POLITECNICO DI MILANO

School of Architecture, Urban Planning and Building Engineering

Master of Science in Building Engineering

Energy Retrofitting of Non-Residential Buildings

Prefabricated Solutions for EPBD Compliance and Economic Sustainability within EU Taxonomy Framework

Candidates:

Melissa Boano, 10869315

Andrea Landi, 10654580

Supervisor:

Prof. **Mario Gualtiero Francesco Motta**

Academic Year 2023/2024

Abstract

Since prehistoric times, human actions have profoundly shaped and altered ecosystems, leaving unconsciously its permanent mark on the surrounding world. Every form of life modifies its environment, and human beings have always been part of this mutation, resulting nowadays in the so-called "climate change". This thesis investigates the role of energy renovation in achieving climate neutrality within the European building sector, with a particular focus on a new retrofit proposal: prefabricated solutions.

The primary aim is to explore innovative renovation approaches to meet the ambitious goals outlined in the latest Energy Performance of Buildings Directive, which sets strict targets for energy efficiency and emissions reduction by 2050. Therefore, a comparison between traditional thermal insulation systems and prefabricated technologies was carried out, necessary to support the advantages achievable with the new proposal in terms of cost-effectiveness, sustainability and timeline's efficiency. The economic feasibility of prefabricated solutions has been examined too, highlighting their significant role in reducing construction times and costs while meeting the zero-emission concept for buildings.

To validate hypothesis, they are applied to a real case study building in Milan, subjected to a series of retrofit interventions that successfully improved its energy performance and CO_2 emissions reduction. Comparing the actual renovation with a hypothetical one based on prefabricated components, it is clear how new technological solutions can bring improvements on all fronts. Thus, the results demonstrate that these solutions offer a more environmentally and economically friendly, as well as faster alternative to traditional renovation methods, addressing the urgent need for rapid action to meet climate objectives. They also contribute to growing the knowledge on sustainable building practices and provide valuable insights for stakeholders in the construction sector, including investors, policymakers, and industry professionals. Indeed, the study also integrates the concept of EU Taxonomy and CRREM tools, providing a framework to ensure investments to be aligned with sustainability goals and contribute to broader efforts for global greenhouse gas emissions reduction.

Since this technology is still in development, future research could focus on scaling these solutions. By refining and expanding their implementation across more complex building typologies and diverse urban context, it would be possible to explore how building renovation rate could vary. Whether future retrofits of the European's building stock were to be carried out with prefabrication, it would be possible to further accelerate the transition towards a climate-neutral built environment.

Sommario

Fin dalla preistoria, le azioni umane hanno profondamente influenzato e modificato gli ecosistemi, lasciando inconsapevolmente un segno permanente nel mondo circostante. Ogni forma di vita modifica l'ambiente in cui vive, e gli esseri umani sono sempre stati parte di questa mutazione, sfociando oggigiorno nel così detto "cambiamento climatico". Questa tesi indaga sul ruolo della ristrutturazione energetica nel raggiungimento della neutralità climatica per il settore edilizio, focalizzandosi su una nuova proposta: le soluzioni prefabbricate.

L'obiettivo principale è esplorare approcci innovativi di riqualificazione per raggiungere gli ambiziosi obiettivi delineati nell'ultima Direttiva sulla Prestazione Energetica degli Edifici, che stabilisce target rigorosi per l'efficienza energetica e la riduzione delle emissioni entro il 2050. Pertanto, è stata effettuata una comparazione tra i tradizionali sistemi di riqualificazione e le tecnologie prefabbricate, necessaria per supportare i vantaggi che possono essere ottenuti con la nuova proposta in termini di efficienza temporale e sostenibile. È stata esaminata anche la fattibilità economica delle soluzioni prefabbricate, evidenziando il loro ruolo significativo nel ridurre i tempi di costruzione e i costi, pur rispettando il concetto di edifici a zero emissioni.

Al fine di convalidare le ipotesi, queste vengono applicate ad uno caso studio reale situato a Milano, sottoposto a una serie di interventi di retrofit che hanno migliorato con successo la sua performance energetica e la riduzione delle emissioni di CO_2. Confrontando la ristrutturazione effettiva con una ipotetica, basata su componenti prefabbricati, è evidente come le nuove soluzioni tecnologiche possano apportare miglioramenti sotto molti punti di vista. I risultati dimostrano che queste soluzioni offrono un'alternativa più ecologica, economica e rapida rispetto ai metodi di ristrutturazione tradizionali, rispondendo all'urgenza di adottare misure rapide per raggiungere gli obiettivi climatici. Contribuiscono inoltre ad ampliare le conoscenze sulle pratiche edilizie sostenibili e forniscono spunti preziosi per gli attori del settore delle costruzioni, tra cui investitori, decisori politici e professionisti del settore. Infatti, lo studio integra anche il concetto di Tassonomia UE e gli strumenti CRREM, fornendo una metodologia per garantire che gli investimenti siano allineati agli obiettivi di sostenibilità e contribuiscano agli sforzi globali per la riduzione delle emissioni di gas serra.

Poiché questa tecnologia è ancora in fase di sviluppo, le ricerche future potrebbero concentrarsi sullo scaling di queste soluzioni. Raffinando ed espandendo la loro implementazione su edifici più complessi e contesti urbani diversi, sarebbe possibile esplorare la variazione del tasso di ristrutturazione degli edifici. Se i futuri interventi di retrofit del patrimonio edilizio europeo venissero realizzati con la prefabbricazione, sarebbe possibile accelerare ulteriormente la transizione verso un ambiente costruito a impatto climatico nullo.

Contents

List of Figures 7

List of Tables 12

Introduction 15

1. Energy Performance of Buildings Directive (IV EPBD) 19

1.1 The Evolution of the Directive 20

1.2 Terms and Definitions 23

1.3 Goals and objectives towards NZEB Buildings 25

1.4 Methodologies: Application to Non-Residential Buildings 28

1.4.1 National Building Renovation Plan & Renovation Passport 29

1.4.2 Minimum Energy Performance Requirements 30

1.5 How To Satisfy EPBD Requirements and Goals 34

2. State of Art 35

2.1 Energy Regulations Evolution within Italian Building Sector 36

2.2 General Analysis of Current Building Stock 37

2.2.1 Intended Use: Residential and Non-Residential Buildings Categories 45

2.2.2 Energy Class Classification 47

2.2.3 Climatic Zone Distribution 51

2.3 Non- Residential Building: National Level Analysis 54

2.3.1 General Considerations 54

2.3.2 From National to Regional Analysis 56

2.4 Non- Residential Building: Lombardy Region Level Analysis 59

2.4.1 CENED Introduction 59

2.4.2 Cened 1.2 & 2.0: Selected Parameters 61

2.4.3 Data selection 64

2.4.4 Data Analysis 65

2.4.5 Category E2 – Office Buildings 66

2.4.6 Category E5 – Commercial Buildings 76

2.4.7 Category E8 – Industrial buildings 86

2.4.8 Final Considerations 96
3. Prefabricated Solutions 100
3.1 Main Goals and Results 101
3.2 Approach and Objectives of Interventions 103
3.2.1 Approach 104
3.2.2 Objectives of Interventions 104
3.2.3 Additional Considerations 105
3.3 Technical Elements 106
3.3.1 Façades 106
3.3.2 Roofs 107
3.3.3 Systems 108
3.4 The Process 109
3.4.1 Analysis 112
3.4.2 Project Design 112
3.4.3 Production 114
3.4.4 Logistics 115
3.4.5 Worksite 116
3.4.6 Building Usage and Management 117
3.4.7 End of Life 118
3.5 Cost Analysis 123
3.6 Examples: Traditional vs Prefabricated Solutions 128
3.7 Prefabricated Approach Considerations 137
4. Sustainable Financial Regulatory Frameworks 138
4.1 ESG Strategies 139
4.2 Net Zero-Carbon Transition 140
4.2.1 Pathway to NZC 141
4.3 Assets Stranding and Transition Risk 142
4.3.1 CRREM 142
4.4 EU Taxonomy 146

4.4.1 Regulatory Context 148
4.4.2 Benefits 150
4.4.3 Taxonomy and EPBD requirements 152
4.5 CRREM and EU Taxonomy 152
4.6 Considerations 154
5. Case Study: An Office Building in Milan 155
5.1 Office Building Selection 156
5.2 Pre-Refurbishment Conditions 158
5.2.1 Structural and Architectural Description 159
5.2.2 Building Services Description 161
5.3 Real Energy Refurbishment 162
5.3.1 Structural and Architectural Intervention 162
5.3.2 Building Services Interventions 167
5.4 Energy Refurbishment with Prefabricated Solutions 173
5.4.1 Design Approach 174
5.4.2 Prefabricated Components for Façade and Roof 176
5.4.3 Comparison Real Retrofit, Traditional Solution and Off-site Solution 179
5.5 CRREM and EU Taxonomy 201
5.5.1 CRREM 201
5.5.2 EU Taxonomy 206
5.6 Considerations 210
6. Conclusions 211
7. References 217

List of Figures

Figure 1.1 - General principles beyond all EPBD normative. 21
Figure 1.2 - EPBD directives time evolution 23
Figure 1.3 - Statistical percentages of total energy consumption and greenhouse gas emissions cause by European building stock 26
Figure 1.4 - nZEB (Nearly Zero-Energy Buildings) and NZEB (Net Zero-Emission Buildings) requirements over time according to all EPBD 27
Figure 1.5 - Main measures to be adopted by each EU Member State..... 27
Figure 1.6 - Methodologies and procedures to be adopted by each EU Member State 29
Figure 1.7 - Cost-optimal level definition and representation based on present requirement and nZEB conditions 31
Figure 1.8 - Minimum energy performance standards and thresholds for non-residential buildings..... 32
Figure 1.9 - Non-residential building stock timeline goals 33
Figure 2.1- Evolution of main Italian energy regulations 37
Figure 2.2 - National mapping of Regions and Autonomous Provinces connected to the SIAPE as of 01/04/2024 (ENEA processing) 38
Figure 2.3 - Percentage of Residential and Non-Residential Buildings belonging to Italian Building Stock 39
Figure 2.4 - Total number of EPCs submitted to SIAPE database for both residential and non-residential building sectors between 2020 and 2024 41
Figure 2.5 - Average values of Global Energy Performance Index ($EP_{gl,average}$), divided into renewable ($EP_{gl,ren,average}$) and non-renewable ($EP_{gl,nren,average}$) components for residential buildings from 2020 and 2024 42
Figure 2.6 - Average values of Global Energy Performance Index ($EP_{gl,average}$), divided into renewable ($EP_{gl,ren,average}$) and non-renewable ($EP_{gl,nren,average}$) components for non-residential buildings from 2020 and 2024 42
Figure 2.7 - CO_2 emissions between 2020 and 2024 for Residential Buildings..... 44
Figure 2.8 - CO_2 emissions between 2020 and 2024 for Non-Residential Buildings 44
Figure 2.9 - Total number of Energy Performance Certifications issued for non-residential buildings and its related percentage of incidence of total number..... 47
Figure 2.10 - Buildings energy classification according to Energy Performance Certificate . 48
Figure 2.11 - Influence percentage of each energy class on total number of residential buildings..... 49
Figure 2.12 - Influence percentage of each energy class on total number of non-residential buildings..... 50

Figure 2.13 - Italian map for climatic zone division 52
Figure 2.14 - Influence percentage of each climatic zone on total number of residential buildings..... 53
Figure 2.15 - Influence percentage of each climatic zone on total number of non-residential buildings..... 53
Figure 2.16 - Percentage of buildings in class F and G over the total number of non-residential buildings in class F and G obtained by summing all buildings belonging to category E2, E5 and E8. 56
Figure 2.17 - Influence percentage of each climatic zone on total number of non-residential buildings in class F..... 57
Figure 2.18 - Influence percentage of each climatic zone on total number of non-residential buildings in class G 58
Figure 2.19 - Heating generators share diagram 67
Figure 2.20 - Energy vectors for heating generation share diagram 68
Figure 2.21 - Frequency chart of seasonal efficiency of heating systems 68
Figure 2.22 - Share diagram of ventilation typology 69
Figure 2.23 - Renewable technologies share diagram and types 69
Figure 2.24 - Number of buildings for each construction years range 70
Figure 2.25 - Frequency chart of useful heated surface 71
Figure 2.26 - Average thermal transmittances of envelope components - Class F 73
Figure 2.27 - Average thermal transmittance of envelope components - Class G 73
Figure 2.28 - Heating generators share diagram 77
Figure 2.29 - Energy vector for heating generation share diagram 78
Figure 2.30 - Frequency chart of seasonal efficiency of heating systems 79
Figure 2.31 - Shear diagram of cooling system 79
Figure 2.32 - Share diagram of ventilation typology 80
Figure 2.33 - Renewable technologies share diagram and types 80
Figure 2.34 - Number of buildings in each construction years range 81
Figure 2.35 - Frequency chart of useful heated surfaces..... 81
Figure 2.36 - Average thermal transmittance of envelope components – Class F 83
Figure 2.37 - Average thermal transmittance of envelope components 83
Figure 2.38 - Heating generators share diagram 87
Figure 2.39 - Energy vectors for heating generation share diagram 88
Figure 2.40 - Frequency chart of seasonal efficiency of heating systems 89
Figure 2.41 - Share diagram of cooling systems 89
Figure 2.42 - Share diagram of ventilation typologies..... 90
Figure 2.43 - Renewable technologies share diagram and types 90

Figure 2.44 - Number of buildings in each construction years range 91
Figure 2.45 - Frequency chart of useful heated surfaces..... 91
Figure 2.46 - Average thermal transmittance of envelope components – Class F 93
Figure 2.47 - Average thermal transmittance of envelope components - Class G 93
Figure 2.48 - Lombardy and Italy typical building comparison to the total number of Non-residential EPCs 99
Figure 3.1 - Requalification rates before 2030..... 100
Figure 3.2 - Expected results of prefabricated retrofits 103
Figure 3.3 - Objectives of interventions 106
Figure 3.4 - Typical façade module composition 107
Figure 3.5 - Features and components of roof modules 108
Figure 3.6 - BIM utilisation diagram..... 110
Figure 3.7 - Dimensions of BIM..... 111
Figure 3.8 - Main phases of the prefabricated process..... 111
Figure 3.9 - Stages of the analysis phase 112
Figure 3.10 - Fields of the BIM approach 113
Figure 3.11 - Stages of the design phase..... 114
Figure 3.12 – Advantages for large scale production..... 114
Figure 3.13 - Stages of the production phase..... 115
Figure 3.14 - Stages of the logistics phase..... 116
Figure 3.15 - Stages of the worksite phase 117
Figure 3.16 - Strategies of buildings usage and maintenance phases..... 118
Figure 3.17 - Circular economy diagram 119
Figure 3.18 - 4RinEU End-of-Life strategy for buildings..... 120
Figure 3.19 - Façade module installation..... 122
Figure 3.20 - TCO diagram, from Energiesprong 124
Figure 3.21 - Costs and benefits comparison of Building as Usual (BAU) and Energiesprong intervention (ES), from Energiesprong 125
Figure 3.22 - CAPEX and OPEX comparison of As-Is, BAU and ES 126
Figure 3.23 - Time reduction of off-site solutions..... 128
Figure 3.24 – Costs' distribution of the prefabricated approach..... 129
Figure 3.25 – Model of the case study, from Energiesprong..... 130
Figure 3.26 - Module composition, from Energiesprong catalogue 131
Figure 3.27 – External insulation layer (thermal coat) application phases 133
Figure 3.28 – Cost analysis and comparison between prefabricated and traditional solutions 135

Figure 3.29 – Time analysis and comparison between prefabricated and traditional solutions 136
Figure 4.1 - ESG criteria 139
Figure 4.2 - Challenges of ESG strategies 140
Figure 4.3 - Pathway to NZC 141
Figure 4.4 - Stranding Chart 143
Figure 4.5 - Stranding Chart: Green Premium VS Brown Discount 144
Figure 4.6 - Stranding Chart: multi-retrofit strategy 146
Figure 4.7 - Six environmental objectives of EU Taxonomy 147
Figure 4.8 - Taxonomy alignment, principal steps 148
Figure 4.9 - EU sustainable finance framework 148
Figure 4.10 - Investment funds classification and definitions, from SFDR 149
Figure 4.11 - CRREM + EU Taxonomy strategy 153
Figure 5.1 - Yearly values of average Non-renewable Global Energy Performance 157
Figure 5.2 - Schematic representation of the building's façade 159
Figure 5.3 - Bodies in which the building is divided 160
Figure 5.4 - Additional blocks added to the existing structure 160
Figure 5.5 - Demolition and construction of volumes, front view 164
Figure 5.6 - Demolition and construction of volumes, back view 164
Figure 5.7 - Final volumes, front view 165
Figure 5.8 - Final volumes, back view 165
Figure 5.9 - Spaces destination of use, ground floor 166
Figure 5.10 - Schematic representation of the control system 168
Figure 5.11 - Typical system layout for internal spaces 170
Figure 5.12 - Schematic drawing of PV modules on the roof 172
Figure 5.13 - Phases of the BIM model creation 174
Figure 5.14 - Differentiation of façade modules, front and back views 175
Figure 5.15 - Façade modules' composition, from Energiesprong catalogue 176
Figure 5.16 - Anchoring phase of modules to the existing façade, from Energiesprong catalogue 177
Figure 5.17 - Schematic representation of the façade module 178
Figure 5.18 - Roofs' modules schematic configuration 178
Figure 5.19 – Real Intervention: Demolition of walls and dismantling of windows, south elevation 179
Figure 5.20 - Prefabricated Solution: Dismantling of windows and new façade module, south elevation 180
Figure 5.21 - Typical demolition's phases 181

Figure 5.22 - Surfaces of façades to be demolished..... 182
Figure 5.23 – Loading platforms and safety guardrails disposition on building's façade 186
Figure 5.24- Unitised curtain wall system 188
Figure 5.25 – Thermal insulation system..... 189
Figure 5.26 – Cost estimation comparison between the three retrofit solutions 194
Figure 5.27 – Timelines comparison between the three retrofit solutions 197
Figure 5.28 – Envelope components' thermal transmittance, Traditional VS Prefabricated Solutions..... 198
Figure 5.29 – Cost, time and energy features comparison between the three solutions 200
Figure 5.30 - Stranding chart of the case study – Pre-intervention 202
Figure 5.31 - Energy intensity diagram of the case study – Pre-intervention 203
Figure 5.32 - Stranding chart of the case study – Post-intervention..... 204
Figure 5.33 – Energy intensity diagram of the case study – Pre-intervention 205
Figure 5.34 - Definition of economic activity for the construction field..... 206
Figure 5.35 - Interventions to improve energy efficiency 206
Figure 5.36 - DNSH principle to the other five objectives 208

List of Tables

Table 2.1 - Total number of Energy Performance Certifications issued for each category of residential and non-residential buildings and its related percentage of incidence of total number for each sector 46
Table 2.2 - Number of buildings' energy certificates for each energy class considering the residential building stock 49
Table 2.3 - Number of buildings' energy certificates for each energy class considering non-residential constructions 50
Table 2.4 - Number of energy certification for each climatic zone for residential and non-residential building stock 52
Table 2.5 - Total number of Energy Performance Certificates (EPC) issued and registered in SIAPE database for all non-residential buildings categories, including certificated placed in F and G energy classes 55
Table 2.6 - Percentage of buildings in class F and G over the total number of non-residential sectors by summing all buildings belonging to category E2, E5 and E8. 55
Table 2.7- Number of energy certification for each climatic zone only for non-residential building sector, including its percentage over the total number 57
Table 2.8 - Total buildings number within Lombardy Region and its influence on national level and zone E 59
Table 2.9 - CENED1.2 and CENED2.0 parameters considered 61
Table 2.10 - Types of heating generators for classes F and G 66
Table 2.11 - Types of energy vectors for heating generation for classes F and G 67
Table 2.12 - Percentage of transparent surface of envelope 71
Table 2.13 - Average thermal transmittance of envelope components - Class F 72
Table 2.14 - Average thermal transmittance of envelope components - Class G 72
Table 2.15 - Hypothesised stratigraphies of external partitions for classes F and G 74
Table 2.16 - Hypothesised stratigraphies of roofs for classes F and G 74
Table 2.17 - Hypothesised stratigraphies of basement floors for classes F and G 75
Table 2.18 - Hypothesised windows technologies for class F and G 75
Table 2.19 - Comparison typical building and total number in classes F and G 76
Table 2.20 – Types of heating generators for classes F and G 77
Table 2.21 - Types of energy vectors for heating generation for classes F and G 78
Table 2.22 - Average thermal transmittance of envelope components - Class F 82
Table 2.23 - Average thermal transmittance of envelope components - Class G 82
Table 2.24 - Hypothesised stratigraphies of external partitions for classes F and G 84
Table 2.25 - Hypothesised stratigraphies of roofs for classes F and G 84

Table 2.26 - Hypothesised stratigraphies of basement floors for classes F and G..... 85
Table 2.27 - Hypothesised window technologies for classes F and G 85
Table 2.28 - Comparison typical building and total number in classes F and G..... 86
Table 2.29 - Types of heating generators for classes F and G 87
Table 2.30 - Types of energy vectors for heating generation for classes F and G 88
Table 2.31 - Average thermal transmittance of envelope components - Class F 92
Table 2.32 - Average thermal transmittance of envelope components - Class G..... 92
Table 2.33 - Hypothesised stratigraphies of external partitions for classes F and G..... 94
Table 2.34 - Hypothesised stratigraphies of roofs for classes F and G..... 94
Table 2.35 - Hypothesised stratigraphies of basement floor for classes F and G 95
Table 2.36 - Hypothesised window technologies for classes F and G 95
Table 2.37 - Comparison typical building and total number in classes F and G..... 96
Table 2.38 - Typical building for each category 97
Table 2.39 - Lombardy and Italy typical buildings comparison..... 98
Table 3.1 - Costs and revenues of interventions 126
Table 3.2 – General information of the case study 130
Table 3.3 - Characteristics of the module 131
Table 3.4 - Worksite costs comparison..... 132
Table 3.5 - Costs of construction works comparison 134
Table 3.6 - Timing comparison..... 136
Table 4.1 - General criteria of Taxonomy alignment for building sector's activities 147
Table 4.2 - Scopes and connections of EU Taxonomy, CSRD, and SFDR..... 150
Table 4.3 - Main features of CRREM and EU Taxonomy 153
Table 5.1 - EPCs number and Non-renewable Global Energy Performance 156
Table 5.2 - Increment of floor area after the intervention 163
Table 5.3 - Module's characteristics, from manufacturer 177
Table 5.4 – Quantity definition of external walls and windows to be demolished 182
Table 5.5 - Estimation of demolitions costs of façades 183
Table 5.6 – Body A, B, C and D perimeter length quantification 186
Table 5.7 – Unitized curtain wall solution worksite set-up total cost..... 187
Table 5.8 - Unitized curtain wall solution supply and installation total cost 188
Table 5.9 - Unitized curtain wall solution total cost 188
Table 5.10 - Traditional solution worksite set-up total cost, considering scaffolding 190
Table 5.11 – Cost per square meter for traditional thermal insulation system..... 190
Table 5.12 – Traditional solution supply and installation total cost..... 191
Table 5.13 - Traditional solution total cost 191
Table 5.14 – Prefabricated solution worksite set-up total cost 192

Table 5.15 - Prefabricated solution supply and installation total cost 192
Table 5.16 – Prefabricated solution total cost 193
Table 5.17 - Costs estimation comparison between the three retrofit solutions 193
Table 5.18 – Unitized curtain wall system timelines 195
Table 5.19 – Prefabricated solution timelines 195
Table 5.20- Traditional solution timelines 196
Table 5.21 – Timelines comparison between the three retrofit solutions 197
Table 5.22 – Thermal transmittance values comparison between the three solutions 200
Table 5.23 - Input used for the CRREM software 201
Table 5.24 - Pre-intervention inputs 201
Table 5.25 - Post-intervention inputs 203
Table 5.26 - Pre and post-intervention CRREM data comparison 205
Table 5.27 - Pre and Post intervention values 207
Table 5.28 - EU Taxonomy alignment verification 209

Introduction

Climate change represents one of the most serious and urgent problems humanity is facing nowadays. Its consequences, often underestimated, are now evident globally and threaten the balance of our entire ecosystem. The construction industry plays a crucial role in this context, both as the main responsible for greenhouse gas emissions and overall energy consumption, and as a key sector for the transition towards a more sustainable future. The renovation of a significant portion of the European building stock would lead to significant environmental improvements, thereby reducing pollution levels and non-renewable sources exploitation. Based on these considerations, the new European Directive EPBD (Energy Performance of Buildings Directive) sets its redevelopment objectives, supported by necessary time constraints, which will serve as the starting point for this thesis development.

The central focus, therefore, lies in the need to comply with the provisions of the fourth, and most recent, edition of the Directive (IV EPBD), which sets ambitious goals in terms of energy efficiency and emissions reduction. This path terminus coincides with the achievement of climate neutrality by 2050 for the entire construction sector, thus transforming the European real estate into zero-emission buildings. However, this goal is the result of a long and gradual process that cannot be achieved without rapid, decisive, and above all, constant action. To this end, a series of mandatory intermediate targets have been set, both for existing buildings (residential and non-residential) and new constructions. For example, by 2030, at least 16% of non-residential buildings must be renovated, with a subsequent increase to 26% by 2033. Residential buildings will also need to undergo a restoration project, by meeting specific deadlines, while even stricter requirements are foreseen for new buildings, oriented towards zero-emission buildings in the coming years. The timeframes are tight, but solutions are available, and this thesis aims to explore and deepen an alternative renovation proposal that can fully and effectively respond to Directive's requirements.

The first step of this study was to analyse and compare the Italian building stock based on the main energy performance indicators, provided by individual certificates. Mapping real estate territory was necessary to obtain a comprehensive view of consumption and emissions associated with each building, in order to identify priorities and determine the primary interventions to be achieved. This sector, indeed, includes a significant share of buildings with very low energy performance, with particular attention given to the non-residential building stock. This category represents an emblematic case for intervention, as, despite being less numerous than residential units, it has a significantly higher energy need and impact translated into a higher average value of Non-Renewable Global Energy Performance Index. According to the available data provided by SIAPE, a large percentage of these structures falls into the

lowest energy classes (F and G), characterized by high thermal transmittance levels, significant heat loss, as well as outdated and inefficient systems. In this context, it was possible to identify the 16% of non-residential buildings with the worst energy performance, which will become the main focus of renovation efforts. The most affected categories within this group include offices (E2), commercial activities (E5) and industrial activities (E8), among which a "typical building" was identified, with common characteristics and poor energy performance, being the starting point for renovation. This characterization was made possible thanks to CENED software, a database containing information regarding Energy Performance Certificates (EPC) within Lombardy Region, thus focusing the analysis on a more specific and localized regional context to obtain more detailed information. Identifying and intervening on these buildings is a crucial step in improving efficiency and reducing consumption across the entire building sector, progressively moving closer to the established climate objectives. The final aim is, therefore, to extend the concept of Net Zero-Emission Buildings, which are buildings with a zero-emissions balance, thus making a decisive contribution to greenhouse gas release's global reduction.

Despite the complexity of this challenge, the research proposes concrete and innovative solutions capable of meeting the efficiency, speed and cost-effective requirements imposed by regulations. The timelines for action are extremely tight, and it will be necessary to demonstrate how new cutting-edge approaches can be faster and more efficient than traditional technologies, such as thermal insulation systems. One of the most promising answers is the adoption of prefabricated and modular solutions as part of renovation processes, able to significantly reduce construction times while simultaneously improving structures' energy performance. The use of prefabricated elements, applicable both for building's envelope and systems, involves shifting the components production from construction site to factory. This process not only leads to a higher level of detail and precision in elements' creation, reducing the risk of errors and unexpected maintenance, but also results in more efficient logistics. Indeed, factory production occurs in parallel with the worksite set-up phase, which avoids the need for scaffolding and associated structures, thereby reducing implementation times and improving the precision of works. Compared to traditional thermal insulation solutions, prefabrication proves to be a quicker and less invasive alternative, more effectively addressing the urgent need to move towards climate neutrality. The value of this approach is further strengthened by the fact that prefabricated solutions not only allow a construction times and costs reduction but also meet the growing demand for sustainability. The possibility of achieving zero-emission buildings, by optimizing energy consumption and complying with the efficiency standards required by the Directive, offers significant advantages for both industry operators and investors. In this context, the adoption of prefabricated

solutions can significantly contribute to reducing operational costs and increasing property values, making investments in the construction sector more attractive and sustainable.

The economic aspect is, therefore, one of the main obstacles in the building renovation process. Investors are often reluctant to undertake projects that require a large initial investment, especially when unable to perceive long-term economic returns. This limitation is already present in traditional retrofit interventions, but it becomes even stronger when talking about innovative prefabricated solutions, which involve a higher initial investment. Although worksite costs are significantly reduced thanks to the elimination of scaffolding and complex operations, the production of prefabricated elements requires more detailed design and planning, thus leading to a slight increase in costs compared to traditional thermal coat. However, this economic barrier can be overcome through the concept of economies of scale: by increasing the number of factories and the demand for prefabricated elements, it is possible to progressively reduce initial costs and achieve faster returns on investments.

In this scenario, a fundamental role is played by the EU Taxonomy, a set of guidelines that certify the sustainability of energy renovation projects, as well as the investments associated with them. This is a crucial tool to encourage investors, offering them the assurance that their capital is directed towards projects with concrete goals that will lead to measurable benefits, both in terms of economy and sustainability. Being aligned with the EU Taxonomy not only makes these projects more attractive, as they will actively contribute to achieving climate neutrality objectives, but it also ensures access to funds and incentives, making investment even more advantageous. Additionally, this study integrates the use of the CRREM (Carbon Risk Real Estate Monitor), a tool that traces the decarbonization path of buildings, assessing their ability to align with the emission reduction targets set by Paris Agreement. CRREM identifies the "stranding point", the moment when a property will no longer comply with climate neutrality standards, therefore requiring retrofit interventions. By combining CRREM with the EU Taxonomy, investors are provided with the opportunity to direct their capital towards projects that respect sustainability goals, making a concrete contribution to achieving climate neutrality by 2050.

This thesis goes beyond theoretical analysis and draws on a practical and concrete case study: a building located in Milan that, through a retrofit intervention, has obtained tangible results in terms of energy efficiency and emissions reduction, fully respecting European regulations. Compared to the actual restoration, which involved the demolition of the entire complex façade and the consequent re-construction, an innovative alternative based on prefabricated technologies was proposed. This choice arises from the desire to compare the two approaches in terms of costs, timelines and impacts, demonstrating how prefabricated

solutions can represent a faster, more economical and sustainable path to achieving the ambitious goals described.

The contribution of this research, therefore, offers a concrete vision of how energy renovation can be undertaken with commitment, even in a complex and stimulating context. The transition towards climate neutrality of the European building stock is not an unattainable utopian concept, but a reality that can be built starting today. It is a challenge that can undoubtedly be successfully faced through the adoption of innovative solutions that combine sustainability, efficiency and speed. This thesis demonstrates that, with the right approach, it is possible not only to meet deadlines and regulatory commitments, but also to face sustainability challenges with confidence. The dream of a future with increasingly greener cities, housing a society even more conscious of the surrounding environment, will always remain a dream unless we manage to turn it into reality.

1. Energy Performance of Buildings Directive (IV EPBD)

The Energy Performance of Buildings Directive (EPBD) represents the main legislative document aiming at promoting and enhancing energy efficiency in buildings, aligning with broader climate and emission reduction goals for a better future. It plays a crucial role in the European Union's efforts to address the current "call to action" for climate change issues by setting limits, solutions and goals.

The directive was introduced for the first time in 2002 and has been subjected to continuous changes and revisions, as the publications in 2010 and 2018, with the aim of expanding, improving and further promoting the reduction of energy consumption and greenhouse gas emissions in buildings. The latest version (IV EPBD) dates to May 2024 and serves as the central focus for the presented building's energy analysis development. This new update can be defined as an improvement over the previous "Green House Directive" from March 2023, in line with the worsening climate conditions observed nowadays and the new European Union's new needs, aimed at addressing this general decline.

