative frequency of gas consumption for the five-year survey period is shown in **Figure 24**.

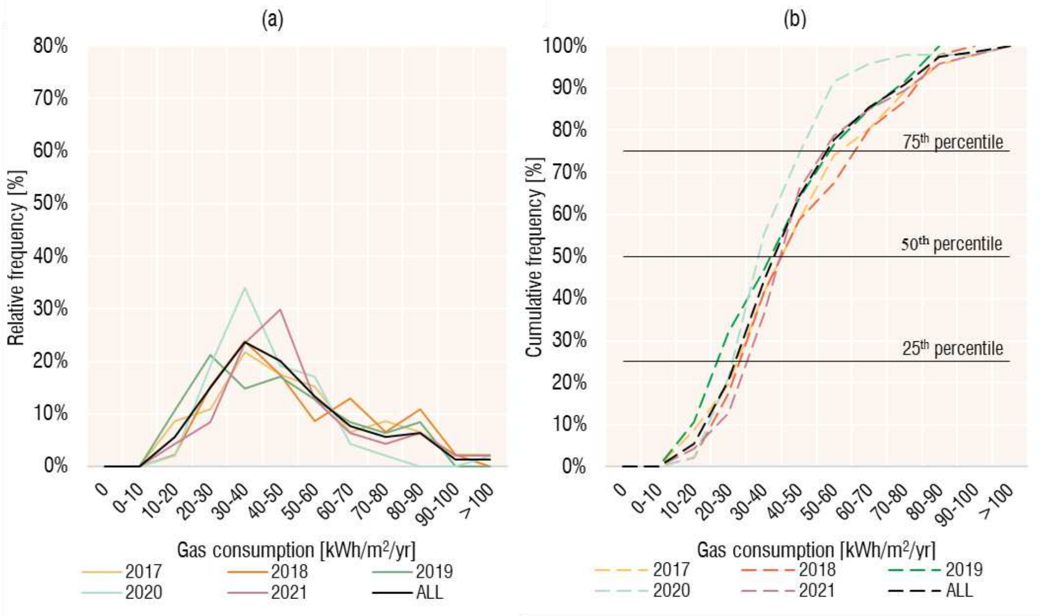


Figure 24. (a) Relative frequency distribution of gas consumption for each year of investigation (2017, 2018, 2019, 2020, 2021) and for the whole five-year survey period (ALL); **(b)** Cumulative frequency distribution of gas consumption for each year of investigation (2017, 2018, 2019, 2020, 2021) and for the whole five-year survey period (ALL). Adapted from the writer's work [48].

Overall, although to different extents, all the curves show a similar pattern, with a right-skewed distribution. In detail, the curves representing years 2017, 2018, 2019 reveal a moderate positive skewness (of about 0.61, 0.52, 0.49 respectively), while it significantly rises in 2020 (1.59), and then declines in 2021 while still remaining high (1.09).

Referring to the first survey year (2017), billed gas consumptions most frequently fall in the range 30-60 kWh/m^2, with a peak occurring between 30-40 kWh/m^2 (22%). Otherwise, limited consumption below 20 kWh/m^2 has been found (9%). Finally, the remaining 26% of the sample presents gas consumption above 60 kWh/m^2, which, however, rarely exceeds 100 kWh/m^2. Similar findings can be drawn for the years 2018 and 2019, although the higher frequencies shift slightly to lower values, showing a downward trend in consumption trends. By contrast, gas consumption distribution in 2020 needs more specific considerations, since it was characterised by the extraordinary school closure due to the Covid-19 pandemic. In fact, in accordance with data collected by UNESCO, a long period of school closure was experienced from March 10, 2020 to June 16, 2020, before the traditional summer break [231]. It results in a one-month reduction of the effective heating period compared to the regulated one (until March 31) [232]. In addition, the opening from September 14, 2020 to November 1, 2020 was succeeded by a period of partial opening that lasted until April 24, 2021. Therefore, as expected, the distribution curve for the year 2020 covers a more limited range of consumption, never exceeding 80 kWh/m^2 and showing a peak between 30 and 40 kWh/m^2. In 2021, the consumption frequency trend returns to be similar to previous years, although it exhibits higher consumption on average, peaking between 40 and 50 kWh/m^2. Once again, variations can be attributed to the adoption of unusual user behaviours, such as the increased ventilation of classrooms required to reduce the diffusion of Covid-19 infection. The present analysis allows for exploring the trend in gas consumption measured over the five years of survey, highlighting any changes in consumption patterns over time. As a result, the analysis revealed that there were no significant variations in gas consumption over the last five years, although slight differences have been found in 2020 and 2021.

Further considerations can be drawn calculating the main data summary indexes (**Table 12**), calculating the central tendency and variability measures of the sample.

Table 12. Data summary indexes referred to gas consumption (kWh/m^2). Pth stands for percentile.

Indexes	2017	2018	2019	2020	2021	ALL	3-years avg	5-years avg
Minimum	12.5	16.5	12.7	12.2	12.0	12.0	14.8	13.8
Maximum	101.1	93.2	88.4	110.3	110.2	110.3	92.2	99.4
Mean	49.04	49.60	44.22	41.92	48.36	46.6	47.55	46.54
St.dv.	21.83	20.21	20.56	16.36	20.21	20.1	19.68	18.24
25th pth	34.96	32.18	28.96	31.35	35.58	31.46	30.09	32.89
50th pth	44.92	43.15	44.25	39.29	44.45	42.6	43.59	41.08
75th pth	59.90	65.57	55.45	50.63	56.08	57.10	59.68	54.12

Each index has been separately calculated in relation to each year of measurement, and then calculated based on: i) all data collected over the whole five-year period (referred as ALL in the table), ii) average consumption calculated for each school over the first three-year survey period from 2017 to 2019 (3-years average), iii) average consumption calculated for each school over the five-year survey period from 2017 to 2021 (5-years average). The two different averages have been calculated to distinguish the data collected in the pre-pandemic period from those affected by the influence of pandemic measures.

According to the statistics, the low-EUI school experiences gas consumption of about 12.0 kWh/m^2 (2021), while the high-EUI school reaches 110.3 kWh/m^2 (2020). Referring to the mean values of the entire sample (ALL), the surveyed schools show gas consumption of 46.6 kWh/m^2, ranging from 49.04 kWh/m^2 (2017) to 48.36 kWh/m^2 (2021), with a minimum average value of 41.92 kWh/m^2 in 2020. The high standard deviation values suggest that data are not homogeneous, as expected from the results of the literature review [131]. Interestingly, in 2020 there was a 12% reduction in gas consumption compared to the average consumption in the previous three years. Although such reduction may have been driven by the concurrence of different factors, it is certainly also related to the restrictive Covid-19 measures, which reduced the heating season by one month. Obviously, the extent to which these differences are related to Covid-19 measurements or other conditions (such as climatic factors) cannot be determined with certainty. Consequently, indices calculated on the basis of average consumption in the three pre-pandemic years differ from those calculated over all five years, which shows slightly lower mean consumption.

As already performed by other scholars, the data collected over the five years (ALL) allows for the calculation of benchmark values, typically equal to the 50 percentiles. For instance, for a sample 31 secondary schools located in Sanandaj (Iran), this value was found to be 252 kWh/m^2 [36], while it is equal to 150 kWh/m^2 for schools in the United Kingdom according to the CISBE TM46 Educational Benchmark [233]. In this study, the typical thermal energy benchmark - identified as the 50th percentile of the entire sample - is 42.6 kWh/m^2, thus far from the values found in the other works.

However, the schools investigated are located in a Mediterranean climate, significantly different from the locations investigated in the other studies.
Similar findings can be drawn for electricity consumption, as shown in **Figure 25**.

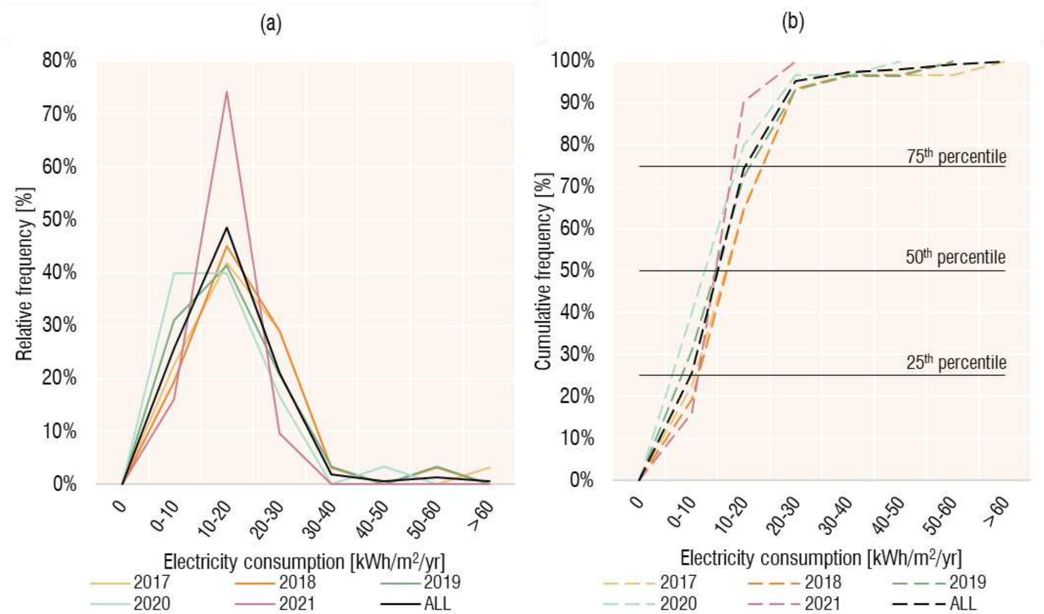


Figure 25. (a) Relative frequency distribution of electricity consumption for each year of investigation (2017, 2018, 2019, 2020, 2021) and for the whole five-year survey period (ALL); **(b)** Cumulative frequency distribution of electricity consumption for each year of investigation (2017, 2018, 2019, 2020, 2021) and for the whole five-year survey period (ALL). Adapted from the writer's work [48].

As in the case of gas consumption, the distribution curves reveal a similar trend, although in all years a higher positive skewness has been found, ranging from an index of 1.0 (2021) to 2.4 (2020).
Overall, there are limited differences in electricity consumption trends over the five years. Further in detail, the first 3 years of survey experience a similar trend, while in 2020 and 2021 a slightly different trend can be detected. In 2017, 2018 and 2019, consumption is mainly between 10 and 30 kWh/m^2, with a limited number of buildings consuming more than 25 kWh/m^2. In contrast, the years 2020 and 2021 are characterized by lower values, with most of the sample not exceeding 20 kWh/m^2 (80% and

90%, respectively). The main data summary indexes have been calculated and reported in **Table 13**.

Table 13. Data summary indexes referred to electricity consumption (kWh/m^2). Pth stands for percentile.

Indexes	2017	2018	2019	2020	2021	ALL	3-years avg	5-years avg
Minimum	4.5	4.8	3.9	3.7	5.6	3.7	4.7	5.5
Maximum	61.5	50.5	57.7	47.5	27.3	61.5	56.6	45.5
Mean	17.40	16.83	16.18	13.29	13.85	15.52	16.93	15.58
St.dv.	10.68	9.55	10.97	8.33	5.06	9.30	10.18	8.07
25th pth	11.03	10.66	8.33	7.97	10.68	9.92	9.55	10.16
50th pth	15.30	16.09	14.02	12.19	12.98	13.55	15.22	14.92
75th pth	21.31	20.54	20.43	16.12	15.87	20.08	20.04	18.92

According to the statistics, the low-EUI school shows electricity consumption of about 3.7 kWh/m^2 (2020), while the high-EUI school reaches 61.5 kWh/m^2 (2017). On average, all the surveyed educational buildings are characterised by mean electricity consumption of 15.52 kWh/m^2, ranging from 17.40 kWh/m^2 (2017) to 13.85 kWh/m^2 (2021), with a minimum value of 13.29 kWh/m^2 in 2020. As for the gas consumption, the year 2020 experienced a reduction in electricity consumption, accounting for 20% compared to the mean of the previous three years. The indexes calculated based on average consumption in the three pre-pandemic years differ from those calculated over all five years, showing higher values in the former case. Interestingly, the dispersion of electricity consumption data appears to be significantly lower than gas consumption, exhibiting lower values of standard deviations in all years. The typical benchmark value - defined by the 50th percentile calculated on the entire data sample - results in an electricity benchmark of 13.6 kWh/m^2. In this case, the value exceeds that found by Vaisi (equal to 9 kWh/m^2) [36] but still remains much lower than the CIBSE benchmark (equal to 40 kWh/m^2).

In conclusion, final considerations concerning total energy consumption can be discussed. As explained in the methodology, while gas and electricity consumptions have been presented separately in terms of "site energy", total energy consumptions have been shown in terms of source energy. Since calculated as the sum of source gas and electricity consumption, total consumption analyses have been conducted on a sample of 31 schools, excluding those lacking electricity data. Previous analyses reveal that gas consumption in Italian schools predominates over electricity consumption, thus influencing total consumption to a greater extent in terms of site energy. In fact, heating consumption accounts for nearly 80% of total consumption on average, ranging from 50% to 90%. However, referring to the source energy values, gas and electricity do not differ significantly, as the PEF of electricity is more than twice the PEF of gas.

Figure 26 depicts the total energy source consumption lies mostly in the range 60-90 kWh/m^2 in all the surveyed years.

Overall, limited schools experience consumption below 60 kWh/m^2 (16%), except for the year 2020, when the number reaches 23%. However, a downward trend can be observed in total consumption: in 2017 the number of buildings with consumption above 90 kWh/m^2 reached 37%, falling to 16% in 2021, with a minimum in 2020 (10%). Such downward trend is validated by the data summary indicators, listed in **Table 14**.

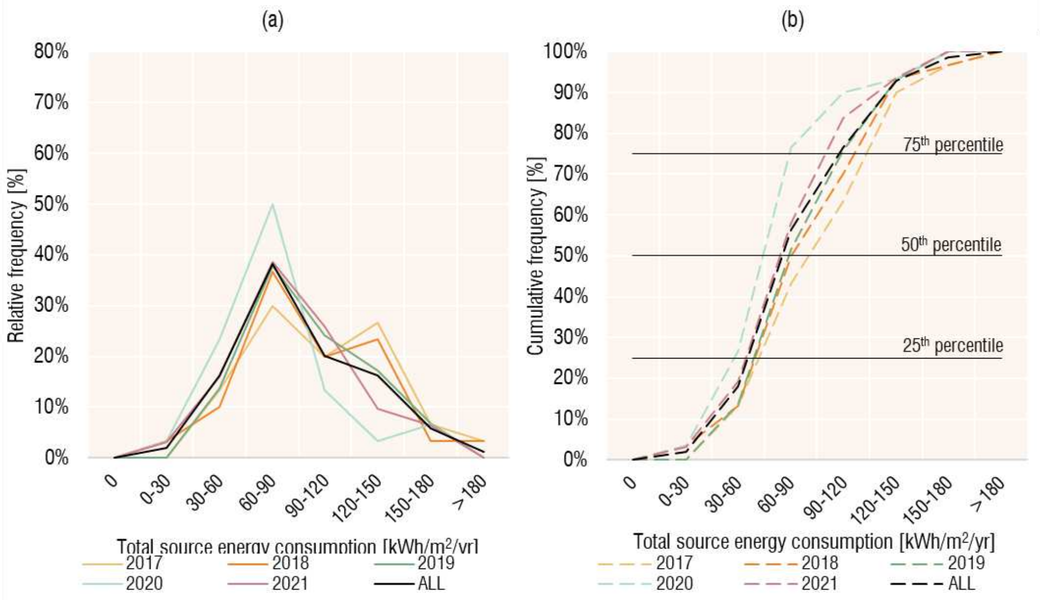


Figure 26. (a) Relative frequency distribution of total consumption for each year of investigation (2017, 2018, 2019, 2020, 2021) and for the whole five-year survey period (ALL); **(b)** Cumulative frequency distribution of total consumption for each year of investigation (2017, 2018, 2019, 2020, 2021) and for the whole five-year survey period (ALL). Adapted from the writer's work [48].

Table 14. Data summary indexes referred to total source energy consumption (kWh/m^2). Pth stands for percentile.

Indexes	2017	2018	2019	2020	2021	ALL	3-years avg	5-years avg
Minimum	37.20	29.6	31.90	21.80	26.2	21.8	32.9	29.30
Maximum	210.6	187.4	178.1	163.6	168.2	210.6	189.1	164.7
Mean	102.8	97.61	93.68	78.86	89.49	92.46	99.19	93.00
St.dv.	40.22	35.37	36.52	32.34	31.76	36.27	37.19	32.78
25th pth	70.90	74.43	73.29	58.35	65.68	66.07	72.53	72.16
50th pth	97.54	91.35	89.39	72.77	82.15	84.82	94.73	87.24
75th pth	125.7	122.3	113.8	87.74	111.2	118.9	120.60	113.70

In fact, total consumption experiences a reduction of about 13% in the five-year survey period, ranging from an average value of 102.81 kWh/m^2 in 2017 to a value of 89.49 kWh/m^2 in 2021, with a mean value over the five years of about 93 kWh/m^2. In addition, in 2020 schools showed a reduction in total consumption of about 19.5% compared to the previous three years' average, also due to the extraordinary measures implemented for the Covid-19 pandemic. Not including the year 2020, the low-EUI school experiences a total source energy consumption of about 26.2 kWh/m^2 (2021), whereas the high-EUI school reaches 210.6 kWh/m^2 (2017). Overall, the typical benchmark value (50th percentile) was found to be equal to 84.82 kWh/m^2.

5.3.2. Annual consumption by school type

This section summarizes the main results of the consumption analysis carried out in relation to the school grade accommodates by the buildings. In fact, **(a)** gas, **(b)** electricity and **(c)** total consumption over the five years of analysis are shown in **Figure 27**, sorted by school grade. The graph of electricity consumption refers to fewer schools due to unavailability of data, as does the graph of total consumption. As already discussed in the previous section, the bar graph allows to clearly appreciate that gas consumption is significantly higher than electricity consumption.

Overall, although both heating and electricity consumption appear variable, such variability does not seem to depend on the type of school host in the building. Indeed, high heterogeneity in the data persists even within the sample consisting of the same grade of school.

Overall, gas consumption seems to increase with increasing school grade, from 45 kWh/m^2 (preschools), 44 kWh/m^2 (primary school), 48 kWh/m^2 (multiple schools), 61 kWh/m^2 (lower secondary schools). Similarly, electricity consumption did not differ by school grade, varying between 17 kWh/m^2 (preschools), 13 kWh/m^2 (primary school), 16 kWh/m^2 (multiple schools), and 16 kWh/m^2 (lower secondary schools). Referring to total consumption, slightly different values can be noted, varying between 74 kWh/m^2 (preschools), 63 kWh/m^2 (elementary school), 67 kWh/m^2 (multiple schools) and 78 kWh/m^2 (lower secondary schools). It should be noted that in this case total consumption is calculated as the simple sum of gas and electricity consumption in terms of site energy, without converting them to source energy. Overall, no significant differences between school levels are identified, outlying that schools belonging to the "first cycle of education" according to the Italian school system share similar pattern in energy use.

An effort to compare the results obtained in the present study with those reported in other manuscripts is shown in **Figure 28**.

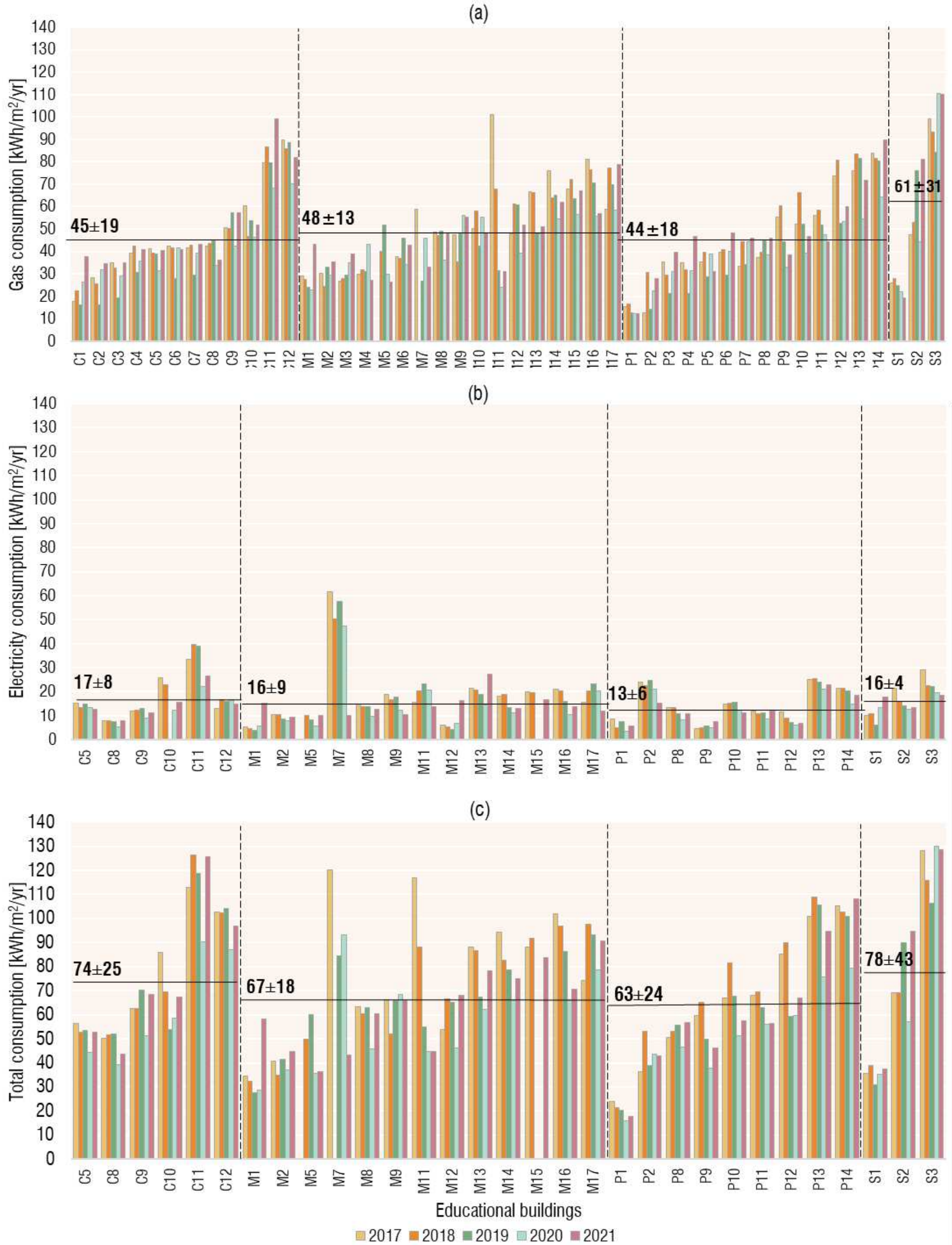


Figure 27. Consumption sorted by school grade over the five-year survey period: **(a)** gas consumption; **(b)** electricity consumption; **(c)** total consumption. Each school is defined by a code, where the letter indicates the school grade: C stands for pre-schools, M stands for multiple schools, P stands for primary schools, S stands for lower secondary schools. Numbers in bold indicate the average value of consumption for each school grade, with the corresponding standard deviation value. Adapted from the writer's work [48].

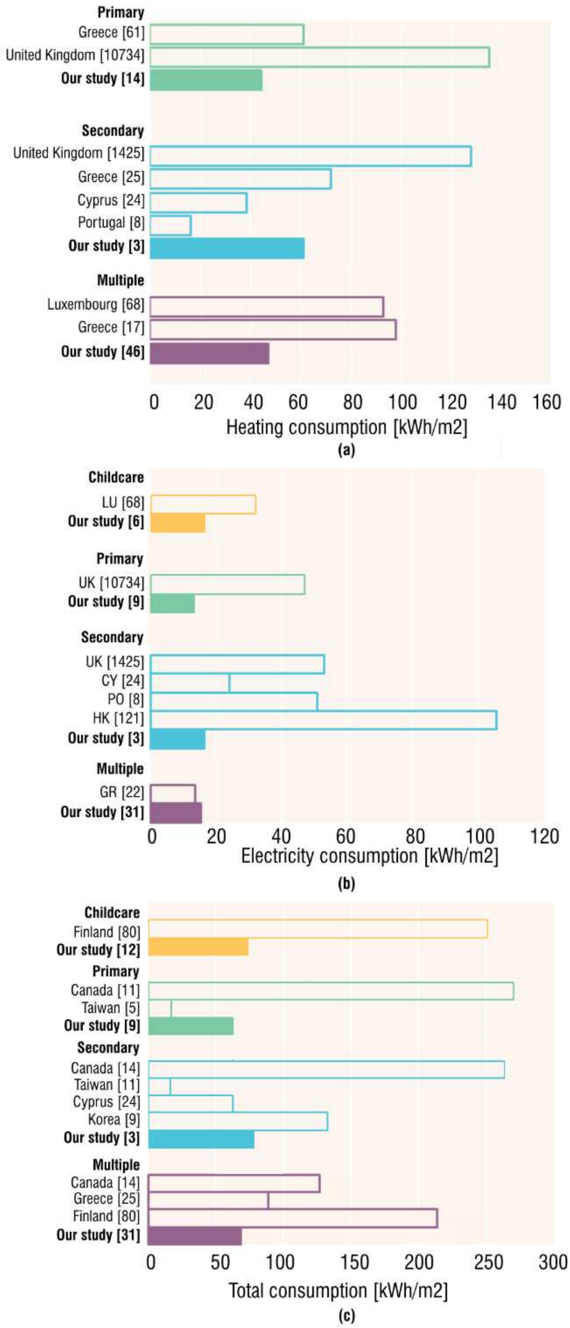


Figure 28. Comparison between average consumptions found in our studies and other international research, in terms of **(a)** heating consumption, **(b)** electricity consumption, **(c)** total consumption. Numbers in square brackets indicates the number of schools involved in the surveyed sample. Author' elaboration based on references [39,40,121,127–129,214,234–237].

To make the comparison, the most recent studies (published up to a decade ago) that provide actual energy consumption in terms of average intensity use have been retrieved from a literature review. Results were then collected separately for heating, electricity, and total consumption, as well as by school type, indicating the country surveyed and the number of buildings that make up the sample (in square brackets). If an article simultaneously investigated different types of schools, giving a single average result, it is classified as “multiple”. Of course, comparisons of results should be made with caution, as schools located in different areas of the planet may have different energy needs, leading to different energy consumption. Indeed, making a comparison of the billed energy consumption of school buildings in different research studies is difficult and can lead to misleading results [119], as not only researchers adopt different metrics, but the school system itself varies depending on the country, resulting in different building uses. For instance, schools located in Taiwan, shown in **Figure 28c**, reported low total consumption compared with other studies, probably because they are not required to provide heating. In addition, in some schools, electricity could also supply the heating needs, thus increasing the relative consumption. Overall, school buildings located in southern Italy appear to have limited consumption compared to other countries. However, these consumptions are not far from those experienced in schools located in other Mediterranean countries. For instance, Italian secondary schools show heating consumption of about 61.3 kWh/m^2/year, not far from Greece schools (72 kWh/m^2/year in secondary schools) or Cyprus schools (38.6 kWh/m^2/year in secondary schools). Not dissimilar values in heating consumption characterize elementary school in southern Italy (45 kWh/m^2/year) and Greece (61 kWh/m^2/year), while studies exploring different school grades show more significant differences. In contrast, Apulian schools show lower electricity consumption than other studies, with the exception of one manuscript that explores different Greek schools, showing a result very close to ours. Even from the point of view of total consumption, southern Italian schools reveal limited consumption compared to other countries, which still remains similar to other Mediterranean educational buildings.

The relationship between heating consumption and climatic conditions has been further explored (**Figure 29**).

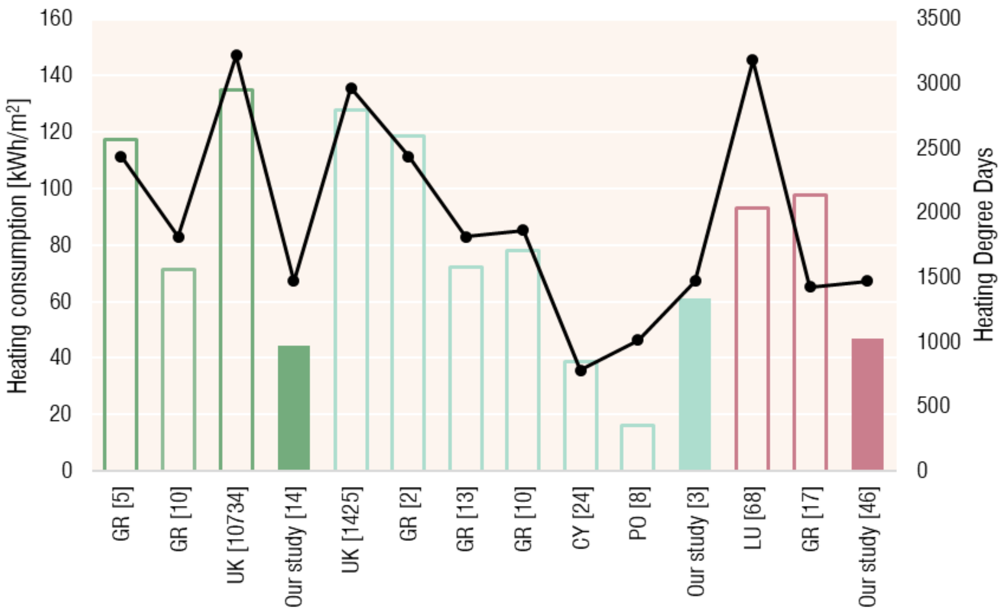


Figure 29. Comparison between average heating consumptions (represented by the bars) and Heating Degree Days (represented by the black line). Writer's elaboration based on references [39,40,121,127–129,214,234–237].

In detail, the heating energy consumption measured from the surveyed manuscripts (represented by the bars) are illustrated along with the heating degree days of the location where the study was conducted (black line). To make all heating degree days comparable, they were extracted from the .stat files available on the Energy Plus website [171], where they are calculated on a base temperature of 18.3 °C. For studies involving different locations in the same country, they were calculated by averaging between the heating degree days of the cities available for that country. With few exceptions, the figure clearly shows that heating consumption and heating degree days are closely related. In fact, the trend in heating consumption clearly follows the trend in heating degree days, with lower consumption in locations with lower heating degree day values and vice versa, highlighting the importance of this parameter in the magnitude of consumption.

5.3.3. Annual consumption by clusters

The 47 surveyed schools belong to the 5 clusters identified in **Section 4.3**, as follows:

- 12 schools belong to Cluster 1;
- 11 schools belong to Cluster 2;
- 14 schools belong to Cluster 3;
- 2 schools belong to Cluster 4;
- 8 schools belong to Cluster 5.

To explore the difference in both gas and electricity consumption sorted by cluster, a box plot has been created, based on the average consumption calculated over the 5 years period (**Figure 30**).

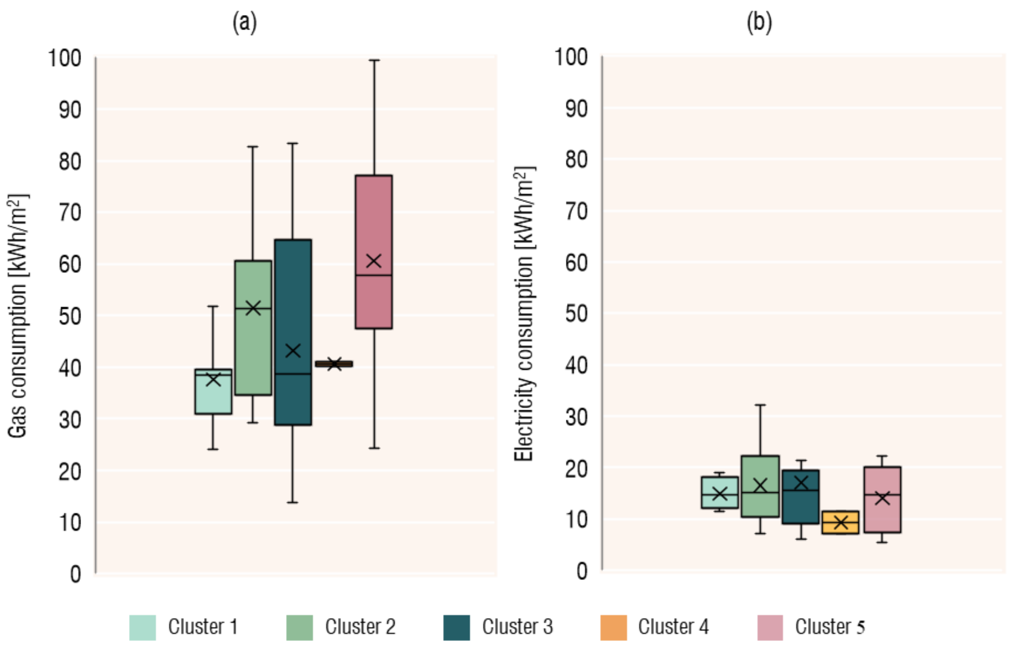


Figure 30. Five-years average consumption sorted by cluster: **(a)** gas consumption; **(b)** electricity consumption.

Undoubtedly, the results are affected by the number of buildings involved in each cluster, but some interesting conclusions can be drawn anyway. For instance, schools belonging to Cluster 5 – which involves the most dated buildings built between 1850 and 1945 – experience the highest average consumption, while presenting a large range of variation. Cluster 2 – involving buildings constructed between 1949 and 1990 with low S/V ratios – ranks second in relation to average gas consumption, also exhibiting a high range of variation. Cluster 4, consisting of schools built in the same years, shows lower average consumptions, although they are calculated based on only two buildings. Likewise, Cluster 1 and Cluster 3 include schools built in the same period (starting from the 1970s), characterised by high and low S/V ratio respectively, showing close median values of gas consumption. The boxplots clearly show the extreme heterogeneity of the data found, highlighting the need for additional studies investigating the reasons behind this heterogeneity. From the electricity consumption perspective, few considerations can be drawn out, since the cluster analysis has been performed based on the year of construction and the surface-to-volume ratio, which typically affect heating and not electricity consumption. Accordingly, no significant differences in electricity consumption by cluster subdivision are revealed.

5.3.4. Monthly consumption trends

To identify the energy consumption profile through the year, a consumption analysis on a monthly basis has been conducted. Among the schools for which monthly data was available, four schools have been selected, each one representative of a school type: pre-school, primary, secondary, and multiple. The monthly consumptions of the 4 schools are shown in **Figure 31** for all the five-surveyed years. As shown, heating consumption are experienced from November to March, when heating systems are turned on in accordance with Italian regulations. The graphs clearly highlight the significative reduction in heating consumption experience during the month of March 2020, experienced in all the schools. Calculating the average monthly consumption over the five years for each school, the highest heating consumption always occurs in January, when the most severe weather conditions occur, while the lowest in November since heating is only allowed to be turned on from the 15th.

Otherwise, electricity consumptions appear significantly limited compared to heating consumption, but in contrast to the latter, they are observable throughout the entire year. Indeed, although limited, they are found even in the summer months when Italian schools are predominantly unoccupied by students.

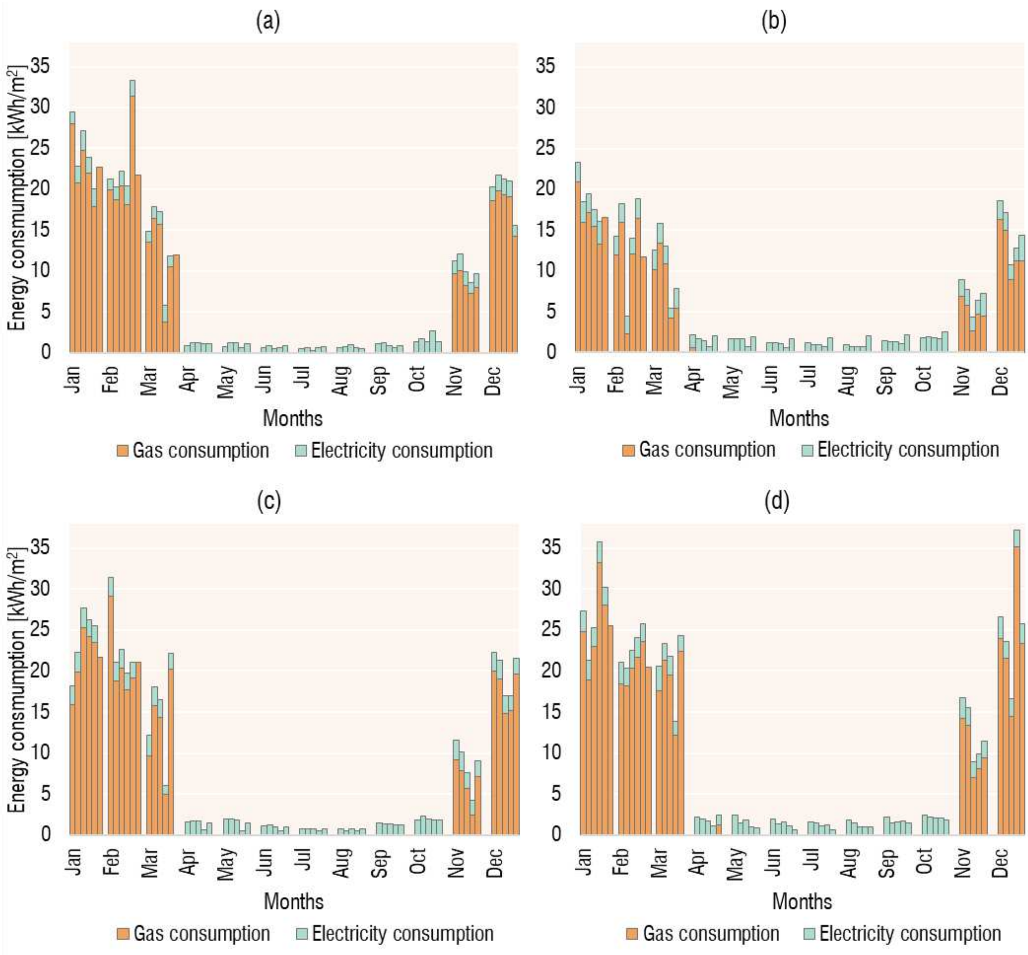


Figure 31. Monthly consumptions over the five-years survey period, recorded in: a) pre-school, b) multiple school, c) primary school, d) lower secondary school.

5.4. Conclusion

This chapter aimed to provide empirical evidence on the current energy conditions of a large-scale sample of school buildings, thus answering the third research question of this dissertation. To this end, gas and electricity billed data collected for 47 schools over a five-year period (2017-2021) were analysed, identifying annual and monthly trends, benchmarks and average values.

- On average, heating consumption accounts for 97.2 MWh (or 46.5 kWh/m^2/yr), electricity consumption accounts for 36.3 MWh (or 15.585 kWh/m^2/yr) in terms of site energy, while total source consumption 208.8 MWh (93 kWh/m^2/yr). In all the cases, great values of standard deviation can be highlighted, suggested data to be not homogeneous.
- Interestingly, in 2020 - concurrently with the Covid-19 pandemic - schools experienced a reduction of consumptions, accounting for 12% in heating consumption, 20% in electricity consumption and 20% in total source energy consumption. Undoubtedly, to some extent, the reduction can be attributed to the Covid-19 restrictive measures that resulted in school closures.
- Typical benchmark values - defined based on the 50th percentile calculated on the whole data sample – were found to be equal to 42.6 kWh/m^2 (site energy for heating), 13.6 kWh/m^2 (site energy for electricity) and 84.82 kWh/m^2 (total source consumption).
- The monthly consumption trends revealed that highest consumption was experienced from November to March, since during that period both heating and electricity consumption are present. Overall, heating consumption dominates electricity consumption, exceeding it by up to three times.
- No significant differences between school levels were identified, showing that schools belonging to the "first cycle of education" - according to the Italian school system - share similar pattern in energy use. Overall, southern Italy schools experience limited consumptions compared to other countries, although similarities can be found with school consumptions located in other Mediterranean countries.

Beyond the results obtained, the methodology proposed in this chapter - based on the systematic collection of energy data and their statistical analyses - helps to provide an interesting reference that could be replicated for the same building type in other territorial contexts, to understand whether significant differences exist (in addition to the typical differences related to the climatic context), thus helping to identify potential areas with the greatest issues. In addition, this methodology could easily be replicated for other building types: for instance, with the aim of surveying all public buildings from an energy perspective, identifying benchmark energy values for each type, to be adopted as a basis for scheduling energy targets for retrofit interventions.

CHAPTER 6

6. FUTURE ENERGY PERFORMANCE ASSESSMENT

6.1. Introduction

Chapter 4 concludes with the identification of four reference buildings, each one representative of a schools cluster. As such, these buildings can become a useful reference - even for Public Administrations - to conduct more in-depth energy analyses, the results of which can then be extended to the whole cluster. Typically, the most widely adopted methodology for energy investigations deals with the generation of the so-called white-box models, physics-based models mainly built through building performance simulation (BPS) software. However, such models require a large number of input parameters, which may be affected by uncertainty, resulting in differences between actual and simulated behaviour and thus requiring a calibration process to minimize these differences. The present Chapter addresses this **research issue**, with the goal of providing accurate energy models that can be adopted for future analysis. Firstly, the reference schools and their main features are presented (**section 6.2**). Then, the validation process has been addressed and discussed. Indeed, once buildings were manually calibrated based on monthly electricity consumption, a multi-objective optimisation-based calibration has been performed by coupling Energy Plus as simulation engine and the Pymoo simulation and optimization manager executed in the Python programming language. Given the numerical feature of the school energy models, the elitist Genetic Algorithm has been selected to execute the optimization processes, aiming to identify the most effective combinations of six uncertain input parameters, affecting the space heating consumption. Indeed, the optimisation problem has been solved to minimize the difference between simulated and monitored space heating consumption based on a five-month control period, adopting two objective functions: Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the RMSE (CV(RMSE). Indeed, the goodness of calibration has been assessed using such ASHRAE 14-2014 metrics, considering the threshold values for analysis on a monthly basis.

Once the calibrated building models were obtained, they have been used to answer the **RQ4**, with the aim of assessing the impact of climate change on schools energy consumption. For this purpose, future climate files for five locations in the Apulia Region, representative of the three main climate zones, have been generated in the Future Weather Generator tool, based on the latest SSP socio-economic scenarios. Then, each of the four representative buildings - assumed to be fully conditioned in both winter and summer – has been simulated both in the current and then future climate conditions.

6.2. Case study: the representative buildings

All the school buildings are located in the city of Barletta (41°18'32.0" N 16°16'50.7" E), a Mediterranean coastal city in Southern Italy (**Figure 32**). The buildings analysed differ in both geometrical and construction features, as they were built in different periods.

(a) Cluster 1

(b) Cluster 2

(c) Cluster 3

(d) Cluster 5

Figure 32. Representative school buildings of: **(a)** Cluster 1, **(b)** Cluster 2, **(c)** Cluster 3, **(d)** Cluster 5.

The representative building of Cluster 1 - hereafter referred to as CL1 - is a preschool built in 1980. According to the Italian education system, the school accommodates children aged 3 to 6 years old, with a total of about 45 pupils. It is a one-story building characterized by a compact layout (25 m x 29 m), with three main classrooms and a large room available for children's activities, which account for a total of about 65% of the net floor area. The residual areas are dedicated to school services, while no areas are dedicated to staff (**Figure 33**). The school represents a typical Italian 1980s educational building, with a reinforced concrete frame structure and opaque walls made of brick blocks with no insulation (thermal transmittance U≈1 W/m^{2}K). The roof consists of a hollow core slab with a low level of insulation (U≈1 W/m^{2}K), whereas the slab consists of an uninsulated hollow core slab (U≈1.5 W/m^{2}K). Large windows feature the school, characterized by air-filled double-glazed panes with aluminium frames without thermal breaks (U≈3W/m^{2}K).

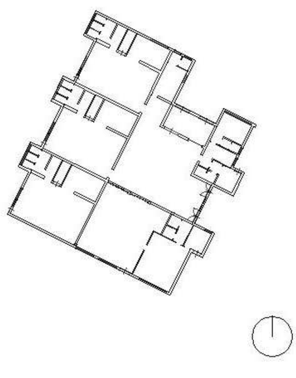


Figure 33. CL1 building plan. Scale 1:1000.

The representative building of Cluster 2 - hereafter referred to as CL2 – is a masonry building constructed in 1961. It accommodates both a preschool and a primary school, accounting for a total of 24 classrooms spread over two stories. The classrooms cover almost 40% of the total school area, while the 4% is occupied by staff office. The residual areas are dedicated to school services, some laboratories, and the gym (**Figure 34**). Referring to the envelope features, the opaque walls are limestone walls - typical of southern Italy – with a thickness of 50 cm (U≈ 1.5 W/m^{2}K). Moreover, the school presents an uninsulated slab, facing an unheated area for one side, and the ground for another side (U≈1 W/m^{2}K). The roof consists of a hollow core slab with a low level of insulation (U≈1.5 W/m^{2}K), while windows have been recently replaced, showing double glazing and aluminium frames with thermal breaks (U≈1.4 W/m^{2}K).