The primary objective of the EPBD directive has consistently been to facilitate the transition to Nearly Zero-Energy Buildings (nZEB), imposing that member states implement measures to enhance the energy efficiency of their building stock. These actions encompass the implementation of minimum energy performance requirements and standards for newly built or extensively renovated structures, the mandatory issuance of energy performance certificates in order to verify energy efficiency through indicators, as well as regular inspection of heating and cooling systems. Furthermore, the EPBD asks for the integration of renewable energy sources, including the installation of smart meters for energy consumption's monitoring and management, with the final aim of decreasing non-renewable energy exploitation. [1]

The European Union's member States have always been responsible for normative implementation since its initial adoption, striving to adopt the most effectiveness strategies and tools available within their respective nations. Nonetheless, the common objective is to enhance the energy efficiency of buildings throughout the entire EU territory in order to reduce energy consumption, greenhouse gas emissions and reliance on non-renewable energy sources. This underscores the necessity for collaboration and efficiency among each member state, as well as consistent promotion of these goals. Indeed, each State must develop a National Renovation Plan for buildings and integrate it into their National Energy and Climate Plan (NECP). This strategy should outline the steps for the gradually passing out fossil fuels in heating and cooling systems by 2040, while formalizing, at the same time, a pathway to transform the national building stock into Net Zero-Emission Building (NZEB) by 2050.

1.1 The Evolution of the Directive

Since 1993, the European Union has tackled the issue of energy efficiency in buildings from a regulatory point of view, starting with the Council Directive 1993/76/EEC[1], commonly referred to as SAVE. The document aimed to lower carbon dioxide emissions not only within the real estate sector but also beyond, by enhancing the energy efficiency of buildings. At that time, this approach was recognized as one of the most cost-effective methods to strengthen energy supply security and decrease both greenhouse gas emissions and other pollutants [1].

However, it was only from 2002 onward that different EU regulations has been introduced, including the current Energy Performance of Buildings Directive (EPBD) in its first, second, thirds and fourth versions, as well as the Energy Efficiency Directive (EED). These legislations established mandatory obligations and performance criteria, facilitating the energy certification of buildings and providing essential guidelines that enhance sustainability in the construction sector. Moreover, they also promoted the use of renewable energy sources, encouraging diversification in energy supply [1].

With the object of improving energy efficiency in buildings across the European Community, it is possible to identify a few key points associated with all four directives, which have been upgraded over time. Among these are [2]:

- a general framework for an integrated energy performance of buildings' calculation methodology;
- the application of minimum requirements on the energy performance of new buildings and large existing buildings that are subject to major renovation;
- energy certification of buildings;
- regular inspection of boilers and of air-conditioning systems in buildings, within an assessment of the heating installation in which the boilers are more than 15 years old.

[1] Council Directive 93/76/EEC of 13 September 1993, issued by the Council of the European Communities, to limit carbon dioxide emissions by improving energy efficiency (SAVE). *Official Journal L 237, 22/09/1993 P. 0028 - 0030*

Figure 1.1 - General principles beyond all EPBD normative.

As previously explained, the Energy Performance of Building Directive has been subjected to several modifications and changes in conjunction with new energy requirements. The first version of the EPBD (Directive 2002/91/EC) was published and approved on December 16th, 2002, entering into force on January 4th, 2003. As its subsequent versions, the directive has required EU Member States to strengthen and broaden building regulations, thus considering the introduction of Energy Performance Certificates (EPC) in order to monitor them throughout their service life. However, the Directive 2002/91/EC was later on replaced by the second version of the EPBD, known as "EPBD recast" (Directive 2010/31/EU), approved on May 19th, 2010. The term recast refers to the process of revising and consolidating the original directive, with the aim of enhancing and widening the scope of tackling climate change and achieving energy efficiency goals. Indeed, the key changes in the second versions included:

- Stronger requirements for energy performance, through which Member States were required to set higher minimum energy performance standards;
- The introduction of Nearly Zero-Energy Buildings (nZEB), comporting that all new buildings must have a high energy performance and very low-energy needs, covered largely by onsite and nearby renewable energy sources, by 2020;
- More detailed energy certifications, including recommendations for improving energy efficiency;
- Regular inspections of heating and cooling system, becoming mandatory to meet efficiency standards.

Before reaching the latest and current version of the Directive, a third revision was drafted and issued on May 30th, 2015, with the Directive 2018/844/EU, in order to «introduce a broad range of policies and support measures to foster energy efficiency in building sector»[2]. Indeed, the 2018 directive's amendments strengthened the EU's commitments to modernizing the construction sector, aligning it with broader climate goals [2]. An improvement has been made

[2] IEA International Energy Agency, *Directive (EU) 2018/844 on the Energy Performance of Buildings Directive (EPBD)*, (last updated September 12, 2024), op. cit

through the introduction of automation and control systems, as well as intelligent technologies, alongside a greater focus on the renovation of existing buildings to enhance their efficiency.

In October 2020, the European Commission introduced its Renovation Wave strategy, which is a key element of the European Green Deal. This strategy includes a comprehensive action plan with specific regulatory, financial and supportive measures designed to accelerate building renovations across Europe. One of its main goals is to double, at least, the rate of energy-efficient building renovations annually by 2030 by promoting deep refurbishments that improve significantly energy performance: almost 35 million structures had to be retrofitted. Based on that, an additional revision and reinforcement of the Energy Performance of Buildings Directive (EPBD) played a crucial role in achieving these objectives, as explained in the following paragraph [3].

In December 2021, the European Commission proposed and published the revision mentioned above, as part of the Delivering the European Green Deal (known as 'Fit for 55'[3]) package, later presented in July 2021. The final aim of this strategy, promoting Europe's growth towards a greener and healthier path, is to meet a minimum 55% EU reduction in greenhouse gas (GHG) emissions by 2030, now legally required under the 2021 European Climate Low[4] [4]. The strategy highlights the need to tackle he energy use and carbon emissions of the building sector as a key part of the EU's overall climate and energy objectives, making it a fundamental element for achieving a sustainable and decarbonized future.

On 7 December 2023, the co-legislators reached a provisional agreement on the revision. The fourth version of the directive (IV EPBD) was published in the EU Official Journal on May 8th 2024 and entered into force 20 days later. [1]

---

[3] European Council, *« 'Fit for 55' is a package of reforms drafted, approved, and promoted by the European Commission in 2021 as part of the Green Deal, with the goal of achieving climate neutrality in Europe by 2050*». ("Ready for 55%"; last updated April 12, 2024)

[4] European Union, *« The European Climate Law writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050. The law also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.*». ("European Climate Law)

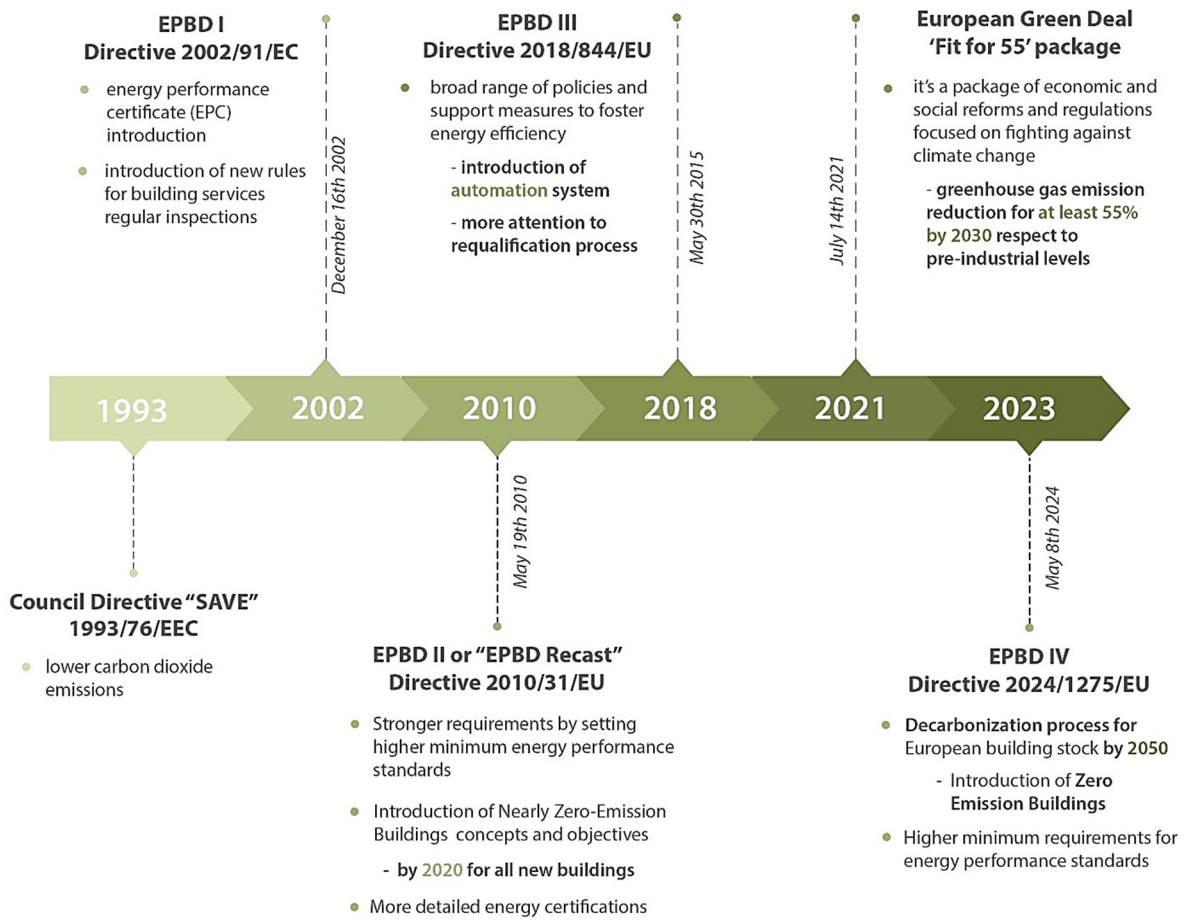

Figure 1.2 - EPBD directives time evolution

1.2 Terms and Definitions

In order to better understand the objectives and requirements outlined in this new edition of the EPBD directive by the European Council, some key terms and definitions taken from the official text are listed below. It is important to note that the following descriptions are quoted as they are stated in Article 2 of the directive [5]. These include:

- 'Building' means a roofed construction having walls, for which energy is used to condition the indoor environment;
- 'Zero-Emission Building' (NZEB) means a building with a very high energy performance, as determined in accordance with Annex I, requiring zero or a very low amount of energy, producing zero on-site carbon emissions from fossil fuels and producing zero or a very low amount of operational greenhouse gas emissions, in accordance with Article 11;
- 'Nearly Zero-Energy Building' (nZEB) means a building with a very high energy performance, as determined in accordance with Annex I, which is no worse than the

2023 cost-optimal level reported by Member States pursuant to Article 6 and where the nearly zero or very low amount of energy required is covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or energy from renewable sources produced nearby;

- ‘Minimum energy performance standards’ means rules that require existing buildings to meet an energy performance requirement as part of a wide renovation plan for a building stock or at a trigger point on the market such as sale, rent, donation or change of purpose within the cadastre or land registry, in a period of time or by a specific date, thereby triggering the renovation of existing buildings;
- ‘Energy performance of a building’ means the calculated or metered amount of energy needed to meet the energy demand associated with a typical use of the building, which includes energy used for heating, cooling, ventilation, domestic hot water and lighting;
- ‘Primary energy’ means energy from renewable and non-renewable sources which has not undergone any conversion or transformation process;
- ‘Renovation passport’ means a tailored roadmap for the deep renovation of a specific building in a maximum number of steps that will significantly improve its energy performance;
- ‘Deep renovation’ means a renovation which is in line with the ‘energy efficiency first’ principle, which focuses on essential building elements, and which transforms a building or building unit:
    (a) before 1 January 2030, into a nearly zero-energy building;
    (b) from 1 January 2030, into a zero-emission building;
- ‘Operational greenhouse gas emissions’ means greenhouse gas emissions associated with the energy consumption of the technical building systems during the use and operation of the building;
- ‘Energy Performance Certificate’ (EPC) means a certificate, recognized by a Member State or by a legal person designated by it, which indicates the energy performance of a building or building unit, calculated in accordance with a methodology adopted pursuant to Article 4;
- ‘Useful floor area’ means the area of the floor of a building needed as parameter to quantify specific conditions of use that are expressed per unit of floor area and for the application of the simplifications and the zoning and allocation or re-allocation rules;
- ‘Energy needs’ means the energy to be delivered to, or extracted from, a conditioned space to maintain the intended space conditions during a given period of time, disregarding any technical building system inefficiencies;

- ‘Energy use’ or ‘energy consumption’ means energy input to a technical building system providing an EPB service intended to satisfy an energy need;
- ‘self-use’ means the use of energy from renewable sources produced on-site or energy from renewable sources produced nearby by on-site technical systems for EPB services;
- ‘Services related to the energy performance of buildings’ or ‘EPB services’ means the services, such as heating, cooling, ventilation, domestic hot water and lighting and others for which the energy use is taken into account in the calculation of the energy performance of buildings;
- ‘Delivered energy’ means energy, expressed per energy carrier, supplied to the technical building systems through the assessment boundary, to satisfy the uses considered or to produce the exported energy;
- ‘Exported energy’ means the proportion of the renewable energy, expressed per energy carrier and per primary energy factor, that is exported to the energy grid instead of being used on-site for self-use or for other on-site uses;
- ‘Indoor environmental quality’ means the result of an assessment of the conditions inside a building that influence the health and wellbeing of its occupants, based upon parameters such as those relating to the temperature, humidity, ventilation rate and presence of contaminants.

1.3 Goals and objectives towards NZEB Buildings

The need to draft a new version of the Energy Performance of Buildings Directive arose from a series of considerations and statistical data related to the severe climate changes, currently affecting our planet. Indeed, it has been defined that 85% of EU buildings were constructed before 2000, and among these, 75% have poor energy performance [1]. Furthermore, as stated in directive’s text, «buildings account for 40 % of final energy consumption in the European Union and 36 % of its energy-related greenhouse gas. Natural gas plays the largest role in the heating of buildings, accounting for around 39 % of energy consumption used for space heating in the residential sector. Oil is the second most important fossil fuel for heating, accounting for 11 % and coal accounts for around 3 %»[5].

[5] Official Journal of the European Union, *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings,* (May 8th, 2024), op. cit p.2

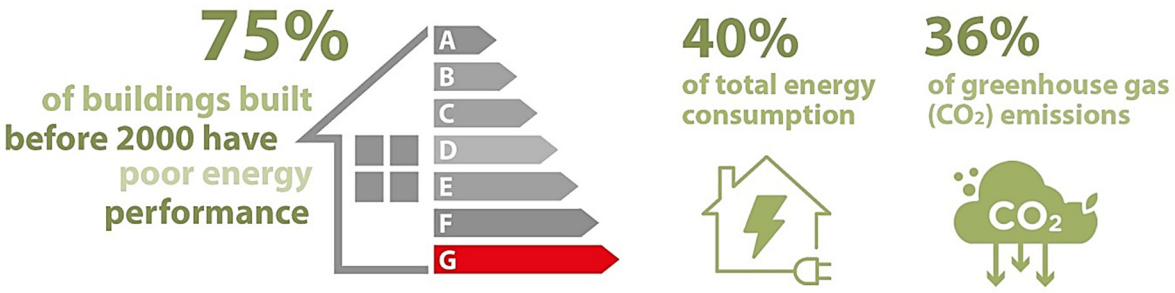

Figure 1.3 - Statistical percentages of total energy consumption and greenhouse gas emissions cause by European building stock

For this reason, the primary focus of the new EPBD (Energy Performance of Buildings Directive) has been placed on the urgent need to reduce fossil fuels dependence in buildings, in order to accelerate efforts to decarbonize and electrify their energy consumption. This need is not the result of a recent "call to action" to mitigate climate change: indeed, directive's main goal has always been to promote the achievement of Nearly Zero-Energy Buildings (nZEBs), requiring Member States to adopt measures to improve their energy efficiency. Just considering the previous versions, starting with EPBD II, which aimed at achieving this goal by 2021 for new buildings owned by public bodies and by 2020 for other remaining buildings. This implied that all new constructions, from those years onwards, had to present very high energy performances, with a very low energy demand, mainly covered by on-site or nearby renewable energy sources.

With the last version of the directive (EPBD IV), a new concept regarding buildings' energy efficiency has been introduced: Net Zero-Emission Buildings (NZEB). As already explained, these constructions require almost no energy, which must be entirely supplied by local or nearby renewable sources, including renewable energy community and high-efficiency district heating and cooling. Furthermore, these buildings will play a fundamental role in strengthening grid flexibility, by providing decentralized renewable energy generation at household or community level, electric and thermal energy storage, better demand response and smart charging. This will help not only to reduce energy demand but also to support the overall energy grid supply [3]. Therefore, the fourth version of the directive establishes that all new buildings, both residential and non-residential, must be zero-emission buildings starting from the following dates:

- January 1st, 2028, for all buildings owned by public bodies;
- January 1st, 2030, for all other buildings, with the possibility of specific exceptions.

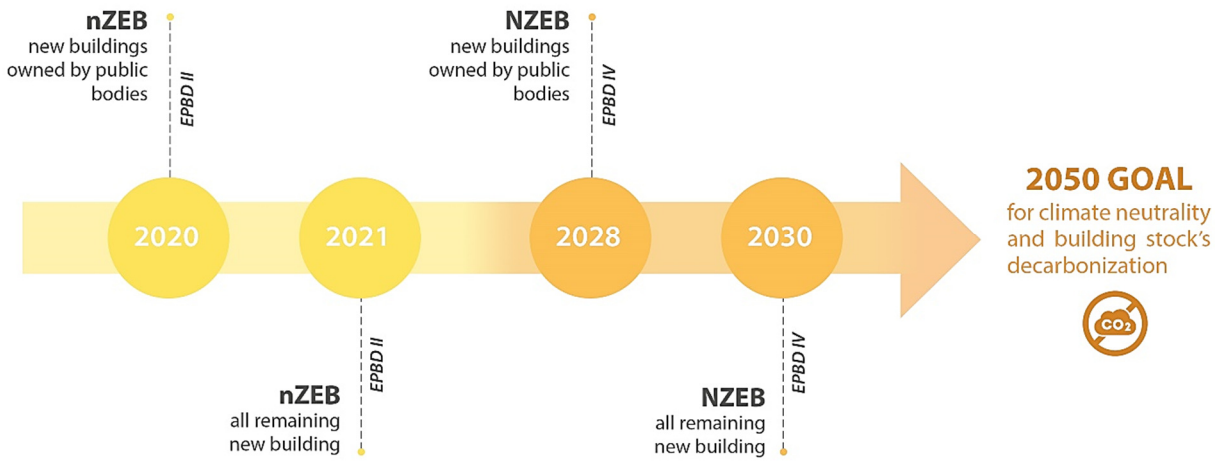

Figure 1.4 - nZEB (Nearly Zero-Energy Buildings) and NZEB (Net Zero-Emission Buildings) requirements over time according to all EPBD

Therefore, the regulations introduced align with the EU's climate neutrality goal by 2050, and strengthen the energy efficiency first principle, already foreseen in the "Fit for 55" package. These objectives imply the adoption of a series of measures by Member States, with the first being the imposition of minimum energy performance requirements for new buildings or those undergoing major renovations, in order to meet the standards, set within a comprehensive renovation plan. Other approaches to be included are the obligations to certify buildings' energy efficiency through Energy Performance Certificates (EPCs), which are the primary indicator of energy consumptions, as well as periodic inspection of air conditioning systems, and informing users about energy indicators. Additionally, there is an emphasis on incentivizing the use of renewable energy sources in buildings, to reduce energy consumption.

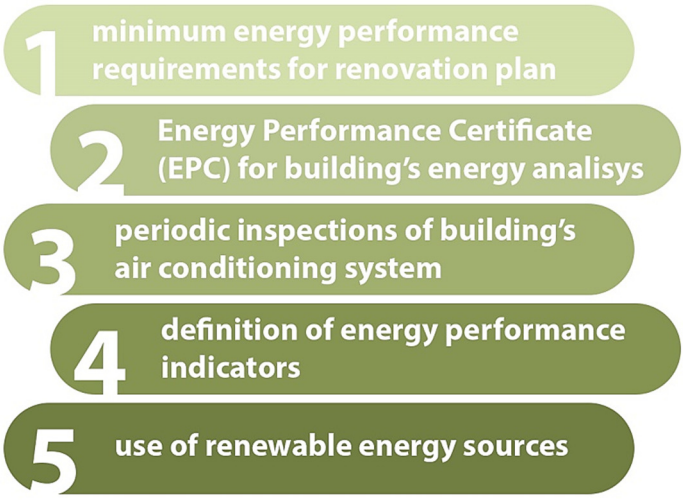

Figure 1.5 - Main measures to be adopted by each EU Member State

The main motivation for this IV EPBD development, beyond improving the energy performance of the European building stock, is undoubtedly the increased emphasis on emissions compared to previous versions. Historically, the Directive was primarily focused on energy, regarding building's consumptions and its associated impacts. Conversely, while emissions were acknowledged, they were treated as a secondary concept. In this most recent edition, however, emissions have become a central element, and their reduction is one of the primary objectives.

In conclusion, it can be stated that this new version of the directive not only aims to improve the energy efficiency of buildings but also emphasizes an integrated and systemic approach that promotes a more resilient, flexible and decarbonized energy network. The shift towards Zero-Emission Buildings is not only a matter of energy performance, but also a crucial element in accelerating the achievement of both European and global climate and economic goals. Therefore, the final objective of this directive is to guide each Member State towards a healthier, greener and cleaner future, with the fully decarbonized building stock being the main character in 2050.

1.4 Methodologies: Application to Non-Residential Buildings

The EPBD regulation assigns to each Member State the responsibility and obligation to implement imposed methodologies and procedures, as well as the common goal of energy renovation achievement, adapting the provisions to their specific national circumstances. Indeed, it mandates:

- The preparation of a national building renovation plan, which must be included in the so-called NECP (National Energy and Climate Plan), as well as the definition of a renovation passport;
- The establishment of minimum energy performance requirements, which can be defined as specifications designed to limit the amount of energy consumed by the entire building stock, imposed to both new constructions and major restorations;
- The definition of a renovation passport, a kind of roadmap that guides each country towards the renovation of its building stock;
- The implementation of a methodology for calculating energy performance, along with the corresponding Energy Performance Certificate and its parameters.

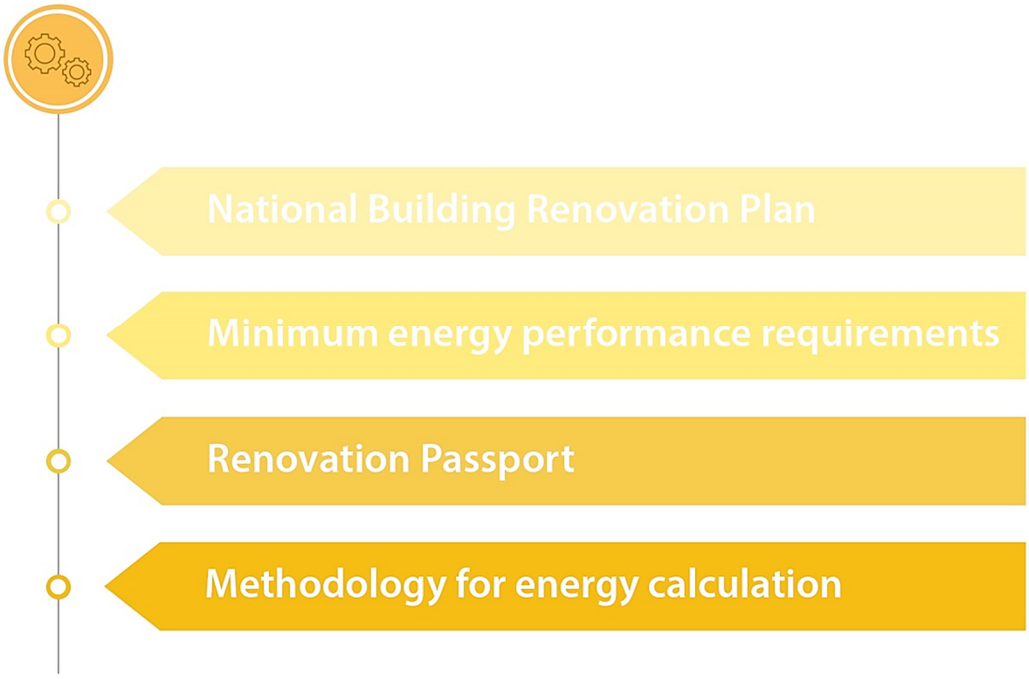

Figure 1.6 - Methodologies and procedures to be adopted by each EU Member State

1.4.1 National Building Renovation Plan & Renovation Passport

Through the National Renovation Plan for Buildings (NBRP) drafting, «each Member State shall establish a national building renovation plan to ensure the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy-efficient and decarbonised building stock by 2050, with the objective to transform existing buildings into zero-emission buildings»[6].

This renovation plan includes several key points that each Member State must meet, while simultaneously introducing a common format (outlined in Annex II of the Directive) that specifies these mandatory indicators. The following must be completed:

a) A review of the national building stock, which identifies the types, construction periods, and different climatic zones of the buildings analysed, based on statistical sampling and the energy performance certificate database;

[6] Official Journal of the European Union, *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy Performance of Buildings,* (May 8th, 2024), op. cit p.20, Article 3

b) A roadmap with national targets for 2030, 2040, and 2050, and measurable progress indicators in terms of the annual energy renovation rate, primary and final energy consumption of the national building stock. This roadmap can be defined through the National Renovation Passport specific to each State, which establishes all the stages to follow for improving the energy performance of buildings;
c) An overview of the investment needs, financing measures, and administrative resources required to achieve the goals, as well as an estimate of the savings;
d) The thresholds for operational greenhouse gas emissions and annual primary energy consumption for a zero-emission building, whether new or renovated;
e) Minimum energy performance requirements for existing non-residential buildings that ensure these buildings do not exceed the maximum energy performance threshold specified in Article 9. These minimum requirements are accompanied by the national trajectory for renovating the residential building stock, which involves identifying a number of poorly performing buildings that must be renovated within specific timeframes.

1.4.2 Minimum Energy Performance Requirements

As previously stated, the need to reduce energy consumption in buildings, as well as greenhouse gas emissions, represents the objectives' cornerstone set by the fourth edition of the Directive. For this reason, it can be asserted that the only way to achieve these goals is by establishing minimum thresholds, also defined as minimum energy performance requirements, in order to limit consumption and achieve the decarbonization process of buildings.

Before defining in detail what this entails, it is necessary to emphasize that these minimum levels must be optimal in relation to costs, which means the financial expenditure required by each Member State to comply with the new demands. The cost-optimal level is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle". According to this approach, construction alternatives for retrofit process must be included and compared in terms of cost and energy performance among the studied solutions. This means that more efficient and innovative technologies will undoubtedly involve higher economic costs compared to simpler, more traditional solutions, but at the same time, the energy efficiency results achieved will be better. To ensure a satisfactory outcome accompanied by an adequate economic level, an optimal point (minimum) from a cost-effectiveness perspective is defined, which represents the starting point for setting the minimum energy performance requirements. Indeed, the cost-optimal configuration presents

the lowest cost maintaining a high performance, respect to nZEB renovation condition and present requirement configuration, as shown in Figure 1.7 below [6].

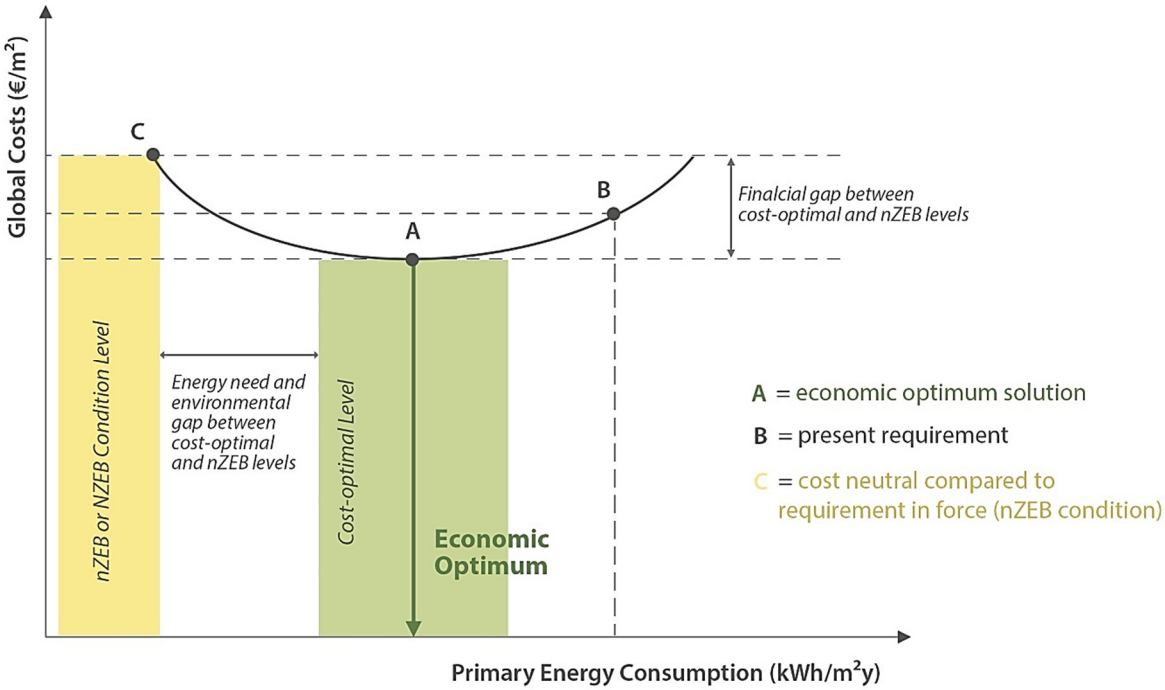

Figure 1.7 - Cost-optimal level definition and representation based on present requirement and nZEB conditions

From the moment that 75% of buildings in the European Union are still energy inefficient, it is clear that the majority of these structures must undergo a retrofitting process by 2050, in order to reach climate neutrality target. According to Renovation Wave statements, nearly 35 million residential and non-residential units across Europe need significant renovations: thus, the annual renovation rate must increase to 3% or more, up from the current 1%.

Therefore, Article 8 of the Directive defines minimum energy performance requirements, which must be met by each Member State in the case of major renovations for non-residential buildings. Impositions are set also for the entire residential sector through the definition of a national trajectory, including different thresholds and requirements; however, these types of buildings will not be addressed or considered in the following discussion. In any case, while more flexibility is granted to Member States in defining their own trajectory for residential buildings, the adoption of "minimum energy performance standards" is mandatory for non-residential constructions. These standards are defined as rules imposed on each EU Country to ensure that non-residential buildings do not exceed the maximum energy performance threshold, based on primary or final energy consumption. Two thresholds must be defined with reference to the existing non-residential building stock as of January 1st, 2020, as follows:

- A maximum energy performance threshold so that 16% of the national non-residential building stock exceeds this threshold (16% threshold).
- A maximum energy performance threshold so that 26% of the national non-residential building stock exceeds this threshold (26% threshold).

Subsequently, each Member State must ensure, through minimum energy performance standards, that all non-residential buildings do not exceed:

- The 16% threshold by 2030;
- The 26% threshold by 2033.

In essence, this means that the energy consumption of all non-residential buildings must be:

- By 2030, less than 16% of the buildings with the worst performance will need to undergo an energy renovation process to improve their consumption.
- By 2033, less than 26% of the buildings with the worst performance will also need to be renovated.