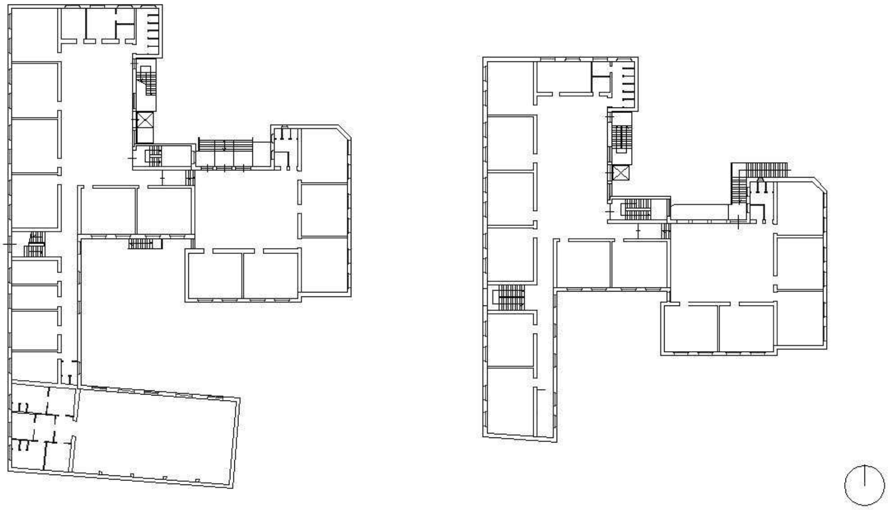


Figure 34. CL2 building plan: first level on the left and second level on the right. Scale 1:1000.

The representative building of Cluster 3 - hereafter referred to as CL3 – is a reinforced concrete structure building constructed in 1989 (**Figure 35**). The building hosts both preschool and primary school classes, distributed on two stories, for a total of around 500 students. Classrooms cover the 32% of the total school area, while the 5% is occupied by staff offices. The residual areas involve the school services, an assembly hall, and a gym.

Referring to the envelope feature, the school presents similar characteristics to CL1, since it has been built a few years later. In fact, the opaque walls are made of brick blocks with no insulation (U≈1 W/m^{2}K), while the roof consists of a hollow core slab with a low level of insulation (U≈1 W/m^{2}K). The slab consists of an uninsulated hollow core slab (U≈1.5 W/m^{2}K), while windows have been recently replaced, showing double glazing and aluminium frames with thermal breaks (U≈1.6 W/m^{2}K).

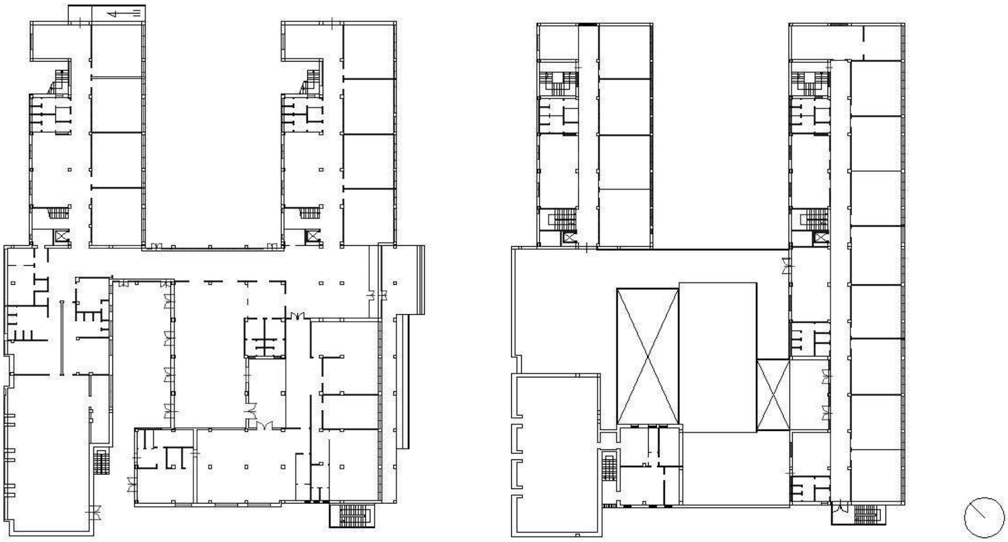


Figure 35. CL3 building plan: first level on the left and second level on the right. Scale 1:1000.

The representative building of Cluster 5 - hereafter referred to as CL5 - is a two-stories masonry building constructed in 1933 (**Figure 36**). The building accommodates a primary school, hosting around 440 students in 25 classrooms. Such classrooms cover almost the half of the total building area (42%), while the 4% is occupied by staff offices. The residual areas involve the school services, three laboratories and a gym.

The building has the typical features of a 1930s Apulian historical building, with massive 70 cm thick limestone bearing walls (U≈1.5 W/m^{2}K). In contrast, the floors are made in reinforced concrete, with a low level of insulation on the roof (U≈1.5W/m^{2}K) and none on the basement. The windows are characterized by air-filled double-glazed panes with aluminium frames without thermal breaks (U≈3 W/m^{2}K).

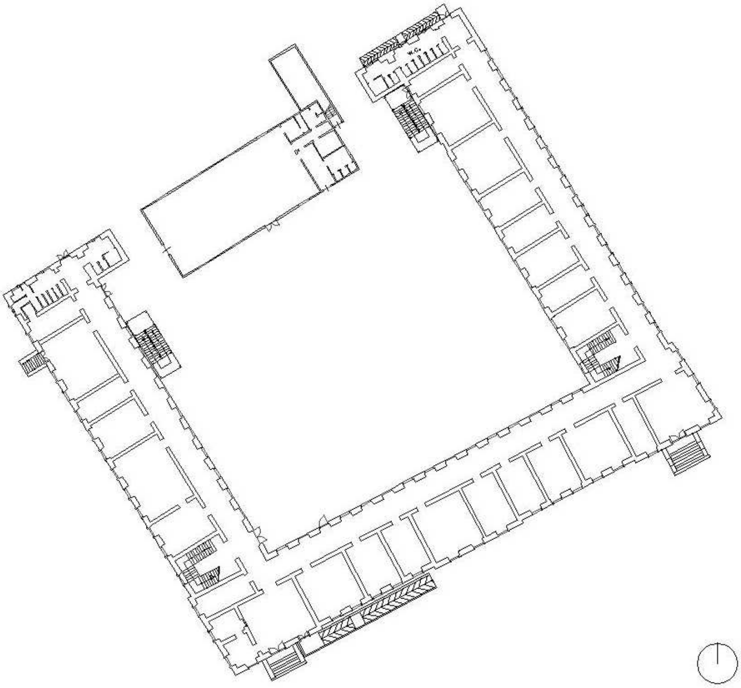


Figure 36. CL5 building plan: first floor. The second floor is not represented as it is exactly the same as the first floor. Scale 1:1000.

To sum up, the main geometrical features of the schools are provided in **Table 15**.

Table 15. Geometrical characteristics of the representative schools.

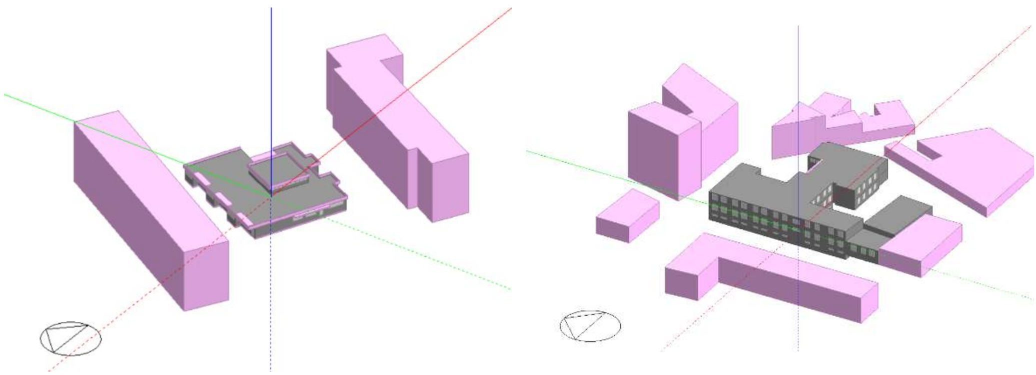
	CL1	CL2	CL3	CL5
Construction year				
	1980	1961	1989	1933
Geometrical features				
Stories (n)	1	2	2	2
Gross floor area (m^2)	656	2873	3782	4132
Gross volume (m^3)	2362	11938	15174	23288
Shape factor (m^2/ m^3)	0.72	0.45	0.49	0.36
Window-to-wall ratio (%)	20%	16%	22%	21%

Although they differ in terms of geometrical and envelope characteristics, all the schools show similar systems features, which comply with those typical of Italian school buildings. Indeed, they are all naturally ventilated buildings, in which electricity provides the energy uses for lighting and appliances, domestic hot water production is provided by dedicated electric boilers, while gas supplies the energy needs for space heating. Both the efficiency and the type of heating system, as well as the operating schedules, have been provided by the local municipalities. In detail, according to the generation efficiencies and the plants components installed in the schools, the global seasonal efficiencies have been calculated based on the UNI TS 11300-2 [238], accounting for 70%, 75%, 77%, 67% for CL1, CL2, CL3, CL5 respectively. Like most Italian school buildings [111], the buildings are not equipped with mechanical cooling systems as almost unoccupied during the summer season (between July and August).

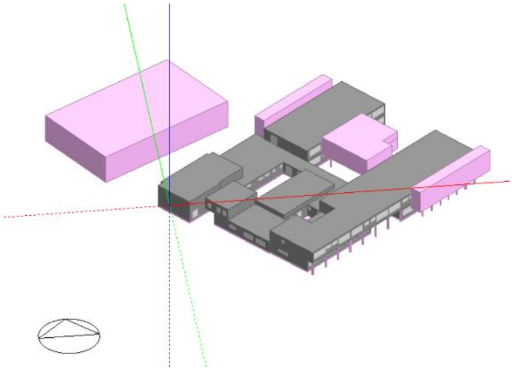
6.3. Methods

6.3.1. Building energy modelling

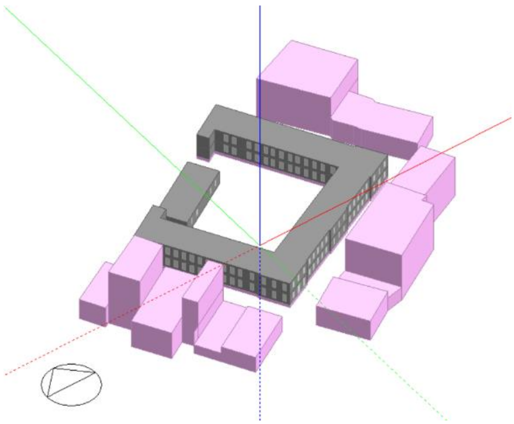
For each representative school building, a building energy model has been developed in Design Builder software (version 7.0.2), which allows to export the IDF file to be run in Energy Plus (version 9.6). Firstly, the building geometry has been modelled (**Figure 37**), then the boundary conditions have been set and finally preliminary input data has been used to run the simulations.



(a) Cluster 1 **(b)** Cluster 2



(c) Cluster 3



(d) Cluster 4

Figure 37. School building energy models, for (a) cluster 1, (b) cluster 2, (c) cluster 3, (d) cluster 4.

The boundary conditions to run energy simulations are provided by weather data stored in a weather file in an epw format [239]. Commonly, dry bulb temperature, solar radiation, relative humidity, wind speed and wind direction are the input variables used to generate the current climate file. To carry out a calibration process, the use of "actual" weather file representative of the control period used in the calibration is essential. These data should be obtained from a local weather station close to the study location, throughout the time interval used for calibration to energy bills [240]. Therefore, in this work, an input weather file has been generated in Elements tool [241], based on the weather data recorded during the year 2019, which is the control period set for the calibration process adopted for all the schools. Since the representative schools are all located in the same city, a single weather station has been used to retrieve data and create the epw weather file to be used in the simulation software. The station is managed by the Regional Environmental Protection Agency (ARPA Puglia) and provides hourly data of dry bulb temperature, relative humidity, and global solar radiation [242]. Nevertheless, the epw file requires the global solar radiation to be divided into its direct and diffuse components, thus the Watanabe method has been adopted to split it [243]. Such method allows for separating the global irradiance into its direct and diffuse components based on simple geographic features of the location, according to the following **Equation 2** and **Equation 3**.

$$I_d = \frac{K_{DS} \times I_0 \sin h - TH}{K_{DS} - 1} \tag{2}$$

$$I_n = K_{DS} \left(I_0 \sin h - I_d\right) \tag{3}$$

where I_d is diffuse solar radiation (W/m^2), I_0 is the solar constant set at 1335 W/m^2, TH is the global radiation (W/m^2), h is the solar altitude, and K_{DS} is calculated according to **Equation 4**.

$$K_{DS} = \begin{cases} K_T - (1.107 + 0.03569 \sin h + 1.681 \times \sin^2 h) \times (1 - K_T)^3 & if\ K_T \geq K_{TC} \\ (3.996 - 3.862 \sin h + 1.540 \sin^2 h) K_T^3 & if\ K_T < K_{TC} \end{cases} \tag{4}$$

where K_T is expressed as $K_T = TH / I_0 \sin h$.

6.3.2. Calibration process

Once the numerical models have been generated for each school and the weather boundary conditions have been established, the identification of the sources of uncertainty with their range of variation is required to perform the calibration procedures. In this work, the sources of uncertainty have been retrieved from the sensitivity analysis performed by Hopfe [244], while the range of variations has been derived from European or Italian standards. For each school, six input variables have been identified as source of uncertainty. Unlike the work of Hopfe, in this study, the geometrical features of each school were provided by local authorities, thus the size of the rooms and the window type have not been considered as uncertain variables. Likewise, the occupants' loads were known since the occupancy of the buildings (in terms of the number of occupants and daily and annual operating schedules) was found through detailed surveys, conducted by searching across the school website and asking questions to occupants and local administrators.

In addition, lighting loads were also known, as they were provided by local authorities. Actually, before performing the automatic calibration process based on heating consumption data, all the schools were manually calibrated with reference to monthly billed electricity consumption, adopting as control period the same year 2019. As mentioned, the loads were known, while the lighting operating schedules have been defined based on the theory developed by Baker and Steemers [245]. They defined a probability curve for turning on the lights, arguing that users would turn on (or none) the lights when they arrived, based on the level of daylight, and remain in the same condition until they left. Thus, for each school room, the daylight level at the centre of the room when the users arrived has been simulated, and if found to be less than 80 lux, the lighting has been assumed to be on until the users left. Thus, only some equipment-related loads remained uncertain, which have been manually calibrated to meet the ASHRAE Guideline 14-2014 metrics: NMBE and CV(RMSE) - explained in detail in the next section -, achieving compliance for all buildings.

Consequently, to perform the automatic calibration process, six sources of uncertainty have been considered, along with the parameter that drives the uncertainty. Three of them were related to the envelope thermal features, involving the thermal transmittance of walls, roofs, and windows. Since in all cases the walls are uninsulated, the uncertainty in thermal transmittance was related to the conductivity λ of the main material (brick or limestone), whose ranges of variation have been derived from the Italian standard UNI 10355 [246]. Moreover, the uncertainty of windows transmittance was related to the uncertainty of both glass and frame transmittance, whose range of variation has been deduced from the Italian standard UNI TS-11300-1 [247]. A further source of uncertainty was related to the heating system features, concerning the heating setpoint temperature, which ranged from 18°C to 22°C, in compliance with the national laws DPR 412/93 [248] and D.Lgs 81/08 [249]. Finally, two sources of uncertainty were related to infiltration and ventilation rates, whose range of variation were defined in accordance with [21]. Accordingly, the sources of uncertainty along with the independent variables that determine uncertainty, and their range of variation are summarised in **Table 16**, for all the representative buildings.

Table 16. Source of uncertainty, independent variable that determines uncertainty and its range of variation, for all the representative buildings.

Source of uncertainty	Independent variable	Range of variation
CL1		
Envelope thermal features		
U-value of opaque walls	λ of brick (W/mK)	{0.36,0.39,0.45,0.48,0.54}
U-value of roofs	Insulation thickness (m)	{0.01,0.02,0.03,0.04,0.05}
U-value of windows	U of windows (W/m^{2}K)	{2.7, 2.8, 3.1, 3.3}
Heating system features		
Setpoint temperature	Temperature (°C)	{18, 19, 20, 21, 22}
Infiltration and ventilation		
Infiltration rate	Infiltration rate (ac/h)	{0.4, 0.6, 0.8, 1.0, 1.2}
Control strategy of window opening	Indoor air temperature (°C)	{22, 23, 24, 25, 26}
CL2		
Envelope thermal features		
U-value of opaque walls	λ of limestone (W/mK)	{0.6,0.8,1.1,1.3,1.5,1.7}
U-value of roofs	Insulation thickness (m)	{0.01,0.02,0.03,0.04,0.05}
U-value of windows	U of windows (W/m^{2}K)	{2.4, 2.2, 2.0, 1.8, 1.6}
Heating system features		
Setpoint temperature	Temperature (°C)	{18, 19, 20, 21, 22}
Infiltration and ventilation		
Infiltration rate	Infiltration rate (ac/h)	{0.4, 0.6, 0.8, 1.0, 1.2}
Control strategy of window opening	Indoor air temperature (°C)	{22, 23, 24, 25, 26}
CL3		
Envelope thermal features		
U-value of opaque walls	λ of brick (W/mK)	{0.36,0.39,0.45,0.48,0.54}
U-value of roofs	Insulation thickness (m)	{0.01,0.02,0.03,0.04,0.05}
U-value of windows	U of windows (W/m^{2}K)	{1.6,1.7,1.8,1.9,2.0}
Heating system features		
Setpoint temperature	Temperature (°C)	{18, 19, 20, 21, 22}
Infiltration and ventilation		

Infiltration rate	Infiltration rate (ac/h)	{0.4, 0.6, 0.8, 1.0, 1.2}
Control strategy of window opening	Indoor air temperature (°C)	{22, 23, 24, 25, 26}
CL5		
Envelope thermal features		
U-value of opaque walls	λ of limestone (W/mK)	{0.6,0.8,1.1,1.3,1.5,1.7}
U-value of roofs	Insulation thickness (m)	{0.01,0.02,0.03,0.04,0.05}
U-value of windows	U of windows (W/m^{2}K)	{2.7,2.8,2,9,3.0,3.1,3.2,3.3}
Heating system features		
Setpoint temperature	Temperature (°C)	{18, 19, 20, 21, 22}
Infiltration and ventilation		
Infiltration rate	Infiltration rate (ac/h)	{0.4, 0.6, 0.8, 1.0, 1.2}
Control strategy of window opening	Indoor air temperature (°C)	{22, 23, 24, 25, 26}

Once the uncertainty parameters and their variation ranges have been defined, the calibration process can be carried out. In this study, the Normalised Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error CV(RMSE) have been selected as metrics to evaluate the goodness of fit of the calibration procedure, based on the threshold values set by the ASHRAE Guideline 14 [45].
NMBE is a normalization of the MBE, which is a non-dimensional measure of the overall bias error between the measured and simulated data in a specific time frame:

$$NMBE = \frac{\sum_{i=1}^{n_i}(m_i - s_i)}{\sum_{i=1}^{n_i} m_i}\ [\%] \tag{5}$$

where m_i are the measured values, s_i are the simulated value at time interval i, and n_i is the total amount of data.
CV(RMSE) measures the variability of the errors between measured and simulated values.

$$CV(RMSE) = \frac{1}{\bar{m}}\sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n_i - p}}\ x\ 100\ [\%] \tag{6}$$

where m_i are the measured values, $\bar{m}$ is the average of measured data, s_i are the simulated value at time interval i, p is the number of adjustable model parameters, which, for calibration purposes, is suggested to be one, and n_i is the total number of data.

For each school, the calibration has been carried out over a five-month period in the year 2019, corresponding to the heating period for the city of Barletta according to Italian law [248]: from January to March and from November to December.

The calibration procedure was based on monthly data; thus, the building energy model has been considered calibrated if the NMBE was not larger than ±5% and CV(RMSE) was not larger than 15%, according to [45]. Actually, the calibration has been conducted for a five-month period for CL1 and CL5, and for a four-month period for CL2 and CL3. Indeed, for both the schools, the month of March exhibited anomalous values, which constituted outliers in the analysis and therefore have been removed.

As mentioned above, calibration procedures based on automatic optimisations are very promising today, thanks to their speed and the low number of simulations required to explore the whole problem of space. Consequently, in this study a double-objective optimisation has been performed to minimise the difference between actual and simulated data over the control period. In detail, an automatic optimisation-based calibration has been performed by coupling Energy Plus as simulation engine and the Pymoo simulation and optimization manager executed in the Python programming language. Given the numerical feature of the school energy models, the elitist Genetic Algorithm (GA) has been selected to execute the optimization process, with the aim of selecting the most effective combinations of six uncertain input parameters. First proposed by Holland [250], GAs belong of the class of evolutionary algorithms, which are heuristic optimization techniques inspired by Darwinian evolutionary principles. Briefly, each combination of the input parameters is considered as an individual with its own genome, consisting of a certain number of genes (corresponding to the optimisation parameters). Accordingly, each individual - and thus each genome - is a point in the space of solutions and shows a particular suitability that represents its fitness for a given problem. First, GA begins with an initial randomly generated population, whose genes are selected, mutated and recombined - based on the fitness of each genome -

generating the offspring of the first population. Then, the process is repeated iteratively by replacing the population with its progeny, increasing the average fitness [251]. Thus, in our study, the six uncertain variables have been ideally associated with a 6-genes genome, and the GA has been used to explore the problem space to find the global minimum of the problem. Given the number of variables, a population size of 100 individuals [252] and 10 different generations have been considered, allowing a total of 1,000 simulations to be achieved, which ensure a proper search in the problem space according to the literature [253,254].
The optimisation problem has been solved based on two objective functions, NMBE and CV(RMSE), according to **Equation 7**.

$$\begin{cases} f_1(genome) = NMBE\ (genome) = min \\ f_2(genome) = CV(RSME)\ (genome) = min \end{cases} \tag{7}$$

6.3.3. Climate change impact assessment

According to the evaluation conducted in the state of the art, in the building field, the most widely adopted approach to assess the impact of climate change on energy performance is a simulation approach, carried out through building performance simulations (BPS). For this purpose, simulation boundary conditions, typically consisting of "average" climate files representative of current climate conditions (i.e. TMY), are replaced by climate files representative of future conditions. Hence, future weather files in a BPS readable format are required. In this study, among the tools reviewed in **Section 2.1.3**, the Future Weather Generator (FWG) has been selected to create future weather file, since it is the only one based on the latest Shared Socio-Economic Pathways (SSPs) scenarios. The FWG is a Java application, which allows for the creation of future weather files adopting the morphing method as downscaling approach, based on an historical weather file (baseline 1985-2014). In this study, five historical weather files have been considered, representative of the three main climate zone of the Apulia Region (**Figure 38**). Two weather files (Bari and Lecce) are representative of the climatic zone C: the former is representative of the coastal areas, and the latter is representative of the in-land areas. Two weather files (Foggia and Martina Franca) are representative of the climatic zone D: the former is representative of the north area (the sub-Apennine zone), the latter is representative of the southern inland areas. One weather file is representative of the climatic zone E, which covers a limited area of the Apulia Region. In that case, since a suitable historical weather file was not available for any Apulian location in this area, a weather file of the city of Campobasso has been adopted, a city a few kilometres far from the Apulian area lying in zone E. Weather files in epw format of these locations have been downloaded from [255] and then used as a baseline to create four future weather files for 2050s, each one based on a SSP emission scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5, for a total of twenty climate scenarios.

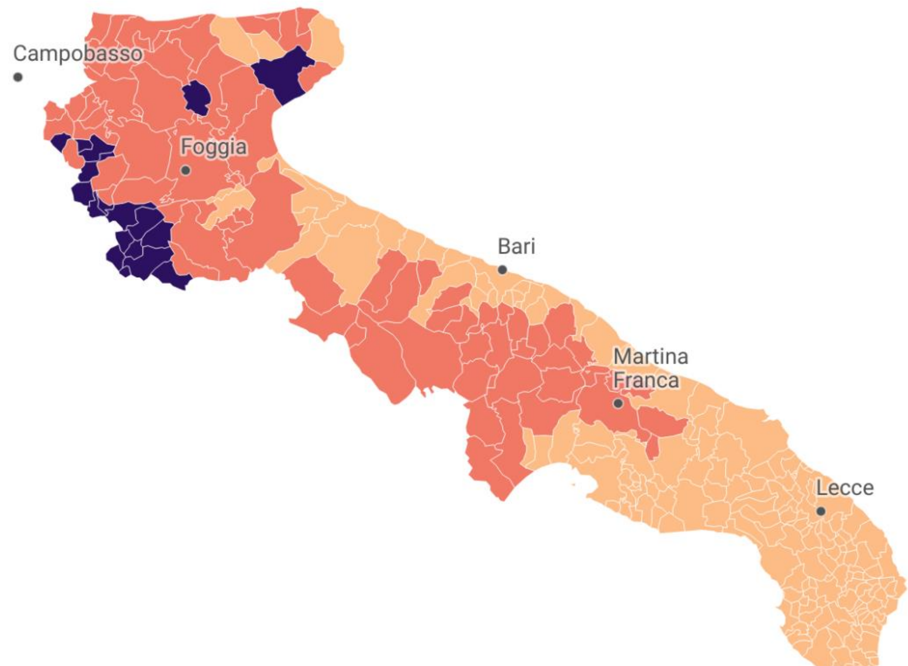


Figure 38. Location of cities whose climate files have been used.

Once the climate scenarios were created, they were used as boundary conditions in the BPS to assess the impact of climate change on consumption. Hence, starting with the calibrated energy models of the 4 representative buildings created in Design

Builder, the idf files have been exported to be run in Energy Plus with the different future climate files. The impact on building consumption has been evaluated in terms of energy needs for heating and cooling – thus without considering the plants features –, normalised to the conditioned area of the buildings. The schools have been considered fully conditioned both in winter and in summer, hence the introduction of an ideal cooling system was assumed, with a turn-on period starting one month after the heating system is turned off and ending one month before the heating system is turned on. The operation schedule for cooling has been set similarly to that used for heating, thus based on the operation of the buildings. However, since the school is predominantly unoccupied in summer, two schedules have been created: one related to the school (typically closed from July 1 to August 30) and the other related to the offices that remain open during the whole summer period.

6.4. Results

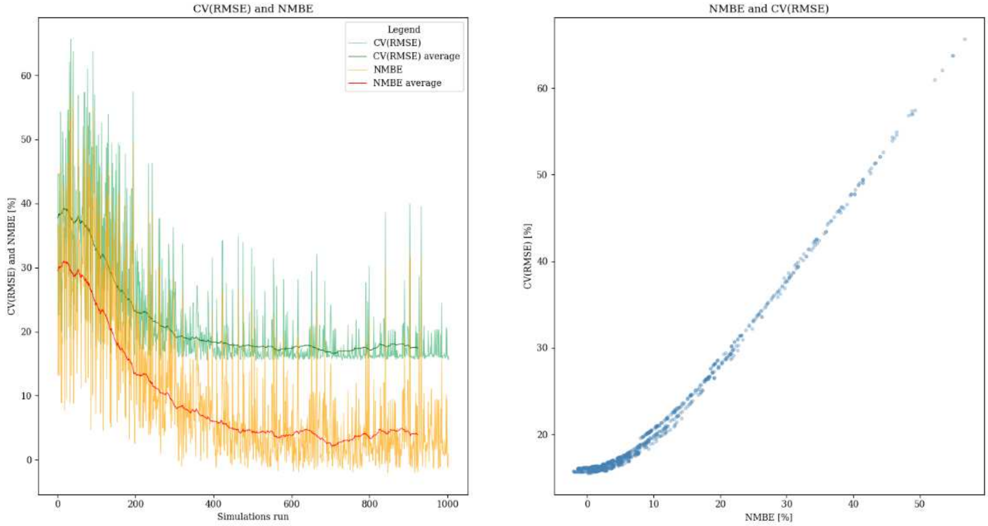
6.4.1. Calibration results

For each school, the building energy model has been calibrated to minimise the difference between actual and simulated performance, based on the billed gas consumption collected over the year 2019. While the uncalibrated models generated in Design Builder exhibited significantly different results from the billed data, the calibration procedure significantly improved such values, enabling compliance with ASHRAE thresholds in all the representative schools. The values assumed by NMBE and CV(RMSE) along all the simulations performed are drawn in **Figure 39** (on the left), which clearly reveals the evolution of such values over the calibration procedure.

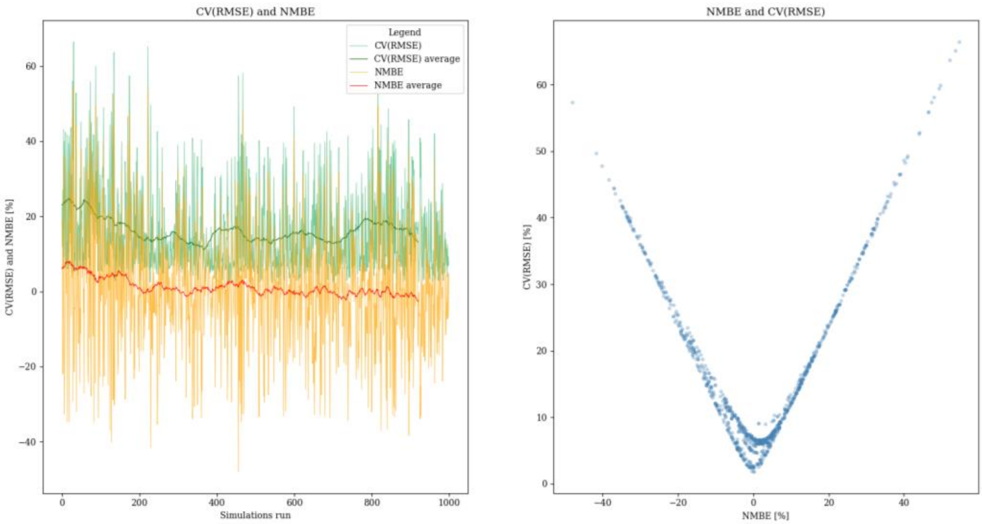
Looking at the results obtained during the calibration processes, the benefits in using the Genetic Algorithm can be easily identified in the rapid minimization of both objective functions (NMBE and CV(RMSE)). Indeed, although to different extents, in all cases significantly reduced results are achieved compared to the starting case, after only 200 simulations. Looking at the moving averages, on the one hand, Cluster 1 and Cluster 3 experience a considerable reduction in indicators up to the 200th simulation, and then fluctuate around similar values. On the other hand, Cluster 2 and Cluster 5 experience a less sudden reduction in indicators, as they start from better starting values than the previous cases.

More considerations can be drawn out by looking at the graphs on the right, showing the CV(RMSE) and the NMBE values in all the simulation conducted in the calibration problems. It should be noted that, based on the equations used for the calculation, the NMBE can assume both positive and negative values, while the CV assumes only positive values. However, referring to the values reached, differences can be outlined in relation to the schools analysed. In fact, in the calibration process performed for CL1, the NMBE never took negative values during all the simulations run, resulting in points that are arranged according to an increasing curve resembling a half parabola, reaching very high values of both CV and NMBE. By contrast, referring to Cluster 2 and Cluster 5, the NMBE reaches both positive and negative values, resulting in points that are arranged in a parabolic pattern, with NMBE values (in absolute terms) increasing as CV values increase. Obviously, due to the optimisation process, most points remain around low values of both indicators, although in some simulations remarkable values were reached (up to 60% and over ±40% NMBE). Finally, Cluster 3 represents an intermediate case, with NMBE values reaching negative values (albeit to a lesser extent than in Clusters 2 and 5), with the points being arranged taking a less pronounced trend than in previous cases.

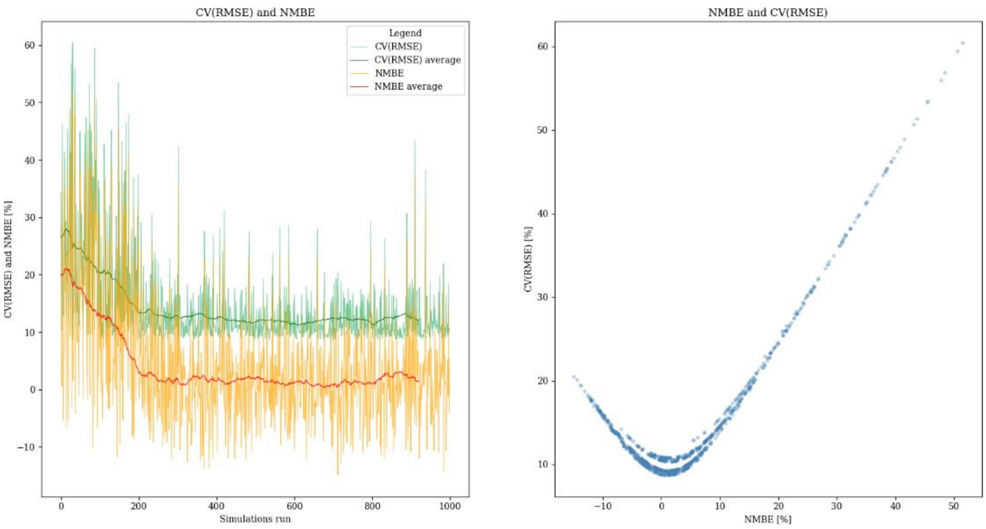
Overall, the indicators are concordant in their trend: the higher the NMBE (in absolute terms), the higher the CV. This confirms the suitability of scalarizing the dual-objective optimization to single-objective optimization, conducted in a further study published by the present writer [256].


CV(RMSE) and NMBE
Legend
CV(RMSE)
CV(RMSE) average
NMBE
NMBE average
CV(RMSE) and NMBE [%]
Simulations run
NMBE and CV(RMSE)
CV(RMSE) [%]
NMBE [%]

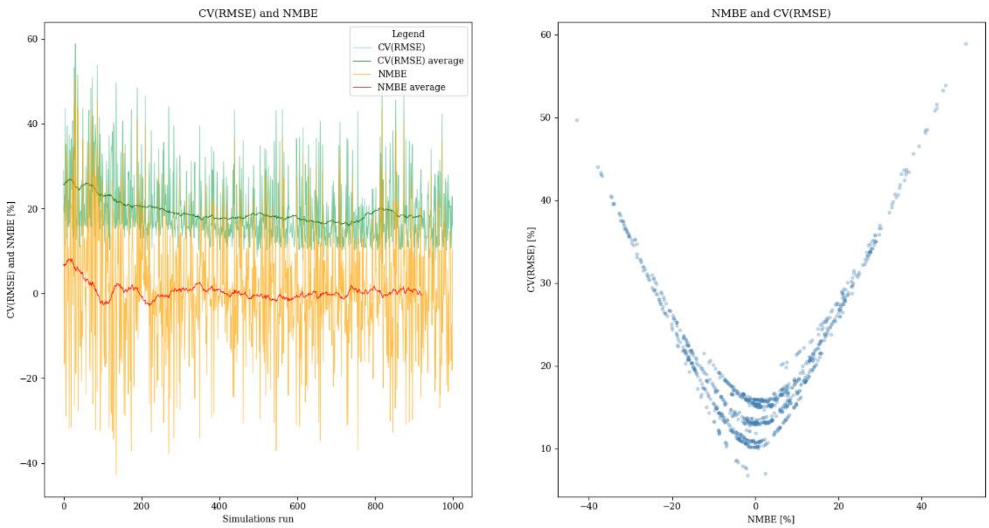
(a) CL1


CV(RMSE) and NMBE
Legend
CV(RMSE)
CV(RMSE) average
NMBE
NMBE average
CV(RMSE) and NMBE [%]
Simulations run
NMBE and CV(RMSE)
CV(RMSE) [%]
NMBE [%]

(b) CL2



(c) CL3



(d) CL5

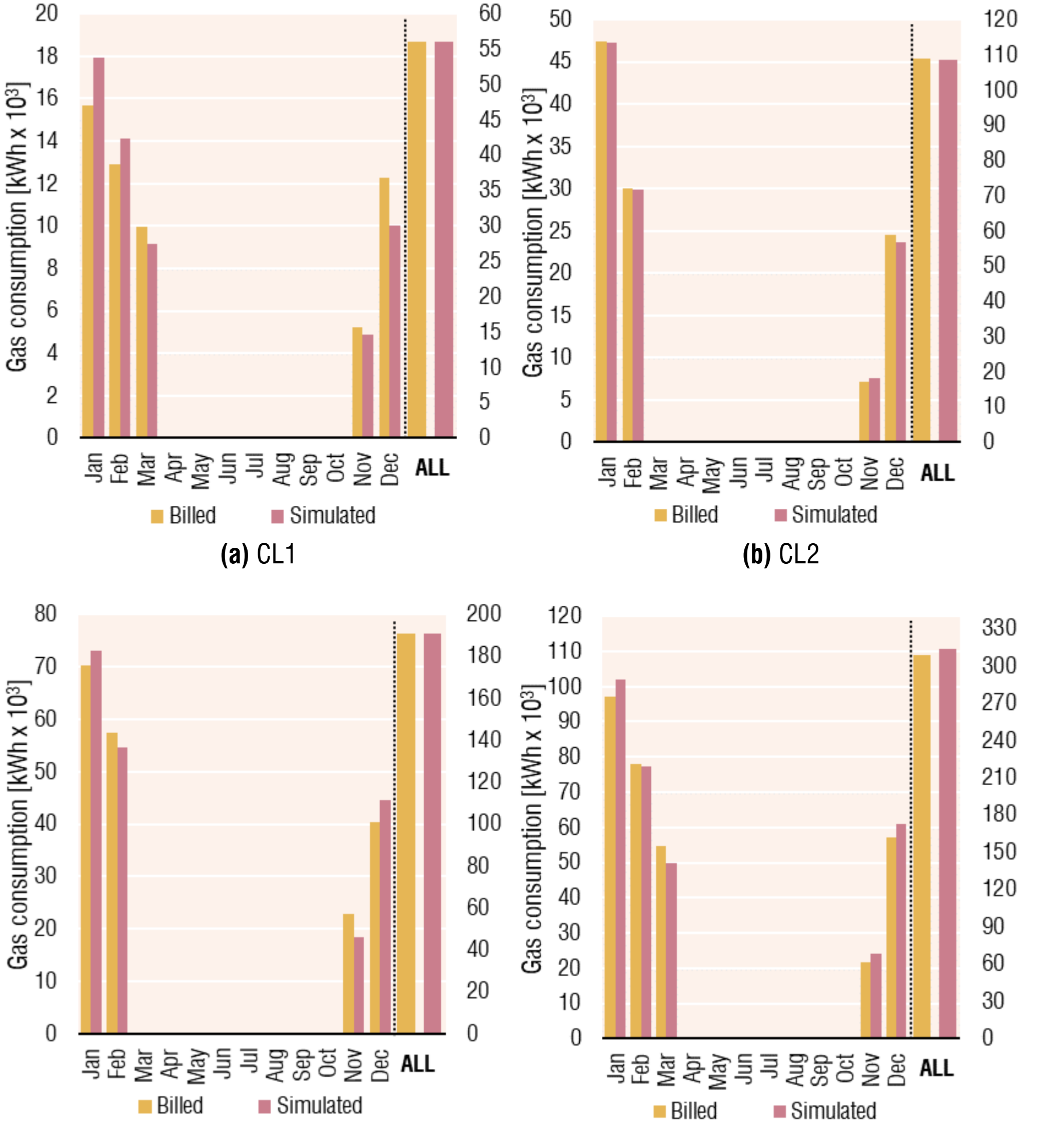
Figure 39. Results of the Genetic Algorithm simulations for **(a)** CL1, **(b)** CL2, **(c)** CL3, **(d)** CL5. On the left side, the evolution of utility functions over the entire period of one thousand simulations is shown, together with their moving average. On the right side, CV(RMSE) and NMBE values in all the simulations performed during the calibration processes.

The figures reveal that the optimisation-based calibration process has led to more than one solution that satisfied the problem (based on minimization of NMBE and CV(RMSE) values). Overall, in the calibration processes of all schools, the problem solutions showed NMBE values well below the threshold value of ±5%, while greater differences were found among the values of CV, a parameter considered as more accurate by the scientific literature, as it is less affected by error compensation phenomena [257]. Therefore, among the solutions that had NMBE values closer to zero percent, those characterized by lower CV values have been selected as optimal values. Accordingly, the relative values of the uncertainty parameters have been identified, as reported in **Table 17**.

Table 17. Source of uncertainty: optimised values.

Source of uncertainty	Independent variable	Optimised value			
		CL1	**CL2**	**CL3**	**CL5**
Envelope thermal features					
U-value of opaque wall	λ of brick (or limestone) (W/mK)	0.54	0.6	0.39	0.8
U-value of roof	Insulation thickness (m)	0.01	0.01	0.01	0.04
U-value of windows	U of windows (W/m^{2}K)	3.3	2.2	1.9	2.8
Heating system features					
Setpoint temperature	Temperature (°C)	22	21	22	22
Infiltration and ventilation					
Infiltration rate	Infiltration rate (ac/h)	1.0	0.6	0.4	0.4
Control strategy of window opening	Indoor air temperature (°C)	22	22	22	22
NMBE [%]		0.04	0.10	0.08	1.78
CV(RMSE) [%]		15.6	1.9	8.8	6.8

From a gas consumption perspective, the calibration procedure allows significantly similar values between simulated and actual data to be achieved. The comparison between simulated and billed data on a monthly basis is reported in **Figure 40** for all the representative schools. Looking at the results in terms of annual heating consumptions, it appears clear that the use of calibrated models allows for a much more reliable study of energy phenomena, especially with reference to annual simulations. Indeed, the calibration process enables to reach simulated annual gas consumptions that are extremely close to the billed ones.



(a) CL1 **(b)** CL2 **(c)** CL3 **(d)** CL5

Figure 40. Billed vs simulated gas consumption for the four representative schools.

6.4.2. Climate change assessment

The present section provides the results of the climate change impact assessment on the four representative buildings, adopting the previously calibrated building energy models. As mentioned, the methodology adopted has required the generation of future weather files, used as a boundary condition to conduct the dynamic simulations. Overall, 25 weather files have been used: for each of the five locations, the TMY climate file representative of the current condition has been selected, and then adopted as basis for creating four future climate files – each one based on a different SSP scenarios - thanks to the Future Weather Generator tool. Then, these files have been adopted to assess the impact of climate change on heating and cooling needs variation of the four representative buildings, for a total of 100 simulations run in Energy Plus.

Brief considerations about future weather files can be drawn from **Figure 41**, where boxplots of outdoor air temperatures are plotted for the 25 climate files. First, the boxplots of the TMY files allow to capture the differences in the climatic features of the investigated locations. Indeed, the two cities representative of climate zone C (**Figures 41a** and **41b**) show annual average air temperature values higher than the other locations, followed by the two cities representative of zone D (**Figures 41c** and **41d**) and the city representative of zone E (**Figure 41e**). Referring to the boxplots of the future climate files, as expected, the figure shows an increasing trend in outdoor air temperatures, moving toward higher values for all climate files considered. In fact, although with slight differences according to the SSP, average air temperatures move to higher values, as do predicted maximum temperatures, which experience an increase that far exceeds the increase in minimum temperatures.

Once the climate files were created, they have been used as boundary conditions to perform the dynamic simulations, with the aim of calculating - for each representative building and for each climate scenario - heating and cooling energy needs, running the schools in a “conditioned mode” both in summer and in winter.