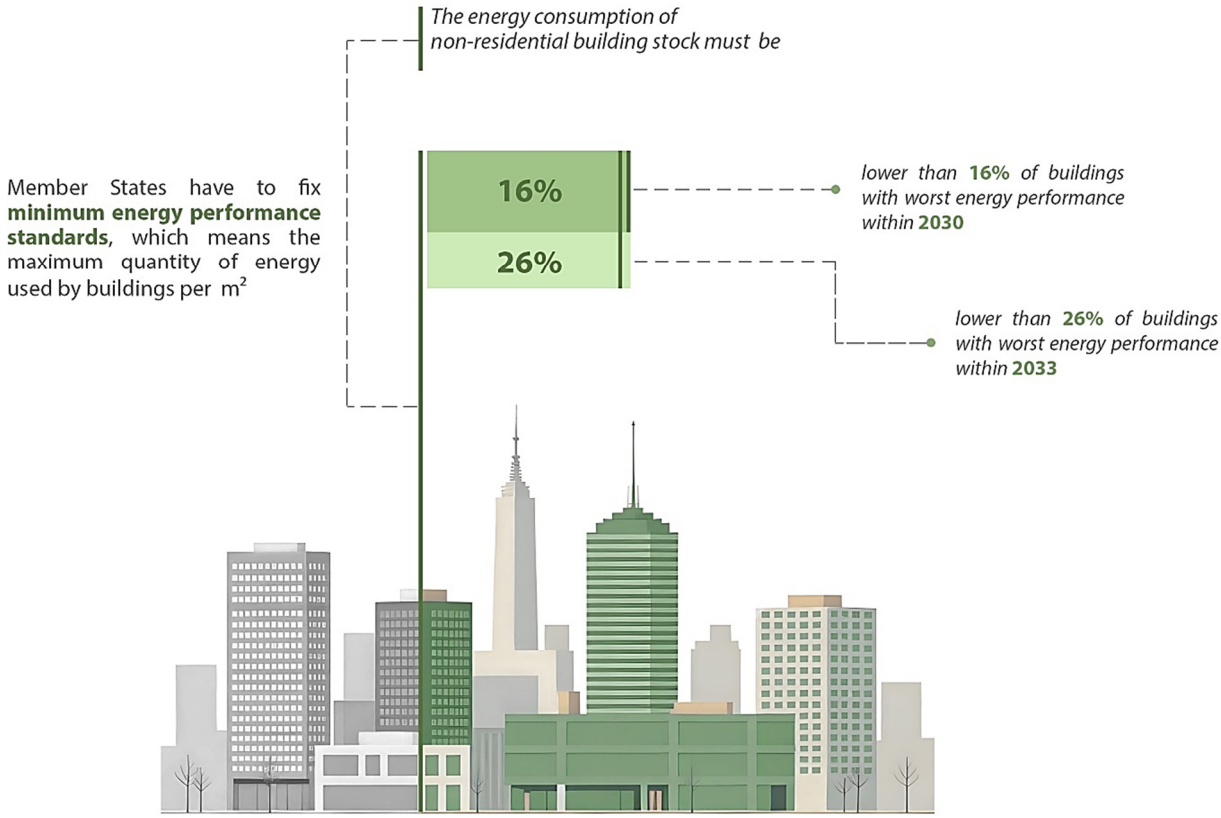

Figure 1.8 - Minimum energy performance standards and thresholds for non-residential buildings

In addition to the two thresholds set for the non-residential sector, an additional percentage of renovation will be required by the end of 2040. This intermediate target is established in order to ensure the ultimate transformation of the national building stock according to NZEB standards by 2050. Therefore, a continuous monitoring and implementation of effective retrofit strategies will be essential to achieve these milestones and transition towards a fully decarbonized built environment by that year, as shown in Figure 1.9 below.

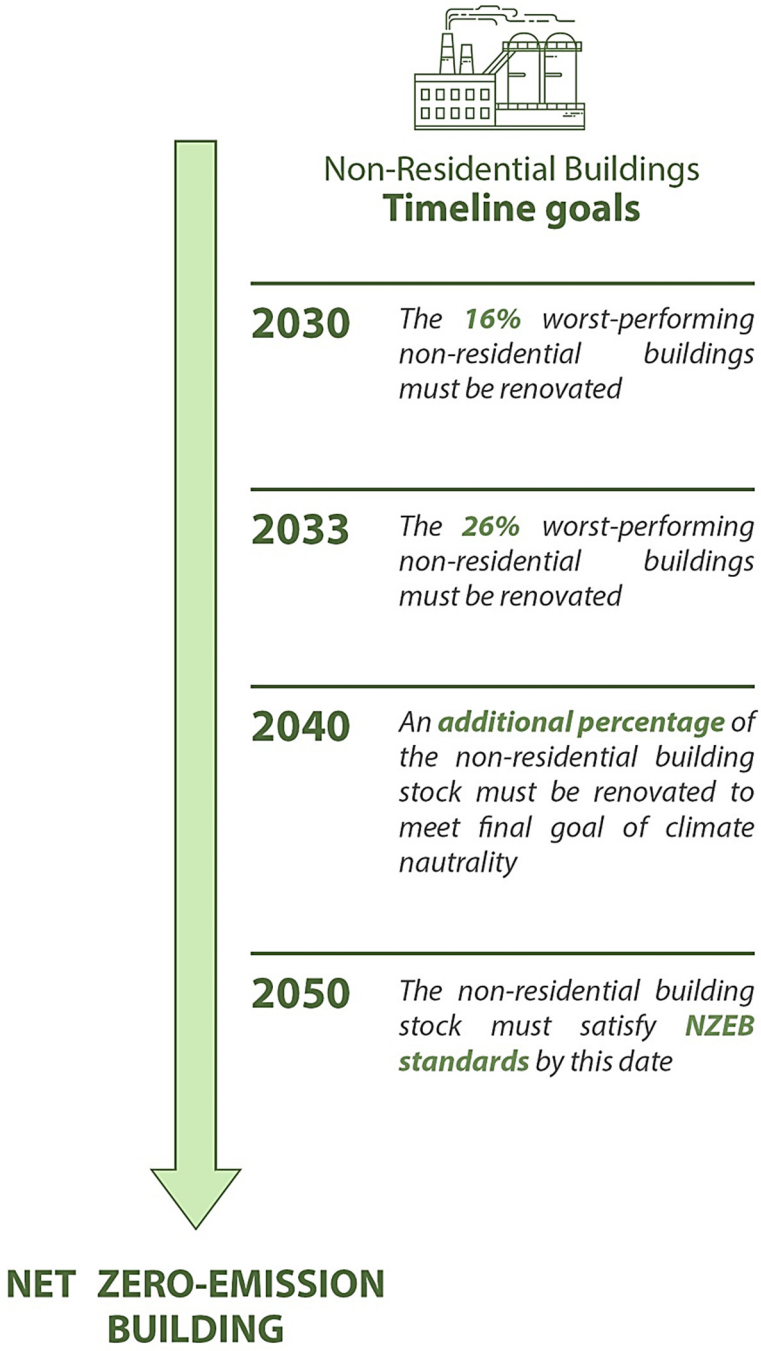

Figure 1.9 - Non-residential building stock timeline goals

1.5 How To Satisfy EPBD Requirements and Goals

As already underlined, the new version of the EPBD Directive (IV EPBD) introduces several innovative aspects and significant challenges for improving the energy efficiency of Europe's building stock. Among the key measures adopted, minimum energy performance requirements have been set for non-residential sector, while each Member State must present a national renovation trajectory for residential constructions, always following the timelines set out in the Directive. It is important to highlight that each step defined is not stand-alone but is part of a broader framework aimed at achieving climate neutrality in 2050.

Therefore, the path towards this objective follows a gradual approach, beginning with the introduction of plans and "renovation passports" at national level, with specific guidelines to be met by each Member State. In this initial phase, the priority will be improving the energy performance of both residential and non-residential buildings, with the ultimate aim of achieving zero-emission buildings as a last stage. It is clear that the time available to achieve these goals is very limited, particularly considering the progressive and urgent deterioration of global climatic conditions and increasingly stringent interventions. The challenge of retrofitting 16% of the non-residential building stock by 2030, in just five years, is already an extremely complex task. Moreover, the goal of meeting climate neutrality by 2050, although seemingly far away, is a close deadline, considering the amount of work that must be undertaken over the coming decades.

For these reasons, it is essential to explore and implement alternative renovation methodologies that can speed up the process and make the achievement of these objectives more realistic. As explained in the following chapters, by following an analysis of the Italian non-residential building stock, some innovative technologies will be presented, whose aim is to meet the requirements and timelines of the regulation. The goal is not only to address the 16% renovation target of non-residential buildings set for 2030, but also to move towards zero-emission buildings by 2050.

2. State of Art

The final goal of climate neutrality by 2050 cannot be achieved overnight, but undoubtedly requires a gradual approach, divided into several phases. For this reason, the main aim of this chapter is to identify the 16% of non-residential buildings belonging to the Italian building stock, presenting the worst energy performance, as these will be the main target for renovation process. This analysis represents the first step towards achieving an even more ambitious goal: reaching zero-emission buildings by 2050, as established by the EPBD Directive. Identifying and intervening in buildings with the worst energy performance is a fundamental step, as it will contribute to progressively improving the efficiency and consumption of the entire construction world, bringing it closer to the defined climate objectives.

Therefore, the following analysis is initially based on the evaluation and comparison of the Italian building stock based on the energy performance indicators provided by the individual certificates. To conduct the analysis, data from ENEA's annual reports and information from the SIAPE database, which represents the Information System on Energy Performance Certificates, have been considered. The evaluation was carried out on 13 different categories of non-residential buildings, with the worst performers being identified based on their construction year and heated usable floor area, expressed in square meters. The choice of the non-residential sector, as explained later, is due to its greater energy impact. Although in lower number, these buildings tend to consume a greater amount of energy than residential units. For this reason, they present significant potential for energy performance improvement, substantially contributing to the overall reduction of emissions in the building sector.

Given the lack of specific data regarding building energy performance from SIAPE, a more in-depth study was conducted within the Lombardy region using CENED data. This allowed for the collection of more detailed information about the thermal transmittance of building envelopes, as well as data on the types of heating, cooling, and ventilation systems in use. As a result, this more refined approach led to a thorough characterization of buildings with the lowest energy performance, culminating in the identification of a "typical building," which will be used as a case study for energy retrofit in the following chapters.

2.1 Energy Regulations Evolution within Italian Building Sector

Global warming and climate change have emerged as two of the most significant and urgent challenges of our time, having a profound impact on life quality and public well-being. Since the construction sector is responsible for 40% of energy use and 36% of greenhouse gas emissions, enhancing building's energy efficiency is a key step towards improving the state of our planet.

Europe has taken a leading role in sustainability with the ambitious targets outlined in the Green Deal, a series of policy initiatives proposed by the European Commission aiming at achieving net-zero emissions by 2050, translated into an initial reduction of at least 55% in greenhouse gas emissions by 2030. Italy itself has proactively embraced, and at time led, EU regulations focused on cutting energy consumption and boosting energy efficiency. Over the years, our country has introduced several fiscal incentives (including Ecobonus, Sismabonus, and the most recent Superbonus) to stimulate he renovation of its real estate sector.

However, the main regulations that influenced energy efficiency within the Italian building stock, listed in order of issuance, are as follows:

- Law 10/1991, which represents the first piece of Italian legislation to explicitly address energy consumption in buildings, making a significant step in the country's efforts to reduce energy use and mitigate the environmental impact of the building sector, mainly focused on reducing heating and cooling energy demand;
- Legislative Decree 192/2005, aimed to implement the provisions of European Directive 2002/91/EC, regulating the energy efficiency of buildings and making it mandatory to issue the Energy Performance Certificate (EPC) mainly for newly constructed buildings;
- Legislative Decree 311/2006, which represents an extension of the previous legislative decree, with the aim of correcting design criteria and methods for controlling building's thermal performance. The concept of energy performance index for winter heating[7] and the maximum thermal transmittance values[8] for the opaque vertical, horizontal, and transparent envelope structures were thus introduced.

---

[7] The energy performance index for winter heating (EPi), expressed in kWh/m² per year, is differentiated by climatic zones and based on the building's shape factor (expressed as the ratio S/V, where "S" is the heat loss surface area of the envelope and "V" is the heated volume).

[8] Limit values for thermal transmittance of the opaque vertical, horizontal, and transparent envelope structures, differentiated by climatic zones and with three temporal thresholds: January 2006, January 2008, and January 2010, the latter also introduced by Legislative Decree 311/2006.

- Legislative Decree 63/2013, which revises and updated regulations on the energy performance of buildings in line with Directive 2010/31/EU. The decree basically brings Italy's regulations into line with the European Union's Energy Performance of Buildings Directive (EPBD).
- Law 90/2013, further updates the regulations on energy performance, mandating that from 2019 all new buildings must be nearly zero-energy buildings (nZEB) as expressed in the previous Directive 2010/31/EU. Indeed, as of January 1, 2019, all newly constructed buildings occupied by public administrations and owned by them, including school buildings, must be nearly zero-energy buildings (NZEB).
- Minimum Requirements 26/06/2015, referring to the Ministerial Decree of June 26, 2015, which sets the minimum energy performance requirements for buildings, in line with European regulations. Indeed, buildings must meet minimum energy performance values, including thermal transmittance limits for the building envelope (walls, roofs, windows) and parameters for heating and cooling systems.

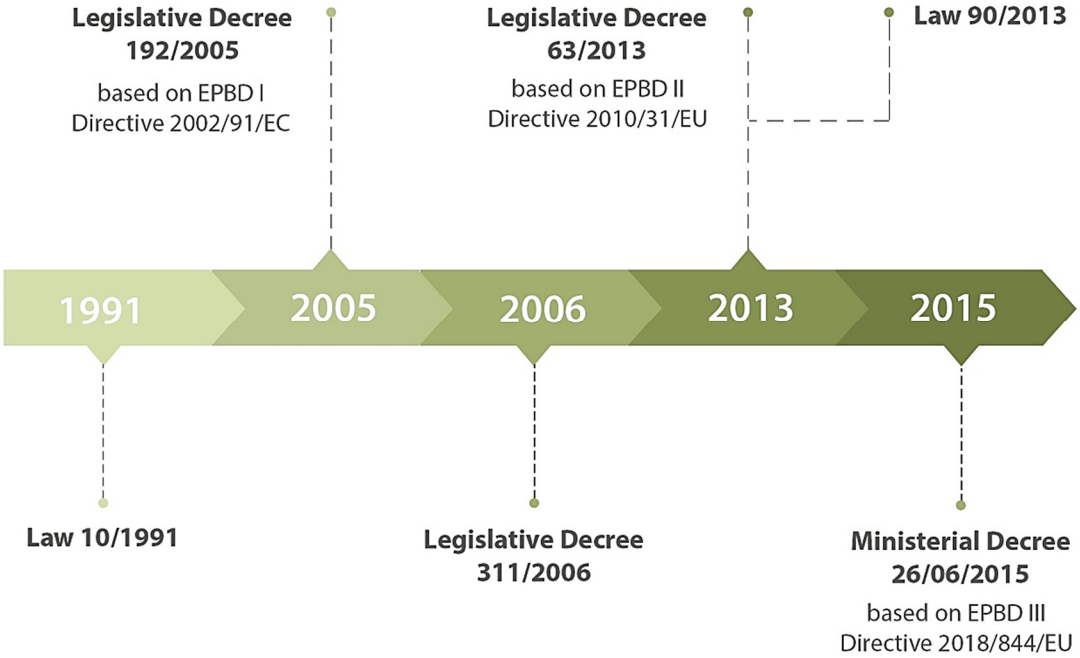

Figure 2.1- Evolution of main Italian energy regulations

2.2 General Analysis of Current Building Stock

The SIAPE (Energy Performance Certificates Information System) is the national tool for the collection of EPCs, which stands for Energy Performance Certificates. These documents have been mandatory since 2005 under Legislative Decree 192/2005 and have been implemented over the years from 2009 to 2015. The main function of this certificate is to monitor the energy

performance of Italian buildings and to provide an organized quantification as a comparison method [8]. This system was implemented by ENEA in 2016 and is fed with EPC data from the local land registries of Regions and Autonomous Provinces, as outlined by Ministerial Decree 26/06/2015. ENEA, indeed, represents the National Agency for New Technologies, Energy, and Sustainable Economic Development, an Italian public research entity operating in the fields of energy, environment, and new technologies to support policies for competitiveness and sustainable development.

As of 01/01/2025, although not representing the legal deadline for EPCs' inclusion issued in the previous year, SIAPE has recorded data on approximately 6,410,000 EPCs distributed between 2015 and 2024, submitted by 17 Regions and 2 Autonomous Provinces (Figure 2.2). Starting from January 7, 2025, the Campania Region will also be connected, with ENEA having already started a collaboration in 2023 for the development of the regional EPC data collection system. Currently, 8 regional databases have been implemented and are managed by ENEA across Italy, with the addition of the new information system "APE-CAMPANIA," created under a collaboration agreement [9].

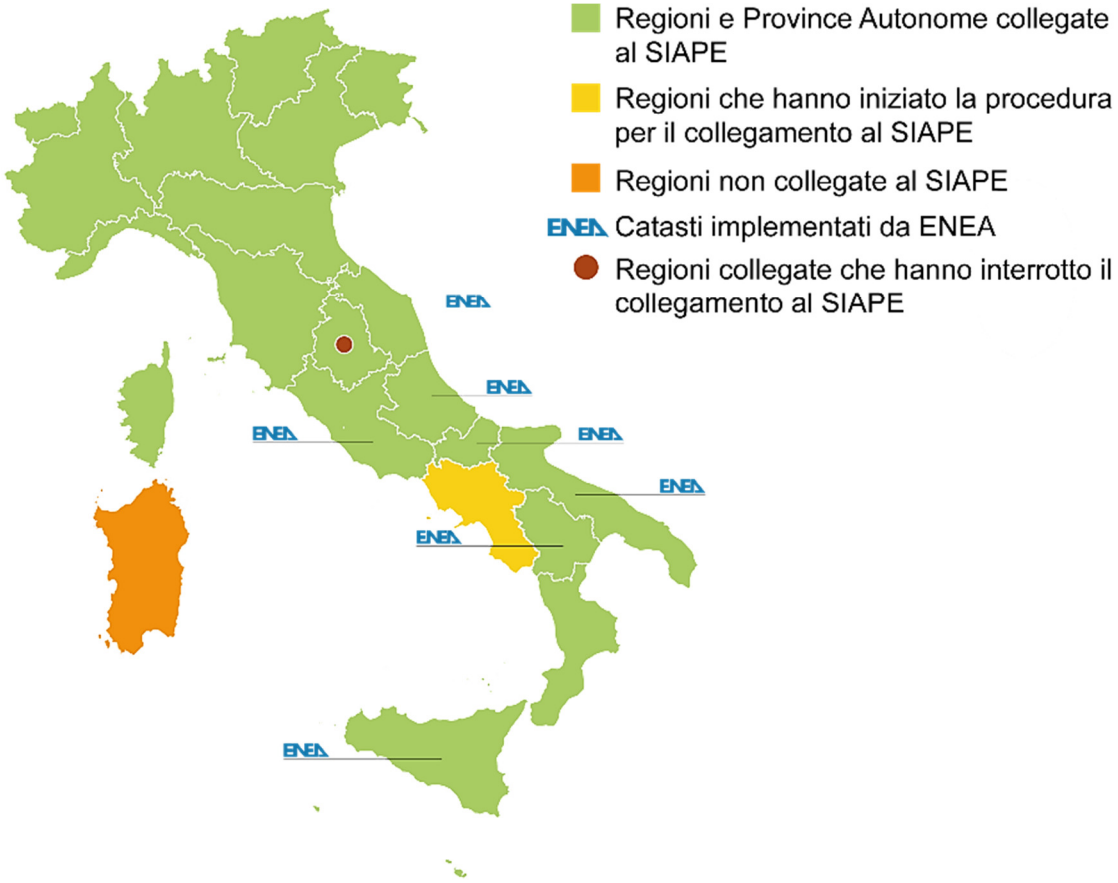

Figure 2.2 - National mapping of Regions and Autonomous Provinces connected to the SIAPE as of 01/04/2024 (ENEA processing)

The total number of energy certificates reported in the SIAPE database, as previously mentioned, includes both the residential sector with a total of 5,616,247 certifications and the overall category of non-residential buildings, which accounts for 792,936 certificates (Figure 2.3).

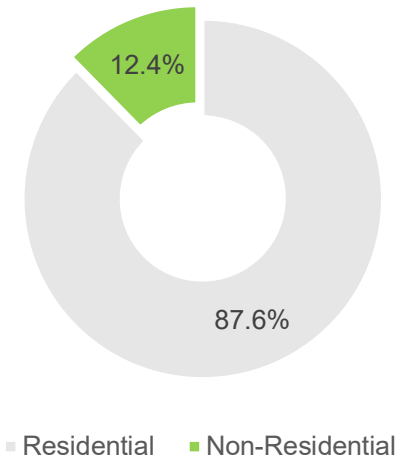

Figure 2.3 - Percentage of Residential and Non-Residential Buildings belonging to Italian Building Stock

As previously explained, the Energy Performance Certificates (EPC) analysis concerning the Italian building stock was carried out based on SIAPE database information. This data was derived from a sample that underwent preliminary review to identify and remove any errors or anomalies in the EPC entries. Specifically, the data sample was subjected to verification filters, which led to the elimination of approximately 16% of the original dataset, representing a 2% improvement compared to the previous year. Since the dataset is periodically revised, in the following report it is considered the most recent update from 2024. The parameters of the EPC analysed include:

- Issuance Year;
- Energy class;
- Climatic zone;
- Certificate issuing reason;
- Building construction period and year;
- Building use, along with its categorization and ownership type;

- Global Energy Performance Index (EP_{gl}), expressed in kWh/m² per year, which represents the total amount of primary energy required to meet the energy needs of a building (including heating, cooling, hot water, lighting, and other uses) per unit area. The non-renewable ($EP_{gl,nren}$) and renewable ($EP_{gl,ren}$) components are also indicated;
- Useful Thermal Performance Index for Winter Heating ($EP_{H,nd}$), expressed in kWh/m² per year, which is particularly related to primary energy consumption for winter heating, taking into account heat losses through the building's components and the efficiency of the heating system. The subscript “nd” indicates that the index is determined based on the useful thermal performance, referring to the energy required to maintain a satisfactory internal temperature, while excluding energy consumed for secondary uses, such as the provision of domestic hot water;
- CO_2 emissions, expressed in kg/m² per year;
- Performance indices for individual energy services (EP_H, EP_C, EP_W, EP_V, EP_L, EP_T) for both the non-renewable (EP_{nren}) and renewable (EP_{ren}) components, expressed in kWh/m² per year. These indicators are used to measure the energy consumption for specific energy-related functions within a building, evaluating at the same time the overall energy efficiency by assessing the demand for each service separately. The definition of these indices is provided by Italian regulations and standards, particularly the Ministerial Decree 26/06/2015, Annex 1, “Methodology for energy performance calculation” as explained below [10][11]:
    - EP_H is the Energy Performance Index for Heating, representing the total primary energy required for building’s space heating system per unit area;
    - EP_C is the Energy Performance Index for Cooling, corresponding to the total primary energy required for building’s space cooling system per unit area;
    - EP_W is the Energy Performance Index for Domestic Hot Water, which is the total primary energy needed for producing domestic/sanitary hot water;
    - EP_V is the Energy Performance Index for Ventilation, representing the total primary energy consumed by the mechanical ventilation system installed inside the building;
    - EP_L is the Energy Performance Index for Lighting, that is the total primary energy consumption for lighting system, considering both natural and artificial lighting;

- EP_T is the Energy Performance Index for People Transport, representing the energy required for the transport of people and stuffs, considering both elevators and escalators, not included for residential buildings;

By analysing the evolution of energy certificates for both the residential and non-residential sectors over time, it is possible to observe how and to what extent the energy performance of the Italian building stock has changed up to the present day. In order to carry out this analysis, it is necessary to understand and quantify the number of EPCs submitted to the SIAPE from 2020 until the end of the previous year, as a higher number of certifications will consequently lead to a greater consumption of primary energy for buildings' operation. Figure 2.4 below illustrates that the residential sector provides a significantly higher number of registrations compared to the total of non-residential buildings, as previously mentioned. Nonetheless, for both categories, a gradual increase in registrations is observed from 2020 to 2023, followed by a slight decrease in 2024.

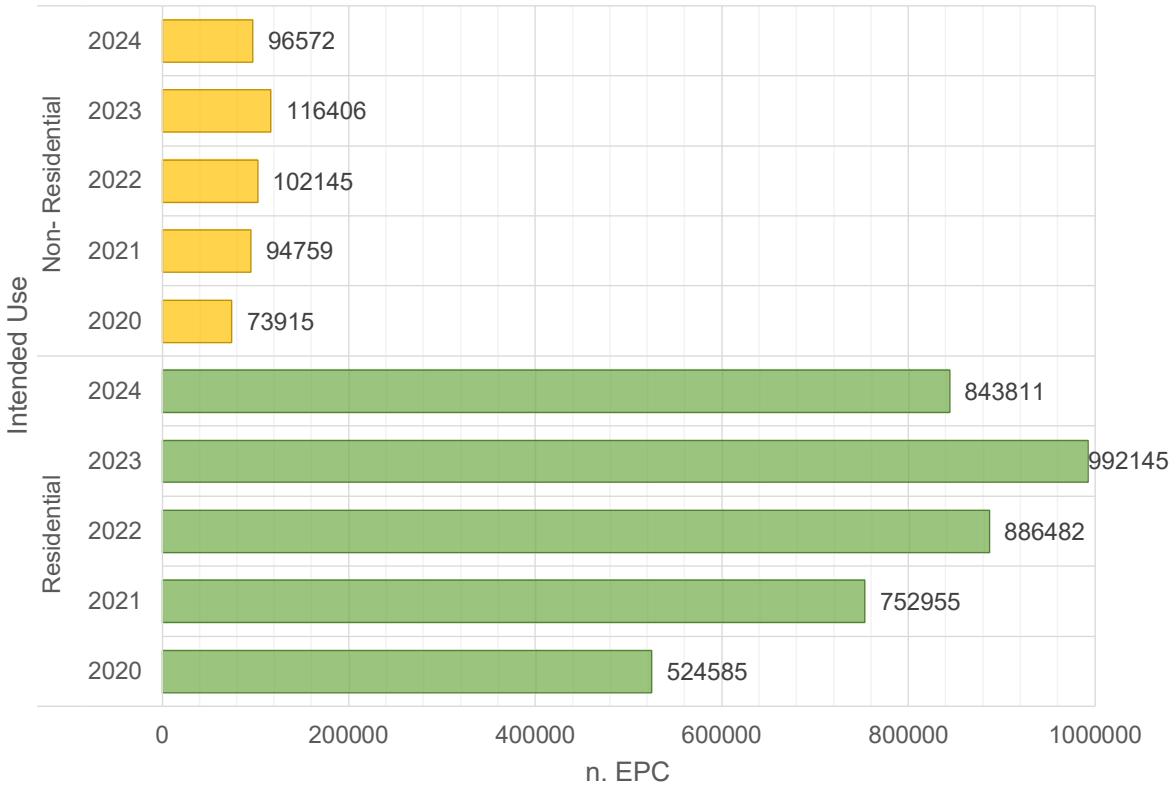

Figure 2.4 - Total number of EPCs submitted to SIAPE database for both residential and non-residential building sectors between 2020 and 2024

As previously stated, the Global Energy Performance Index (EP_{gl}) and its Renewable ($EP_{gl,ren}$) and Non-Renewable ($EP_{gl,nren}$) components serve as the primary benchmark for analysing the improvement or deterioration of energy performance in buildings, particularly from a sustainability perspective through renewable energy sources exploitation.

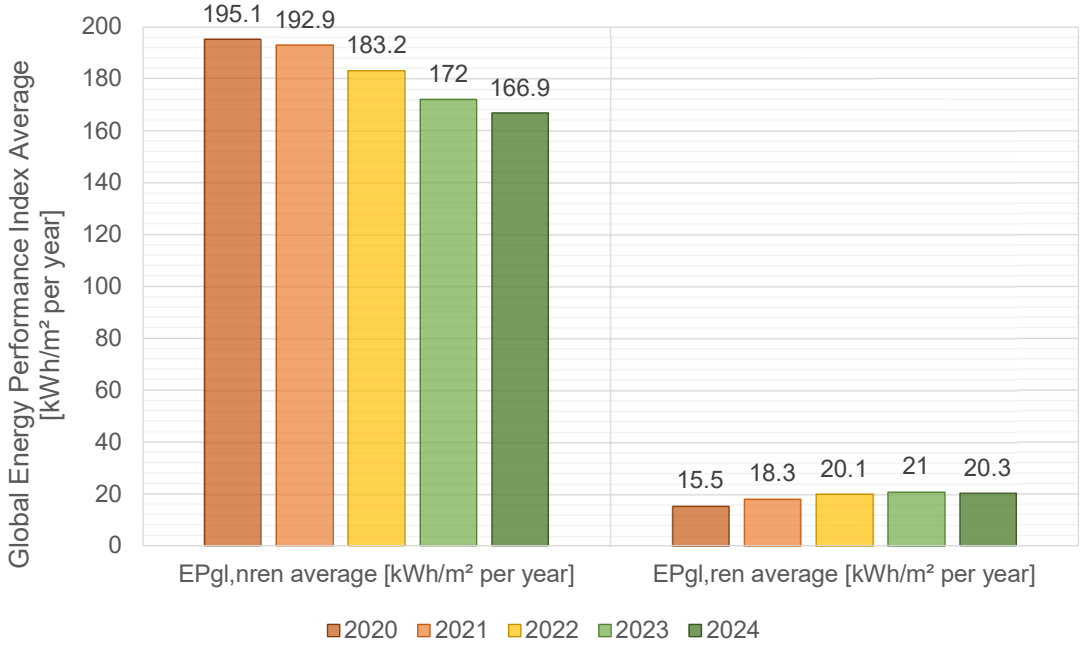

Figure 2.5 - Average values of Global Energy Performance Index ($EP_{gl,average}$), divided into renewable ($EP_{gl,ren,average}$) and non-renewable ($EP_{gl,nren,average}$) components for residential buildings from 2020 and 2024

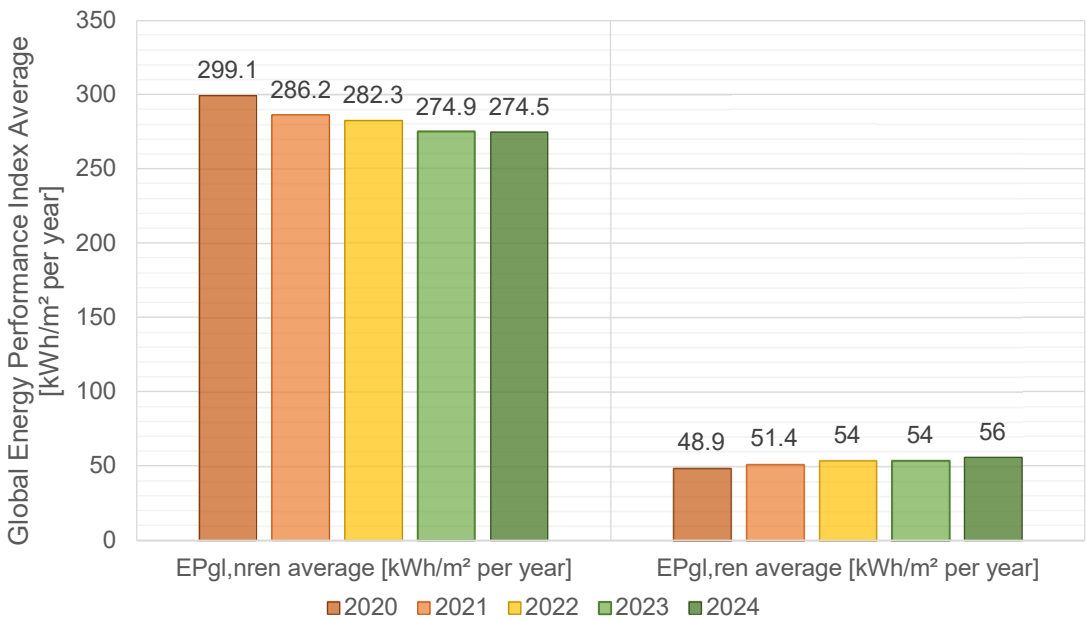

Figure 2.6 - Average values of Global Energy Performance Index ($EP_{gl,average}$), divided into renewable ($EP_{gl,ren,average}$) and non-renewable ($EP_{gl,nren,average}$) components for non-residential buildings from 2020 and 2024

The average index values distribution for certified buildings from 2020 to 2024 demonstrates an overall improvement in energy efficiency for both residential and non-residential sectors. As shown in Figure 2.5 for residential constructions and in Figure 2.6 for non-residential building stock, there is a general decrease in the average value of Non-Renewable Global Energy Performance Index ($EP_{gl,nren,average}$), which consequently results in a reduction of primary energy consumption required to maintain building's services. However, it is noteworthy that, in the residential sector, there was a slight decrease in energy consumption between 2020 and 2021, followed by a more pronounced reduction in 2024. In contrast, the non-residential sector shows a more consistent and steady reduction over time, apart from a more significant drop between 2020 and 2021. In any case, the $EP_{gl,nren,average}$ values are higher for non-residential buildings compared to those in the residential sector, as these categories of buildings, such as offices, shops, schools, require a higher energy demand not only for heating and cooling but also for lighting, ventilation systems, and other services.