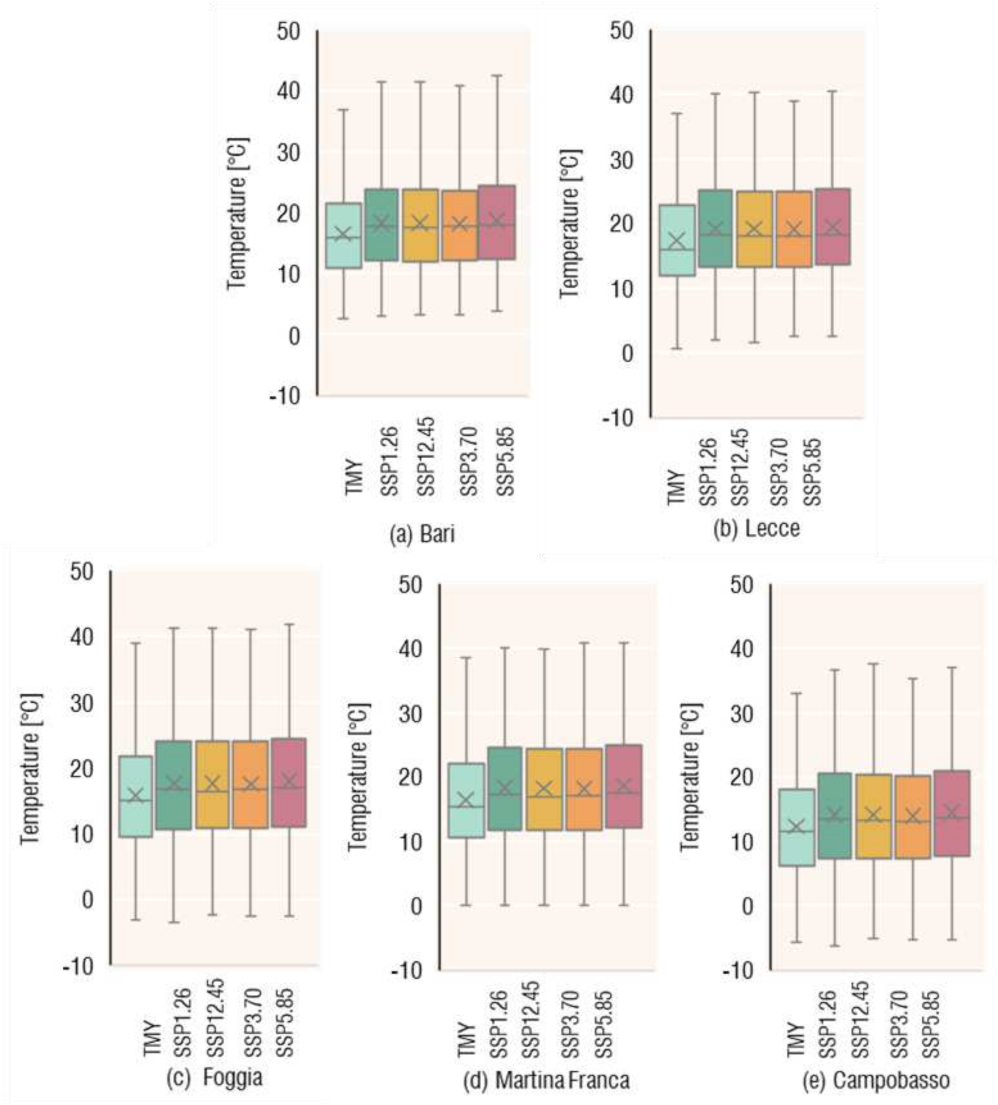
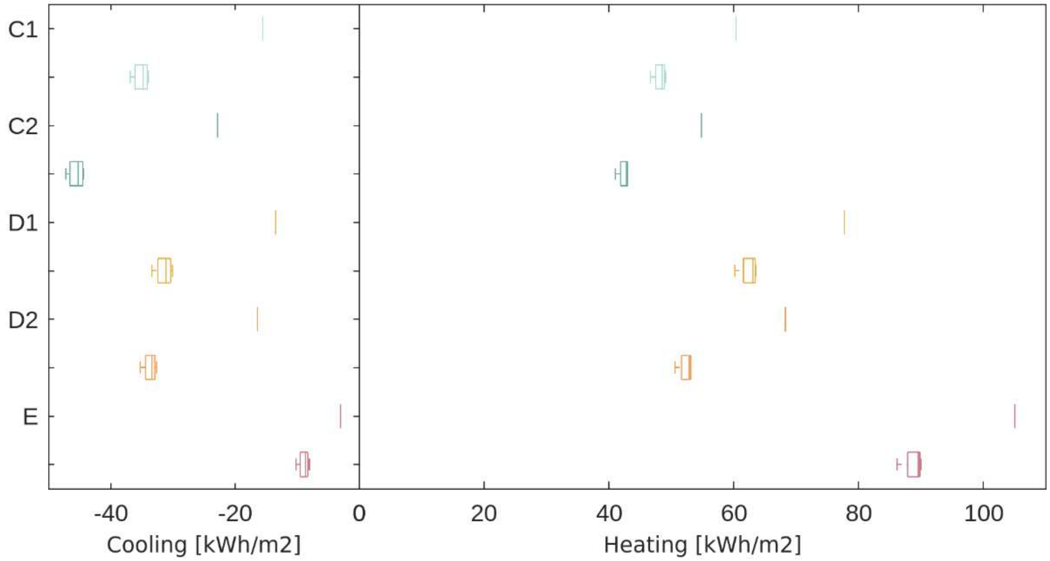


Figure 41. Boxplot of outdoor air temperatures for both actual and future weather files, for Bari and Lecce (climatic zone C), Foggia and Martina Franca (climatic zone D), Campobasso (climatic zone E).

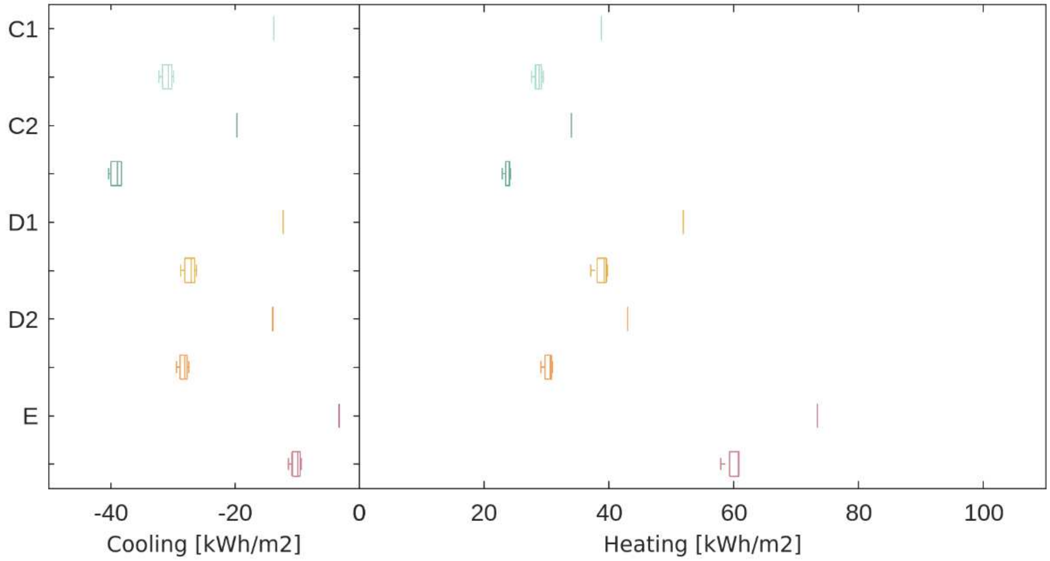
The results obtained from the 100 simulations are shown in **Figure 42**, in which heating (on the right) and cooling (on the left) needs are shown separately, normalised according to the buildings conditioned area, in the current climate and future climate scenarios. In detail, while energy needs in the current climate are represented through the

vertical lines, those in the future climate are represented through boxplots, the span of which results from the four SSP scenarios considered, allowing to understand the magnitude of uncertainties in the energy calculation related to the scenario adopted. The findings are reported separately for the four representative buildings analysed.
Overall - although differences in the extent of variations can be drawn - a shift in energy needs due to rising temperatures can be observed in all the schools, characterized by a reduction in heating needs and an increase in cooling needs. However, some differences arise referring to the climatic zone considered. Indeed, in cities representative of climate zone C - denoted by C1 and C2 in the figure - the reduction in heating is smaller than the increase in cooling, leading to an overall increase in energy needs. By contrast, in the representative cities of climate zone D - indicated by D1 and D2 in the figure - the two variations seem to be equalled, while an opposite trend is outlined in zone E, where the reduction in heating exceeds the increase in cooling. With reference to the different SSP scenarios used, the span of the boxplots shows that the selection of emission scenarios slightly affects the results obtained in terms of annual energy needs, with variations between the different SSP not reaching 5kWh/m^2. As expected, the SSP5-8.5 scenario turns out to be the worst-case scenario, leading to the largest changes in energy needs compared to the current climate, both in terms of cooling and heating. However, it should be noted that the above considerations are made with reference to energy needs, without considering the efficiency of heating and cooling plants, which could result in different data. Indeed, if we consider current conditions, heating needs are met by gas plants, which exhibit lower efficiencies than cooling plants typically supplied by electricity.

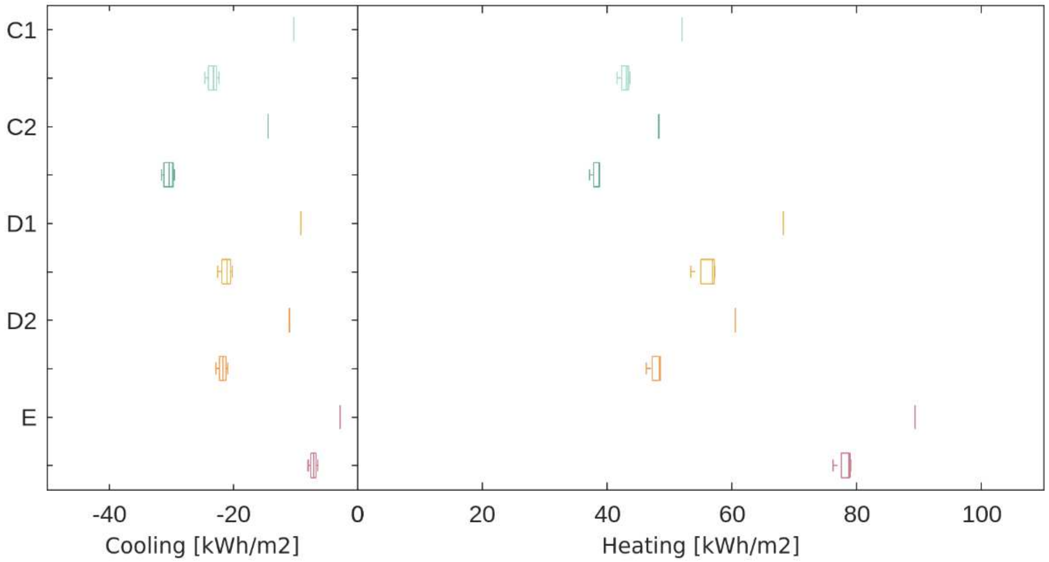
Beyond this, the graph is intended to show how - even for school buildings, which have extremely low occupancy in the summer period - climate change will necessarily lead to address cooling requirements. Indeed, although schools are mostly unoccupied in July and August, due to rising temperatures, cooling loads also occur in seasons previously considered as “intermediate”, such as May and September, as well as in June. Accordingly, although they remain heating-dominated buildings, the fulfilment of cooling needs must necessarily be considered, both for new school buildings and for energy renovations. Clearly, cooling requirements need to be properly investigated, to understand whether passive measures are sufficient to ensure adequate indoor temperatures. However, the increasing temperatures we are seeing will make the use of active measures inevitable in the long term.



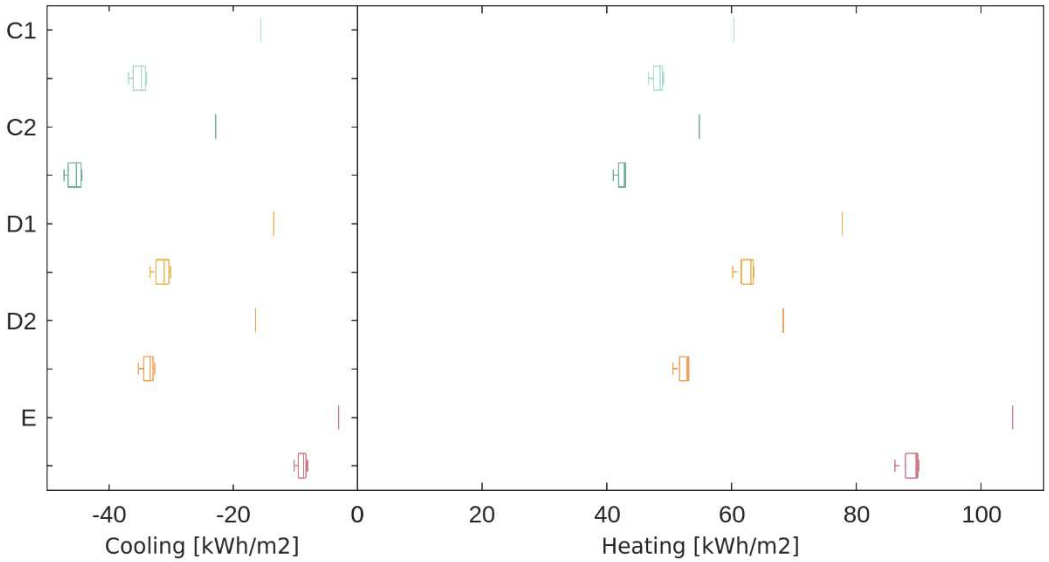
(a) CL1



(b) CL2



(c) CL3



(d) CL5

Figure 42. Cooling and heating needs in the current (vertical line marker) and future weather scenarios (boxplot) for the climatic zone C (C1 and C2), D (D1 and D2) and E, referred to **(a)** Cluster 1, **(b)**, Cluster 2, **(c)** Cluster 3, **(d)** Cluster 5.

6.5. Conclusion

The present chapter aimed to provide accurate energy models of the reference school buildings, useful for further energy analyses. To that end, a calibration process has been performed, aiming to minimize the difference between simulated and billed space heating consumption, based on a five-month control period. Accordingly, six uncertain variables have been identified, whose most effective combination has been evaluated by solving a double-objective optimisation problem, by coupling Energy Plus and Python. To assess the goodness of fit of the calibration process, the ASHRAE Guideline 14-2014 metrics have been adopted: the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the RMSE (CV (RMSE)). The optimisation problem has been executed based on a Genetic Algorithm, with the goal of minimizing the ASHRAE metrics. The calibration process allowed excellent results to be achieved, largely meeting the threshold values set by the Guideline 14. For instance, the results in terms of annual consumption are extremely close to reality, thus studies based on annual simulations would be very accurate.

In addition, starting from the calibrated energy models, the present chapter aimed to answer the fourth research question of the thesis, exploring the impact of climate change on schools energy consumption. To that end, the representative schools have been simulated both in the current and in the future weather scenarios, in five locations representative of the three climatic zones of the Apulia Region. The results showed that - although schools are almost unoccupied during the summer period - climate change still leads to a significant increase in cooling needs, which outweigh the reduction in the heating ones. In fact, as shown in the analysis of outdoor air temperatures, the rise in maximum temperatures far exceeds the rise in minimum temperatures, afflicting cooling more than heating. Moreover, although the school is unoccupied during the hottest periods such as July and August when the highest temperatures are reached, rising temperatures result in the occurrence of cooling requirements even in the intermediate seasons, like May and September. Consequently, meeting cooling needs is a necessity that can no longer be neglected.

CHAPTER 7

7. LIFE CYCLE COST ANALYSIS OF ENERGY RETROFITS

7.1. Introduction

The previous chapters have highlighted the poor condition of existing schools, whose performance will be further worsened by climate change. As known, multiple renovation opportunities are now available for existing buildings, incentivized with a view to climate change mitigation [28]. Frequently, consistent with economic availability, renovation activities of existing buildings seek not only to achieve the regulation requirements, but also to exceed them, assuming that achieving better performance values will ensure better performance for the building. However, this is not always truthful, especially in the current climate context where global warming can change typical trends in building performance. Similarly, current climate policies are increasingly focused on establishing the obligation of retrofitting existing buildings in compliance with regulatory energy standards to contain the CO_2 emission fit [18]. In this light, the question arises as to whether adapting buildings by merely meeting regulatory standards is already sufficient or whether greater benefits would be gained by achieving better performance values. In other words, if we were obliged to renovate our buildings by meeting the normative values, would it be sufficient to achieve them or would it be appropriate to exceed them, also considering how the climate context will evolve?

The present chapter aims to answer this research question (**RQ5**) by exploring different energy renovation strategies. The effectiveness of the measures has been evaluated not only in terms of energy performance improvement, but also in terms of cost implication, comparing each identified strategy - as well as their possible combinations - with the reference building provided by the Italian regulation [216], through the life cycle cost approach (LCC) [258]. To identify optimal combinations, a single-objective optimisation has been performed by coupling Energy Plus as simulation engine and Python as optimisation manager, with the aim of minimizing the global investment cost, considering a time frame of 30 years. A novelty in this approach has been to consider an additional factor of variation, that is, changing climatic conditions: the first 11 years has been simulated using an epw weather file representative of the current climate (TMY) and the remaining 19 using an epw representative of future climate (2050), created using the morphing method based on the latest SSP5-8.5 socio-economic development scenario. The methodology has been applied to one of the representative buildings identified within the cluster analysis explained in **Chapter 4**, and thus replicated for the five locations representative of the three climate zones of the Apulia region (already identified in **Section 6.3.3**). In particular, the representative building of CL2 has been selected as a case study for two reasons: first, because it was representative of the largest group of schools, and second, because the buildings constructed in that period were found to be in particular need of intervention.

7.2. Methods

The methodology adopted in this chapter includes two main steps: the modelling of the reference building energy models for the three Apulian climate zones (C,D,E) and the application of the life cycle cost approach through a single-objective optimisation analysis.

7.2.1. Reference buildings

The case study adopted for the analyses is the representative building of Cluster 2, whose calibrated energy model had already been created for previous investigations (see **Chapter 6**). However, for the analysis purposes, the starting model has been updated: three different energy models have been created - each for a climate zone - in compliance with the performance requirements set by Italian legislation [216] for the reference building (**Table 18**).

Table 18. Envelope features in compliance with the Italian legislation [216].

Envelope features	Climatic zone			Parameters of variation
	C	D	E	
Thermal transmittance of windows	2,2	1,8	1,4	Thermal transmittance of windows
Solar Heat Gain Coefficient	0,35	0,35	0,35	SHGC
Thermal transmittance of walls	0,34	0,29	0,26	Insulation thickness
Thermal transmittance of slab	0,38	0,29	0,26	Insulation thickness
Thermal transmittance of roof	0,33	0,26	0,22	Insulation thickness

Referring to HVAC system, the school has been considered full conditioned both in winter and in summer, to ensure fulfilment of setpoint temperatures required by the national law (assumed as 20°C for heating and 26° for cooling [226,249]). Hence, in addition to the heating system already installed in the school, a cooling system and a mechanical ventilation system have been also considered, which ensures the hourly air changes required by the national regulation [226]. The heating season has been set in accordance with the current regulation for each climate zone [248]: from 15 November to 31 March for climate zone C, from 1 November to 15 April for climate zone D, and from 15 October to 15 April for climate zone E. Otherwise, since there is no indication for the cooling period, it has been calculated based on the regulations [247,259], considering the building envelope features, the internal heat loads and the external temperatures. Accordingly, the cooling system has been turned on during days in which the following equation was satisfied (**Equation 8**).

$$\theta_{e,day} > \theta_{i,set,C} - \frac{Q_{gn,day}}{H \times t_{day}} \tag{8}$$

where $\theta_{e,day}$ is the daily mean outdoor temperature (derived from the epw weather file), $\theta_{i,set,C}$ is the cooling setpoint temperature (set at 26°C), $Q_{gn,day}$ are the daily mean internal and solar gains (derived from the energy model), H is the overall heat transfer coefficient of the building [W/K] and t_{day} is the duration of a day [seconds].

More in detail, since the LCC analysis has been conducted by considering both the energy behaviour of the building under current climate conditions (represented by the TMY climate file), and then under future climate conditions (represented by the 2050s future climate file), the equation has been used to calculate the cooling seasons in both periods. Consequently, in the actual climate conditions, the cooling period for the climatic zone C spans from 13 May to 15 October, for the climatic zone D spans from 23 May to 27 September, and for the climatic zone E spans from 10 June to 21 August. Otherwise, considering future climate conditions, the cooling period for the climatic zone C spans from 9 May to 19 October, for the climatic zone D spans from 20 May to 5 October, and for the climatic zone E spans from 27 May to 27 September.
For both the heating and cooling systems, the overall seasonal efficiency has been set as required by the regulations for the reference building: 0.77 for the heating system and 2.05 for the cooling system [216].

7.2.2. Life cycle cost analysis

The life cycle cost analysis conducted in this work complies with the EN15459:1–2018 standard [258], which provides the main reference for calculating the global cost of investments, as well as comparing the cost-benefit ratios of different improvement interventions. In detail, the present methodology is based on an adaptation of equation (8) of EN15459:1–2018, which allows to compare one or more interventions with a reference option, by calculating the investment payback period. In this study, the same equation has been adopted but considering a priori a calculation period of 30 years, as suggested by the standard for public buildings and considering as reference option the reference building described above [216]. The equation is based on a simple concept: assessing the retrofit cost-effectiveness of an alternative solution - hereinafter referred to as “alternative building” - against a reference solution, by comparing their global costs, expresses as the sum of the discounted value of the initial investment costs, annual operating costs, and replacement costs (neglected in our analysis since the useful life of the proposed interventions exceeds 30 years). In the present study, the reference solution is the building renovated in compliance with the performance parameters required by the Italian regulations for the reference building.

Instead, the alternative solutions are manifold: each alternative building can be characterized by one or more performance parameters that are improved compared to the reference building (with reference to the six categories of interventions). For this purpose, the following equation has been applied (**Equation 9**):

$$-\Delta costs(j) + \ savings_{ATT}\ (j) \tag{9}$$

where $\Delta costs(j)$ represents the difference between the initial investment costs of alternative option j and the initial investment cost of the reference option (**Equation 7**) while $savings_{ATT}\ (j)$ is the present value of the difference between the annual operational costs of the alternative option and the reference case (**Equation 8**). Consequently, if **Equation 9** returns a value greater than zero, the alternative option performs better than the reference option and vice versa.

$$\Delta costs(j) = costs^{j} - costs^{REF} \tag{10}$$

$$savings_{ATT}(j) = (EC^{REF} - \ EC^{j}) \times \sum_{i=1}^{30} EnCosts_i \times R_{d,i} \tag{11}$$

where EC^{REF} represents the energy consumption of the reference building (kWh/m^2 year), EC^{j} is the energy consumption of the alternative building (kWh/m^2 year), $EnCosts_i$ are the energy operating costs for the year i, $R_{d,i}$ is the discount rate for the i-th year, expressed as $\sum_i^n 1/(1+a)^i$.

In this study, values concerning energy consumption EC have been calculated using the dynamic simulation software Energy Plus, both for the reference building and for all alternative buildings. Furthermore, to consider the variation in building energy needs due to climate change, the calculation period of 30 year has been divided in two time frames. The former covers the years between 2025 and 2035 and has been considered using the TMY climate file as the boundary condition for the simulations; the latter covers the years 2036 to 2054, considered using the 2050 future climate file (SSP5-8.5) as boundary condition. Consequently, the discounted savings $savings_{ATT}(j)$ became the sum of the discounted savings calculated during the period P1 (2025-2035) and the discounted savings calculated during the period P2 (2036-2054), according to **Equation 12** and **Equation 13**.

$$savings_{ATT}\,(j) = savings_{ATT}^{P1}(j) + savings_{ATT}^{P2}(j) \tag{12}$$

$$\begin{aligned} savings_{ATT}\,(j) = {} & \left[(EC^{REF,P1} - EC^{j,P1}) \times \sum_{i=1}^{P1} EnCosts_i \times R_{d,i}\right] \\ & + \left[(EC^{REF,P2} - EC^{j,P2}) \times \sum_{i=P1}^{P2} EnCosts_i \times R_{d,i}\right] \end{aligned} \tag{13}$$

In addition, since the building is equipped with both heating and cooling system, savings during each period are calculated as the sum of the present value of savings related to heating consumption and the present value of savings related to cooling consumption (**Equation 14**), each one calculated according to **Equation 15** and **16** respectively.

$$savings_{ATT}^{P1} = savings_{ATT,HEATING}^{P1} + savings_{ATT,COOLING}^{P1} \tag{14}$$

$$\begin{aligned} & savings_{ATT,\,HEATING}^{P1} \\ & = \begin{cases} \displaystyle\sum_{i=1}^{P1}[(HC^{REF} \times GasCosts_i) - (HC^j \times GasCosts_i)] \times \frac{1}{(1+a)^i} & gas\ (12.1) \\ \displaystyle\sum_{i=1}^{P1}[(HC^{REF} \times GasCosts_i) - (HC^j \times ElectrCosts_i)] \times \frac{1}{(1+a)^i} & electr(12.2) \end{cases} \end{aligned} \tag{15}$$

where HC^{REF} is the annual heating consumption of the reference building - constant for each i-th year -, expressed as $HC^{REF} = (Q_H^{REF}/\eta_H^{REF})$. Q_H represents the heating energy need of the reference building (derived from Energy Plus), η_H is the overall efficiency of the heating system. HC^j is the annual heating consumption of the alternative building, expressed as $HC^j = (Q_H^j/\eta_H^j)$. Q_H^j represents the heating energy need, η_H^j is the overall efficiency for the heating system, which is also a variable option. The alternative options involve the variation of the heating system type: in some options the heating system is supplied by gas (thus the **Eq.15.1** is adopted), while in other options it is supplied by electricity (thus the **Eq.15.2** is adopted). $GasCosts_i$ and $ElectCosts_i$ are the gas and electricity costs in the i-th year respectively. The average values of energy prices came from the actual tariffs in the regulated market in Italy, provided by ARERA [260]. The rates of increase in energy prices have been derived from projections to 2030 for the EU-28 countries, given in [261] and obtained from the PRIMES results. Since the base year for the analyses was 2010, it was chosen to adopt as current energy prices those observed in 2010 and calculate the rate of increase by assuming constant annual price growth. Accordingly, the actual gas average price has been assumed to be 0.091€/kWh with a gas price development rate of 2,12%, while average electricity price of 0.224€/kWh, and an electricity price development rate of 2,51%. The discount rate a has been calculated based on the EUR 30 Years Interest Rate Swap (IRS) provided by the European Central Bank, assumed equal to 2.96% [262].

$$savings_{ATT,COOLING}^{P1} = (CC^{REF} - CC^{j}) \times \sum_{i=1}^{P1} ElectrCosts_i \times \frac{1}{(1+a)^i} \qquad (16)$$

where CC^{REF} is the annual cooling consumption of the reference building – constant for each i-th year –, expressed as $CC^{REF} = (Q_C^{REF}/\eta_C^{REF})$. Q_C represents the cooling energy need of the reference building (derived from Energy Plus), η_C is the overall efficiency of the cooling system. CC^j represents the annual cooling consumption of the building associated with the j-th option expressed as $CC^j = (Q_C^j/\eta_C^j)$. Q_C^j represents the cooling energy need, η_C^j is the overall efficiency for the cooling system.

The previous equations (**14 to 16**) refer to the calculations performed for period P1 (2025-2035), in which energy consumptions (both for the reference and the alternative buildings) have been obtained by considering current climate conditions, i.e., by simulating the buildings in Energy Plus adopting the TMY file as boundary condition. Then, the same calculations have been performed with reference to the P2 period (2036-2054), in which consumption has been calculated considering future climate conditions, using the 2050 future weather file, generated with the Future Weather Generator tool, based on the SSP5-8.5 scenario (see **Section 6.3.3**). In conclusion, the discounted savings for the two periods have been summed according to **Equation 12**.

It is worth mentioning that the LCC analysis has been conducted five times, considering the five locations representative of the three climate zones of the Apulia region - Bari, Lecce, Foggia, Martina Franca and Campobasso - already introduced in **Section 6.3.3**.

7.2.3. Design option

As explained, the LCC performed aimed to compare the building renovated in compliance with the reference building required by the national law with other retrofit alternatives characterized by improved performance values than the reference building. The retrofit options concern both the building envelope and building systems, selected based on the most common retrofit measures adopted in school retrofit. In detail, six categories of interventions have been considered, presented below.

- Reduction in thermal transmittance of windows (intervention G), assuming their replacement.
- Reduction in the Solar Heat Gain Coefficient of window glass (intervention SR), assuming an increase in cost compared to the base windows of intervention G.
- Reduction in thermal transmittance of opaque walls (intervention W), assuming the implementation of thermal insulation. For analysis purpose and cost calculation, EPS has been assumed to be the insulation material, as among the most applied in building retrofit. It should be noted that - among the intervention options - the increase of thermal mass of the opaque walls was not considered. Indeed, the national regulation requires a thermal mass value of 230 kg/m^2, which is largely met by the large limestone masonry of the building analysed.
- Reduction in thermal transmittance of roof (intervention R), assuming the implementation of thermal insulation. In this case, XPS has been assumed to be the insulation material. As in the previous case, the increase of thermal mass of the roof was not considered as an intervention option. In fact, on the one hand it is not a common intervention and on the other hand there is not a law-

compliant reference value to be used as the base value for the reference building and then improved, as in other intervention options.

- Reduction in thermal transmittance of slab (intervention S), assuming the implementation of thermal insulation. Once again, XPS has been considered as insulation material.
- Replacement of heating and cooling systems (intervention I). For the reference building (I0), a heating system supplied by a gas boiler has been considered, with radiators as terminals, assuming the global efficiency required by the national standard. For the cooling system, a chiller with fan coils as terminals has been assumed. Intervention I1 involved the overall replacement of both systems, installing radiant floor heating and cooling systems supplied by a heat pump. Intervention I2 involved the complete replacement of both systems with a VRF HVAC system, which adopted fan coils as terminals. Finally, intervention I3 involved maintaining the existing system, with the replacement of the gas boiler with a heat pump. The global efficiency values of the aforementioned systems have been calculated based on the most common generation efficiencies of systems available in the market and thus provided in the regional price list, as well as in accordance with UNI 11300-2 [238].

Thus, for each type of intervention, several alternative options have been considered. In detail, for each intervention, option 0 coincides with the value required by Italian regulations [216], while the subsequent options are improved values. Since the methodology has been applied to five different locations, corresponding to three climate zones, the alternatives have been calculated three different times (**Table 19**).

Finally, to obtain the initial investment cost for each alternative - and thus for different combinations of them - required in **Equation 9**, the retrofit option costs have been calculated based on the Apulian regional price list [263]. If the cost of a retrofit measure did not exist, the regional price list of Basilicata Region has been adopted [264]. In addition, the yearly maintenance costs of heating and cooling systems have been considered, as a percentage of their investment cost, as indicated by the EN15459:1–2018 based on the system components.

Table 19. Range of variation of retrofit alternatives for the three climatic zones, with the indication of the parameters of variation.

Inter-vention	Alternatives	Parameters of variation	Value
Climatic zone C (location C1 e C2)			
G	{G0, G1, G2, G3}	U windows	{2.2; 1.8; 1.4; 1.0}
SR	{SR0, SR1, SR2}	SHGC	{0.35; 0.29; 0.22}
W	{W0, W1, W2, W3}	Insulation Thickness	{0.08; 0.10; 0.12;0.14}
R	{R0, R1, R2, R3}	Insulation Thickness	{0.08; 0.10; 0.12;0.14}
S	{S0, S1, S2, S3}	Insulation Thickness	{0.06; 0.08; 0.10;0.12}
I	{I0, I1, I2, I3}	Global efficiency (heating; cooling)	{0.77,2.05;3.16,2.71; 3.13,2.68;1.95,2.05}
Climatic zone D (location D1 e D2)			
G	{G0, G1, G2, G3}	U windows	{1.8; 1.4; 1.0; 0.8}
SR	{SR0, SR1, SR2}	SHGC	{0.35; 0.29; 0.22}
W	{W0, W1, W2, W3}	Insulation Thickness	{0.10; 0.12;0.14;0.16}
R	{R0, R1, R2, R3}	Insulation Thickness	{0.10; 0.12;0.14;0.16}
S	{S0, S1, S2, S3}	Insulation Thickness	{0.08; 0.10;0.12;0.14}
I	{I0, I1, I2, I3}	Global efficiency (heating; cooling)	{0.77,2.05;3.16,2.71; 3.13,2.68;1.95,2.05}
Climatic zone E			
G	{G0, G1, G2, G3}	U windows	{1.4; 1.2; 1.0; 0.8}
SR	{SR0, SR1, SR2}	SHGC	{0.35; 0.29; 0.22}
W	{W0, W1, W2, W3}	Insulation Thickness	{0.10; 0.12;0.14;0.16}
R	{R0, R1, R2, R3}	Insulation Thickness	{0.13; 0.15;0.17;0.19}
S	{S0, S1, S2, S3}	Insulation Thickness	{0.10; 0.12;0.14;0.16}
I	{I0, I1, I2, I3}	Global efficiency (heating; cooling)	{0.77,2.05;3.16,2.71; 3.13,2.68;1.95,2.05}

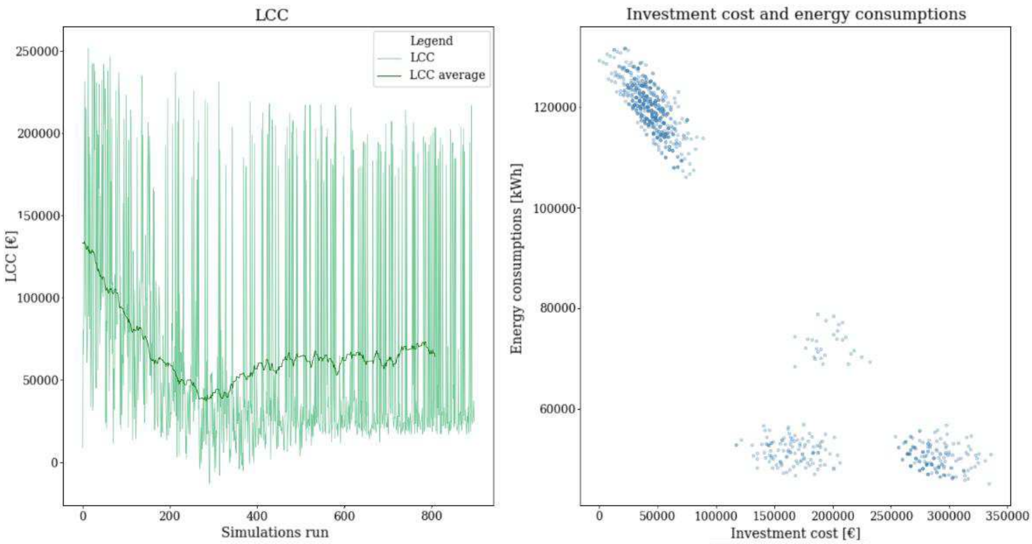
7.2.4. Process for comparison: optimisation problem

As mentioned, six categories of interventions have been considered, each comprising 3 or 4 alternatives. Hence, such alternatives can be matched for a total of 3072 combinations to create an alternative building to be compared with the reference building. Given this large number, to avoid establishing a priori a priori possible combinations for the life cycle cost assessment, an automatic single-objective optimisation has been performed in Python to consider the most effective combinations of the six alternatives. The most effective combination is the one that achieves the greatest savings compared to the reference option, with the lowest investment cost. The life cycle cost procedure has been implemented in the Python programming language, directly coupled with Energy Plus to extract the energy consumption outcomes for the alternative options. The Pymoo library has been used to set up the optimisation problem, executed based on the elitist Genetic Algorithm (GA). As in the calibration process (see **Chapter 6**), each permutation of these six variables has been ideally associated with a 6-genes genome, and the genetic algorithm has been used to explore the problem space to find the global minimum of the considered problem. Considering the number of variables, a population size of 90 individuals [252], and 10 different generations have been considered, allowing a total of 900 simulations to be achieved [253], exploring about 30% of the problem space. The optimisation problem has been solved based on the following utility function:

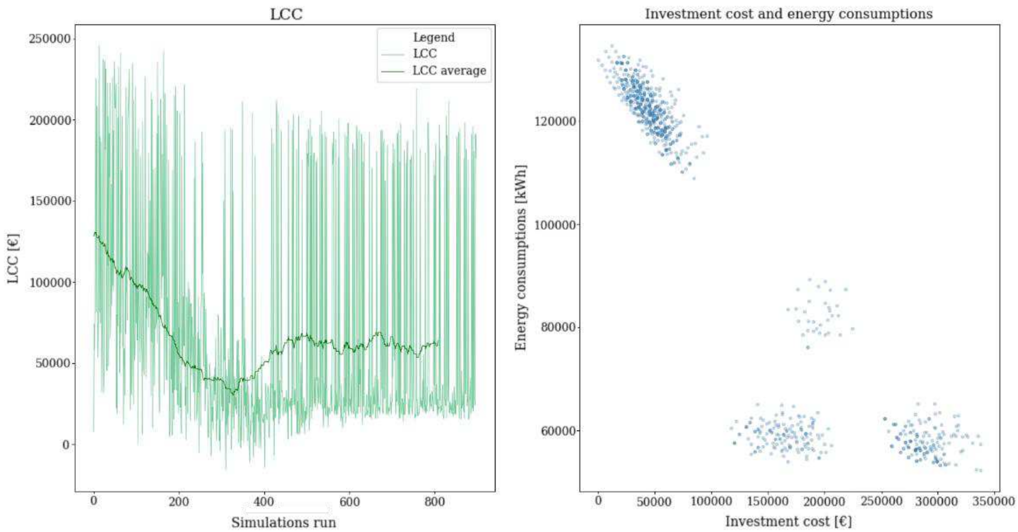
$$f(genome) = -\big(-\Delta costs(genome) + \ savings_{ATT}\ (genome)\big) = min \tag{17}$$

7.3. Results and discussion

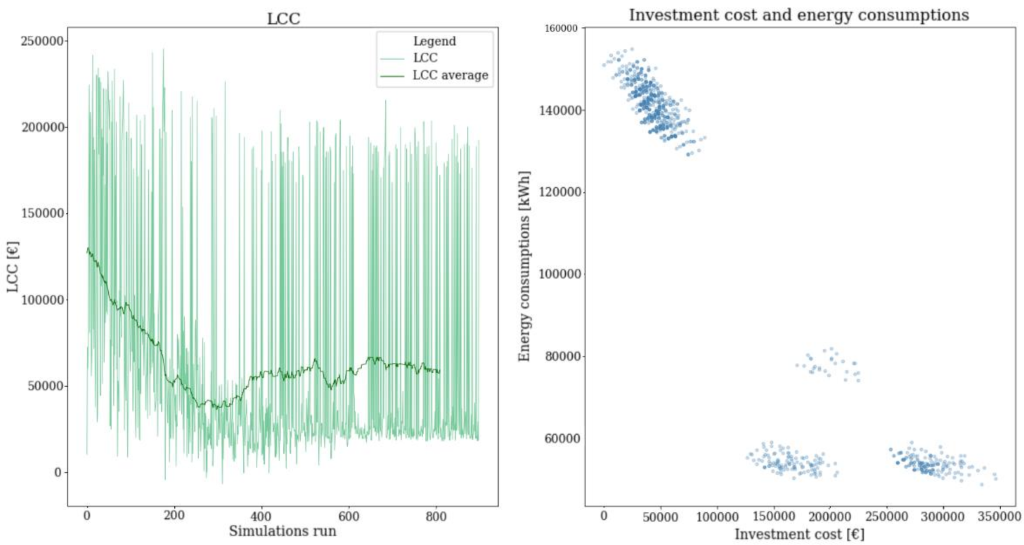
The LCC analysis has been applied to several retrofit measures to compare their cost-effectiveness and energy performance against the reference retrofit option, consisting of the reference building required by the Italian Law. Given the large number of possible combinations of retrofit measures, the optimal solution has been sought through an automatic optimisation analysis, performed by coupling Python to Energy Plus. This section explores the results obtained, for the five locations considered.



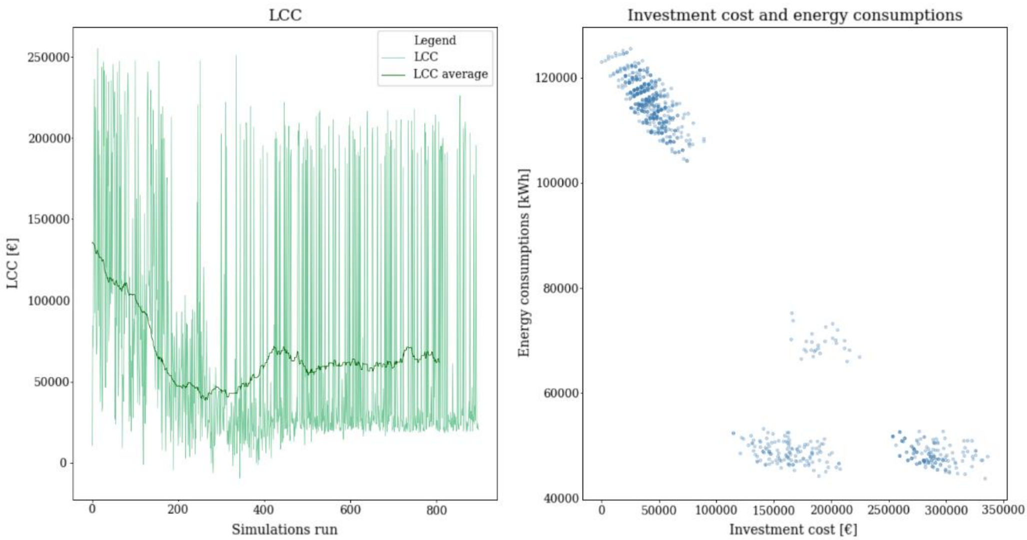
(a) Bari



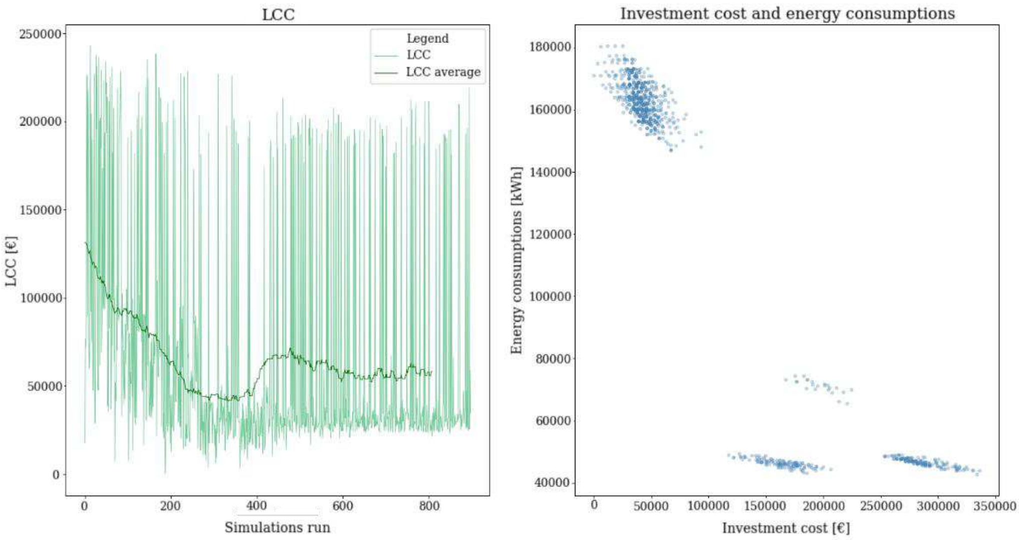
(b) Lecce



(c) Foggia



(d) Martina Franca



(e) Campobasso

Figure 43. Results of the GA simulation: on the left, values of the utility function (LCC) over the simulations run and its moving average; on the right, values of cumulative energy consumption over the 30 years of analysis and investment cost in all the simulations conducted.

The trend of the LCC results - referred to different retrofit strategy combinations - over the 900 simulations performed, as well as the moving average of the values obtained are shown in **Figure 43** (on the left). As mentioned in the methods section, the equation used is an adaptation of the one provided by EN15459:1–2018, which allows to compare the different retrofit options with respect to the reference option, in our case represented by the reference building. Therefore, based on the optimisation utility function, a retrofit measure - or a combination of them - that leads to values less than zero is ameliorative compared to the reference option from a cost-benefit point of view, while values greater than zero are pejorative.

Interestingly, the graphs revealed that there are no significant differences based on the locations considered, even though they belong to different climate zones. Indeed, it appears clear that - out of the 900 simulations performed - very limited combinations of interventions lead to values less than zero, and thus performing better than the reference building. In more detail, for all locations except Campobasso, the optimization process identifies as the optimal solution the alternative building that complies with the values required for the reference building for intervention options G, W, R, S, I, while for the SR intervention it shows a SGCH value of 0.22 (versus 0.35 for the reference building). However, it is worth noting that the cost savings achieved over the 30-year period appear significantly limited: accounting for 12800€ for Bari, 15900€ for Lecce, 6900€ for Foggia, and 9219€ for Martina Franca. Obviously, the combinations of alternatives that lead to savings with respect to energy retrofit in compliance with the reference building are not univocal, albeit very limited (13 for Bari, 14 for Lecce, 5 for Foggia, and 7 for Martina Franca). In contrast, the optimisation process carried out for the city of Campobasso did not identify any combination of alternatives that would lead to an improvement compared to the reference building.

The reason behind these results lies in the fact that the reference building exhibits high-performance thermal features, already ensuring reduced heat losses through the envelope. Consequently, increasing the thermal properties, by further reducing thermal transmittance values, leads to a not significant reduction in heating consumption, especially considering the P2 period, in which heating needs are already limited by rising temperatures due to climate change. In addition, increased levels of thermal insulation, conducts to increased cooling needs, leading to an overall increase in energy consumption, making alternative solutions limited to this type of intervention less effective than the reference building. By contrast, the alternative solution that complies with the parameters of the reference building but reduces the SHGC of windows appears beneficial, since - although generating a slight increase in heating - it results in a significant reduction in cooling consumption, especially in the P2 period, thus generating overall cost benefits. The importance of considering solutions to address cooling requirements is confirmed by the fact that, all solutions of the optimisation problem, present alternative buildings with reduced SHGC value compared to the reference building, then differently combined with other interventions. Clearly, the benefit of this solution is appreciable in warmer climates characterized by higher cooling needs, such as in climate zone C (represented by the city of Bari and Lecce), where it achieves the highest cost savings. In contrast, such effectiveness is reduced in climate zone D (represented by the city of Foggia and Martina Franca), in which the starting cooling consumptions are lower, thus the economic benefit achieved by their reduction counterbalances to a lesser extent the increase in heating requirements and related costs. Finally, this solution is ineffective in climate zone E, where starting cooling needs are very low. Therefore, it is possible to conclude that meeting the minimum performance requirements for the reference building already largely constitutes an effective retrofit strategy for these cities.