On the other hand, the average value of Renewable Global Energy Performance Index ($EP_{gl,ren,average}$) shows an increase over time for both sectors, except for residential buildings, which report a slight decrease between 2023 and 2024. Again, the $EP_{gl,ren,average}$ values are higher for non-residential buildings, which can be related to the higher energy needs of these buildings and, consequently, to the greater availability of space for the installation of renewable systems, such as photovoltaic panels and solar thermal systems. Moreover, as non-residential buildings tend to be larger than residential ones, their capacity to generate and use renewable energy may be greater. In other words, despite having higher overall energy consumption, these buildings can compensate significantly for their energy demand through renewable energy production, especially in buildings equipped with photovoltaic or solar systems. Nonetheless, this continuous increase in the eco-friendly energy component signals a steady use of renewable sources for building operations, with a greater impact on heating and cooling systems. This is due to the range of incentives promoted at national level and the goal set by the European Union to achieve zero-emission buildings by 2050, in order to reduce the ecological footprint on the environment and meet energy efficiency standards.

Another key parameter for analysing buildings' environmental impact is the CO_2 emissions parameter, expressed in kg/m² per year, which represents the primary contribution to global warming. Indeed, this refers to the total amount of carbon dioxide released into the atmosphere due to energy consumption and other activities associated with building's operational systems. The following graphs illustrate the trend in average CO_2 emissions for residential sector (Figure 2.7) and non-residential one (Figure 2.8). It is immediately evident that the data shows higher values for the latter compared to residential category, likely related to the same factors mentioned for the Global Energy Performance Index (EP_{gl}). Nevertheless,

for both categories, there is a noticeable decrease, at times substantial and at other times slight, in CO_2 emissions between 2020 and 2023, likely due to policies and innovations that have improved this condition. On the other hand, while this decline continues for residential buildings, it is interesting to observe a slight increase for non-residential real estate in 2024. This increase observed may be the result of an upturn in economic activity, higher energy demand, or a non-residential buildings' number growth.

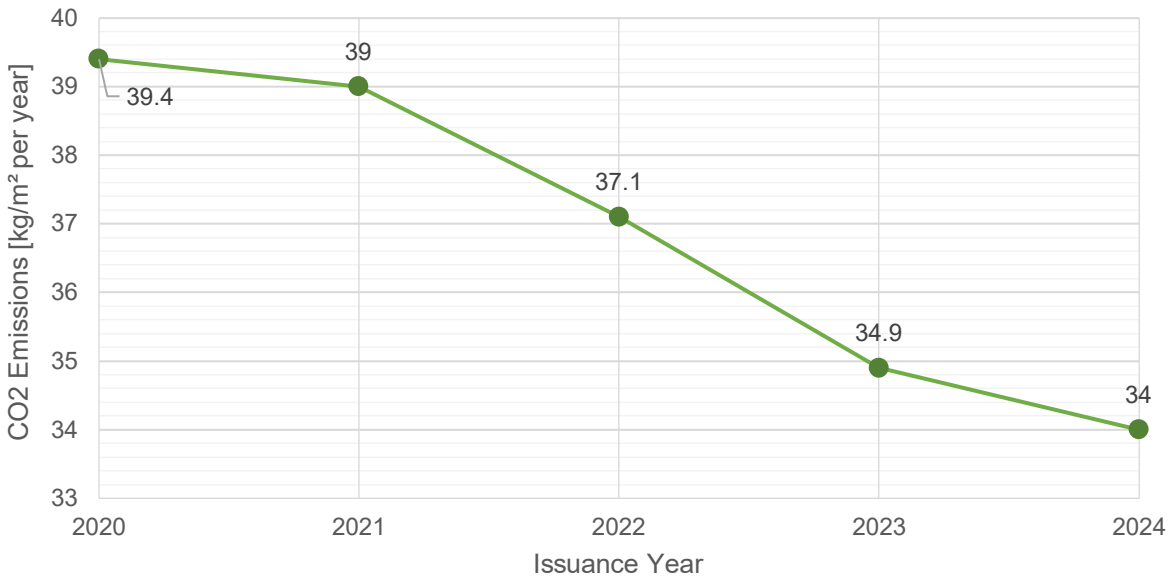

Figure 2.7 - CO_2 emissions between 2020 and 2024 for Residential Buildings

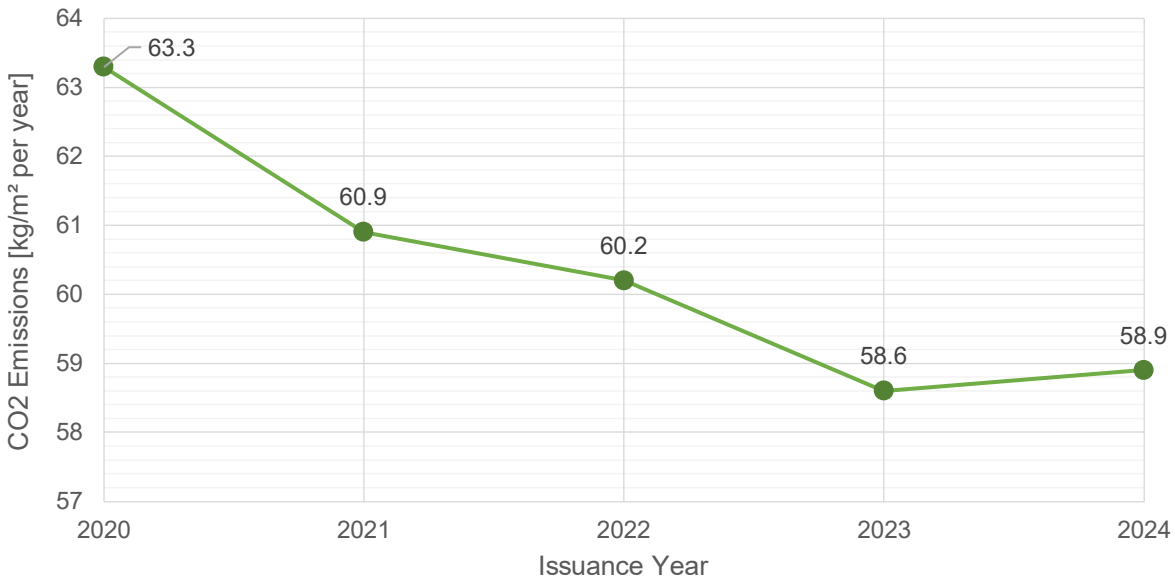

Figure 2.8 - CO_2 emissions between 2020 and 2024 for Non-Residential Buildings

2.2.1 Intended Use: Residential and Non-Residential Buildings Categories

According to the President of the Republic Decree, August 26, 1993, No. 412[9], buildings are classified based on their intended use into the following categories:

- E.1: Residential Buildings and Similar:
  - E.1 (1): Dwellings used for continuous residential purposes, such as residential and rural homes, boarding schools, convents, prisons, barracks.
  - E.1 (2): Dwellings used for occasional residential purposes, such as holiday homes, weekend homes, and similar.
  - E.1 (3): Buildings used as hotels, inns, and similar establishments.
- E.2: Office Buildings and Similar: Public or private offices, whether independent or adjacent to buildings used for industrial or craft activities, provided that they can be separated from these constructions for the purpose of thermal insulation.
- E.3: Healthcare Buildings: Buildings used as hospitals, clinics, or nursing homes and similar, including those for the care or shelter of minors or elderly people, as well as facilities for the assistance and rehabilitation of drug addicts and other individuals under public social services.
- E.4: Buildings for Recreational, Social, or Religious Activities and Similar:
  - E.4 (1): Such as cinemas, theatres, and conference halls.
  - E.4 (2): Such as exhibition halls, museums, libraries, and places of worship.
  - E.4 (3): Such as bars, restaurants, and dance halls.
- E.5: Commercial Buildings and Similar: Such as shops, wholesale or retail warehouses, supermarkets, and exhibition spaces.
- E.6: Sports Facilities:
  - E.6 (1): Swimming pools, saunas, and similar.
  - E.6 (2): Gyms and similar.
  - E.6 (3): Services supporting sports activities.
- E.7: Educational Buildings at all levels and Similar.
- E.8: Industrial and Craft Buildings and Similar.

---

[9] The Decree of the President of the Republic, August 26, 1993, No. 412 is an Italian regulation containing rules for the design, installation, operation, and maintenance of thermal systems in buildings, aimed at reducing energy consumption. It is implemented in accordance with Article 4, Paragraph 4, of Law No. 10 of January 9, 1991.

For each category mentioned, the total number of buildings having registered an energy certification within SIAPE database has been identified, where each subcategory's characteristics can be extracted through a data filtering system. Although the non-residential sector, as explained in the following sections, will be the main focus of the actual energy renovation, all categories have been considered in this initial phase to provide a more comprehensive analysis. Table 2.1 below represents the total number of Energy Performance Certification issued for each category of residential and non-residential buildings, followed by their percentage of incidence on the total number of buildings considered for the two respective sectors. This means that the percentages marked in grey represent the incidence on the total amount of residential properties, while the remaining ones in green correspond to the influence on the overall non-residential construction stock. Excluding category E1(1) of residential buildings for continuous use, which represent the highest quantity, the main categories highlighted are public or private offices (E2), commercial activities (E5), and industrial or artisanal activities (E8), which together account for 88.6% of the total number of non-residential buildings (Figure 2.9). Since the number of energy certificates issued for these categories represents more than two-thirds of the total for the non-residential sector, they will serve as the cornerstone on which the analysis will be focused.

Table 2.1 - Total number of Energy Performance Certifications issued for each category of residential and non-residential buildings and its related percentage of incidence of total number for each sector

Category	Number	Incidence [%]
E1(1)	5467100	97.3%
E1(2)	149147	2.7%
E1(1)bis	**4411**	0.6%
E1(3)	**16845**	2.1%
E2	**219968**	27.7%
E3	**7073**	0.9%
E4(1)	**2732**	0.3%
E4(2)	**2279**	0.3%
E4(3)	**33872**	4.3%
E5	**316824**	40.0%
E6(1)	**663**	0.1%
E6(2)	**5462**	0.7%
E6(3)	**2109**	0.3%
E7	**14710**	1.9%
E8	**165968**	20.9%

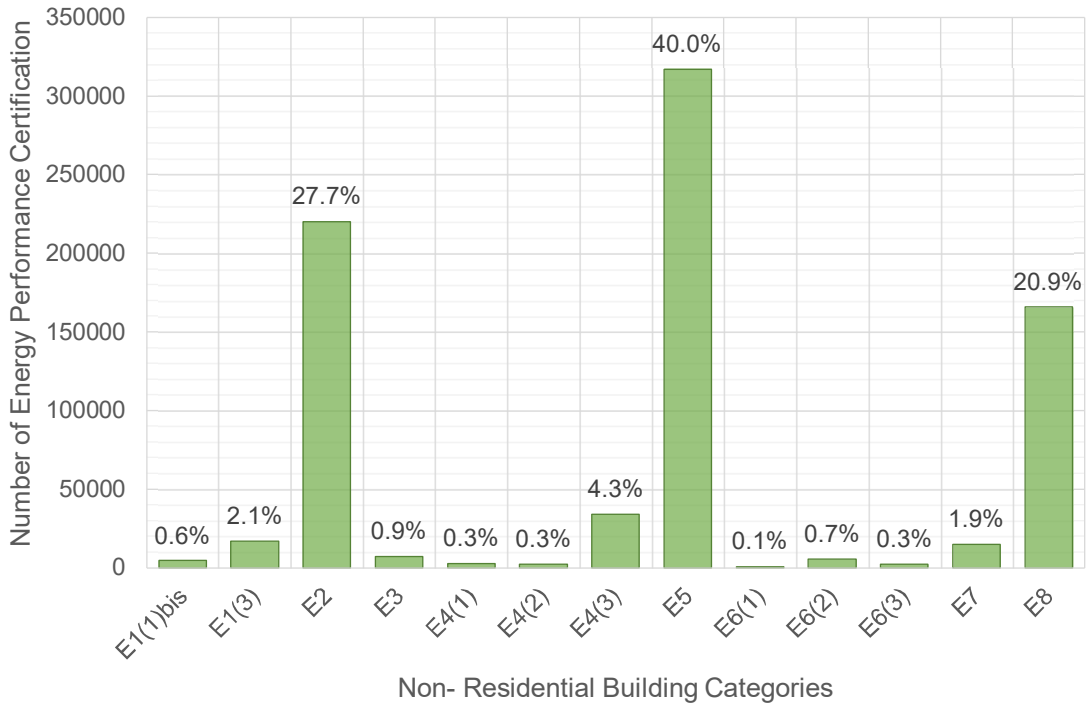

Figure 2.9 - Total number of Energy Performance Certifications issued for non-residential buildings and its related percentage of incidence of total number

2.2.2 Energy Class Classification

As previously explained, the Energy Performance Certificate (EPC) is a fundamental and mandatory document for buildings' characterization, introduced by Legislative Decree 192/2005 and later completed by Ministerial Decree 162/2015. Through this certification, each building is assigned to an energy class, which represents a score measured according to specific structural and functional parameters, in order to assess energy consumption and savings. At the same time, the new EPBD specifies that this classification must be modified by Member States in accordance with the newly imposed guidelines. Nevertheless, the classes currently defined at the national level are 10, ranging from class A4 to class G, as outlined in Figure 2.10 as:

- Class A4 represents the highest rank in the classification and refers to buildings with optimal energy performance, moving towards a concept of zero-emission buildings with no environmental impact. It is associated with consumption values equal to or below 0.40 EPgl.
- Class B includes many buildings characterized by good insulation and properly functioning windows, with consumption between 1.00 and 1.20 Epgl, and an average expenditure ranging between 31 and 50 kWh/m² per year, making it very low.

- Class C typically includes refurbished properties with consumption between 1.20 and 1.50 Epgl, requiring less than 50 kWh per square meter per year. This means they have structural and system characteristics that favor improvements in energy performance, such as a condensing boiler, thermostatic valves with low inertia on radiators, and attic insulation.
- Class D includes relatively recent buildings with consumption between 70 and 90 kWh/m² per year (1.50/2.00 Epgl), which are neither too low nor excessively high.
- Class E buildings are generally characterized by inadequate thermal insulation, external walls without cladding, poor window fittings, and consequently significant thermal dispersion and energy loss. These buildings consume between 90 and 120 kWh/m² per year.
- Class F is associated with buildings that have even higher consumption, ranging from 120 to 160 kWh/m² per year (2.60/3.50 Epgl), three times higher than class A. These buildings mainly belong to the group constructed between the 1970s and 1980s, which have never been renovated or upgraded, and are characterized by structural and system elements that are inadequate to limit thermal losses.
- Class G represents the lowest level in the energy classification, encompassing a large number of both residential and non-residential buildings. The energy inefficiency of buildings in class G leads to energy consumption up to 10 times higher compared to buildings in class A. In fact, the typical consumption for this classification exceeds 160 kWh/m² per year (>3.50 Epgl), mainly because they lack heating systems or have structural characteristics that fail to retain heat inside [12].

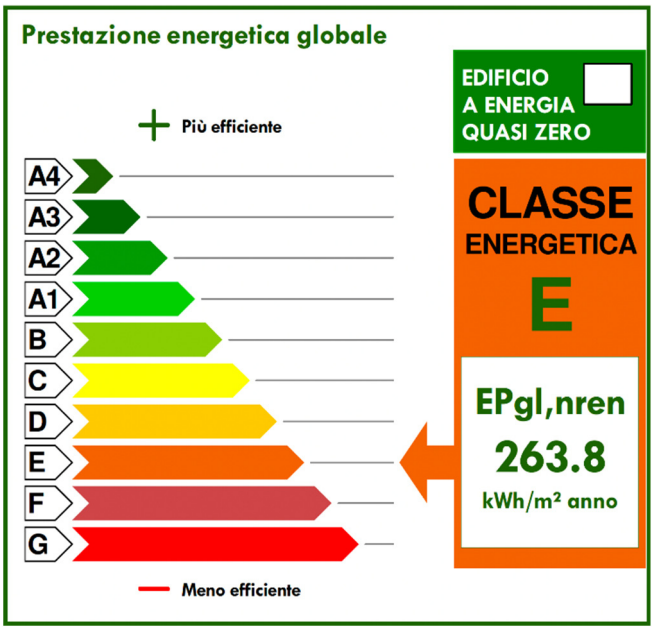

Figure 2.10 - Buildings energy classification according to Energy Performance Certificate

First, in Table 2.2 and the corresponding Figure 2.11, the distribution of energy classes for the residential sector is reported based on the energy certificates issued. It is noticeable that the graph follows an exponential trend visually, but not actually, as buildings in class G have a greater influence, both in terms of number and energy consumption, compared to class A3.

Table 2.2 - Number of buildings' energy certificates for each energy class considering the residential building stock

Energy Class-Residential	
A4	236478
A3	118890
A2	140815
A1	163530
B	188162
C	303624
D	608479
E	900789
F	1292401
G	1663079

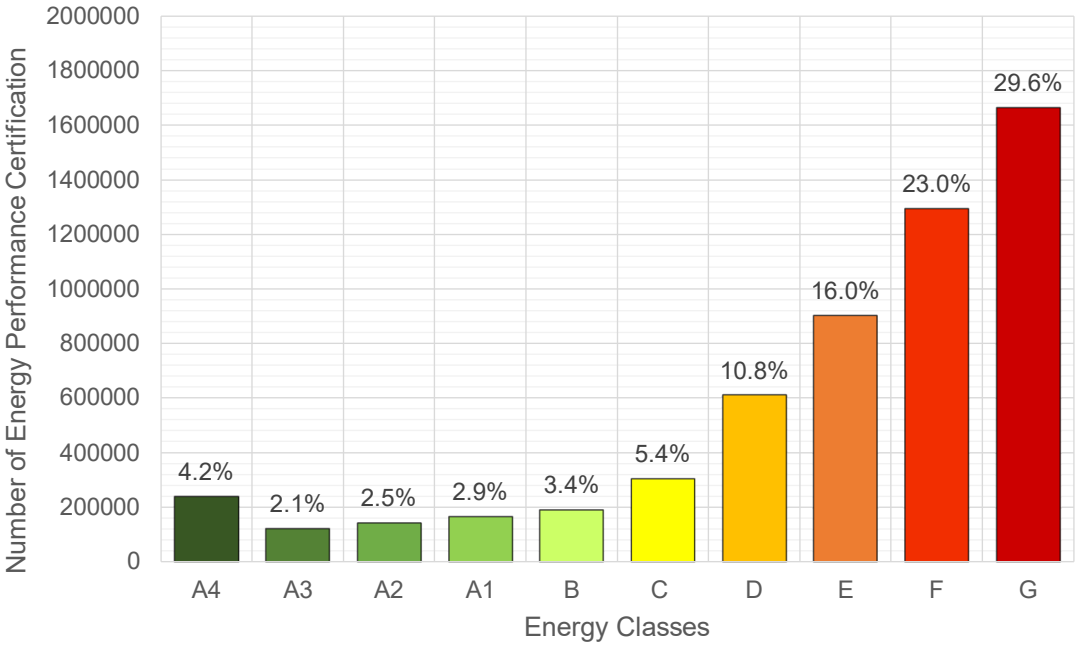

Figure 2.11 - Influence percentage of each energy class on total number of residential buildings

On the other hand, for the non-residential sector, it is noticeable that most buildings belong to the lower energy classes, from D to G, thus representing the largest number of certifications (Figure 2.12). Indeed, the number of energy certificates associated with buildings in class A (ranging from A4 to A1) is of little significance, even less so compared to the residential sector.

Table 2.3 - Number of buildings' energy certificates for each energy class considering non-residential constructions

Energy Class- Non Residential	
A4	10350
A3	10002
A2	16741
A1	28014
B	48567
C	97815
D	158623
E	141712
F	123318
G	157794

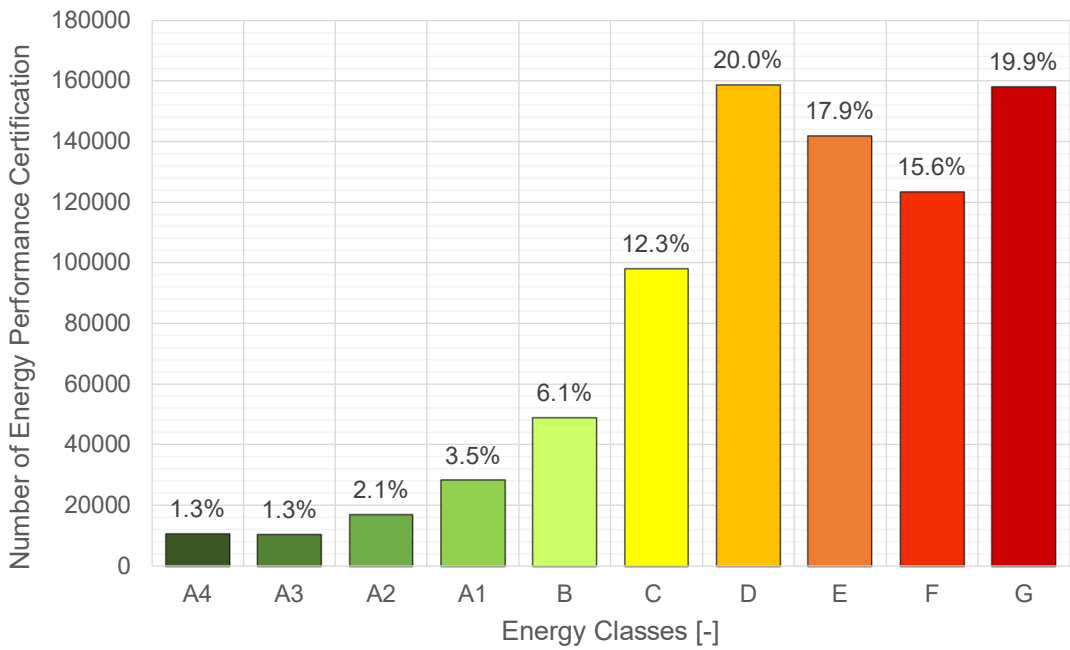

Figure 2.12 - Influence percentage of each energy class on total number of non-residential buildings

Although the percentage of buildings associated with energy classes E and D is higher than those in class F, the latter represent a greater influence in terms of overall energy consumption, as they present worse performances. For this reason, as will be explained in more detail in the following sections, the categories of buildings to be considered, in order to comply with the new Directive's requirements for energy improvement of the Italian building stock, are those with the highest consumptions: class F and class G.

2.2.3 Climatic Zone Distribution

According to DPR 412/93, the Italian territory is divided into 6 climatic zones, according to the type of climate and, therefore, to different ranges of degree-days. The most important parameter is represented by the Degree Days (DDs), expressed in °C, which indicates a measure of how cold or warm the temperature was on a given day of the year. It is calculated for each municipality by summing the positive differences between the internal comfort temperature (conventionally set at 20°C in summertime and 26°C in wintertime for Italy) and the external temperature. Once the annual sum is obtained, the municipality is placed into a climatic zone, which are labelled with 6 letters from the warmest (A) to the coldest (F) and defined based on intervals of degree days [13].

- Climatic zone A - degree days from 0 to 600. Included in this group are Lampedusa, Porto Empedocle, and Linosa;
- Climatic zone B - degree days from 601 to 900. This group includes the provinces of Agrigento, Catania, Crotone, Messina, Palermo, Reggio Calabria, Siracusa, and Trapani;
- Climatic zone C - degree days from 901 to 1400. Included in this group are Bari, Benevento, Brindisi, Cagliari, Caserta, Catanzaro, Cosenza, Imperia, Latina, Lecce, Naples, Oristano, Ragusa, Salerno, Sassari, and Taranto;
- Climatic zone D - degree days from 1401 to 2100. This group includes the provinces of Ascoli Piceno, Avellino, Caltanissetta, Chieti, Florence, Foggia, Forlì, Genoa, Grosseto, Isernia, La Spezia, Livorno, Lucca, Macerata, Massa Carrara, Matera, Nuoro, Pesaro, Pescara, Pisa, Pistoia, Prato, Rome, Savona, Siena, Teramo, Terni, Vibo Valentia, and Viterbo;
- Climatic zone E - degree days from 2101 to 3000. Included in this group are the provinces of Alessandria, Aosta, Arezzo, Asti, Bergamo, Biella, Bologna, Bolzano, Brescia, Campobasso, Como, Cremona, Enna, Ferrara, Frosinone, Gorizia, L'Aquila, Lecco, Lodi, Milan, Modena, Novara, Padua, Parma, Pavia, Perugia, Piacenza, Pordenone, Potenza, Ravenna, Reggio Emilia, Rieti, Rimini, Rovigo, Sondrio, Turin, Treviso, Trieste, Udine, Varese, Venice, Verbania, Vercelli, Verona, and Vicenza;
- Climatic zone F - degree days greater than 3001. Included in this group are the provinces of Belluno, Cuneo, and Trento.

Figure 2.13 shows the division of Italy in the different climatic zones.

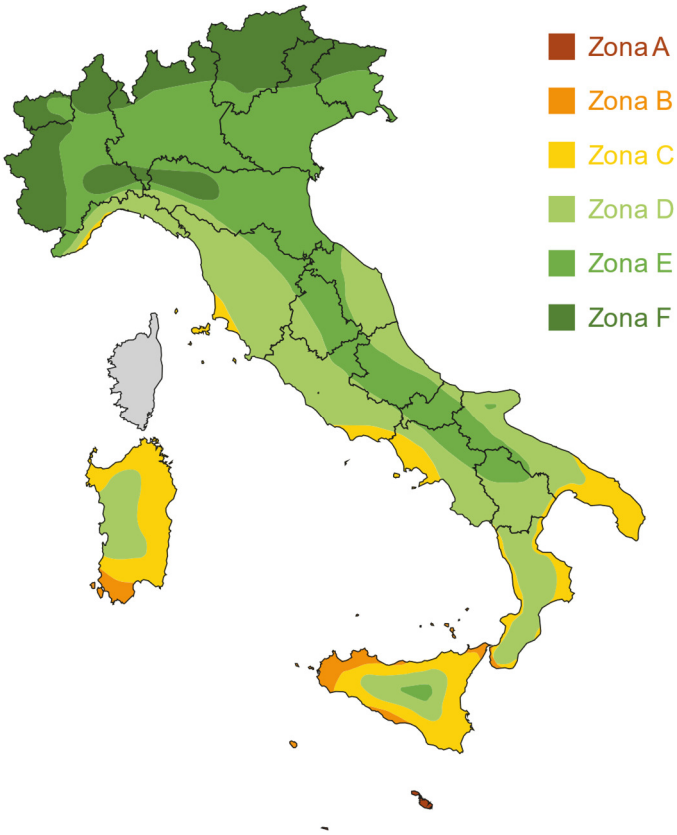

Figure 2.13 - Italian map for climatic zone division

Both for the residential and non-residential sectors, a significant number of energy certifications have been issued for climatic zone E, as shown in the following percentage diagrams. Figure 2.14 illustrates the number of energy certificates distribution for each climatic zone for the residential section, while Figure 2.15 is focused on the non-residential building stock. Indeed, 62.7% of residential buildings and 72.2% of non-residential constructions fall within the range of 2101 to 3000 heating degree days. This identifies a key characteristic of the most representative sample, which will be further analysed in more detail later, as the majority of certified buildings belong to this climatic zone.

Table 2.4 - Number of energy certification for each climatic zone for residential and non-residential building stock

Climatic Zone	Residential	Non-Residential
A	1282	121
B	177873	16552
C	494264	49284
D	1147159	128833
E	3518281	572769
F	277388	25377

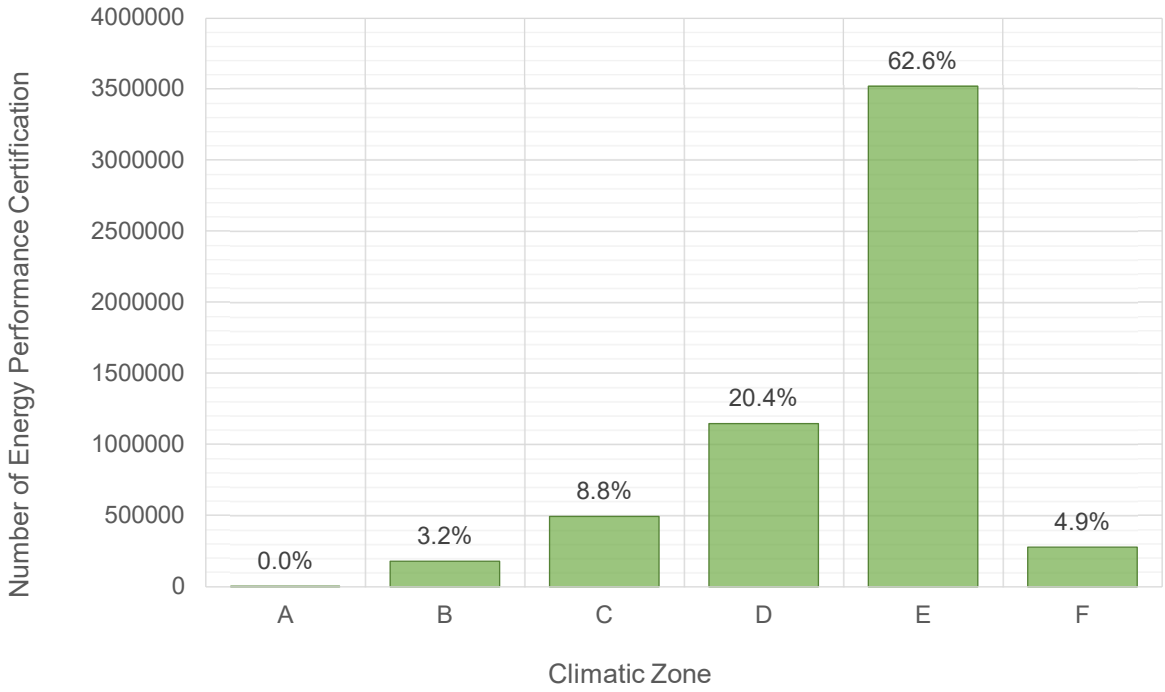

Figure 2.14 - Influence percentage of each climatic zone on total number of residential buildings

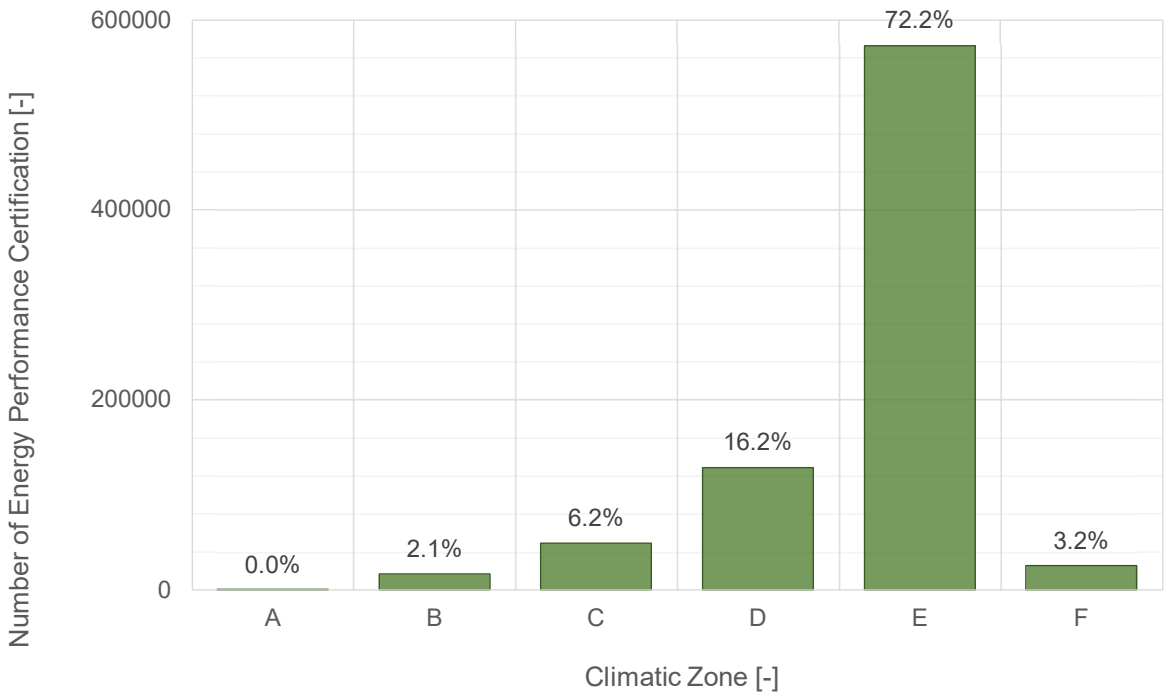

Figure 2.15 - Influence percentage of each climatic zone on total number of non-residential buildings

2.3 Non- Residential Building: National Level Analysis

Although representing the minority in terms of energy certificates issued and registered in the SIAPE database at national level, non-residential buildings are the main focus of this energy retrofit according to the new EPBD requirements. One of the key reasons for selecting this type of property is that buildings such as offices, shops, schools, and healthcare facilities are often more energy-intensive than residential buildings. Indeed, these buildings tend to have longer operating hours, more complex heating and cooling systems, and a higher use of technological and electrical devices. For this reason, even though they are fewer in number, their overall impact on energy consumption is significant due to their extended use, as shown in Figure 2.6. Furthermore, energy retrofit projects for non-residential buildings can lead to significant cost savings for businesses, while investing in energy improvements can reduce long-term operational costs, representing a major incentive for many commercial and public entities.

In line with the forth version of the Energy Performance of Buildings Directive requirements, the primary goal of the following analysis is to identify buildings with the worst energy performance within the entire Italian building stock. In particular, the focus is on identifying the 16% mandated by the Directive, which must be improved by 2030 (with the percentage increasing to 26% by 2033). As previously outlines, this step is not an isolated action: rather, the renovation of this apparently small portion of the non-residential real estate will represent a crucial part of the broader effort towards achieving climate neutrality by 2050. This means that non-residential buildings belonging to the worst energy classes (F and G) will need to undergo an energy retrofit process in order to improve their performance, thus moving to a higher classification level. This process will be the basis of the long-term goal of reducing emissions and ensuring a more sustainable built environment.

2.3.1 General Considerations

In order to outline this group of underperforming properties, the following section analyses all the categories of non-residential buildings presented in subparagraph 2.2.1. As shown in Table 2.5, the total number of energy certificates for each category is highlighted based on SIAPE data, and consequently, the number of buildings in the two worst-performing classes, F and G, is also provided. The third and fourth column of the table, instead, represent the incidence of construction in class F and class G, respectively, related to the individual number of each category (N° tot), and not compared to the total number of non-residential buildings.

As previously stated, the non-residential building categories with the highest number of energy certificates in both class F and class G are offices (E2), commercial or craft activities (E5), and

industrial activities (E8). This means that these types of buildings have a negative impact on building sustainability, as they significantly contribute to non-renewable resources consumption and greenhouse gas emissions on our planet.

Table 2.5 - Total number of Energy Performance Certificates (EPC) issued and registered in SIAPE database for all non-residential buildings categories, including certificated placed in F and G energy classes

Category	N° tot	% Cat. F	% Cat. G	N° F	N° G
E1(1) bis	4411	20.10%	25.50%	887	1125
E1(3)	16845	9.70%	9.70%	1634	1634
E2	219968	**15.20%**	**14.80%**	**33435**	**32555**
E3	7073	8.20%	6.50%	580	460
E4(1)	2732	10.00%	13.20%	273	361
E4(2)	2279	14.30%	15.00%	326	342
E4(3)	33872	7.70%	10.20%	2608	3455
E5	316824	**16.10%**	**18.50%**	**51009**	**58612**
E6(1)	663	8.90%	13.40%	59	89
E6(2)	5482	11.80%	11.70%	647	641
E6(3)	2109	10.70%	14.90%	226	314
E7	14710	12.30%	8.00%	1809	1177
E8	165968	**17.90%**	**34.30%**	**29708**	**56927**

Considering the total number of non-residential buildings registered in the SIAPE database, which amounts to 792,936 energy certificates, the sum of buildings in categories E2, E5, and E8, in both class F and class G, represents about 33% over the total non-residential properties. This is a crucial point for the following analysis, as it far exceeds the minimum threshold of buildings that need to be retrofitted, required by the IV EPBD document. Moreover, as shown in Table 2.6, when analysing the individual energy classes F and G, the percentages do not deviate significantly from the 16% threshold set by the regulation. Indeed, when adding the energy certificates for offices (E2), commercial activities (E5), and industrial activities (E8) and comparing them to the entire non-residential sector, 14.4% and 18.7% represent the total buildings in classes F and G, respectively.

Table 2.6 - Percentage of buildings in class F and G over the total number of non-residential sectors by summing all buildings belonging to category E2, E5 and E8.

	Data	Class F	Class G	Class F + G
E2+E5+E8	N. tot	114152	148094	262246
	% on tot	**14.4%**	**18.7%**	**33%**

Moreover, only considering the worst classes of non-residential sector, namely classes F and G, the three selected categories represent 92.7% and 93.9% of the certificates in classes F and G registered in SIAPE. This means that the largest contribution of buildings with poor energy performance, belonging to the two indicated classes, comes from these building categories. This highlights the relevance of the three classifications compared to all other sector subcategories, where the energy improvement of these constructions and the subsequent reduction of these values could become a key factor in achieving the goals of the new Directive EPBD.

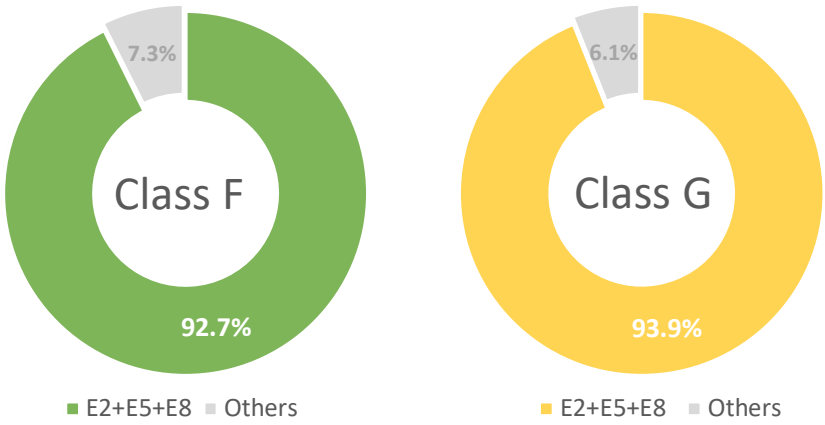

Figure 2.16 - Percentage of buildings in class F and G over the total number of non-residential buildings in class F and G obtained by summing all buildings belonging to category E2, E5 and E8.

2.3.2 From National to Regional Analysis

Once establishing that only E2, E5, and E8 categories would be subject to further investigations, with a more detailed focus on buildings' properties and characteristics, it was advisable to further simplify the Italian building stock. Indeed, since the SIAPE database provides a limited amount of information, as it does not offer any data related to building envelope's thermal transmittances and systems, a more detailed analysis at local level was necessary. After a careful evaluation, it was found that the CENED database offers an organized and sufficient level of information needed to conduct the study and identify the "typical building" subject to future renovation. This database, as will be explained more accurately in the following section, is the equivalent of the national SIAPE database but contains information specific to the Lombardy Region. In the subsequent parts of the study, reasons behind the regional choice are provided and explained.

As explained earlier, Italy's territory is divided into six different climatic zones, from A to F, based on climatic conditions and characteristic degree-day values (Figure 2.13). Based on SIAPE data, a national-level analysis was conducted to determine the incidence of energy performance certificates in the different climatic zones. Considering only the non-residential

sector, which accounts for a total of 792,936 buildings nationwide, Table 2.7 illustrates the total number of buildings belonging to each climatic zone and their share over the total number. As already highlighted in Table 2.4, 72.2% of non-residential buildings' total number is recorded in climatic zone E. This means that by considering only the energy performance certificates in this specific climatic zone, the data reliability exceeds 50%, even though not all non-residential buildings are taken into account.

Table 2.7- Number of energy certification for each climatic zone only for non-residential building sector, including its percentage over the total number

Climatic Zone	N. EPC	Percentage [%]
A	121	0.0%
B	16552	2.1%
C	49284	6.2%
D	128833	16.2%
E	572769	72.2%
F	25377	3.2%
All	792936	100.0%

Moreover, only considering buildings in class F and G, climatic zone E shows the highest number of cases in both categories, accounting respectively for 10.8% and 12.6% of the total non-residential constructions. These considerations are illustrated in Figure 2.17 for energy class F and in Figure 2.18 for class G, where a minimal influence from the other climatic zones is observed. However, these percentages do not differ significantly from those defined in Table 2.6, although slightly lower, as not all climatic zones are taken into account. Nevertheless, when considering the total number of buildings in both class F and G, their sum corresponds to 23.4% of the total.

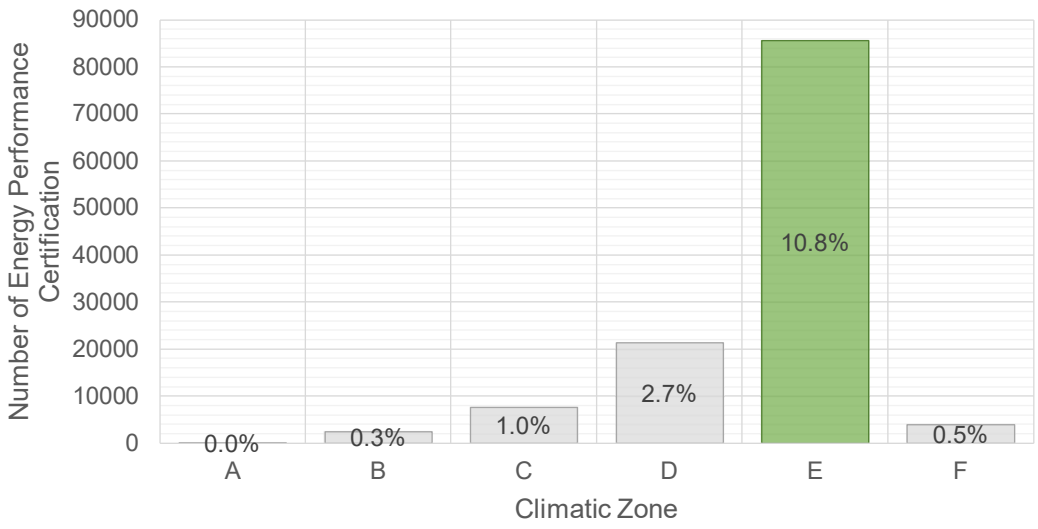

Figure 2.17 - Influence percentage of each climatic zone on total number of non-residential buildings in class F

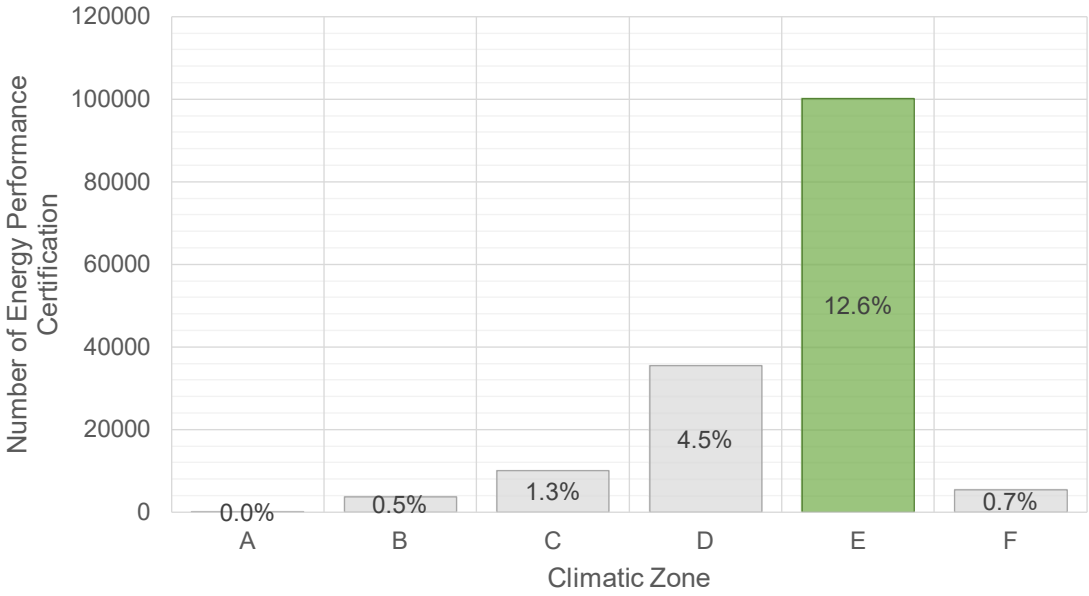

Figure 2.18 - Influence percentage of each climatic zone on total number of non-residential buildings in class G

Climatic zone E was chosen just due to its significant influence over the total number of non-residential buildings, proofing the validity of the selection of Lombardy Region as the analysis database. Indeed, this choice represents the link between regional-level analysis and national-level study, with the aim of applying approximations to facilitate the process.

By analysing data exported from different certification systems, the total number of non-residential buildings registered in Lombardy Region was determined, as shown in Table 2.8. In addition, two percentages are provided in the second and third columns: the first represents the incidence of buildings in the region relative to the total number on national scale, while the second refers to the proportion within climatic zone E. This means that the first percentage compares the number of non-residential buildings in Lombardy to national total, and the second compares it specifically to the number of constructions in zone E. Thanks to the data obtained, it was possible to conduct an analysis approximation at regional level in order to obtain all the necessary information, which was then extended and supported at the national scale. Indeed, since 53% of the energy certificates for non-residential buildings are issued in Lombardy, the research obtained was subsequently applied to the entire climatic zone E. This is because more than half of the buildings in this climatic zone are registered exclusively in Lombardy, significantly influencing the statistics compared to other regions in this area.

Moreover, given the significant influence of climatic zone E above all Italian energy certificates and the considerable impact of Lombardy itself, accounting for 38.3%, the reasoning was extended by approximation to the national level.

Table 2.8 - Total buildings number within Lombardy Region and its influence on national level and zone E

Area of Interest	N. tot	% on National Level	% on Zone E
Lombardy	303444	**38.3%**	**53.0%**
Zone E	572769	72.2%	-
National Level	792936	-	-

2.4 Non- Residential Building: Lombardy Region Level Analysis

As previously stated, the SIAPE database does not provide sufficient data to carry out the Italian building stock's characterization, as no information regarding the thermal transmittance of the envelope and the air conditioning systems specifications is made available to the public. For this reason, it was necessary to consult a new certification database able to provide all the relevant specifications: it turned out to be the CENED database.

The following section will analyse and classify all constructions located in Lombardy Region within climatic zone E, based on the technical specifications of building's envelope as well as of heating and cooling systems. An analysis was also conducted on systems such as mechanical ventilation and the use of renewable energy sources, considering the construction year and the heated usable floor area too. This study was essential in order to identify, for each category of non-residential buildings, a "typical building", which represents a structure with specific properties and characteristics that lead to poor energy performance. Indeed, this building will serve as the starting point for the energy retrofit process that need to be address to the entire European real estate, as expressed in the Directive.

2.4.1 CENED Introduction

CENED (acronyms of Energy Certification of Buildings) is the energy certification system for buildings in Lombardy Region, managed by ARIA S.p.A. (Regional Agency for Innovation and Procurement). This system operates as a regional accreditation organism for building energy certification and manages CENED activity in accordance with Article 10 of Regional Law 24/2014 and Regional Government Resolution No. VIII/5018 of June 20, 2007 [14]. As stated on their website, «among the main activities of the Accreditation Organism are:

- The development and management of the Regional Energy Building Register (CEER), which produces the Energy Performance Certificate (EPC) and the calculation engine, CENED+;

- The accreditation of the regional list of certifying bodies and training courses for professionals;
- Monitoring the compliance of EPCs;
- Updating the calculation procedure for determining the energy performance requirements of buildings;
- Providing technical-scientific consulting and assistance to local authorities and professionals for implementing building energy performance regulations;
- Enhancing the informational assets contained in the CEER»[10].

CENED is an essential tool as it provides a digital platform through which it is possible to register, update, and consult Energy Performance Certificates (EPCs) in accordance with regional regulations. Indeed, as mentioned on the organization's website, «CENED and ARIA S.p.A.'s Digital Information Hub have launched a collaboration aimed at enhancing the informational assets of energy certifications in Lombardy, with a particular focus on the perspective affected by the new EPBD Directive on energy performance in buildings»[11].

Since the initiation of the energy certification process in Lombardy, which took place more than sixteen years ago, over 3.5 million Energy Performance Certificates have been filed in the Regional Energy Building Register. As will be outlined in the following subparagraph, the energy certification databases provided by CENED consist of two main categories:

- 52% of the energy certificates are produced in accordance with the updated calculation procedure in compliance with the latest technical standards UNI TS 11300 (DDUO 6480/2015 and subsequent amendments) using the new CENED+2.0 calculation engine.
- 48% of the certifications were produced considering the regulations in effect up to October 1, 2015 (DDG 5796/2009) using the old CENED+1.2 calculation software [15].

The main difference between the two databases lies not only in the different energy certificates' issuance year, as CENED1.2 includes all certificates issued up until 2015, while CENED2.0 starts from that year and continues to the present day, but also in other parameters that distinguish them.

---

[10] ARIA Regional Agency for Innovation and Procurement, *Cened – Energy Certification: A New Way of Designing, Constructing and Living in Buildings* (2007), op. cit

[11] CENED Building Energy Certification, *Digital Information Hub and Cened: New Project for Data Visualization of Certified Buildings in Lombardy* (June 26, 2023), op. cit

2.4.2 Cened 1.2 & 2.0: Selected Parameters

As previously mentioned, CENED is composed and divided into two different databases according to the applicable regulations. Indeed, CENED1.2 contains all the information related to Energy Performance Certificates (EPC) registered before 2015, while CENED2.0 shows all subsequent and future ones. Several changes and updates have been made between the two information systems: the new database has been expanded in terms of parameters provided, but at the same time, some data present in CENED1.2 has not been retained in the new version.

Table 2.9 illustrates all the parameters considered for the analysis to be explained in the following sections, both related to CENED1.2 and CENED2.0, as they are named differently. It is important to note that some indicators are not present in both databases, but through appropriate consideration, it was still possible to obtain the necessary information. Regarding the thermal transmittance values of the building envelope, foundation, roof, and windows, these values are not available in the downloadable file from the website (CENED2.0). Therefore, it was necessary to consult an additional database, accessible through programming and code-reading software, where an association between these values and the practice identification code was established.

Table 2.9 - CENED1.2 and CENED2.0 parameters considered

Parameter	Database name	
	Cened 1.2	Cened 2.0
Practice identification code	CODICE_IDENTIFICATIVO_PRATICA	COD_APE
Non-residential sector	-	NON_RESIDENZIALE
Intended use	DESTINAZIONE_DI_USO	CLASSIFICAZIONE_DPR
Hole building selection	-	INTERO_EDIFICIO
Climatic zone	ZONA_CLIMATICA	ZONA_CLIMATICA
Construction year	ANNO_COSTRUZIONE	ANNO_COSTRUZIONE
Heated useful surface	SUPERFICIE_NETTA	SUPERF_UTILE_RISCALDATA
Energy class	CLASSE_ENERGETICA	CLASSE_ENERGETICA

Thermal transmittance of building envelope	TRASMITTANZA_MEDIA_INVOLUCRO	TRASM_MEDIA_OPACHI
Thermal transmittance of building roof	TRASMITTANZA_MEDIA_COPERTURA	TRASM_MEDIA_COPERTURA
Thermal transmittance of building ground floor	TRASMITTANZA_MEDIA_BASAMENTO	TRASM_MEDIA_BASAMENTO
Thermal transmittance of building windows	TRASMITTANZA_MEDIA_SERRAMENTO	TRASM_MEDIA_SERRAMENTI
Heating system generation type	TIPOLOGIA_GENERATORE	CI_TIPO_IMPIANTO_1
Heating system fuel type	TIPOLOGIA_COMBUSTIBILE	CI_VETTORE_ENERGETICO_1
Heating system efficiency	EF_GLOB_MEDIA_RISCALDAMENTO	CI_EFFICIENZA_MEDIA
Heating system nominal power	POTENZA_GENERATORE	CI_POTENZA_NOMINALE_1
Auxiliary heating system	-	CI_TIPO_IMPIANTO_2
Cooling system generation type	-	CE_TIPO_IMPIANTO_1
Cooling system fuel type	-	CE_VETTORE_ENERGETICO_1
Cooling system efficiency	-	CE_POTENZA_NOMINALE_1
Cooling system nominal power	-	CE_EFFICIENZA_MEDIA
Ventilation system type	TIPOLOGIA_VENTILAZIONE	VM_TIPO_IMPIANTO
Energy production from renewable energy sources typology	TIPOLOGIA_PANNELLO_ST	PFR_TIPO_IMPIANTO_1
	TIPOLOGIA_PANNELLO_FV	
Glazed surface percentage	SUPERFICIE_VETRATA_OPACA	-

The definition of each parameter considered is reported below:

- **Practice identification code**: it represents the number (code) through which each EPC is identified.
- **Non-residential sector**: the field contains the value "true" if only non-residential buildings are considered, selected for the analysis.
- **Intended use**: intended use of non-residential buildings pursuant to DPR 412/1993 and subsequent amendments. By using filters, it was possible to select only the relevant categories, namely E2, E5, and E8.
- **Hole building selection**: the field contains the value "true" if the EPC refers to the entire building, considered in the following analysis.
- **Climatic zone**: climatic zone definition on Italian territory, where zone E has been considered for the study.
- **Construction year**: building construction year, starting from before 1930 to after 2015.
- **Heated useful surface:** the heated useful surface of a building refers to the part of the building that is actually heated or intended to be heated and is expressed in square meters (m^2).
- **Energy class:** building energy class, where class F and class G have been considered in order to define the worst energy performance buildings.
- **Thermal transmittance of building envelope:** thermal transmittance average value of building's vertical structures, expressed in W/m^2K.
- **Thermal transmittance of building roof:** thermal transmittance average value of building's roof, expressed in W/m^2K.
- **Thermal transmittance of building ground floor:** thermal transmittance average value of building's ground floor (basement), expressed in W/m^2K.
- **Thermal transmittance of building windows:** thermal transmittance average value of building's windows expressed in W/m^2K.
- **Heating system generation type:** type of plant for winter air conditioning (CI).
- **Heating system fuel type:** energy carrier considered for heating air conditioning system.
- **Heating system efficiency:** average seasonal efficiency of the heating plant considered, not expressed in %.
- **Heating system nominal power:** nominal power for winter (heating) air conditioning system, expressed in kW.
- **Auxiliary heating system:** auxiliary type of plant considered inside the building for winter air conditioning (CI).

- **Cooling system generation type:** type of plant for summer air
- conditioning (CE). No value registered means no cooling system is considered inside the building.
- **Cooling system fuel type:** energy carrier considered for cooling air conditioning system.
- **Cooling system efficiency:** average seasonal efficiency of the cooling plant considered, not expressed in %.
- **Cooling system nominal power:** nominal power for summer (cooling) air conditioning system, expressed in kW.
- **Ventilation system type**: type of plant for mechanical ventilation VM. No value registered means just natural ventilation is considered.
- **Energy production from renewable energy sources typology:** type of plant for production of energy from renewable sources (PFR), including both photovoltaic panels and solar panels in this section.
- **Glazed surface percentage:** the ratio between the glazed heat loss surface area and the opaque heat loss surface area of the building subject to certification, expressed in square meters (m²).

2.4.3 Data selection

By downloading the two databases, it was possible to obtain all the registered information about certifications. Since many categories were not relevant for this study purposes, an initial data filtering phase was carried out in order to reduce the number of certificates analysed. In particular, only the three categories determined in the previous chapters - class E2, E5 and E8 - have been considered. Moreover, in each database, energy classes have been taken into account too, with a focus on the worst two classes, F and G.

Another fundamental parameter is related to buildings' configuration. Since the EPC could refer to only a small part of the building, and the entire structure might have different uses, only certificates for entire constructions were included. For the CENED 2.0 system, the "entire building" filter is available, while for the version 1.2, this option isn't directly selectable. In these cases, only certificate specifying thermal transmittance values for the roof and the basemen slab, thus indicating that the whole building is certified, were considered.

During the analysis, it was necessary to certificate the values associated o each parameter, as some data entries were inaccurate due to errors in certificate drafting. Indeed, values that were clearly incorrect have been excluded to ensure the most accurate representation of the non-residential sector in the analysed area. As a result of this selection process, the number

of EPC was reduced from around 3,500,000 to less than 60,000, allowing for easier data handling.

At the end of this preliminary selection, data was organized into separate arrays based on the category of use (which means the classification between offices E2, commercial activities E5, and industries E8), the energy class (F and G) and the database version (1.2 and 2.0). This characterization simplified the data to be handled, making it more organized and suitable for the analysis.

2.4.4 Data Analysis

In the following paragraph, the main parameters and procedures that will be used for the characterisation of each buildings category are listed below. First of all, parameters are divided into two classes: the first one is related to systems' configuration, while the second class considers the characteristics of the building itself.

2.4.4.1 Systems Evaluation

According to data availability and significancy, the systems are characterized based on:

- Heating system: boiler typology, main fuel and seasonal efficiency;
- Cooling system: presence or not;
- Ventilation type: presence of mechanical ventilation systems or natural ventilation;
- Renewable sources: production systems or systems that exploit them.

2.4.4.2 Construction Characterization

For what concerns the building typology, the following parameters have been analysed:

- Years of construction;
- Net surfaces distribution, which means considering the useful heated surface;
- Envelope's thermal transmittances and technologies.

As previously explained, the CENED database often contains some EPCs with incorrect data. For this reason, a threshold is set for each analysed parameter in order to delete possible errors and prevent the use of misleading values. Reducing the EPCs' overall number of around 20%. By combining the results of these classifications, a "typical building" can be identified and determined, which consists of a representative case of the majority. This building will turn out to be the starting point for the renovation process imposed by the Directive, meaning that the requalification should begin from those kinds of construction with worst performances.

2.4.5 Category E2 – Office Buildings

The first category analysed is related to office buildings, defined as class E2 within non-residential buildings classification. The following chapter will be focused on explaining in detail the performed evaluation, by showing the process behind the results obtained and the definition of the "typical building" for this group.

2.4.5.1 Overall Number – Category E2

After filtering data for the selected category, the number of certificated buildings obtained by merging CENED 1.2 and 2.0 is 13,858, among which 3,951 belong to class F and 9,907 to class G. Considering the total number of E2 category certificates in Lombardy, accounting for 97,202, the analysed classes represent the 14.3% of cases.

2.4.5.2 System Evaluation – Category E2

From the available set of information regarding building services explained above, the main typologies of systems have been analysed and compared.

The heating system was the first parameter to be considered, mainly characterised by the type of generator used for heating production and the fuel employed in the process. At first, classes F and G were evaluated separately and then combined to provide a comprehensive overview of the results. Varius types of generators have been identified based on the solutions used to provide thermal energy to the system. Therefore, for each class, the number of EPCs corresponding to specific typologies of generation is reported in Table 2.9 below, showing the results of the first analysis. As it possible to notice, the most commonly used generator type for both classes are the combustion boiler: this category includes all technologies that rely on combustion, typically of gas, for heating generation.

Table 2.10 - Types of heating generators for classes F and G

Typology	Class F	Class G
Cogeneration	3	-
Heat pump	314	614
District heating	196	286
Hot air generator	60	287
Infrared heater	12	39
Joule's effect generator	2	1
Combustion boiler	3325	8647
Biomass generator	-	1
Not defined	39	32

In Figure 2.19, the results of both classes are combined, and the share for each generator is reported. The majority of buildings present a combustion boiler for providing heating, with 86.4% of the overall number relying on this technology as heat source. Non-readable values have been excluded from the plot, to enhance the clarity of the diagram.

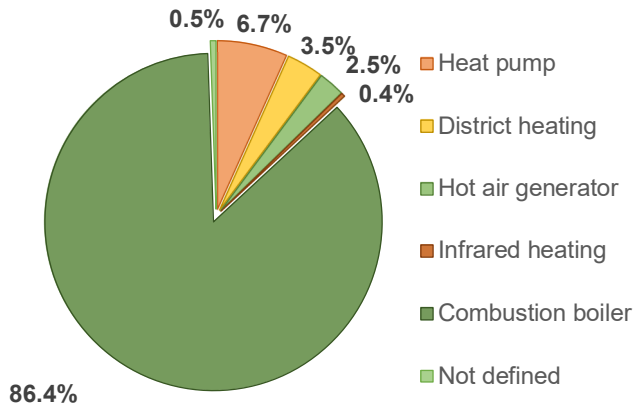

Figure 2.19 - Heating generators share diagram

A second analysis on the generation system was made by defining the energy vector used for heat production. As with the previous analysis, the shares for both energy classes are determined and then combined to have an overall result. Table 2.11 below presents the number of buildings for each fuel type: a significant number of buildings use natural gas for heating generation, followed by oil and electricity in minor quantities.

Table 2.11 - Types of energy vectors for heating generation for classes F and G

Typology	Class F	Class G
Natural gas	3293	8249
Oil	208	663
GPL	56	188
Electricity	223	655
District heating	112	74
Biomass	20	46
Not defined	39	32

The share of the total numbers is reported below. The primary fuel is natural gas, with 83.3% of buildings relying on it. Therefore, considering the previous results, a typical configuration of heating generation is composed of a combustion boiler, supplied by natural gas.