Further considerations can be drawn out by looking at **Figure 43** (on the right), which shows the investment cost (defined as the difference cost between the considered alternative option and the reference building) compared to the total energy consumption over the whole study period (equal to 30 years). It is worth noting that - although consumption slightly differs according to the climate zone considered - in all the cases the optimisation outcomes clustered into 4 groups. Exploring the results in more detail, it is worth noting that all the elements belonging to each cluster share the same type of plant, thus suggesting that this type of intervention is the factor that most affects the effectiveness of any combination of retrofit measures, both in term of energy consumption and intervention cost. In addition, the extent of each cluster suggests whether and how much the plant replacement influences the effectiveness of the other types of interventions: the smaller the extent of the cluster, the lower the influence of the other types of interventions compared to plant substitution. In all five cities analysed, the clusters are similarly distributed, as briefly described below. The largest cluster (depicted in the upper left) corresponds to the combinations of solutions that exhibit the same plants of the reference building. It involves retrofit interventions characterised by the lowest costs but considerably higher consumption than the other clusters. Interestingly, the solutions to the optimisation problems - the only ones in which the economic benefits from reduced consumption exceed the costs of intervention - all belong to the above cluster. In contrast, the clusters corresponding to plants I1 and I2 show similar consumption, in both cases extremely low, about one half of the previous cluster. In contrast, the investment cost is much higher than in the previous case, reaching the highest values for cluster I2. Finally, the cluster characterised by intervention I3 appears in an intermediate location, as it is characterized by consumption in the mid-range between the previous cases, as well as intermediate costs between clusters I1 and I2. Referring to the extent of each cluster, in all the cities they seem to have a similar extent, especially from the point of view of cost variation, which is around 100 thousand euros for each cluster. In contrast, the variations in terms of energy consumption appear different: cluster I0 is the one whose points differ the most in terms of energy consumption, while the others are characterised by less noticeable variations, suggesting that in the latter case the implementation of other retrofit interventions in addition to plant replacement does not lead to considerable benefits. This is most noticeable in the location of Campobasso (climatic zone E), where the variations in consumption for clusters I1, I2, and I3 are almost negligible.

Although, in terms of life cycle cost assessment, the reference building appears in all cases to be an optimal solution, these graphs highlight how the variation in consumption can be significantly reduced compared to the reference building itself, certainly contributing to significant reductions in emissions related to the operation of the building. Therefore, the selection of retrofit solutions to be implemented should be properly assessed, also in relation to the goal to be achieved.

7.4. Conclusion

The present Chapter aimed to answer the fifth – and last – research questions of this dissertation (**RQ5**), aiming to compare the cost-effectiveness of a retrofit intervention in compliance with the reference building required by the Italian regulation with improved retrofitted options. To that end, a life cycle cost analysis has been performed, selecting the most effective solutions through an automatic optimisation approach. The representative building of Cluster 2 has been selected as a case study, and the analysis has been carried out for five locations in the Apulia Region, representative of the three climatic zones. The novelty in the approach was not only to select combinations of interventions through the optimization problem (and not a priori), but also to include the changing climatic conditions in the analysis. Indeed, the LCC has been carried out by dividing the analysis period (equal to 30 years) into two periods: the first representative of current climate conditions (simulated through the TMY climate files), the second of future climate conditions (simulated with the 2050 climate files, based on the SSP5-8.5 scenario).

The results of the analysis clearly showed the need of carefully evaluating the retrofit measures to be implemented, without making the mistake - often made in the presence of public fundings - of expecting that adopting solutions that perform much better than those required by the law will lead to greater benefits. Indeed, the analysis demonstrated the inaccuracy of this assumption, as adopting the parameters of the reference building was already found to be an optimal configuration for all climate zones considered, from the cost-benefit point of view. Actually, in representative cities of climate zones C and D, the optimization analysis led to defining better cost-benefit solutions than the reference building, which, however, led to a benefit that was not significant in economic terms when compared to the period of analysis. In all cases, the retrofit solutions comply with the parameters of the reference building, except for the reduction of the solar heat gain coefficient of the windows. Delving into the results merely in terms of energy consumption, it appears evident that the energy performance of the reference building can be improved, reaching even one-half of the reference value. To this end, the goal can be easily achieved by replacement of the building's system. However, it requires a considerable investment cost, which is not balanced by the energy savings in economic terms achieved over the 30-year period of analysis. Despite of this, even with a large economic expense, it could contribute to drastically reduce the building energy consumption, and thus its GHGs emissions. Therefore, the selection of solutions must be thoughtful, especially considering that these solutions have an environmental cost, that cannot be neglected. Consequently, further development of this work could involve a comprehensive life cycle assessment of the retrofit intervention, analysing not only the environmental impacts of the solutions used, but also the savings in environmental terms related to reduced consumption.

8. CONCLUSIONS

The work illustrated in the present dissertation aimed to explore the energy resilience to climate change of a school building stock in the Mediterranean area, starting from a typological and technological classification, continuing with a field study of the current energy status, and ending with a predictive investigation of climate change resilience, based on energy simulations run for representative buildings. The whole analysis was focused on the municipally owned schools (pre-schools, primary and lower secondary schools) located in the Apulia Region.

Two main objectives were pursued in conducting the research. The first objective was to provide a comprehensive overview of the current condition of Apulian school building stock, based on current actual data. The results obtained are undoubtedly useful in helping local municipalities get an overview of the main features and actual conditions of such heritage, which is a fundamental basis for planning intervention programs. The second macro-objective was to assess the impact of climate change on schools at the building level, so as to increase policy makers' awareness of the critical issues related to changing climatic conditions, drawing attention to the importance of carefully evaluating solutions. While pursuing these two macro-objectives, different research activities - each presented and discussed in a thesis chapter - have been conducted, which may have potential scientific impact at different levels.

The quantitative review presented in **Chapter 3** highlighted the extreme heterogeneity of research outcomes related to the impacts of climate change on buildings, the reasons behind which should be further investigated. The extreme heterogeneity of the results makes it difficult to deduce summary data, which would, however, be extremely useful in deriving guidelines for potential solutions. Beyond the results obtained in the specific work, the research is based on a methodology – the meta-analysis – which, although still rarely applied in the building research field, could be a good methodological reference to be adopted in future work to summarise the results obtained by the scientific community on this topic. In addition, the literature review highlighted the need to expand studies related to climate change impacts to include building types different from residential and office, a need met by this thesis.

The overview of the school building stock of the Apulia Region, as well as its classification and subdivision into homogeneous groups presented in **Chapter 4**, represents a novelty in the literature. Indeed, no such study had ever been conducted on schools in the region, nor in southern Italy. From the analysis of the data collected in the ARES database, it was clear that the investigated schools are outdated and poor-performing, and their need for maintenance can no longer be neglected. In addition, the cluster analysis allowed to identify four representative buildings (described in **Chapter 6**), whose energy models were created and validated through an automatic optimisation-based calibration process, the characteristics of which can be extended to the entire reference cluster. Such models could have immediate applicative value, as they can already be used by Public Administrations as a basis for evaluating the effectiveness of potential retrofit interventions, that can be extended to schools of the same type. Undoubtedly, the results of the cluster analysis - and thus the identification of representative buildings - are closely related to the predictors adopted to conduct the analysis, the selection of which was affected by the limited availability of data for the schools. Hence, beyond the results obtained, the research activity aims to emphasize the potential of the methodology adopted, whose process could be improved thanks to a greater availability of data concerning buildings (e.g., clusters analysis could be based on a greater number of predictors). This consideration could lead public administrations to reflect on the importance of properly sharing data on schools features, taking advantage of the opportunity that the ARES database constitutes. In addition, future research developments may involve the improvement of the identified representative buildings, which can be the starting point for making proper reference buildings for Italian school construction, currently lacking in the literature.

The field analysis of billed energy consumption of school buildings conducted in this thesis (**Chapter 5**) is also a novelty in the literature, as studies concerning southern Italy are still absent. Again, the reason is found in the extreme difficulty in retrieving data regarding schools energy consumption, often not adequately collected and thus not easily shared by stakeholders, an obstacle that was also found in this research. The difficulties addressed are intended to draw attention to the idea that a useful update of the regional ARES database could involve the inclusion of data regarding school consumption, hopefully on a monthly basis. This would allow more in-depth research to be conducted that could provide much more reliable outcomes. Anyway, the collected data, based on a sample of about 50 schools, showed that heating consumption in schools predominates over electricity consumption in terms of site energy, although schools experienced very heterogeneous consumption. The analysis conducted allowed for identifying, for the first time in literature, benchmark values for Apulian schools, which accounted for 42.6 kWh/m^2 (site energy for heating), 13.6 kWh/m^2 (site energy for electricity) and 84.82 kWh/m^2 (total source consumption). Such benchmarks can be a useful reference for assessing the effectiveness of retrofit solutions, as well as a useful finding to be compared with any regulatory benchmarks to be met that might be introduced by Fit for 55 action. Beyond the results obtained, the methodology adopted in this chapter - which involves the systematic collection and statistical analysis of data - is intended to make public administrations aware of the significance of knowing the actual features of the existing building stock, which should be a prerequisite to the effective application of any improvement intervention. In addition, in the light of the possibility of mandatory buildings retrofits to minimum performance standards, the knowledge of the actual energy performance provides an essential reference for understanding the feasibility of interventions, as well as the real potential for fulfilling the requirements.

Thanks to the representative buildings – modelled and validated - the predictive analysis of the impact of climate change on school buildings was conducted (**Chapter 6**). This study represents one of the earliest applications of the new SSP scenarios in the generation of future climate files, which are still little adopted in the literature. Overall, the analysis conducted showed that cooling needs in schools can no longer be neglected due to climate changes. In fact, although schools are predominantly unoccupied in July and August (with the exception of offices), rising temperatures lead to the occurrence of cooling needs in the intermediate seasons, such as in May and September. The analysis conducted is intended to be a warning to public administrations to carefully consider retrofit interventions to be implemented, as cooling needs must be addressed.

To this end, a life cycle cost analysis was conducted in order to compare a retrofit intervention based on the normative benchmark parameters of the reference building with improved retrofit solutions (**Chapter 7**). The main purpose was to understand whether exceeding the properties required by the national law could be beneficial in terms of cost-benefit ratio, considering a period of 30 years. Two factors of novelty were considered in the study: firstly, the most effective combinations of retrofit interventions were selected based on an optimisation problem; secondly, the variation of climatic conditions and thus of energy consumptions were considered in the analysis. Indeed, the life cycle cost analysis has been carried out by dividing the analysis period (equal to 30 years) into two periods: the first representative of current climate conditions (simulated through the TMY climate files), the second of future climate conditions (simulated with the 2050 climate files, based on the SSP5-8.5 scenario). The analysis - applied to the reference buildings of Cluster 2 and conducted for five locations representative of the climatic zones C, D, E - has shown that improving the parameters of the reference building does not lead to significant benefits from the cost-benefit point of view. However, considering only the benefits in terms of energy consumption, analyses have shown that the energy performance of the reference building can be improved, even reaching half of the reference value. This can easily be achieved by replacing the building's systems, which, however, requires a significant investment cost that fails to be balanced by the resulting energy savings. Nonetheless, even with a great economic expense, it could help to drastically reduce the building's energy consumption and hence its greenhouse gas emissions. Therefore, the selection of retrofit solutions must be thoughtful, also considering that such solutions have an environmental cost. Consequently, further studies could be carried out by evaluating the entire life cycle of the retrofit intervention, analysing not only the environmental impacts of the solutions used, but also the savings in environmental terms related to reduced consumption.

In conclusion, it is worth pointing out that the analyses carried out throughout the whole thesis work focused on evaluations of the energy performance of school buildings, not considering aspects related to indoor comfort, although it is recognized to significantly affect students' learning abilities. For instance, climate change has noticeable effects on indoor thermal comfort, thus increasing the risk of overheating, which schools were already particularly vulnerable to due to high occupancy rates during the hottest hours of the day. Accordingly, future developments of the present dissertation will include assessments related not only to energy performance, but also to indoor comfort. For instance, building simulations of representative buildings in future climate scenarios could be useful to assess the risk of overheating in school spaces. In addition, the retrofit interventions could be compared and optimized not only from the perspective of energy savings, but also from the point of view of improving indoor thermal comfort conditions.

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"*I know to whom my gratitude belongs.*"

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"*I know where my happiest memories will be.*"

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"*I know where my safe harbour is.*"

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"*I know where my heart belongs.*"

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AHC	Agglomerative Hierarchical Clustering
AR	Assessment Report
ARERA	Regulatory Authority for Energy, Networks and Environment
ARES	Regional Register of School Buildings (Anagrafe Regionale dell'Edilizia Scolastica in italian)
ARPA	Regional Environmental Protection Agency
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPS	Building Performance Simulation
CDDs	Cooling Degree Days
CMIP	Coupled Model Intercomparison Project
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
D.Lgs	Legislative Decree
D.M.	Ministerial Decree
DPR	Decree of the President of the Republic
EPBD	Energy Performance of Buildings Directive
EPW	Energy Plus Weather
EU	European Union
FWG	Future Weather Generator
GA	Genetic Algorithm
GCMs	General Circulation Models (or Global Climate Models)
GHGs	Greenhouse gases
GIS	Geographic Information Systems
HDDs	Heating Degree Days

HVAC	Heating Ventilation and Air Conditioning
IDF	Input Data File
IPCC	Intergovernmental Panel of Climate Change
LCC	Life Cycle Cost
NMBE	Normalized Mean Bias Error
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCMs	Regional Climate Models
RCPs	Representative Concentration Pathways
RQ	Research Question
SHGC	Solar Heat Gain Coefficient
SNAES	National Register of School Buildings (Anagrafe Nazionale dell'Edilizia Scolastica in italian)
SRES	Special Report of Emission Scenarios
SSPs	Shared Socioeconomic Pathways scenarios
TMY	Typical Meteorological Year
U	Thermal transmittance
UNFCCC	United Nations Framework Convention on Climate Change
UNI	Italian National Unification
WG	IPCC Working Group
λ	Thermal conductivity

ANNEX A
Dataset for meta-analysis (Chapter 3)

List of reviewed studies selected for the quantitative analyses, in order of year of publication. Corresponding building type, location, climate zone, reference period, emission scenario, downscaling technique, future time slice, and target are reported. N.A. stands for “not available”; EC stands for “energy consumption”, EU stands for “energy use”, ED stands for “energy demand”, H stands for “heating”; C stands for “cooling”.

Ref	Building type	Location	Climate zone	Reference period	HDDs	CDDs	Emission scenario	Downscaling	Future time slice	Target	Year
[186]	Office, residential	New York, San Antonio	Dfa, Cfa	2020	N.A.	N.A.	SSP126 SSP245 SSP370 SSP585	new XAI model	2100	Incremental cooling consumption	2021
[78]	Office	Hanoi	Cfa	1961 - 1990	166	2070	RCP4.5, RCP8.5	Morphing	2056-2075 2080-2099	Yearly EC	2021
		Da Nang	Afm		0	2862					
		Kuala Lumpur	Af		0	3065					
		Bangkok	Aw		0	3536					
[265]	Supermarket	London	Cfb	1984 - 2013	2866	32	A1B, A1F, B1	Modified morphing	2050, 2080	Yearly EC	2021
[266]	Office	Canberra	Cfb	1982 - 1999	2120	195	A2	Morphing	2080	Yearly EU	2021
		Brisbane			329	1061					
[267]	University	Reading	Cfb	1961 - 1990	3185	453	A1B, A1F	NA	2030, 2050, 2080	H EC	2021
[268]	Office	Chengdu	Cwa	2010 - 2017	1456	929	RCP8.5	Hybrid	2095	ED (kWh/m^2)	2021
		Kathmandu			1027	911					
		Hanoi			188	2339					
		Islamabad			829	2223					
		Lucknow			362	2733					
		Zhengzhou			2267	1052					

[269]	Resi-dential	Rome	Csa	1982 - 1999	1444	649	RCP8.5, A2	Morph-ing Sto-chastic Dynam-ical	2050	H and C net en-ergy needs	2021
[270]	Office	Montreal	Dfb	2020	N.A.	N.A.	RCP2.6, RCP4.5, RCP6.0, RCP8.5	Hybrid classifi-cation-regres-sion model	2050	ED	2020
[199]	Resi-dential	Malaga	Csa	1961 - 1990	863	818	B1, B2, A2, A1F1	Morph-ing	2020, 2025, 2030, 2050, 2080	Primary EC	2020
[271]	Resi-dential	New York	Cfa	1958	N.A.	N.A.	+1,5°C	Offset method	2017, 2100	Primary EC	2020
[272]	Resi-dential, hospi-tal, healthc areres-tau-rant, hotel, office, retail, school, ware-house.	Toronto	Dfb	1959 - 1989	4089	232	A2, RPC8.5	Morph-ing	2050	Yearly EU	2020
[273]	Univer-sity	Gaines-ville	Cfa	2018	N.A.	N.A.	NG	Dynam-ical	2041, 2063, 2057	ED	2020
[274]	Resi-dential	Hong Kong	Cwa	1979 - 2003	202	2064	RCP4.5, RCP8.5	Morph-ing	2035, 2065, 2090	C demand	2020
[275]	Resi-dential	Madrid	Csa	1982 - 1999 CTE	1965	628	Rec-orded data	Rec-orded data	2008-2017	Energy needs	2020

[276]	Residential	Istanbul	Csa	2010	N.A.	N.A.	A2	Stochastic	2030	H and C EC	2020
[277]	Residential	Fresno	Csa	1991 - 2005	1275	1238	RCP4.5	Morphing	2026-2045 2056-2075 2080-2099	Net energy	2020
		Riverside	Cfa		909	710					
		San Fracesco	Csb		1557	22					
[79]	Residential	Aberdeen	Cfb	1961 - 1990	3719	1	A2	Morphing	2050	Yearly EC	2020
		Belfast	Cfb		3371	2					
		Berlin	Dfb		3471	124					
		Bordeaux	Cfb		2169	248					
		Clermont	Dfc		2729	175					
		Cluj-Napoca	Dfb		3573	120					
		Copenhagen	Dfb		3687	40					
		Göteborg	Dfb		4005	29					
		Granada	Bsk		2105	353					
		London	Cfb		3131	44					
		Milan	Cfa		2682	379					
		Palermo	Csa		915	858					
		Paris	Cfb		2663	176					
		Pescara	Cfa		1793	497					
		Plovdiv	ET		2563	493					
		Porto	Csb		1526	211					
		Prague	Dfb		3549	135					
		Rome	Csa		1503	619					
		Salamanca	Bsk		2648	315					
[278]	Residential	Calama	BWk	1990 - 2010	N.A.	N.A.	RCP4.5 RCP8.5	Stochastic	2045-2054	H and C energy needs	2019
		Antofagasta	BWk								
		Vallenar	BWk								
		Valpara-	Csb								
		Santiago	Csb								
		Concepción	Csb								
		Temuco	Csb								
		Punta Arenas	ET								
[279]	Hospital	Antana-	Cwb	1961 - 1990	490	425	Recorded data B1, A1B, A2	Stochastic	1990-2009 2030, 2060, 2090	Yearly EC	2019
		Victoria	Af		0	3223					
		Moroni	Dfb		0	2697					
		Mamoudzou	Aw		N.A.	N.A.					

		Port-Louis	Aw		0	1968					
		Saint-Denis	As		0	2510					
[280]	Residential	Greater Accra, Ghana	Aw	2000 - 2009	0	3407	A1B	Stochastic	2030, 2050	C EC	2019
[281]	Residential	Izmir	Csa	NG	N.A.	N.A.	RCP8.5	Morphing	2060	Yearly EC	2019
		Istanbul	Csa								
		Ankara	Csb								
		Erzurum	Dfb								
[282]	Residential	Santa Rosa	Cfa	1961 - 1990	1580	619	A2	Morphing	2080	Yearly EC	2019
		Mendoza	BWk		1386	909					
		Cordoba	Csa		1242	1013					
		Oran	Cwa		414	1550					
[137]	Restaurant, hospital, hotel, office, residential, school, retail, supermarket, warehouse	Los Angeles	Csb	1991 - 2005	648	224	A2	Morphing	2050	ED	2019
[283]	Campus	Ann Arbor	Dfa	1970 - 1999	N.A.	N.A.	RCP2.6, RCP4.5, RCP6.0, RCP8.5	Morphing	2010-2039 2040-2069 2070-2099	Change in EC %	2019
[284]	Residential	Valencia	Csa	1961 - 1990	1167	765	RCP4.5, RCP8.5	Morphing	2048-2052 2096-2100	ED	2018
[285]	Residential	Cordoba	Csa	1971 - 2000	1121	936	A2	Morphing	2050	ED	2018
	Office	Marseille	Csa		1735	578				ED	

[286]		Montpellier	Csa	1979 - 2000	1693	531	RCP2.6, RCP4.5, RCP6.0, RCP8.5	Morphing	2035, 2065, 2090		2018
		Nice	Csa		1454	551					
		Athens	Csa		1112	1076					
		Thessaloniki	Cfa		1741	792					
		Genoa	Csa		1348	653					
		Messina	Csa		758	1085					
		Naples	Csa		1364	756					
		Palermo	Csa		724	1022					
		Pisa	Csa		1757	520					
		Rome	Csa		1444	649					
		Venice	Csa		2262	526					
		Barcelona	Csa		1419	588					
		Valencia	Csa		1052	796					
		Izmir	Csa		1391	926					
[179]	Office	Harbin	Dwa Cfa	1961 - 2010	5229	362	Recorded data	Recorded data		Yearly C loads (W/m^2 per year)	2018
		Tianjin			N.A.	N.A.					
		Shanghai			N.A.	N.A.					
		Guangzhou			N.A.	N.A.					
[287]	Residential, hotel, office, school	Daytona	Cfa	1961 - 1990 1991 - 2005	447	1576	A2	Morphing	2020, 2050, 2080	H and C demand	2018
		Jacksonville	Cfa		1379	690					
		Key West	Aw		29	2790					
		Miami	Am		67	2442					
		Orlando	Cfa		282	1694					
		Pensacola	Cfa		624	1517					
		Tallahassee	Cfa		816	1309					
		Tampa	Cfa		375	1805					
[288]	Residential	Helsinki-Vantaa	Dfb	1980 - 2009	4589	83	B1, A1B, A2	Morphing	2030, 2050, 2100	Net ED	2018
[289]	Residential	Florence	Csa	2000 - 2009	1767	906	RCP8.5	Morphing	2036-2065 2066-2095	H and C net energy needs	2018

[290]	Com-mercial	Montreal	Dfb	1953 - 1995	4493	234	A2	Morph-ing	2020, 2050	Yearly EC	2018
[291]	Resi-dential	Curitiba Floria-nópolis Belem	Cfb Cfa Af	1961 - 1990	886 250 0	305 1077 2896	A2	Morph-ing	2020, 2050, 2080	ED	2016
[202]	Office Resi-dential	Philadel-phia Chicago Phoenix Miami	Cfa Dfa Bwh Am	1961 - 1990	2787 3557 628 64	602 431 2280 2369	A1F1, A2	Morph-ing	2040-2069	H and C EU	2017
[194]	Resi-dential	Santa Rosa	Cfa	2011 - 2014	N.A.	N.A.	RCP4.5	Others	2015-2039	EC of gas and elec-tricity	2017
[292]	Resi-dential	London	Cfb	2011	N.A.	N.A.	A2	Morph-ing	2020, 2050, 2080	Yearly EC	2017
[203]	Resi-dential	Hong Kong Seoul Tokyo	Cwa Dwa Cfa	1983 - 2005	202 2782 2311	2064 560 508	Rec-orded data RCP4.5, RCP8.5	Other	2006-2014 2015-2044	Yearly ED	2017
[293]	Office	Seoul Tokyo Hong Kong	Dwa Cfa Cwa	1961 - 1990	2925 1730 215	658 846 2004	A2	Morph-ing	2020, 2050, 2080	C EC	2017
[294]	Resi-dential	Kaunas	Dfb	1980 - 1999	4137	71	RCP2.6, RCP8.5	Morph-ing	2020, 2050, 2080	Primary EC	2017