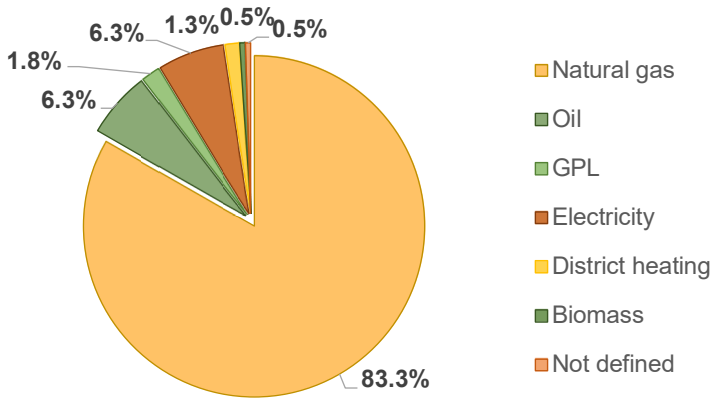

Figure 2.20 - Energy vectors for heating generation share diagram

The last parameter related to the heating system is the seasonal efficiency of the plant. Figure 2.21 below illustrates the frequency distribution of the heating system, for classes F and G, alongside the cumulative curves to better understand the overall trend of the results. The system exhibits varying levels of efficiency, with a large proportion – approximately 85% - falling below a seasonal efficiency of 0.8. The most common efficiency range is between 0.6 and 0.8, which accounts for 45% of the cases. This indicates that a significant number of buildings are equipped with heating systems that operate at relatively low efficiency levels, highlighting a potential area for improvement in energy performance.

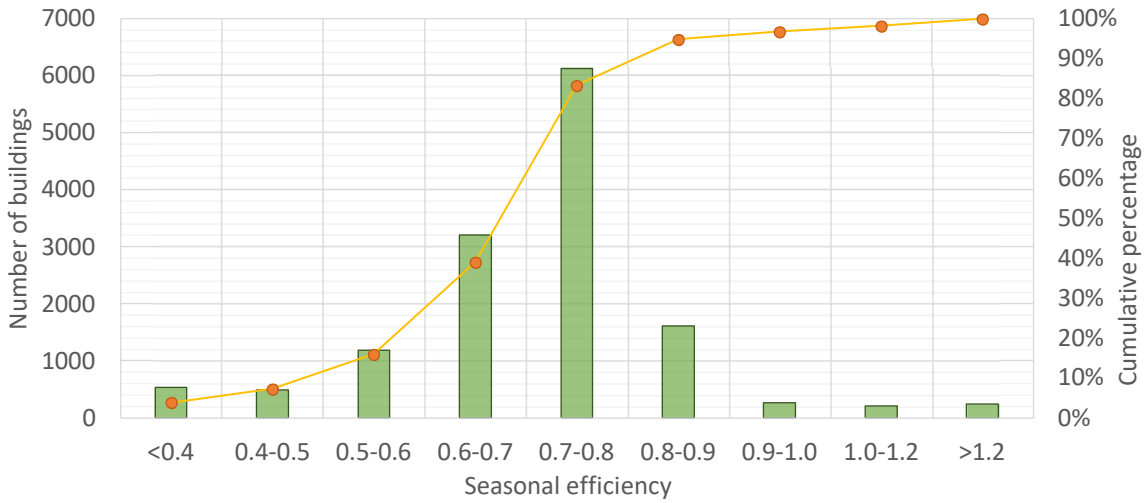

Figure 2.21 - Frequency chart of seasonal efficiency of heating systems

The cooling system is often absent in the analysed buildings, and for this reason it has been evaluated by checking the number of certificates with an active summer strategy. Since this information is only provided by the CENED 2.0 database, and a small percentage of cases features a cooling system, the absence of this plant is considered as the worst-case scenario.

Regarding mechanical ventilation, since the information is provided by both databases, a verification on its presence has been made. Figure 2.22 illustrates the percentage of buildings equipped with this technology, focusing on class F and G combined, considering both CENED 1.2 and 2.0. In the majority of cases the ventilation is natural, accounting for 91.5% of the total, while only 8.5% of buildings have mechanical ventilation systems.

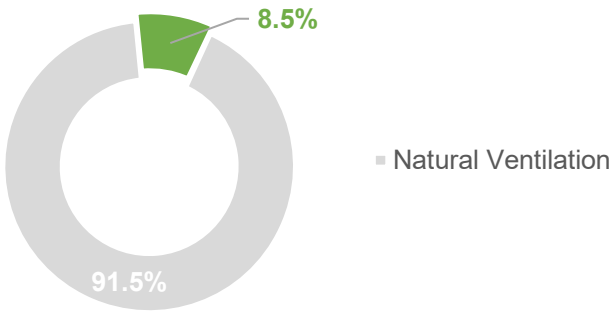

Figure 2.22 - Share diagram of ventilation typology

Renewable technologies in buildings are considered as energy production plants in databases, including systems such as photovoltaic and solar thermal panels, as well as generators supplied by renewable energy sources, such as biomass generators and heat pumps. Figure 2.23 illustrates the percentage of buildings that incorporate these renewable technologies, along with the types of systems installed. The data reveals that only a small fraction of certified buildings, almost 2.8%, have such systems, with the majority relying on photovoltaic panels. The graph on the right further breaks down the different types of renewable technologies installed, showing also in this case the prevalence of photovoltaic panels related to only 224 cases.

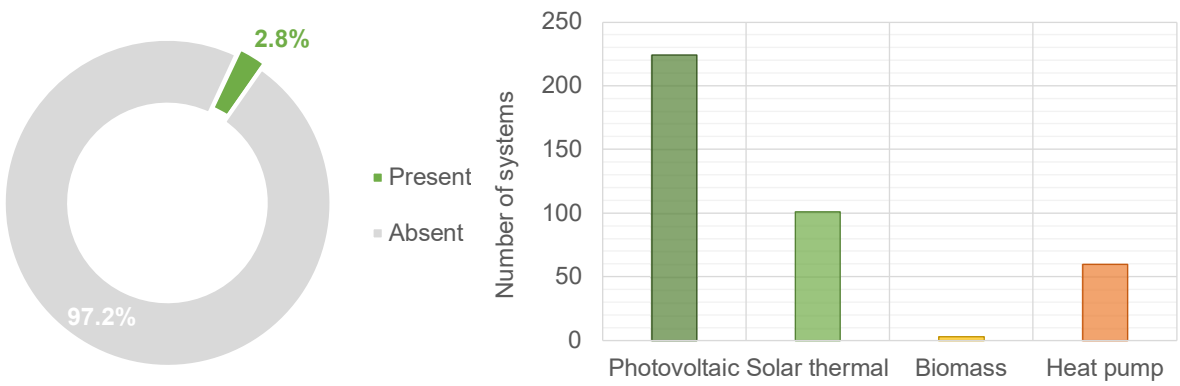

Figure 2.23 - Renewable technologies share diagram and types

2.4.5.3 Construction Characterization – Category E2

The second part of the analysis is the evaluation of construction characteristics to properly define the typology of buildings, as well as the technologies used for their construction. In this way, it was possible to understand how different configurations of buildings are distributed across the regional stock.

Firstly, the construction year for each building was categorized into 15-year ranges according to database definition, subdividing and grouping buildings with similar construction characteristics. In the chart below, the distribution of construction years for both database is presented. Approximately 50% of the analysed buildings were constructed between 1960s and 1990s, about 20.6% was built between nineties and the early 2000, while the remaining 30.6% is divided into buildings from before 1960 and after 2006.

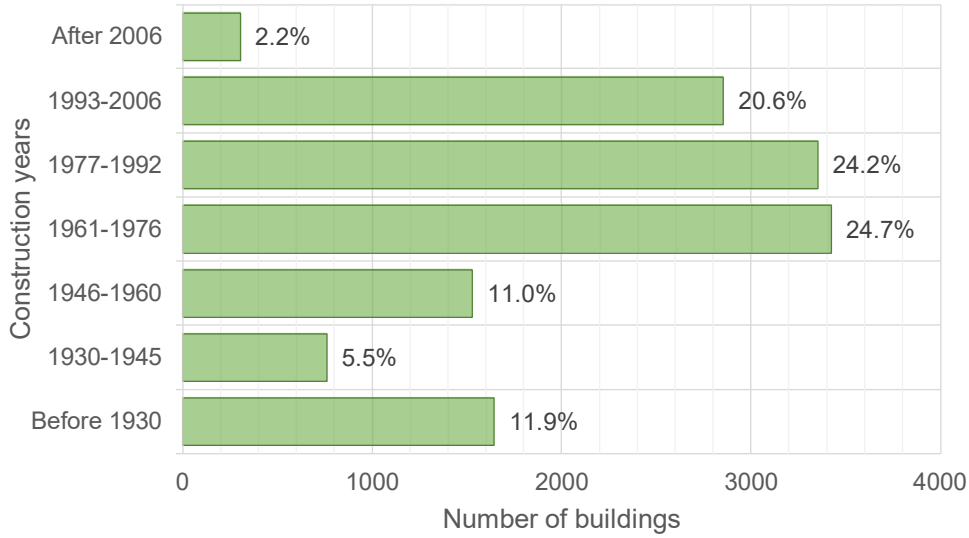

Figure 2.24 - Number of buildings for each construction years range

The useful heated surface is the second parameter considered to evaluate the number of square meters for buildings belonging to this category in the worst energy classes. Different surface ranges have been defined, in which constructions have been grouped and analysed. A total surface area is then calculated to assess the impact of strategies focused on larger buildings. The chart below shows the number of buildings in each range, along with the cumulative curve representing the sum of areas. The distribution of EPCs number highlights that most buildings have smaller surfaces, under 200 m^2, while buildings over 500 m^2 are less numerous. Even though many buildings fall within this configuration, a strategy targeting buildings larger than 200 m^2 would have a greater impact, covering approximately 70% of the total area of office buildings in energy classes F and G.

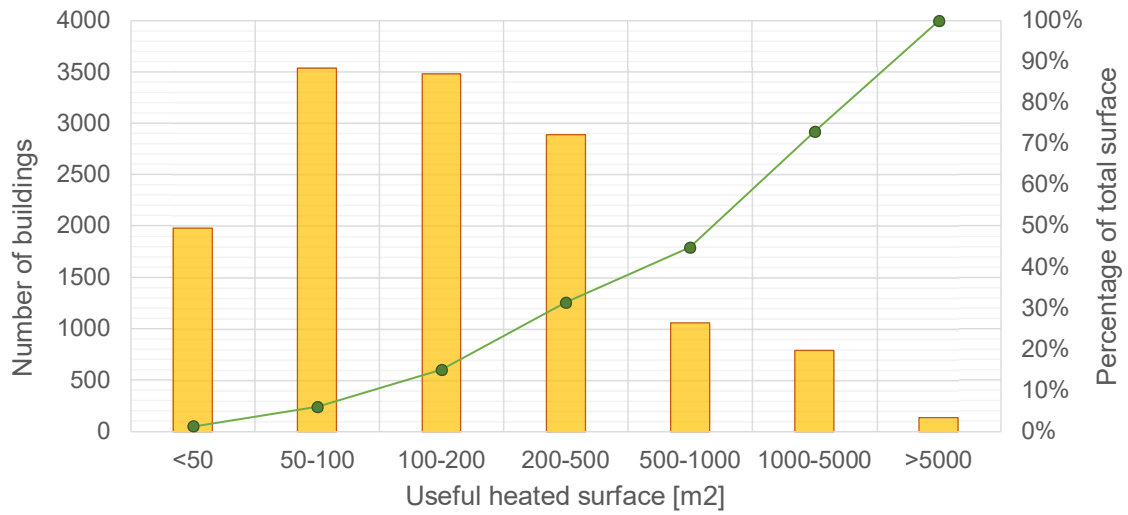

Figure 2.25 - Frequency chart of useful heated surface

Since office buildings' façades are often constructed with a curtain wall system, a brief evaluation has been conducted based on the data provided by databases. In CENED 1.2, there is a metric information called "Superficie Vetrata Opaca", which represents the ratio between transparent and opaque surfaces of the envelope. For this evaluation, a threshold of 50% was set to consider the impact of the roof and the basement floor, which are included in the ratio. The results, shown in Table 2.12, indicate that more than 99% of buildings have a percentage below the set limit, meaning they feature façades with a combination of opaque external walls and windows. For this reason, this will be the technology used for next phases' considerations.

Table 2.12 - Percentage of transparent surface of envelope

Transparent surface	N° EPC		
<10%	9563	**73.8%**	
10-30%	3131	**24.2%**	**99.5%**
30-50%	198	**1.5%**	
50-70%	36	**0.3%**	
70-90%	9	**0.1%**	**0.5%**
>90%	18	**0.1%**	

Based on the previous considerations, hypotheses regarding the typology of envelope stratigraphies were made. The databased provide thermal transmittance values for each external partition. As with the analysis of construction years, different year ranges have been considered, and an average thermal transmittance value was calculated for each stratigraphy. The average value for external walls, roofs, basement floors, and windows are presented in Tables 2.13 and 2.14.

Table 2.13 - Average thermal transmittance of envelope components - Class F

Average thermal transmittances of envelope [W/m2k] - Class F

Construction year	External walls	Roof	Basement floor	Windows
Before 1930	1.419	1.406	1.406	3.621
1930-1945	1.409	1.466	1.490	3.817
1946-1960	1.379	1.376	1.427	3.806
1961-1976	1.352	1.399	1.404	3.971
1977-1992	1.317	1.289	1.390	3.610
1993-2006	1.153	1.180	1.293	3.339
After 2006	1.066	1.019	1.146	2.889

Table 2.14 - Average thermal transmittance of envelope components - Class G

Average thermal transmittances of envelope [W/m2k] - Class F

Construction year	External walls	Roof	Basement floor	Windows
Before 1930	1.576	1.566	1.557	3.884
1930-1945	1.562	1.674	1.542	3.938
1946-1960	1.503	1.510	1.531	4.172
1961-1976	1.498	1.453	1.480	4.265
1977-1992	1.522	1.541	1.512	3.987
1993-2006	1.442	1.592	1.555	3.586
After 2006	1.206	1.392	1.369	3.189

To provide a clear visualisation of the results, a graphical representation of thermal transmittance values for each construction year range considered is shown in Figures 2.26 and 2.27. For both class F and G, the trend is similar: more recent constructions show lower thermal transmittance values across all components respect to older buildings, probably due to the increasing focus on energy efficiency in newer structures. However, even with these advancements and sensibility towards sustainability concepts, thermal transmittance values still remain relatively high compared to modern technologies that should comport better results. This is because, until 2015, there were no specific regulations or strict standards on thermal transmittance values. As a result, although newer buildings are more efficient than older ones, they still rely on outdated configurations and materials that lead to poor envelope performance.

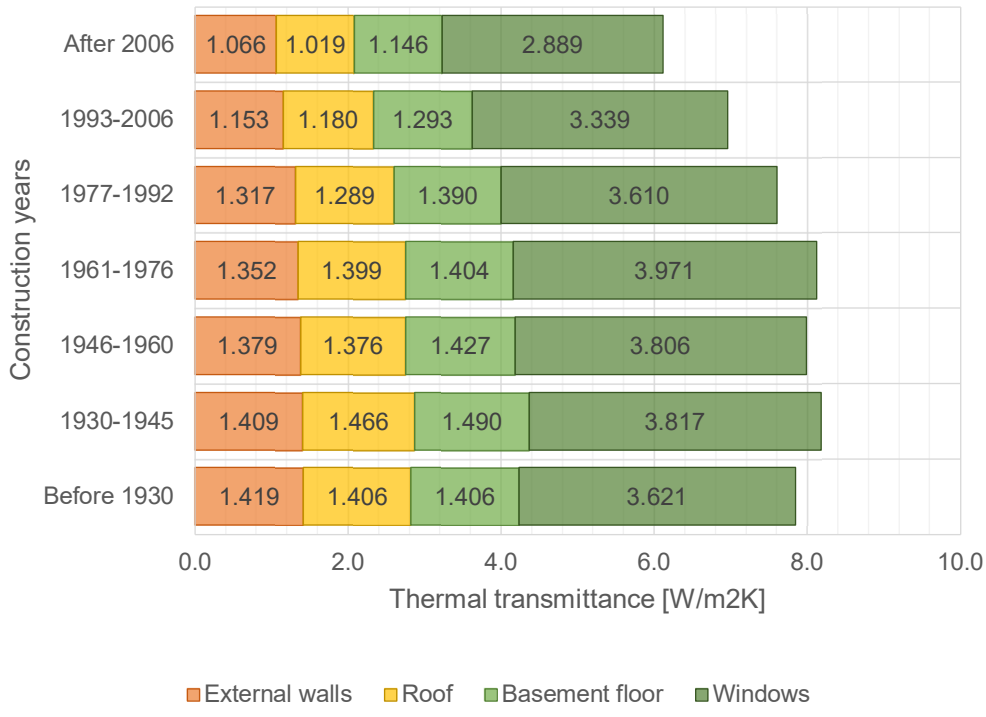

Figure 2.26 - Average thermal transmittances of envelope components - Class F

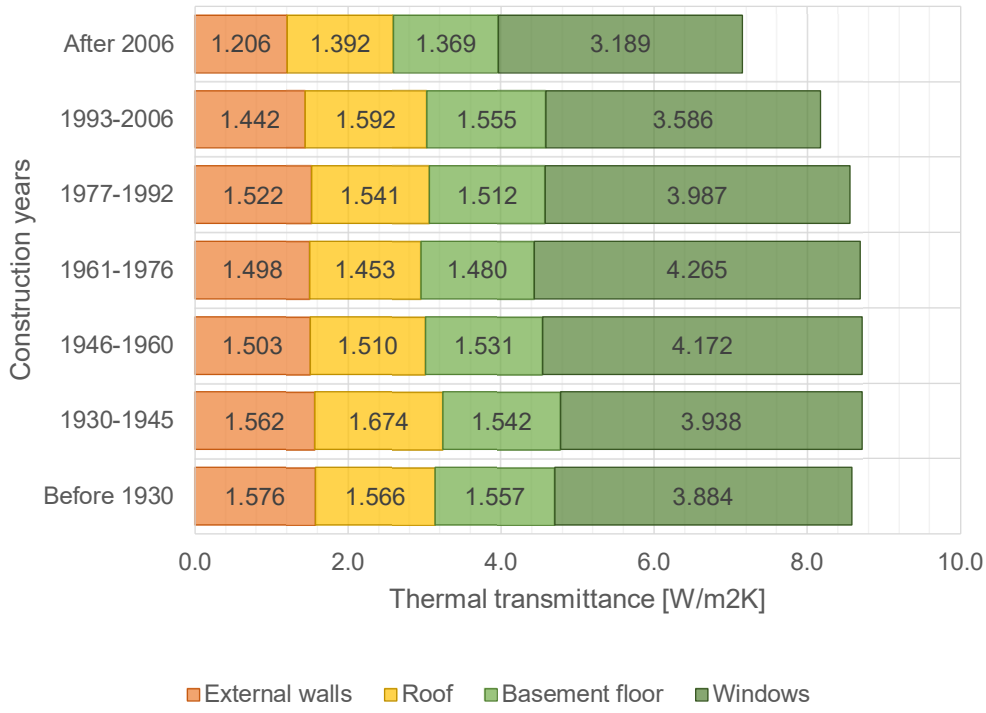

Figure 2.27 - Average thermal transmittance of envelope components - Class G

According to the obtained thermal transmittance values, hypotheses regarding the typology of opaque and transparent partitions were made. As a baseline for appropriate technology's selection, an ENEA report [3] was used, which outlines the primary stratigraphies historically employed in Italian constructions. Thermal transmittance values are then compared to tabular ones of older technologies, extracted from archives and knowledge related to different construction periods. Furthermore, construction types with values close to the calculated ones have been selected for comparison. Tables 2.15, 2.16, 2.17, and 2.18 list technologies for each building component, divided by construction years ranges.

Table 2.15 - Hypothesised stratigraphies of external partitions for classes F and G

Construction year	Class F	Class G
Before 1930	1.419 Solid bricks masonry 40cm	1.600 Stone and solid bricks masonry 40cm
1930-1945	1.409 Solid bricks masonry ca 40cm	1.546 Solid bricks masonry ca 40cm
1946-1960	1.379 Perforated bricks masonry 40cm	1.517 Solid bricks masonry 40cm
1961-1976	1.352 Masonry of perforated bricks 40cm	1.473 Solid bricks masonry 40cm
1977-1992	1.317 Masonry of perforated bricks 40cm	1.483 Solid bricks masonry 40cm
1993-2006	1.153 Hollow box masonry with perforated bricks	1.407 Hollow box masonry with solid and perforated bricks
After 2006	1.066 Perforated bricks masonry with poor level of insulation	1.206 Hollow box masonry with perforated bricks

Table 2.16 - Hypothesised stratigraphies of roofs for classes F and G

Construction year	Class F	Class G
Before 1930	1.406 Pitched roof with wooden structure and planking	1.820 Pitched roof with wooden structure and planking
1930-1945	1.466 Flat roof in brick and concrete 34cm	1.536 Flat roof in brick and concrete 34cm
1946-1960	1.376 Flat roof in brick and concrete 34cm	1.494 Flat roof in brick and concrete 34cm
1961-1976	1.399 Flat roof in brick and concrete 34cm	1.565 Flat roof in brick and concrete 34cm
1977-1992	1.289 Flat roof in brick and concrete with poor level of insulation 37cm	1.618 Flat roof in brick and concrete with poor level of insulation 37cm
1993-2006	1.180 Flat roof in brick and concrete with poor level of insulation 37cm	1.696 Flat roof in brick and concrete with poor level of insulation 37cm
After 2006	1.019 Flat roof in brick and concrete with poor level of insulation 37cm	1.392 Flat roof in brick and concrete with poor level of insulation 37cm

Table 2.17 - Hypothesised stratigraphies of basement floors for classes F and G

Construction year	Class F	Class G
Before 1930	1.406 Slab with steel profiles and volterrane 29 cm	1.640 Slab with steel profiles and volterrane 29 cm
1930-1945	1.490 Slab with steel profiles and volterrane 29 cm	1.522 Slab with steel profiles and volterrane 29 cm
1946-1960	1.427 Slab with steel profiles and volterrane 29 cm	1.492 Slab with steel profiles and volterrane 29 cm
1961-1976	1.404 Brick-cement slab 33cm	1.516 Brick-cement slab 33cm
1977-1992	1.390 Brick-cement slab 33cm	1.565 Brick-cement slab 33cm
1993-2006	1.293 Concrete slab on ground with poor level of insulation 37 cm	1.402 Concrete slab on ground with poor level of insulation 37 cm
After 2006	1.146 Concrete slab on ground with poor level of insulation 37 cm	1.369 Concrete slab on ground with poor level of insulation 37 cm

Table 2.18 - Hypothesised windows technologies for class F and G

Construction year	Class F	Class G
Before 1930	3.621 Single glazing, wooden frame	3.840 Single glazing, wooden frame
1930-1945	3.817 Single glazing, wooden frame	4.029 Single glazing, wooden frame
1946-1960	3.806 Double glazing air-filled, metal frame without thermal break	4.143 Double glazing air-filled, metal frame without thermal break
1961-1976	3.971 Double glazing air-filled, metal frame without thermal break	4.052 Double glazing air-filled, metal frame without thermal break
1977-1992	3.610 Double glazing air-filled, metal frame without thermal break	3.945 Double glazing air-filled, metal frame without thermal break
1993-2006	3.339 Double glazing air-filled, metal frame with thermal break	3.602 Double glazing air-filled, metal frame with thermal break
After 2006	2.889 Double glazing air-filled, wooden frame	3.189 Double glazing air-filled, wooden frame

2.4.5.4 Typical Building – Category E2

At the end of the analysis for category E2, a typical building, representative of most office buildings in class F and G, has been defined. This identification was made to proceed in the following steps with the selection of case studies, used for the application the retrofitting strategies aligned to the EPBD.

For what concerns the systems, the following characteristics were selected:

- Combustion generator for heating production;
- Natural gas as fuel for the generator;
- Seasonal efficiency below 0.8;
- Absence of cooling systems;
- Absence of mechanical ventilation systems;
- Absence of renewable sources production and systems that use them.

Considering this first selection, the overall percentage of buildings with those characteristics is 71.9%, which covers a wide sample of constructions. In the table below are shown numbers of EPCs that present the selected parameters, for class F, G, and the total value.

Table 2.19 - Comparison typical building and total number in classes F and G

	Class F	Class G	Total
Typical building	**2656**	**7309**	**9965**
Tot E2	3951	9907	13858
Percentage	67.2%	73.8%	**71.9%**

For what concerns the construction characteristics, the following criteria were selected:

- Buildings constructed between 1961 and 1992, with the appropriate thermal transmittances;
- A useful heated surface greater than 200 m^2;
- Opaque external walls and windows, not a curtain wall system.

2.4.6 Category E5 – Commercial Buildings

The second category analysed, presenting the worst energy performances as well as office constructions, concerns the commercial buildings. The following paragraph shows the analysis and the evaluation conducted for this category, both in terms of system and envelope characteristics.

2.4.6.1 Overall Number – Category E5

After filtering data for the selected category, the number of certificated buildings obtained by merging CENED 1.2 and 2.0 is 16,749, among which 3,274 belongs to class F and 13,475 to class G. This number covers 17.1% of all commercial buildings certified in Lombardy Region, accounting for a total number of 97,882 certificates.

2.4.6.2 System Evaluation – Category E5

The available data on building services has been analysed to identify the main types of systems used. As with the previous category, the first analysed parameter was the heating system, which is characterized by the type of generator and the energy carrier used for heat production. Class F and G have been separately evaluated and later combined to determine the overall distribution. In Table 2.20 below, the numbers of buildings associated with a specific type of generator are reported. As for category E2, the most common heating system in these buildings is powered by a combustion boiler. However, in commercial constructions, heat pumps are also used for heating generation, as air-based heating distribution systems are often employed.

Table 2.20 – Types of heating generators for classes F and G

Typology	Class F	Class G
Cogeneration	1	1
Heat pump	505	1274
District heating	147	532
Hot air generator	193	678
Infrared heater	8	39
Joule's effect generator	5	4
Combustion boiler	2352	10912
Biomass generator	1	1
Not defined	62	34

Figure 2.28 shows the distribution of heating generation systems in category E5. The combustion boiler is the most used heat generator, accounting for 79.2%, while heat pumps share the 10.6% of the whole number. Other solutions are less used and together represent the 10.2% of the total.

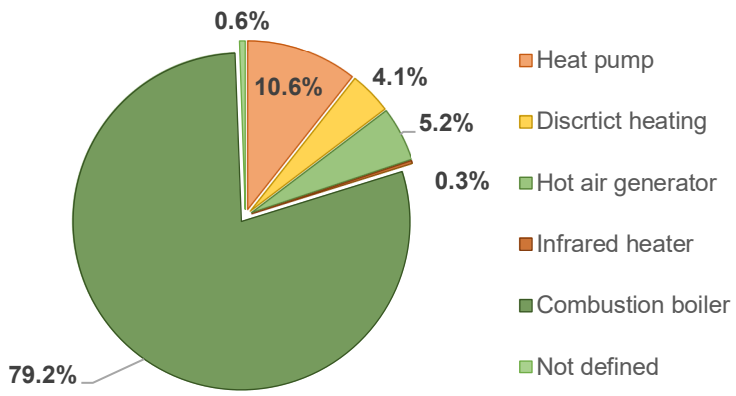

Figure 2.28 - Heating generators share diagram

The second parameter was the fuel used to supply the generator. Also in this case, class F and G have been separately evaluated and then summarized in the pie chart to highlight the results. In Table 2.21 different types of energy vectors are reported, as well as the number of buildings using them as heating generation. According to the different generator technologies, the most used fuel is the natural gas. As expected also the electricity has higher values than offices' result, following the number of heat pumps discovered in the generator's analysis.

Table 2.21 - Types of energy vectors for heating generation for classes F and G

Typology	Class F	Class G
Natural gas	2484	11055
Oil	122	756
GPL	30	130
Electricity	510	1290
District heating	40	137
Biomass	26	73
Not defined	62	34

The share diagram below highlights percentages of each type of fuel. Natural gas is used in 80.8% of the total certificates, while, consistent with the generator distribution, electricity accounts for 10.7%, primarily used to power heat pumps. Considering all fuels that imply a combustion of gas or oil, the percentage increases up to 87.0%, which means that a wide number of buildings produces emissions during heating generation.

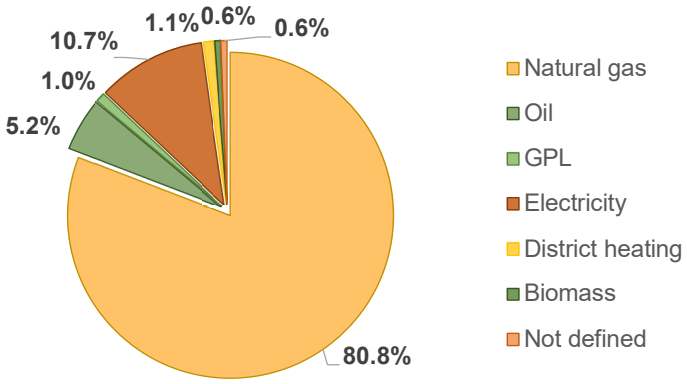

Figure 2.29 - Energy vector for heating generation share diagram

The seasonal efficiency of the heating system was the last analysed data. Figure 2.30 reports the frequency of the heating system, for both classes F and G, as well as the cumulative curves to comprehend the trend of results. Systems have different ranges of efficiency, with a high number below 0.8, around 80%. The most common range is between 0.6 and 0.8, which represents the 40% of cases.

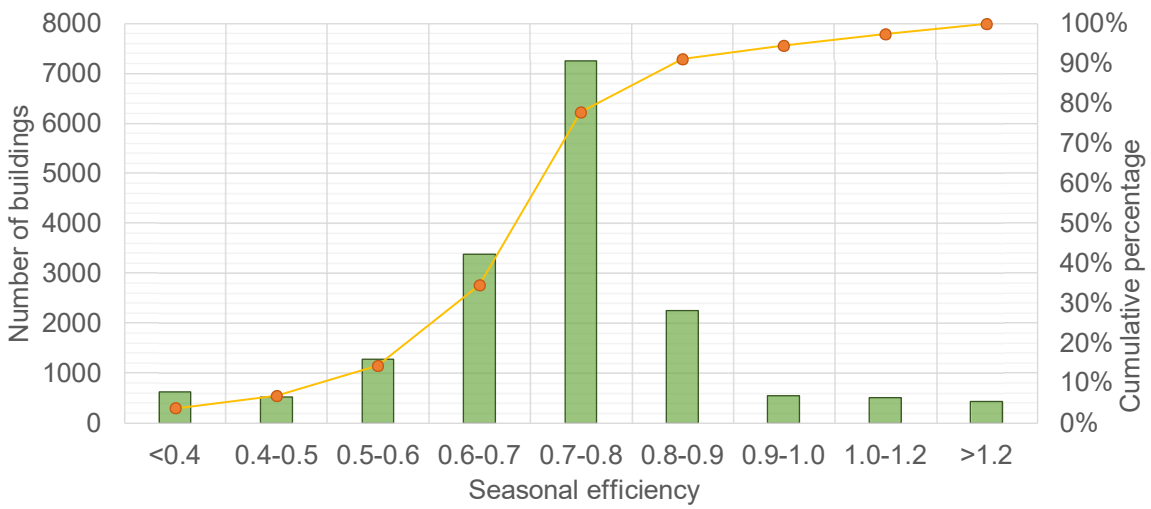

Figure 2.30 - Frequency chart of seasonal efficiency of heating systems

Similar to office buildings, the presence and the type of cooling systems have been analysed. This information is only available in the CENED 2.0 database, and results are shown in Figure 2.31. Among all buildings belonging to this category, only 17.9% have cooling systems with heat pumps as generators. Due to the lack of information and the small percentage of analysed cases, the worst-case scenario is assumed to be the one without any cooling system.

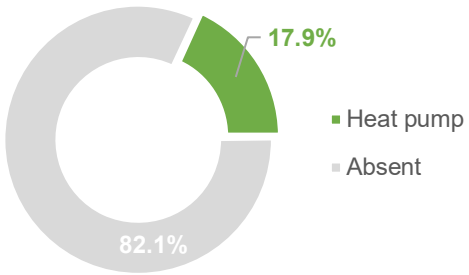

Figure 2.31 - Shear diagram of cooling system

Regarding mechanical ventilation, since the information is provided by both databases, a verification on its presence has been made. Figure 2.32 illustrates the percentage of buildings with this technology, considering a sum of class F and G belonging to both CENED 1.2 and 2.0. Natural ventilation represents the majority of cases, accounting for 90.2% of the total, while just 9.8% of total buildings is characterized by a mechanical ventilation system.