[295]	Residential, restaurant, hospital, hotel, office, outpatient, school, retail, mall, supermarket, warehouse	Different locations in US	Different climate zones	1991 - 2005	N.A.	N.A.	A1B, A2, B1	Offset method	2040, 2090	Change in EC %	2016
[296]	Office	Sapporo Tokyo Naha	Dfb Cfa Cfa	1981 - 2000	3578 2311 226	236 508 1969	A2	Dynamical	2040, 2090	Energy loads	2016
[195]	Residential	Tokyo	Cfa	2005	N.A.	N.A.	RCP4.5	Dynamical	2029	Heat loads in August	2016
[297]	Residential	Taipei	Cfa	1993 - 2014	N.A.	N.A.	A2, B2, A1B	Morphing	2020, 2050, 2080	Yearly C EC	2016
[205]	Residential	Vaxjo	Cfb	1961 - 1990	4174	38	Recorded data RCP4.5, RCP8.5	Morphing	1996-2005 2050, 2090	H/C demand	2016
[298]	Residential	Qatar	BWh	1961 - 1990	101	3253	A2	Morphing	2080	Yearly primary EU	2016
[299]	School	Milan	Cfa	1951 - 1970	1767	906	A2	Morphing	2020, 2050, 2080	H and C energy needs	2016

[196]	Residential	Tokyo	Cfa	2006 - 2010	1492	1029	RCP4.5	Dynamical	2031-2035	Heat loads in August	2015
[300]	Residential, office, warehouse commercial	Florida Louisiana Minnesota Missouri New York Virginia	Cfa Cfa Dfb Dfa Dfa Cfa	2004	N.A.	N.A.	A2	Statistical	2052 2089	Change in EC %	2015
[301]	Day-care centre	Copenhagen	Cfb	1975 - 1989	3563	29	A1B	Hourly, monthly and annual offset method	2021-2050	Yearly H/C demand	2015
[302]	Office	Sydney Melbourne Canberra Adelaide Darwin	Cfa Cfb Cfb Csb Aw	1982 - 1999	687 1733 2120 1122 0	634 210 195 479 3355	A2	Morphing	2020, 2050, 2080	EC	2014
[180]	Residential	Tianjin	Dwa	1971 - 2010	2735	867	B1 A1B	PCA	2011-2050 2051-2100	H/C loads	2014
[193]	Office	Vienna	Cfb	1961 - 1990	3156	201	Recorded data A1B	Recorded data Dynamical	1980-2009 2011-2040 2036-2065	Yearly ED	2014
[181]	Office	Tianjin	Dwa	1961 - 1970 1971 - 2010	2735	867	Recorded data B1 A1B	Recorded data PCA	2001-2010 2051-2100	Heating loads (%)	2013
[303]	Residential	Singapore	Af	1990	0	3454	N.A.	Offset method	+0,5 +1,3 +2,4	Cooling loads (%)	2013

[304]	Office	Hong Kong	Cwa	1961 - 1990	215	2004	A1B B1	Morph-ing	2011-2030 2046-2065 2080-2099	Change in EC (%)	2013
[305]	Office	Ningbo	Cfa	1990 - 2009	N.A.	N.A.	A2	Morph-ing	2010-2039 2040-2069 2070-2099	ED	2012
[306]	Resi-dential	Montreal	Dfb	1961 - 1990	3578	254	A2	Morph-ing	2011-2040 2041-2070	Electricity consump-tion	2012
[182]	Office	Harbin Beijing Shanghai Kunming Hong Kong	Dwa, Cfa, Cwb, Cwa	1971 - 2000	N.A. N.A. N.A. N.A. 202	N.A. N.A. N.A. N.A. 2064	B1, A1B	PCA	2001-2100 2009-2100	H and C EU	2012
[307]	Office	Burkina Faso	BSh	1977 - 2010	N.A.	N.A.	A1, A2, B2, B1 (aver-age)	N.A.	2010-2029 2030-2049 2060-2079	Yearly C loads	2012
[139]	Office School	Crete West Central Macedo-nia Cyclades Eastern Central Greece	Cfa Csa Csa BSh	1961 - 1990	774 1801 778 N.A.	1026 915 820 N.A.	A1B, A2, B2	Other	2041-2050 2091-2100	H and C EU (kWh/m^2)	2012
[308]	Office Resi-dential	Hong Kong	Cwa	1979 - 2003	202	2064	B1, A1B	Morph-ing	2011-2030 2046-2065 2080-2099	A/C EC	2011
[64]	Resi-dential	Darwin Brisbane Alice Springs Mildura Sydney Mel-bourne Hobart	Aw Cfa Bwh Bsh Cfa Cfb Cfb	N.A.	0 329 665 1160 687 1733 2073	3355 1061 1816 769 634 210 52	+6	Offset method	N.A.	H and C loads	2011

		Cabra-murra	Cfb		3586	49					
[309]	Resi-dential	Dhaka	Aw	1961 - 1990	10	2853	A2	Morph-ing	2020 2050 2080	Cooling ED	2011
[183,310]	Office	Hong Kong	Cwa	1979 - 2008	202	2064	B1 A1B	PCA	2009-2100	H and C loads & Yearly EU	2011
[191]	Resi-dential	Athens	Csa	1983 - 1992	N.A.	N.A.	Rec-orded data	Rec-orded data	1993-2002	Energy re-quire-ments	2010
		Thessa-loniki	Cfa								
[206]	Resi-dential	Alice Springs	Bwh	1990	665	1816	550ppm	Morph-ing	2050	Energy re-quire-ments (MJ/m^2)	2010
		Darwin	Aw		0	3355					
		Hobart	Cfb		2073	52					
		Mel-bourne	Cfb		1733	210					
		Sydney	Cfa		687	634					
[311]	Resi-dential	Ljubljana	Cfb	1961 - 1990	3208	201	+1°C +3°C Rec-orded data	Offset method Rec-orded data	2050, 2003	EU	2010
		Portoroz			1829	577					
[312]	Resi-dential	Al-Ain	Bwh	1961 - 1990	61	577	+1,6°C, +2,9°C, +2,3 , +5,9°C Rec-orded data	Offset method	2050 2100	H, C, Fans, Electricity	2009
[313]	Office	London Cardiff Birming-ham Man-chester Edin-burgh	Cfb	2005	N.A.	N.A.	Me-dium-high	Morph-ing	2010-2040	H and C EU	2008
[314]	Resi-dential Office	Zurich–Kloten	Dfb	1961 - 1990	3643	85	+0,7°C, +1, +4,4	Offset method	1984-2003 2050-2100	Yearly ED	2005
		Algarve	Csa		979	669	gga2		2080-2100		

		South Inland	Csa		1475	796			
		Lisbon	Csa		1059	608			
		Centre Littoral	Csb		1297	271			
[315]	Resi-dential	Centre Inland	Csb	1961 - 1990	1735	667	Sto-chastic	H and C loads	2002
		North Littoral	Cfb		1632	317			
		North Inland	Csb		2546	426			

ANNEX B
Dataset for Life Cycle Cost analysis (Chapter 7)

Range of variation of retrofit alternatives for the three climatic zones, with the indication of the parameters of variation and the investment cost (Δcost) calculated as the difference between the initial investment costs of alternative option j and the initial investment cost of the reference option (alternative 0).

Inter-ven-tion	Parameter of variation	Alternatives	Value	Δcost (€)
Climatic zone C				
G	U windows (W/m^2K)	G0	2.2	0
		G1	1.8	14774
		G2	1.4	21193
		G3	1.0	25370
SR	Solar Heat Gain Coefficient	SR0	g 0.35 (TL 60%)	0
		SR1	g 0.28 (TL 51%)	2984
		SR2	g 0.22 (TL 40%)	5963
W	Insulation thickness (m)	W0	0.08	0
		W1	0.10	10369
		W2	0.12	20761
		W3	0.14	31153
R	Insulation thickness (m)	R0	0.08	0
		R1	0.10	7397
		R2	0.12	14793
		R3	0.14	22190
S	Insulation thickness (m)	S0	0.06	0
		S1	0.08	6116
		S2	0.10	12115
		S3	0.12	18654
I	Global efficiency (heating; cooling)	I0	0.77 ; 2.05	0
		I1	3.16 ; 2.71	253437
		I2	3.13; 2.68	114394
		I3	1.95 ; 2.05	139171

Climatic zone D				
G	U windows (W/m^2K)	G0	1.8	0
		G1	1.4	14774
		G2	1.0	21193
		G3	0.8	25370
SR	Solar Heat Gain Coefficient	SR0	g 0.35 (TL 60%)	0
		SR1	g 0.28 (TL 51%)	2984
		SR2	g 0.22 (TL 40%)	5963
W	Insulation thickness (m)	W0	0.10 m	0
		W1	0.12 m	10392
		W2	0.14 m	20784
		W3	0.16 m	31153
R	Insulation thickness (m)	R0	0.10 m	0
		R1	0.12 m	7397
		R2	0.14 m	14793
		R3	0.16 m	22190
S	Insulation thickness (m)	S0	0.08 m	0
		S1	0.10 m	5999
		S2	0.12 m	12538
		S3	0.14 m	18756
I	Global efficiency (heating; cooling)	I0	0.77 ; 2.05	0
		I1	3.16 ; 2.71	253437
		I2	3.13; 2.68	114394
		I3	1.95 ; 2.05	139171
Climatic zone E				
G	U windows (W/m^2K)	G0	1.4	0
		G1	1.2	6420
		G2	1.0	6420
		G3	0.8	10597
SR	Solar Heat Gain Coefficient	SR0	g 0.35 (TL 60%)	0
		SR1	g 0.28 (TL 51%)	2984
		SR2	g 0.22 (TL 40%)	5963
W	Insulation thickness (m)	W0	0.10 m	0
		W1	0.12 m	10392
		W2	0.14 m	20784
		W3	0.16 m	31153

R	Insulation thickness (m)	R0	0.13 m	0
		R1	0.15 m	7397
		R2	0.17 m	14793
		R3	0.19 m	22190
S	Insulation thickness (m)	S0	0.10 m	0
		S1	0.12 m	6539
		S2	0.14 m	12757
		S3	0.16 m	18362
I	Global efficiency (heating; cooling)	I0	0.77 ; 2.05	0
		I1	3.16 ; 2.71	253437
		I2	3.13; 2.68	114394
		I3	1.95 ; 2.05	139171

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CURRICULUM

Ludovica Maria Campagna is a chartered Building Engineer and PhD candidate at Polytechnic University of Bari (Italy). After receiving a master's degree in Building Engineering with a thesis on the energy performance of passive school buildings in the Mediterranean area, she has continued to investigate issues related to school buildings behaviours considering future climate scenarios.

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CURRENT POSITION

February 2024 - ongoing

Polytechnic University of Bari, DICATECh department
Research Assistant
"*Assessment of the interaction of air mobility systems with the built environment*"

November 2020 - ongoing

PhD candidate in Risk and Environmental, Territorial and Building Development, XXXVI cycle
Thesis: *"Energy resilience to climate change of the school building stock in the Mediterranean area: the case of Apulia Region"*
Supervisor: Prof. Eng. Francesco Fiorito

RESEARCH ACTIVITIES

2021 - ongoing

PUBLICATIONS

JOURNAL PAPERS

1. **Campagna LM**; Fiorito F (**2023**). On the energy performance of the Mediterranean school building stock: The case of the Apulia Region, *Energy and Buildings*, vol. 293, 113187. https://doi.org/10.1016/j.enbuild.2023.113187
2. Fiorito F; Vurro G; Carlucci F; **Campagna LM**; De Fino M; Carlucci S; Fatiguso F (**2022**). Adaptation of Users to Future Climate Conditions in Naturally Ventilated Historic Buildings: Effects on Indoor Comfort, *Energies*, vol. 15, 4984. https://doi.org/10.3390/en15144984
3. **Campagna LM**; Fiorito F (**2022**). On the Impact of Climate Change on Building Energy Consumptions: A Meta-Analysis, *Energies*, vol. 15, 354. https://doi.org/10.3390/en15010354
4. **Campagna LM**; Carlucci F; Russo P; Fiorito F (**2021**). Energy performance assessment of passive buildings in future climatic scenarios: The case of study of the childcare centre in

Putignano (Bari, Italy), *Journal of Physics: Conference Series*, vol. 2069, 012146. https://doi:10.1088/1742-6596/2069/1/012146

PAPER IN CONFERENCE PROCEEDINGS

5. **Campagna LM**; Carlucci, F; Carlucci S; Fiorito F (**2024**), Automatic optimization-based calibration using genetic algorithms: a case study of a school energy model. In *Sustainability in Energy and Buildings 2023*; Littlewood, J.R., Jain, L., Howlett, R.J. Eds; Springer Singapore (*in print*). ISBN 978-981-99-8500-5
6. **Campagna LM**; Fiorito F (**2023**). Efficienza energetica degli edifici scolastici pugliesi: un'indagine basata sulla rilevazione dei consumi reali. In Proceedings of the Colloqui.AT.e 2023 - In Transizione: sfide e opportunità per l'ambiente costruito; Fatiguso, F., Fiorito, F., De Fino, M., Cantatore, E. Eds.; EdicomEdizioni: Monfalcone, Italy, 2023, pp. 709-726. ISBN 979-12-81229-02-0
7. **Campagna LM**; Fiorito F (**2022**). On the clustering of large educational building stock in the Apulia Region. In Proceedings of the Colloqui.AT.e 2022 – Memoria e Innovazione; Dassori, E., Morbiducci, R., Eds.; EdicomEdizioni: Monfalcone, Italy, 2022; pp. 743–759. ISBN 978-88-945937-4-7.
8. Carlucci F; **Campagna LM**; Fiorito F (**2022**). Technological and energy assessment of an origami-based kinetic shading system in typical and future climate scenarios. In Proceedings of the Colloqui.AT.e 2022 – Memoria e Innovazione; Dassori, E., Morbiducci, R., Eds.; EdicomEdizioni: Monfalcone, Italy, 2022; pp. 1007–1022. ISBN 978-88-945937-4-7.

PUBLICATIONS ACCEPTED

9. Crespino E; **Campagna LM**; Carlucci F; Martellotta F; Fiorito F. Indoor environmental conditions in Italian childcare buildings: results from a monitoring campaign (accepted for the Indoor Air **2024**: Sustaining the Indoor Air Revolution, Honolulu)
10. **Campagna LM**; Carlucci F; Fiorito F. School energy retrofit in a changing climate: optimization of retrofit strategies and cost implications. (accepted for the 9th International Building Physics Conference **2024**, Toronto)
11. Crespino E; **Campagna LM**; Carlucci F; Martellotta F; Fiorito F; Impact of stochastic and deterministic behaviour on natural ventilation: energy and indoor air quality performances in a preschool case study. (accepted for the 9th International Building Physics Conference **2024**, Toronto)
12. **Campagna LM**; Carlucci F; Fiorito F. Climate change impact assessment and evaluation of retrofit measures of a representative school in Southern Italy (accepted for the Colloqui.AT.e **2024** Conference, Palermo)
13. Crespino E; **Campagna LM**; Carlucci F; Martellotta F; Fiorito F. Indoor Air Quality in Apulian school buildings: the case of J. F. Kennedy pre-schools in Bari (accepted for the Colloqui.AT.e **2024** Conference, Palermo)

MONOGRAPHS

14. Carlucci F; **Campagna LM**; Fiorito F; Responsive Envelopes and Climate Change: State of the Art, Design Strategies, and Future Perspectives for Resilient Buildings. Springer Chamb. ISBN 978-3-031-58100-7. (in print, due to 11 August 2024)

AWARDS

Artec InnovATi 2023 competition for young researchers in the SSD ICAR/10 field - awarded 2nd place, with the work on "Temporary architecture: challenges and perspectives"

Best Paper Award - Colloqui.AT.e 2022 – Memoria e Innovazione, for the work:
Carlucci, F.; Campagna, L.M.; Fiorito, F. "Technological and energy assessment of an origami-based kinetic shading system in typical and future climate scenarios".

Artec InnovATi 2021 competition for young researchers in the SSD ICAR/10 field - awarded 2nd place, with the project entitled: "FACE - FAcade in Changing Environment".

TEACHING ACTIVITIES — 2021 - ongoing

CO-SUPERVISION OF MASTER'S THESES

Polytechnic University of Bari, master's degree in Building Systems Engineering.
Thesis in **High Performance Building Design**:

1. "*Energy resilience of school buildings in the province of Foggia"*
   Student: Noemi Matera, Supervisor: F. Fiorito, Co-supervisor: **L.M. Campagna**.
2. *"Passive buildings in the Mediterranean area: performance, technological and energy analyses".*
   Student: Matteo Fiore, Supervisor: F. Fiorito, Co-supervisor: **L.M. Campagna**.
3. *"Advanced prefabrication systems for hospitals: energy and performance analysis for new buildings under future climate scenarios"*.
   Student: Ilenia Festa, Supervisor: F. Fiorito, Co-supervisor: **L.M. Campagna**.
4. *"Advanced prefabrication systems for hospitals: energy and performance analysis for existing buildings under future climate scenarios. the case of the "Chini" Pavilion.*
   Student: Simona Parisi, Supervisor: F. Fiorito, Co-supervisor: **L.M. Campagna**.

Polytechnic University of Bari, master's degree in Building Systems Engineering.
Thesis in **Integrated Building Design**:

5. "*Urban heat island and mortality rate in the Apulia region: a correlation study".*
   Student: Elisa Appio, Supervisor: F. Fiorito, Co-supervisor: **L.M. Campagna,** F. Carlucci
6. "*Guidelines for Covid-free school design: the case of the 'Monte San Michele' school in Bari".*
   Student: Elena Crespino, Supervisor: F. Fiorito, Co-supervisor: **L.M. Campagna**.
7. "*Energy refurbishment of the school buildings stock: the case study of the schools 'San Domenico Savio', 'Giuseppe Saverio Poli', 'Rosa e Carolina Agazzi'".*
   Student: Filomena Germinario, Supervisor: F. Fiorito, Co-supervisor: **L.M. Campagna**.

TEACHING SUPPORT ACTIVITIES

1. Teaching support activities for the course **Integrated Building Design**, master's degree in Building Systems Engineering, Prof. Eng. F Fiorito. A.A. 2023/2024.
2. Teaching support activities for the course **High Performance Building Design**, master's degree in Building Systems Engineering, Prof. Eng. F Fiorito. A.A. 2023/2024.
3. Teaching support activities for the course **Integrated Building Design**, master's degree in Building Systems Engineering, Prof. Eng. F Fiorito. A.A. 2022/2023.

4. Teaching support activities for the course **Integrated Building Design**, master's degree in Building Systems Engineering, Prof. Eng. F Fiorito. A.A. 2021/2022.
5. Teaching support activities for the course **Building Technology**, bachelor's degree in Building Engineering, Prof. Eng. E Conte. A.A. 2021/2022.
6. Teaching support activities for the course **Integrated Building Design**, master's degree in Building Systems Engineering, Prof. Eng. F Fiorito. A.A. 2020/2021.
7. Teaching support activities for the course **Building Technology**, bachelor's degree in Building Engineering, Prof. Eng. E Conte. A.A. 2020/2021.

EDUCATION

April 2023 – July 2023

The Cyprus Institute (Nicosia, Cipro), Energy, Environment and Water Research Center (EEWRC)
PhD visiting (supervisor Prof. Salvatore Carlucci)

November 2020 - ongoing

Polytechnic University of Bari, DICATECh department
PhD candidate in Risk and Environmental, Territorial and Building Development, XXXVI cycle
Thesis: *"Energy resilience to climate change of the school building stock in the Mediterranean area: the case of Apulia Region"*
Supervisor: Prof. Eng. Francesco Fiorito

September 2018 – July 2020

Polytechnic University of Bari
MSc in building systems engineering - Curriculum Sustainable Buildings [LM-24]
110/110 cum Laude
Defended thesis in High Performance Buildings Design: "*Passive school buildings in the Mediterranean area: comfort and energy performance with a view to the climate change*"
Supervisor: Prof. Eng. Francesco Fiorito, Co-supervisor: Eng. Pietro Russo.

Award "*Best Graduate Student of the Department of Civil, Environmental, Land, Building and Chemical Engineering in 2020,*" *awarded by the Poliba Alumni Association and Bari Polytechnic University*

September 2015 – July 2018

Polytechnic University of Bari
BSc in building engineering [LT-23]
110/110 cum Laude
Defended Thesis in Structural Design:
"Innovative materials and technologies applied to structural engineering".
Supervisor: Prof. Eng. Francesco Porco

Abstract
The growing adverse consequences of the climate crisis require an increases of studies concerning the relationship between climate change and the built environment, since the construction field appears to be among the most impactful sectors, while showing a high vulnerability to the effects of climate change. Accordingly, this research field is called upon to play a crucial role, as policymakers' choices concerning mitigation and adaptation policies are significantly influenced by the research advancements of the scientific community. However, although the body of literature on the topic has been growing exponentially in recent years, it still seems limited compared to the breadth of the problem, remaining associated to specific building types, such as residential and office buildings, but neglecting others. This thesis aims to provide scientific advancement in this field by investigating a building typology that is still poorly addressed in the literature. Indeed, the present dissertation aims to explore the energy resilience to climate change of a school building stock in the Mediterranean area, starting from a typological and technological classification, continuing with a field study of the current energy status, and ending with a predictive investigation of climate change resilience, based on energy simulations run for representative buildings, as well as exploring potential solutions. The whole analysis is focused on the municipally owned schools (pre-schools, primary and lower secondary schools) located in the Apulia Region, involving a sample of buildings never previously explored in the literature. Two main objectives are pursued in conducting the research. The former is to provide a comprehensive overview of the current condition of Apulian school building stock, based on current actual data. The results obtained will be undoubtedly useful in helping local municipalities get an overview of the main features and actual conditions of such heritage, which is a fundamental basis for planning intervention programs. The latter is to assess the impact of climate change on schools at the building level, with the aim of increasing the policymaker's awareness of the critical issues related to changing climatic conditions, drawing attention to the importance of carefully evaluating retrofit solutions.

On the cover: Map of the Apulia Region (Southern Italy), showing the school buildings investigated in the thesis, adapted from Google Earth Pro ©

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