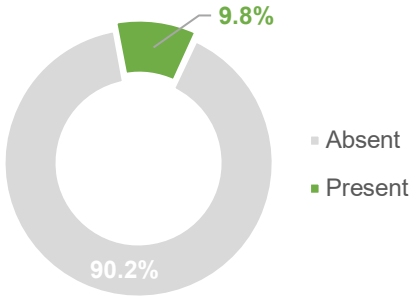

Figure 2.32 - Share diagram of ventilation typology

Additionally, renewable technologies have been analysed, and their presence is reported in the share chart below, considering the types of system generally adopted. The majority of cases, accounting for 99% of the total, do not have those type of solutions: only 1.0% (162 certificates) has installed renewable technologies, among which 102 buildings have a photovoltaic system, while other solutions are less used.

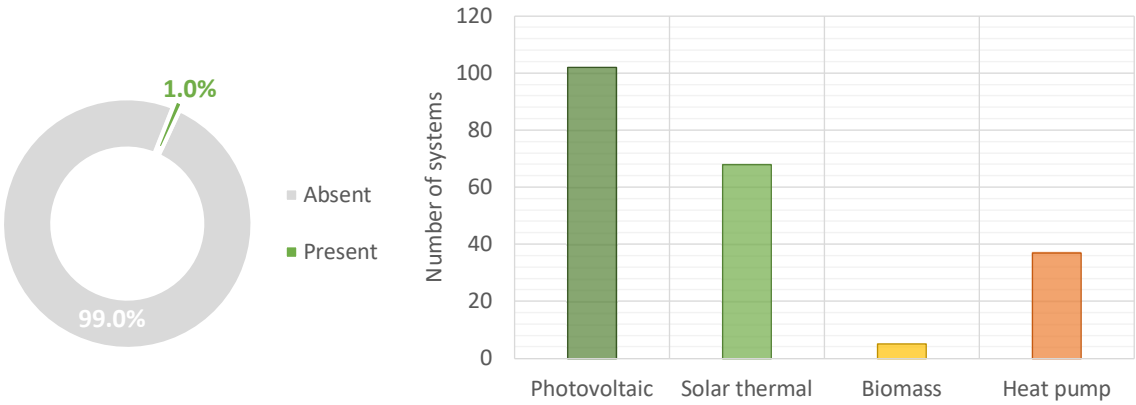

Figure 2.33 - Renewable technologies share diagram and types

2.4.6.3 Construction Characterization – Category E5

The second part of the analysis is the evaluation of construction characteristics to properly define buildings typology, and the technologies used for their construction. As for offices, the construction year was the first parameter analysed and Figure 2.34 illustrates their distribution considering both databased. Approximately 50% of the analysed buildings was constructed between the 1960s and the 1990s, 15.5% was built between the nineties and the early 2000, while the remaining 34.0% is divided into buildings from before 1960 and after 2006.

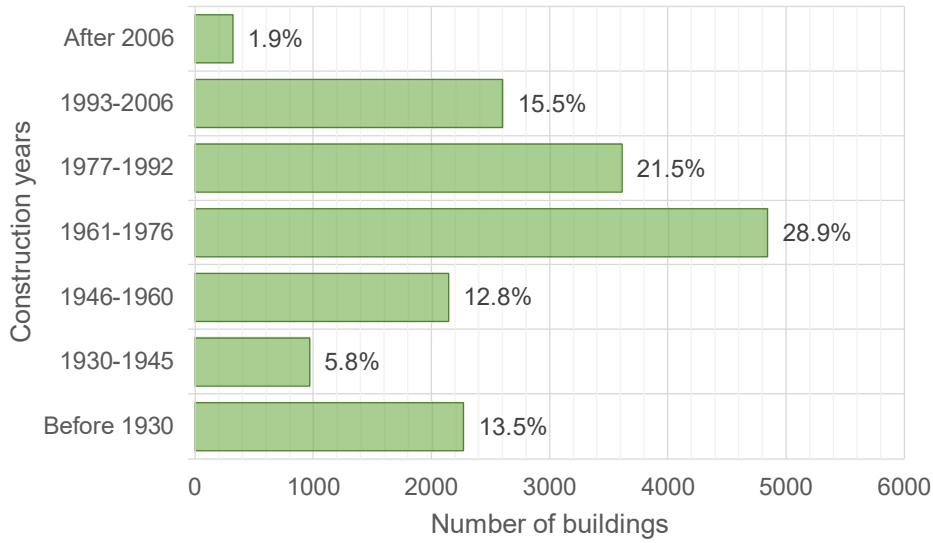

Figure 2.34 - Number of buildings in each construction years range

The second construction aspect considered was the useful heated surface, through the definition of different surface ranges taken into account to categorize and examine the commercial activities. The number of buildings in each range and the cumulative curve associated with the sum of areas are shown in Figure 2.35. Most commercial buildings in classes F and G have a heated surface area lower than 200 m². However, an analysis of the cumulative surface curve suggests that a strategy on larger buildings would have a greater impact on the total area of requalified square meters.

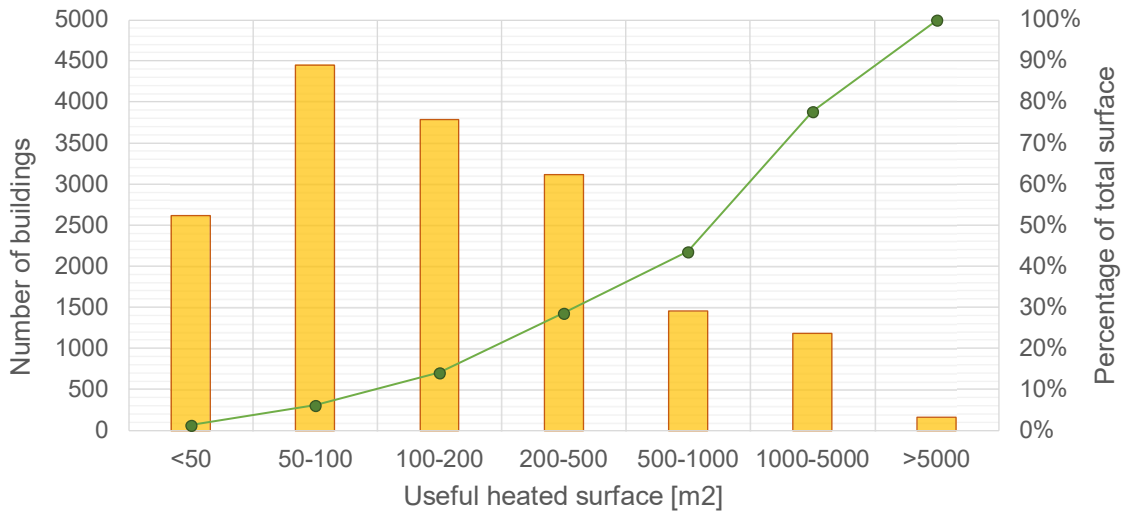

Figure 2.35 - Frequency chart of useful heated surfaces

Average thermal transmittances of the envelope have been calculated for each range of construction years, as what had been done for office constructions. Tables 2.22 and 2.23 reports values respectively for classes F and G, which have been divided between opaque components and transparent elements, such as windows or glazed doors. The following averages have been used as the basis for the hypothesis on construction technologies to characterize the buildings, developing in the so-called “building typology”.

Table 2.22 - Average thermal transmittance of envelope components - Class F

Average thermal transmittances of envelope [W/m2k] - Class F

Construction year	External walls	Roof	Basement floor	Windows
Before 1930	1.391	1.371	1.408	3.990
1930-1945	1.342	1.319	1.368	4.054
1946-1960	1.342	1.300	1.343	4.058
1961-1976	1.412	1.333	1.359	4.152
1977-1992	1.394	1.167	1.320	3.923
1993-2006	1.148	1.022	1.128	3.550
After 2006	1.118	1.022	1.069	3.151

Table 2.23 - Average thermal transmittance of envelope components - Class G

Average thermal transmittances of envelope [W/m2k] - Class G

Construction year	External walls	Roof	Basement floor	Windows
Before 1930	1.503	1.536	1.476	4.340
1930-1945	1.485	1.522	1.471	4.385
1946-1960	1.468	1.465	1.428	4.533
1961-1976	1.483	1.458	1.405	4.717
1977-1992	1.548	1.400	1.409	4.350
1993-2006	1.437	1.279	1.266	3.820
After 2006	1.175	1.275	1.163	3.240

In order to show the trend in envelope properties across different construction years, two charts are presented: Figure 2.36 for class F and Figure 2.37 for class G. Both representations have a similar pattern, with values decreasing in more recent buildings due to advances in construction techniques, while higher values are reported for older ones. Moreover, thermal transmittance values are higher for class G, since those constructions have lower insulation levels.

Figure 2.36 - Average thermal transmittance of envelope components – Class F

Figure 2.37 - Average thermal transmittance of envelope components

As for category E2, reference values from known stratigraphies have been used to make assumptions about the typologies of enclosures. For each part of the envelope, a table that outlines the hypothesized technological solution for each construction year range, specifically for class F and G, is provided.

Table 2.24 - Hypothesised stratigraphies of external partitions for classes F and G

Construction year	Class F	Class G
Before 1930	1.391 Solid bricks masonry 38cm	1.503 Solid bricks masonry 38cm
1930-1945	1.342 Solid bricks masonry 38cm	1.485 Solid bricks masonry 38cm
1946-1960	1.342 Solid bricks masonry 38cm	1.468 Solid bricks masonry 38cm
1961-1976	1.412 Solid bricks masonry 38cm	1.483 Solid bricks masonry 38cm
1977-1992	1.394 Solid bricks masonry 38cm	1.548 Solid bricks masonry 38cm
1993-2006	1.148 Hollow box masonry with perforated bricks 30cm	1.437 Solid bricks masonry 38cm
After 2006	1.118 Hollow box masonry with perforated bricks 40cm	1.175 Hollow box masonry with perforated bricks 30cm

Table 2.25 - Hypothesised stratigraphies of roofs for classes F and G

Construction year	Class F	Class G
Before 1930	1.371 Pitched roof in brick and concrete	1.536 Pitched roof with wooden structure and planking
1930-1945	1.319 Pitched roof in brick and concrete	1.522 Pitched roof with wooden structure and planking
1946-1960	1.300 Pitched roof in brick and concrete	1.465 Flat roof in brick and concrete 34cm
1961-1976	1.333 Pitched roof in brick and concrete	1.458 Flat roof in brick and concrete 34cm
1977-1992	1.167 Pitched roof in brick and concrete with poor level of insulation 28cm	1.400 Flat roof in brick and concrete with poor level of insulation 37cm
1993-2006	1.022 Flat roof in brick and concrete with poor level of insulation 37cm	1.279 Pitched roof in brick and concrete with poor level of insulation 28cm
After 2006	1.022 Flat roof in brick and concrete with poor level of insulation 37cm	1.275 Pitched roof in brick and concrete with poor level of insulation 28cm

Table 2.26 - Hypothesised stratigraphies of basement floors for classes F and G

Construction year	Class F	Class G
Before 1930	1.408 Slab with steel profiles and volterrane 29 cm	1.476 Slab with steel profiles and volterrane 29 cm
1930-1945	1.368 Slab with steel profiles and volterrane 29 cm	1.471 Slab with steel profiles and volterrane 29 cm
1946-1960	1.343 Slab with steel profiles and volterrane 29 cm	1.428 Slab with steel profiles and volterrane 29 cm
1961-1976	1.359 Brick-cement slab 33cm	1.405 Brick-cement slab 33cm
1977-1992	1.320 Brick-cement slab 33cm	1.409 Brick-cement slab 33cm
1993-2006	1.128 Concrete slab on ground with poor level of insulation 37 cm	1.266 Concrete slab on ground with poor level of insulation 37 cm
After 2006	1.069 Brick-cement slab with poor level of insulation 36 cm	1.163 Concrete slab on ground with poor level of insulation 37 cm

Table 2.27 - Hypothesised window technologies for classes F and G

Construction year	Class F	Class G
Before 1930	3.990 Single glazing, wooden frame	4.340 Single glazing, wooden frame
1930-1945	4.054 Single glazing, wooden frame	4.385 Single glazing, wooden frame
1946-1960	4.058 Single glazing, wooden frame	4.533 Single glazing, wooden frame
1961-1976	4.152 Single glazing, wooden frame	4.717 Single glazing, metal frame without thermal break
1977-1992	3.923 Double glazing air-filled, metal frame without thermal break	4.350 Single glazing, wooden frame
1993-2006	3.550 Double glazing air-filled, metal frame without thermal break	3.820 Double glazing air-filled, metal frame without thermal break
After 2006	3.151 Double glazing air-filled, metal frame with thermal break	3.240 Double glazing air-filled, metal frame with thermal break

2.4.6.4 Typical Building – Category E5

At the end of the analysis for category E5, a typical building, representative of most commercial activities in class F and G, has been defined. This identification was made to proceed in the following steps with the selection of case studies, used for the application the retrofitting strategies aligned to the EPBD.

For what concerns the systems, the following characteristics were selected:

- Combustion generator for heating production;
- Natural gas as fuel for the generator;
- Seasonal efficiency below 0.8;
- Absence of cooling systems;
- Absence of mechanical ventilation systems;
- Absence of renewable sources production and systems that use them.

Considering this first selection, the overall percentage of buildings with those characteristics is 65.3%, which covers a wide sample of constructions. Table 2.28 shows numbers of EPCs that have the selected parameters, for class F, G, and the total value.

Table 2.28 - Comparison typical building and total number in classes F and G

	Class F	Class G	Total
Typical building	**1813**	**9130**	**10943**
Tot E5	3274	13475	16749
Percentage	55.4%	67.8%	**65.3%**

For what concerns construction characteristics, the following criteria were selected:

- Buildings constructed between 1961 and 1992, with the appropriate thermal transmittances;
- A useful heated surface greater than 200 m^2.

2.4.7 Category E8 – Industrial buildings

The third and last category of buildings taken into consideration is related to industrial activities and the following chapter offers the same analysis conducted for the previous ones, highlighting their characteristics to define the final “typical building”.

2.4.7.1 Overall Number – Category E8

After filtering data for the selected category, the number of certificated buildings obtained by combining CENED 1.2 and 2.0 is 28,071, among which 9,220 belongs to class F and 18,851 can be associated to class G. The total number of industrial buildings certified in Lombardy Region is equal to 78,903, which represents the 23.9% of the overall number.

2.4.7.2 System Evaluation – Category E8

From the available set of information regarding building services, the main typologies of heating and cooling systems, as well as ventilation and renewable technologies, have been analysed. As for the previous categories, the first parameter considered was the heating system, which is characterized by the generator type and the energy carrier used for working it. In order to have a more detailed representation, class F and G are separately evaluated, further combined to have an overall share of results. Table 2.29 illustrates the numbers of buildings associated with a specific type of generator. As for category E2 and E5, the most common heating system is powered by a combustion boiler and heat pumps are often used for heating generation, since an air-based heating distribution system is generally considered.

Table 2.29 - Types of heating generators for classes F and G

Typology	Class F	Class G
Cogeneration	5	10
Heat pump	351	783
District heating	95	248
Hot air generator	2227	4018
Infrared heater	17	120
Joule's effect generator	20	31
Combustion boiler	6134	13136
Biomass generator	9	8
Not defined	362	497

Data of F and G classes are presented in the pie chart below, highlighting the share of each generator type. As previously said, the most used generator is the combustion boiler, representing the 68.6% of cases. In this category, also the hot air generator is quite common, considering an overall 22.2% of buildings: indeed, in industrial warehouses is often used an air system to heat up spaces, resulting in a more common usage of those systems.

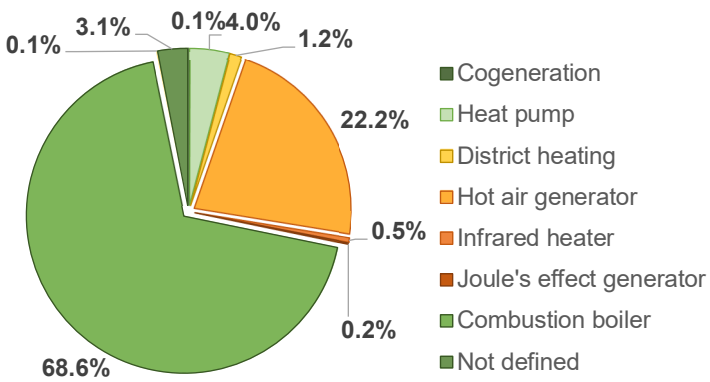

Figure 2.38 - Heating generators share diagram

Since the type of generator is not enough to characterise buildings, a study on fuel used for heating generation was performed. At first, classes F and G have been separately evaluated, to understand whether behaviours are similar or nor, later combined in the pie chart below. Table 2.30 list the numbers of buildings related to the different fuel used for heating purposes. The trend is similar for both classes, with a greater number of cases using natural gas.

Table 2.30 - Types of energy vectors for heating generation for classes F and G

Typology	Class F	Class G
Natural gas	7758	15606
Oil	465	1267
GPL	195	462
Electricity	321	860
District heating	32	57
Biomass	87	102
Not defined	362	497

Class F and G sum is reported in Figure 2.39 below, resulting natural gas as the most used energy vector among all, counting 83.2% of certificates. Considering other types of fuel used in combustion, the overall percentage increases up to 91.7%. That means that also for the hot air generators combustion of natural gas, GPL or oil is used to provide heat to the system.

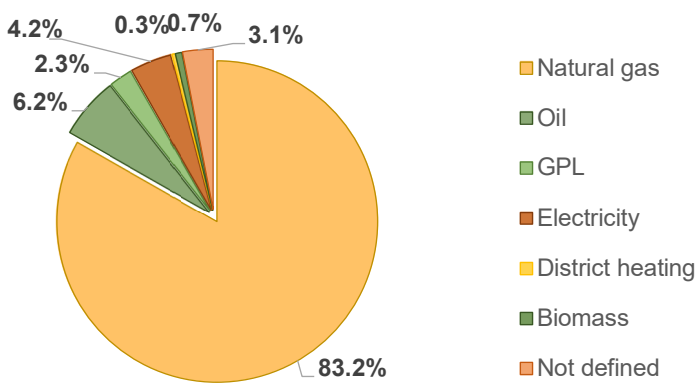

Figure 2.39 - Energy vectors for heating generation share diagram

The seasonal efficiency of the heating system was the last analysed data regarding heating systems. In Figure 2.40 the frequency of the heating system is reported, for classes F and G, as well as its related cumulative curves to comprehend the trend of results. Systems have different ranges of efficiency, with a high number below 0.8, around 90%. However, the most common range is between 0.7 and 0.8, which represents the 50% of cases.

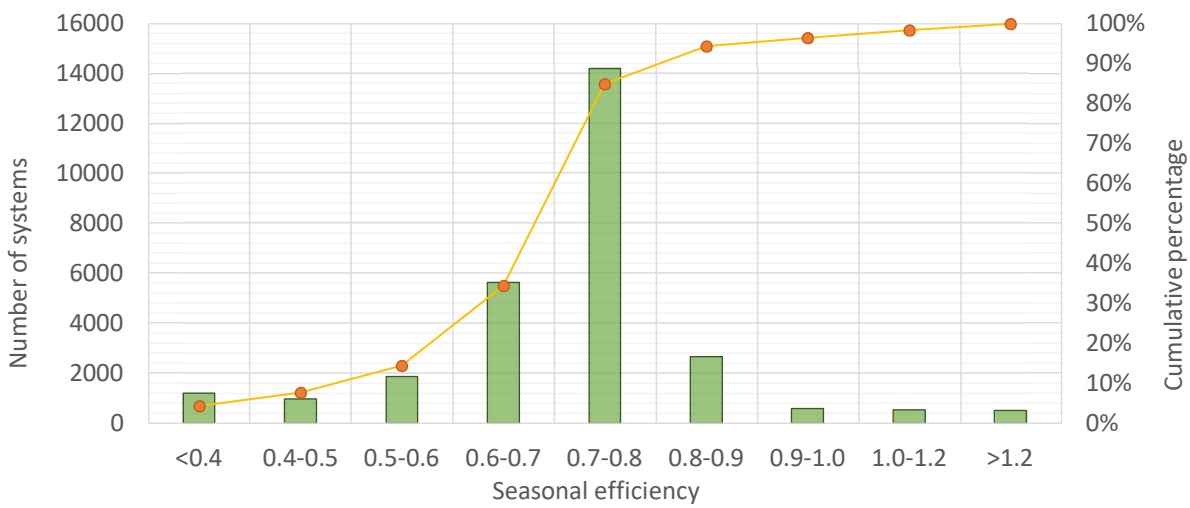

Figure 2.40 - Frequency chart of seasonal efficiency of heating systems

As previously explained for category E2 and E5, information about cooling system is only reported in CENED 2.0, which means that the percentage of systems for summer conditions have been evaluated only according to that database. Figure 2.41 represents the share of cooling systems, just defining the absence or the presence of it, as well as the type. In the majority of cases this type of system is missing, while only 9.0% of buildings is characterized by a heat pump installed for cooling purposes. Considering the result and the unavailability of data for the CENED 1.2 database, cooling system will be excluded from the configuration of the characteristic building and its absence is considered as the worst-case scenario.

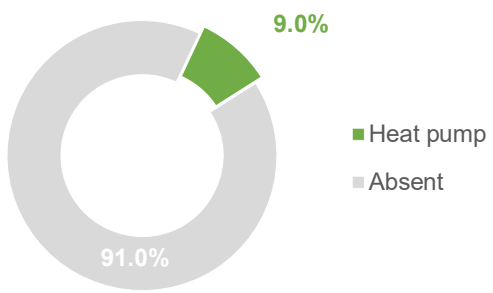

Figure 2.41 - Share diagram of cooling systems

On the other hand, mechanical ventilation has been verified for both databases and the two typologies of ventilation are shown in Figure 2.42. In 97.2% of certificates the ventilation relies on natural forces, with only 2.8% of buildings based on a mechanical system for spaces ventilation.

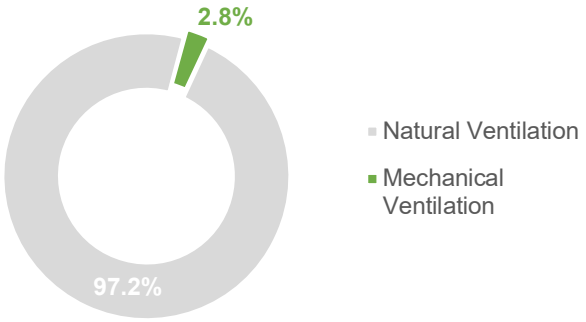

Figure 2.42 - Share diagram of ventilation typologies

The last systems' characteristic was related to renewable source production and use. In Figure 2.43 the percentage of buildings with one of these technologies installed is plotted, specifying also the typology of solutions adopted and the cases involved. It results that only 3.0% of buildings have those type of systems and, considering the different technologies, the most used is the photovoltaic system, with 471 cases.

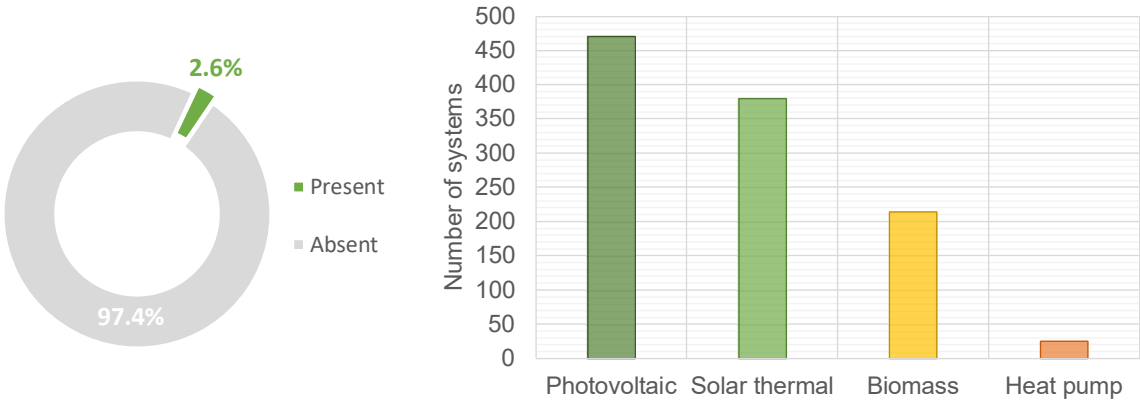

Figure 2.43 - Renewable technologies share diagram and types

2.4.7.3 Construction Characterization – Category E8

The second part of the analysis was the evaluation of construction characteristics to properly define the typology of buildings, and the technologies used for their construction. The first parameter identified was the construction year for each certificate. To group buildings with similar characteristics, 15 years-ranges of construction years have been considered according to databases specifications. In Figure 2.44 the number of buildings in each range of construction years are reported, where the percentages of each group are reported to highlight the share of construction years. Buildings with a construction year between 1961 and 1992 are the most common, having a percentage of 61.1% over the total number, while 20.7% of

cases has a construction year between nineties and early 2000 and the remaining 18.1% represents buildings constructed before 1960 and after 2006.

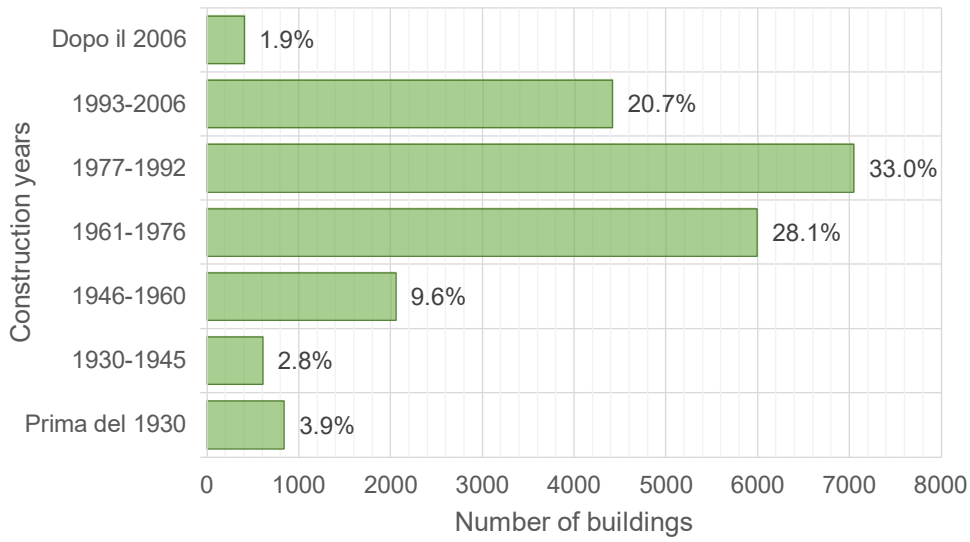

Figure 2.44 - Number of buildings in each construction years range

Another important parameter for the evaluation was the useful heated surface, a value that helped determine which building sizes would be more relevant and impactful to maximize the requalification of built surfaces. Constructions are divided into different ranges of heated surfaces, as shown in Figure 2.45, reporting also the cumulative curve of areas to evaluate the optimal requalification strategy. Most buildings have a surface between 200 and 500 m^2: although a greater number of cases have surfaces below 500 m^2, the amount of area above this value covers the 65% of the total heated surface of industrial buildings.

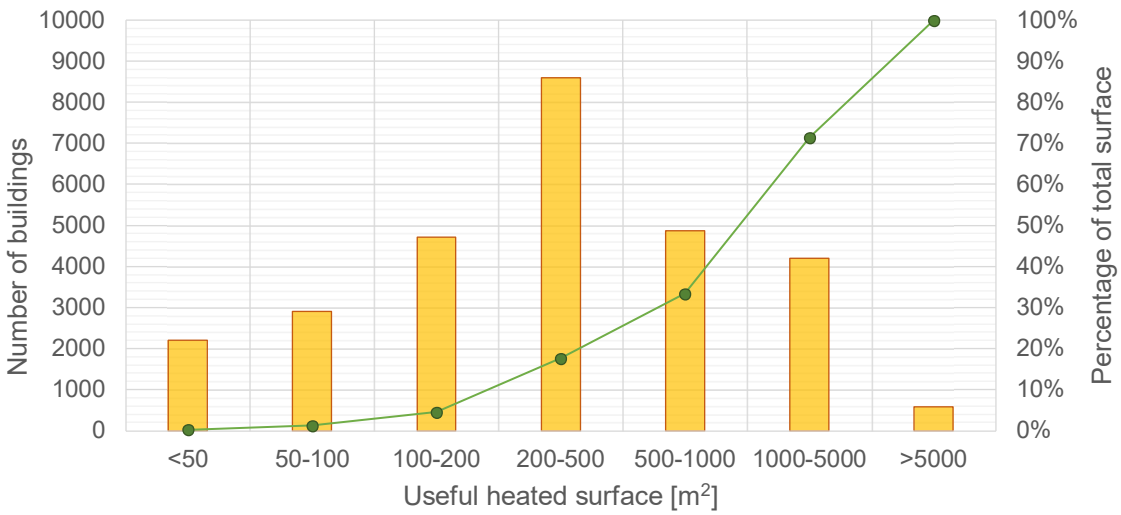

Figure 2.45 - Frequency chart of useful heated surfaces

A last analysis has been performed on the evaluation of buildings' envelope thermal transmittances. Average values have been calculated for each range of construction years to define a value used for the characterisation of the construction technologies. In Tables 2.31 and 2.32 average values of thermal transmittance for each part of the envelope are summarised, both for class F and G.

Table 2.31 - Average thermal transmittance of envelope components - Class F

Average thermal transmittances of envelope [W/m2k] - Class F

Construction year	External walls	Roof	Basement floor	Windows
Before 1930	1.723	1.518	1.643	4.719
1930-1945	1.638	1.545	1.677	4.622
1946-1960	1.683	1.488	1.704	4.736
1961-1976	1.829	1.570	1.739	4.881
1977-1992	1.939	1.598	1.753	4.656
1993-2006	1.737	1.503	1.634	4.002
After 2006	1.424	1.215	1.435	3.445

Table 2.32 - Average thermal transmittance of envelope components - Class G

Average thermal transmittances of envelope [W/m2k] - Class G

Construction year	External walls	Roof	Basement floor	Windows
Before 1930	1.805	1.609	1.700	4.651
1930-1945	1.757	1.584	1.671	4.680
1946-1960	1.788	1.565	1.715	4.895
1961-1976	1.929	1.644	1.719	4.931
1977-1992	2.056	1.707	1.732	4.693
1993-2006	1.894	1.655	1.721	4.170
After 2006	1.602	1.440	1.631	3.332

The following Figures 2.46 and 2.47 display the average thermal transmittance values, calculated in the previous section. These charts highlight the trend of values according to the year of construction of buildings. In general trends are similar for both class F and G, from the moment that values decrease starting with ancient buildings to more recent ones, with a small increase registered after 1961. This slight rise is probably due to the use of concrete for opaque partitions, which comported higher losses through envelope components.

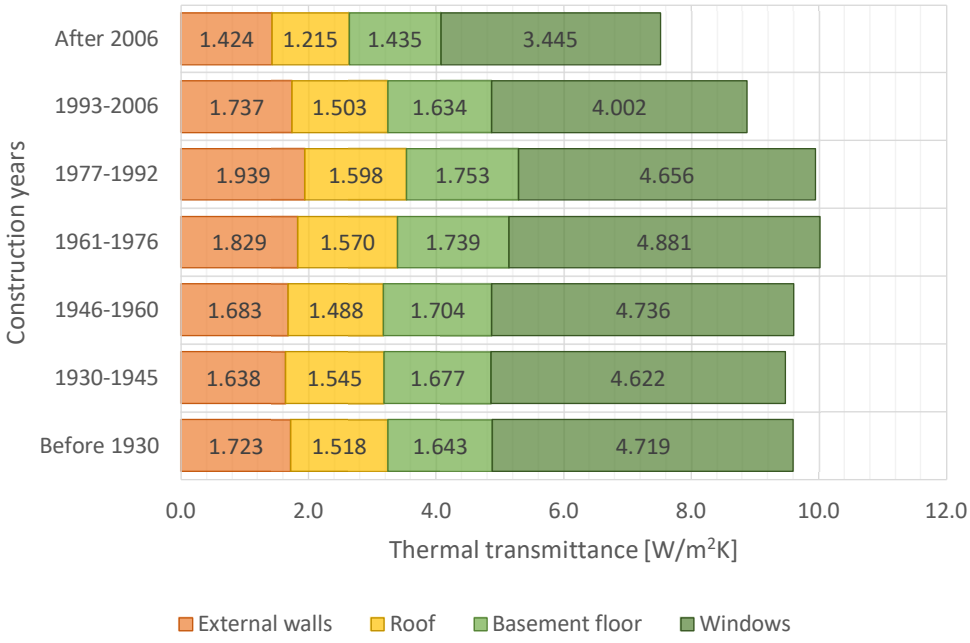

Figure 2.46 - Average thermal transmittance of envelope components – Class F

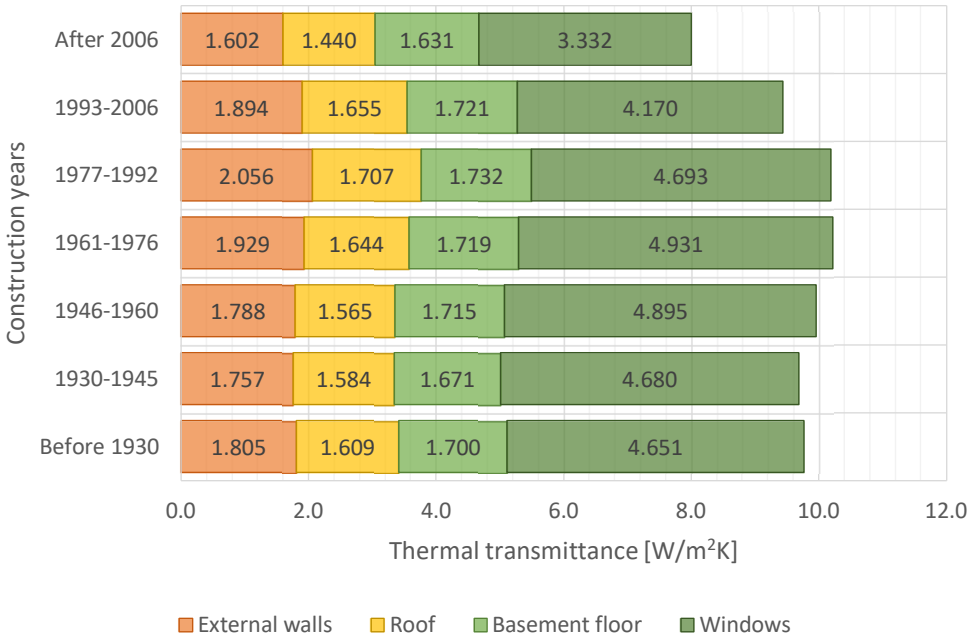

Figure 2.47 - Average thermal transmittance of envelope components - Class G

As explained with categories E2 and E5, starting from calculated thermal transmittance average values, different types of stratigraphies have been identifies, according to the period of construction and the available techniques at that time. In Tables 2.33, 2.34, 2.35, and 2.36, for each part of the envelope, hypothesis on the technological solution used for enclosures in classes F and G were made. In general, buildings used for industrial purposes, such as industrial warehouses, have poor technological features. According to results in tables, in particular for the external walls, the typologies of envelope components are related to previous construction years' techniques, and they have poor levels of thermal insulation.

Table 2.33 - Hypothesised stratigraphies of external partitions for classes F and G

Construction year	Class F	Class G
Before 1930	1.723 Stone and solid bricks masonry 40cm	1.805 Solid bricks masonry 25cm
1930-1945	1.638 Stone and solid bricks masonry 40cm	1.757 Solid bricks masonry 25cm
1946-1960	1.683 Stone and solid bricks masonry 40cm	1.788 Solid bricks masonry 25cm
1961-1976	1.829 Solid bricks masonry 25cm	1.929 Solid bricks masonry 25cm
1977-1992	1.939 Solid bricks masonry 25cm	2.056 Solid bricks masonry 25cm
1993-2006	1.737 Perforated bricks masonry 25cm	1.894 Solid bricks masonry 25cm
After 2006	1.424 Solid bricks masonry 38cm	1.602 Solid bricks masonry 38cm

Table 2.34 - Hypothesised stratigraphies of roofs for classes F and G

Construction year	Class F	Class G
Before 1930	1.518 Flat roof in brick and concrete 40cm	1.609 Flat roof in brick and concrete 40cm
1930-1945	1.545 Flat roof in brick and concrete 40cm	1.584 Flat roof in brick and concrete 40cm
1946-1960	1.488 Flat roof in brick and concrete 40cm	1.565 Flat roof in brick and concrete 40cm
1961-1976	1.570 Flat roof in brick and concrete 40cm	1.644 Flat roof in brick and concrete 40cm
1977-1992	1.598 Flat roof in brick and concrete 40cm	1.707 Flat roof in brick and concrete 40cm
1993-2006	1.503 Flat roof in brick and concrete 40cm	1.655 Flat roof in brick and concrete 40cm
After 2006	1.215 Flat roof in brick and concrete with poor level of insulation 28cm	1.440 Flat roof in brick and concrete with poor level of insulation 28cm

Table 2.35 - Hypothesised stratigraphies of basement floor for classes F and G

Construction year	Class F	Class G
Before 1930	1.643 Slab with steel profiles and volterrane 29 cm	1.700 Slab with steel profiles and bricks 31cm
1930-1945	1.677 Slab with steel profiles and volterrane 29 cm	1.671 Slab with steel profiles and bricks 31cm
1946-1960	1.704 Slab with steel profiles and bricks 31cm	1.715 Slab with steel profiles and bricks 31cm
1961-1976	1.739 Slab with steel profiles and bricks 31cm	1.719 Slab with steel profiles and bricks 31cm
1977-1992	1.753 Slab with steel profiles and bricks 31cm	1.732 Slab with steel profiles and bricks 31cm
1993-2006	1.634 Concrete slab on ground	1.721 Slab with steel profiles and bricks 31cm
After 2006	1.435 Concrete slab on ground with poor level of insulation 37 cm	1.631 Brick-cement slab 33cm

Table 2.36 - Hypothesised window technologies for classes F and G

Construction year	Class F	Class G
Before 1930	4.719 Single glazing, wooden frame	4.651 Single glazing, wooden frame
1930-1945	4.622 Single glazing, wooden frame	4.680 Single glazing, wooden frame
1946-1960	4.736 Single glazing, wooden frame	4.895 Single glazing, metal frame without thermal break
1961-1976	4.881 Single glazing, metal frame without thermal break	4.931 Single glazing, metal frame without thermal break
1977-1992	4.656 Double glazing air-filled, metal frame without thermal break	4.693 Double glazing air-filled, metal frame without thermal break
1993-2006	4.002 Double glazing air-filled, metal frame without thermal break	4.170 Double glazing air-filled, metal frame without thermal break
After 2006	3.445 Double glazing air-filled, metal frame with thermal break	3.332 Double glazing air-filled, metal frame with thermal break

2.4.7.4 Typical Building – Category E8

At the end of the analysis for category E8, a typical building, representative of most industrial buildings in class F and G, has been defined. This identification was made to proceed in the following steps with the selection of case studies, used for the application the retrofitting strategies aligned to the EPBD.

For what concerns the systems, the following characteristics were selected:

- Combustion generator for heating production;
- Natural gas as fuel for the generator;
- Seasonal efficiency below 0.8;
- Absence of cooling systems;
- Absence of mechanical ventilation systems;
- Absence of renewable sources production and systems that use them.

Considering this first selection, the overall percentage of buildings with those characteristics is equal to 59.6%. In Table 2.37 the numbers of EPCs that have the selected parameters are shown, for class F, G, and the total value.

Table 2.37 - Comparison typical building and total number in classes F and G

	Class F	Class G	Total
Typical building	**5078**	**11664**	**16742**
Tot E8	9220	18851	28071
Percentage	51.1%	61.9%	**59.6%**

For what concerns the construction characteristics are selected the following criteria:

- Buildings constructed between 1961 and 1992, with the appropriate thermal transmittances;
- A useful heated surface greater than 500 m^2.

2.4.8 Final Considerations

After a detailed analysis regarding the three categories of the non-residential real estate, it was possible to define a typical building for each category. As previously explained, the “typical building” represents a construction with poor and inadequate performances, both in terms of energy consumption and greenhouse gas emissions. This identification has been necessary in order to define the starting point for the renovation process according with the new European Directive (EPBD). It means that by starting to retrofit this type of buildings, classified as some of the worst performers, it would already be possible to achieve improvements in terms of climate and energy performance in Italy. Moreover, as explained in the following section, this group of “typical buildings” among office, commercial and industrial activities account for over 16% of the non-residential sector to be retrofitted by 2030, thus meeting the new Directive’s requirements. At the same time, a combinations and comparison of parameters for the three destinations of use are reported in Table 2.38, from which a strong similarity between them all can be observed. For what concerns thermal transmittances and

construction technologies defined in the following chapters, during the evaluation of the case study, values will be selected considering this analysis results. It means that the example regarding an office building in Milan, reported and analysed as a representative case at the end of this study, shows the reported characteristics as the existing condition. Since the characteristics of the three typical buildings are similar, solutions to their weaknesses are listed below.

Table 2.38 - Typical building for each category

	E2 - Office Buildings	E5 - Commercial buildings	E8 - Industrial buildings
Heating generator	Combustion boiler	Combustion boiler	Combustion boiler
Fuel for heating	Natural Gas	Natural Gas	Natural Gas
Seasonal efficiency	Below 0.8	Below 0.8	Below 0.8
Cooling system	Not present	Not present	Not present
Ventilation type	Natural ventilation	Natural ventilation	Natural ventilation
Renewable technology	Not present	Not present	Not present
Construction years	1961-1993	1961-1993	1961-1993
Useful heated surface	Greater than 200 m^2	Greater than 200 m^2	Greater than 500 m^2

As a result of the analysis, a list of solutions that could be applied to the selected buildings to increase their energy performance is listed below:

- **Electrification of the heating system and hot sanitary water generation**: the generator is substituted with a new one, typically an electrical one, to enhance system efficiency and avoid the usage of combustion for any purpose.
- **Installation of cooling system**: according to the increase of yearly temperatures, systems for controlling indoor conditions in summer periods are fundamental to avoid overheating.
- **Installation of mechanical ventilation system**: the addiction of a controlled ventilation ensures the indoor air quality in both summer and winter, while avoiding thermal losses due to user controlled natural ventilation.
- **Production of renewable energy on-site**: by installing systems for energy production, such as photovoltaic panels, it is possible to reduce the energy needs from the grid and promote the auto-consumption of electrical energy.
- **Insulation of the envelope**: due to the poor performance of the envelope the amount of required energy for maintaining comfort conditions inside the building is high; by increasing the insulation of enclosures the needed amount of energy is minimized.
- Other considerations, depending on the specific case.

The implementation of those interventions could play a significant role in the contribution to Climate Change Mitigation, such as the electrification of systems and the introduction of renewable energy production, as well as Climate Change Adaptation, such as the installation of cooling systems and the improvement of thermal characteristics of the envelope. The typical building is used for the generation of buildings clusters, which will be useful during the planning of a massive retrofit of the non-residential sector. Defining the common characteristics of constructions is a key starting point to implement a strategy able to maximise outcomes in terms of timing and costs.

The results obtained during the identification of the typical building in Lombardy Region are then transposed to the National building stock. In this section, calculated percentages are extended to the Italian framework, in order to understand how the identified type influences the overall conditions. It is assumed that the share of regional data is similar to the total, perhaps values are proportionally calculated.

Considering the three buildings' destination of use, the total number of non-residential buildings in classes F and G is 262,246, among which 65,990 in category E2, 109,621 in E5 and 86,635 in E8. Using the characteristics identified for each category, it is determined a percentage of buildings having these configurations, summarized for both regional and national level in Table 2.39 below. Under a regional level those percentages are: 71.9% for office buildings, 65.3% for commercial buildings, and 59.6% for industrial buildings. The last column on the right, instead, shows the overall number of buildings, divided by category, that are covered by the typical building's configuration. The total number of certified Italian buildings is 170,665, which is the 65.1% of the overall number.

Table 2.39 - Lombardy and Italy typical buildings comparison

	Lombardy			Italy	
	Total number	**Typical building**	**Percentage**	**Total number**	**Typical building**
E2	13,858	9,965	71.9%	65,990	47,447
E5	16,749	10,943	65.3%	109,621	71,583
E8	26,071	16,742	59.6%	86,635	51,635
Total	**56,678**	**37,650**	**66.4%**	**262,246**	**170,665**

After the identification of typical buildings in the Italian territory, the number for the selected categories is compared to the total number of non-residential buildings. In Figure 2.48 is plotted the comparison of Lombardy Region and Italy. Considering the whole non-residential sector, the percentage of typical buildings in Lombardy is 12.4%, while at national level, this percentage is increased to 21.5%. Since the new EPBD requires the energy refurbishment of

the worst 16% of non-residential buildings, the presented cluster of typical configurations could be effective in alignment with the European standards, even theoretically higher. It is important to state that the analysis is based on assumptions, from the moment that further investigations on the national database of EPCs are necessary to verify the validity of those percentages. Another consideration concerns the performance positioning at National level of identified buildings, in this study classes F and G are considered together, while regulatory requirements are specified for the worst 16%, regardless of their energy classes.

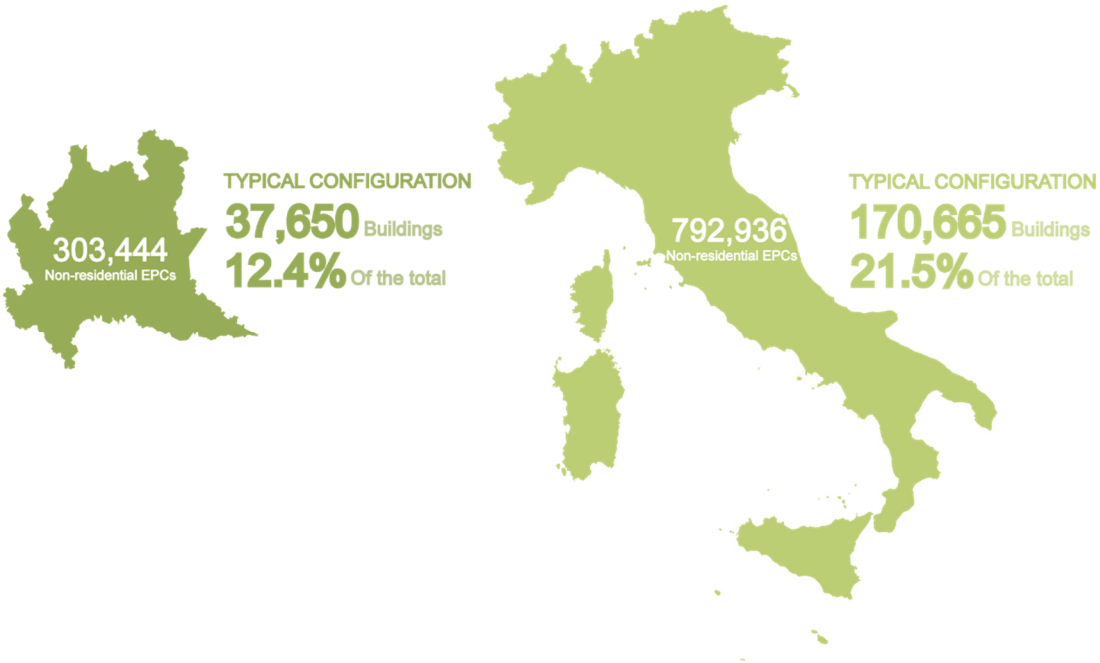

Figure 2.48 - Lombardy and Italy typical building comparison to the total number of Non-residential EPCs

3. Prefabricated Solutions

In order to meet the new EPBD requirements, a large-scale requalification of buildings must be completed in a short period of time. In particular, an energy improvement of at least 16% of the Italian non-residential building stock, showing worst performances, must be guaranteed by 2030, a very hard challenge to face and overcome. Moreover, considering that the Directive imposes all non-residential buildings, along with residential ones, to meet zero-emission standards by 2050, the available time is extremely limited. This makes it clear that immediate action and accelerated implementation of renovation measures are essential to meet these ambitious goals and ensure the achievement of climate neutrality within declared deadlines.

In any case, it goes without saying that traditional retrofitting strategies are insufficient to satisfy these objectives, as they often involve extended implementation periods and lack standardized solutions. For this reason, a limited number of companies have begun to explore about components' mass production used in buildings' retrofits, shifting the creation of customized parts from building site to factory. Indeed, the introduction of prefabricated elements could minimize renovation times and speed up the overall building sector's transition.

According to the annual energy certification report issued by ENEA, only the 1.5% of buildings in classes F and G undergoes refurbishment each year. This percentage falls shorts of covering the European Union's target of a 16% improvement before 2030. Although the renovation rate may increase in the coming years, it must reach at least 3.2% annually to meet the required threshold, by doubling the current rate. Therefore, a change in methodology would be necessary to address and solve the insufficient speed of retrofit interventions. The following chart illustrates the projected annual renovation rates, assuming a slight increase each year. By reporting the percentage of refurbishment requested by the new EPBD, set at 16%, it is clear that the retrofitted buildings percentage is not enough to meet the imposed requirements at the end of 2030.

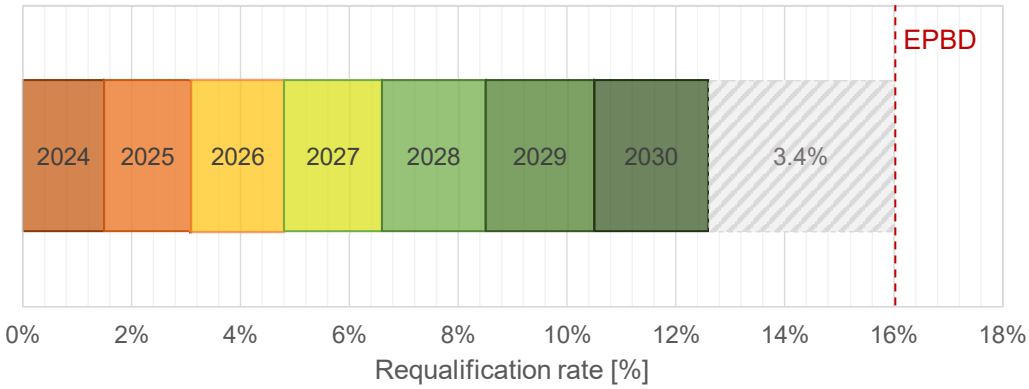

Figure 3.1 - Requalification rates before 2030

This chapter provides a detailed description of the ideas and solutions proposed by different companies, based on a new concept of prefabrication for energy renovation processes. By considering the final objective of the Directive and the tight deadlines to achieve it, these new proposals will be compared to traditional solutions, in order to offer an adequate alternative to current situations. The objectives and processes underlying this new approach to building requalification have been developed by three European companies: Ecoworks, 4RinEU (Eurac Research), and EnergieSprong.

The former represents the first German agency to implement serial renovation, by developing, professionalizing and optimizing the process since 2019. “Rethinking energy-efficient renovation” is the core of this company, the foundation on which their building renewal project is based, and which is conveyed to this study [16]. On the other hand, both 4RinEU and EnergieSprong cannot be considered as companies themselves, but rather as projects and initiatives proposed at an international level, aimed at innovative, rapid and sustainable energy renovation of buildings. 4RinEU is a project developed by a team of researchers led by the Eurac Research, which enables deep energy renovation by using modular and prefabricated solutions. Based on the same objectives, principles and strategies, there is EnergieSprong, an initiative coordinated at the Italian level by EDERA, a non-profit organization founded by ACNE, Redo Sgr, and Housing Social Foundation [17].

Thus, the proposed solution is a completely new approach to building solutions’ design, with a clear method and a standardized path to follow during the development of the requalification project. This introduces many aspects of a more sustainable design, merging new technologies and strategies to maximize any retrofit benefits. Thanks to the industrialization of components production, results are more predictable and reliable, in terms of performance and completion time, and other benefits, described in the following parts.

3.1 Main Goals and Results

Considering the increasing stringency of requirements in this field, construction costs are rising, and workers are becoming overwhelmed by the growing number of practices. This situation reduces the affordability of renovations and the availability of resources and skilled labour.

In the last years, firms have implemented and optimised serial renovation to better achieve results in sustainable energy efficient restorations. A wide part of the work has been shifted from the construction site to the factory, allowing to generate a standardised method and

promoting a widespread requalification of the existing buildings stock. By rethinking the whole process in a more energy-efficient way, the construction sector could overcome limits related to the renovation goal. [18]

In general, the main focuses of prefabricated solutions are the same of a traditional approach: reducing the energy demand of buildings, proving their energy efficiency and performance, as well as minimizing construction waste. According to preliminary analyses obtained from the applicating of this approach, it is possible to state that benefits are common but achieved in a smarter and more efficient way. The main results are listed and briefly explained below:

- Intervention times are reduced, especially associated to construction site duration, thanks to the shifting of components production and assembly to factory;
- Costs are reduced, even though prefabricated elements are more expensive than traditional parts, the overall cost decreases due to the reduction in intervention times;
- Housing continuity is guaranteed, as the renovation is less intrusive and faster than traditional methods, with minimal provoked discomfort for inhabitants;
- Workers on the construction site are safer, due to the factory production and the absence of scaffolding. These changes reduce the risk of injuries and the amount harmful particles generated by materials manipulation;
- The environmental impact of the renovation is enhanced by a reduction of emissions, during the production and the expected life of the construction, and guaranteed performance, resulting from more precise component manufacturing. Another important sustainable consideration regards the life cycle of elements, which is implemented in the design phase of projects;
- Investment affordability is increased, as, after large-scale implementation of the process, interventions costs are reduced, making it easier to access this type of renovation;
- The quality of components is guaranteed by the production in a controlled environment and tests are made to maximise performance. The combination of these two factors allows to increase durability and actual results;
- The design phase is optimised from the moment that it is modular and multidisciplinary, ensuring a reduction in retrofitting time and cost;
- The productivity is increased due to the reduction of specialised labour on-site;
- Maintenance is programmed in detail during the design phase, ensuring a decrease of unexpected failures and so a reduction in maintenance costs.

Figure 3.2 - Expected results of prefabricated retrofits

The perspectives of this new design approach are explained and used as the basis for the standardization of the process, deviating in many aspects from the traditional one. Two main differences have been identified between these two approaches:

- The doubling of the production phase, where the worksite loses its importance, and the factory is introduced as the new operational centre;
- The creation of a new expert figure, the system integrator. Its main role during the project development is to apply its knowledges for the multidisciplinary coordination of off-site elements' production from the early stages of design development, in order to optimise timing and processes. He is responsible for communication with the panel manufacturer, who manages the production of prefabricated components in factory. In the traditional method, initial multidisciplinary collaboration is often not considered, leading to problems in the subsequent phases.

3.2 Approach and Objectives of Interventions

In this paragraph, approach and interventions are analysed and explained. During the retrofitting of a building, solutions for enhancing the energy efficiency are usually the increase of envelope and systems' performances. Typically, a new insulation layer on opaque surfaces of the building envelope is added, while transparent elements are substituted with more performant ones. Systems are replaced by new typologies and are added missing plants, such as mechanical ventilation and cooling systems, while it is installed an on-site production facility, able to exploit energy from renewable sources. For the analysed methodology, class of interventions are the same, but strategies to achieve them are modified.

3.2.1 Approach

The approach of the process is built on principles designed to establish an effective and efficient strategy. In general, it can be categorized into six main areas of intervention:

- Systems integration: in traditional design processes, an initial collaboration between disciplines is often not considered. In this solution, instead, the introduction of a system integrator ensures seamless collaboration from the very beginning of the design phase, facilitating coordinated efforts throughout.
- Time reduction: by shifting production phase to the factory, times are minimised thanks to more efficient and faster processes, as well as the overlapping of the worksite preparation with the elements' production. Additionally, systems installation benefit from this time-saving approach.
- Modular designs: due to poor quality and aesthetics matters, modular design has evolved. The improvement of production techniques and logics has enabled the creation of modular systems with diverse shapes and finishes, offering innovative aesthetic solutions. This includes enhancing the visual appeal of urban areas during energy retrofit projects.
- Circular economy: the basis of refurbishment designs is based on the principles behind circular economy, taking into account the life cycle of materials and products. At the same time, the Design for Disassembly (DfD) approach promotes reuse and recycling, further reducing environmental impacts.
- Energy autonomy: a crucial aspect of the overall process, energy autonomy aims to simplify and accelerate technical evaluations for large-scale applications, ensuring compliance with European standards. The focus is on promoting on-site energy production in order to maximize the energetic independence of structures.
- Energy communities: it includes the creation of districts in which energy self-consumption is maximised. They are generated by the definition of urban plannings for prefabricated retrofitting of entire urban areas.

3.2.2 Objectives of Interventions

The three main components of this innovative renovation process using prefabricated elements focus on building's external envelope, including both the façade and the roof, as well as the key integrated systems.

The first objective to be considered is the façades, which are insulated by directly attaching prefabricated panels, also defined as modules, to the existing external walls. These elements are pre-finished at the factory and then delivered to the construction site, where they are

mounted and refined. Modules can be configured in a variety of ways, with different levels of prefabrication and complexity, a condition that may include windows and vertical components of the distribution systems, offering flexibility and customization.

The second components taken into account is the roof, which is replaced with prefabricated blocks produced in factories. The composing elements arrive at the worksite, where they are installed on top of buildings, avoiding the creation of custom-made structures to withstand loads. System integration is typically incorporated into these panels during the production process in the factory, leaving only final connections to be made on-site. For other building systems, prefabricated slots and housing for machinery and components are provided, facilitating an easy installation.

In terms of building systems, traditional combustion-based solutions are entirely replaced with electrical ones in order to avoid fossil fuels' combustion inside the retrofitted buildings. Heat pumps are commonly used for space heating and sanitary hot water production, which are often coupled with cooling solutions in order to enhance overall comfort. On the other hand, mechanical ventilation systems are installed to ensure air quality and avoid useless losses due to uncontrolled natural ventilation. In order to reduce energy demand and consumption from non-renewable sources, renewable energy systems are installed on the roof or directly connected to façade's components, further improving building's sustainability and performance.

3.2.3 Additional Considerations

Alongside these principal interventions, other aspects may be considered during the renovation process to enhance the building's overall comfort and sustainability:

- The electrical mobility is promoted by installing recharging stations for residents, supporting the transition to sustainable transportation;
- The accessibility to the building is guaranteed thanks to the removal of architectural barriers, by adding ramps to the ground floor and elevators' installation for easier movements between floors;
- The integration with surrounding urban areas is promoted, thanks to the generation of new green spaces around the building, enhancing both its environmental impact and its connection to the community;
- New energetic communities are created, by developing urban plans for the requalification of entire areas and maximising the self-consumption in districts.
- The aesthetic of old and damaged buildings is improved, restoring their visual appeal and their functionality

- New external spaces for inhabitants, such as balconies or terraces, are added in order to increase residents' well-being and to provide spaces for relaxation, social interaction or gardening;

For each specific case a combination of those strategies is used to develop a design project, and it is realised by following the methodology explained in the following chapter.

Figure 3.3 - Objectives of interventions

3.3 Technical Elements

In this chapter, technical elements used for requalification are analysed. Those products have high levels of customisation, allowing a wide range of application possibilities. Companies cooperate with different manufacturers for the realisation of components and materials, which will be assembled in factories and then installed.

3.3.1 Façades

The first prefabricated element is the modular integrated façade, which has a key role in the retrofitting process. Modules have different functions, depending on the specific requirements since they can be used for thermal and acoustic insulation, water and air tightness, aesthetic purposes and they can be integrated with systems. Moreover, some modules proposed by both EnergieSprong and 4RinEU projects are designed to provide an additional earthquake resistance to the entire building, thanks to the use of cross-laminated timber panels (CLT) for their lightness and satisfactory dissipative response.

The envelope modules are designed with an integrated approach to minimize the number of components and ensure seamless operation. The interfaces between these components are carefully planned and tested after the assembly of the complete module, which guarantees system's efficiency and reliability, by reducing complexity and potential issues during

implementation. Moreover, these elements are designed by following sustainability considerations, adhering at the same time to the principles of circular economy: this approach, indeed, emphasizes the reuse and recycling of materials, from the production to the disassembly of the components. Therefore, the design is thought to speed up those two phases, following rules for DfMA (Design for Manufacture and Assembly) and DfD (Design for Disassembly). Thanks to the usage of recycled products for the production and well-planned end of life strategies, the overall amount of construction waste is drastically reduced.

Modules are composed of different parts, according to the required properties and the final use they are produced for. In general, they are characterized by a structural frame, which is anchored to the existing building's façade through brackets, an insulation layer, a waterproofing membrane and an external finishing panel made of specific materials. Sometimes windows and systems are already integrated in the façade, in order to provide a complete module for all features. Figure 3.4 below represents a typical layout of façade module.

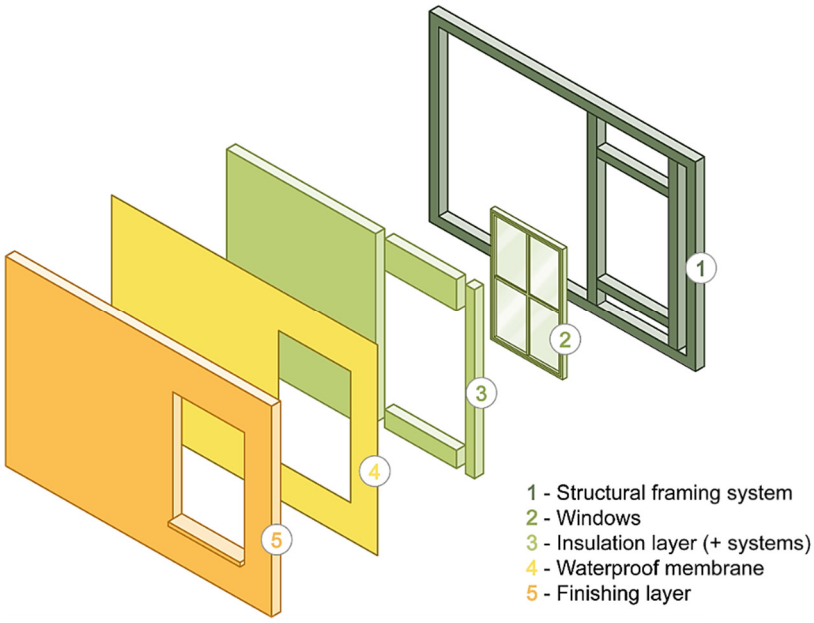

Figure 3.4 - Typical façade module composition

3.3.2 Roofs

The roof is the second element of the envelope that can be substituted with prefabricated components. As for the façades modules, the expected features are mainly thermal and acoustic insulation, water and air tightness, and aesthetic purposes. Alongside with these properties, roofing systems arrive to building sites with mounted systems or plants' predispositions. Usually, modules are completed with solar thermal or photovoltaic panels, whose integration allows to cover inhabitants' needs, reducing the environmental impact. On

the other hand, the connections to electrical and thermal systems are completed during the finishing stage of the worksite.

The new prefabricated roof is lighter than the original one, which reduces the load applied to the entire building structure, allowing the recovery of the attic for new purposes. By refurbishing building's roof, the attic becomes a new space for the installation of systems' components: an example is represented by new heating generators and storage tanks, connected to the solar panels on the rooftop. Since the heating generation and storage systems are placed on top of the building, the distribution can exploit the gravity, without the use of pumps, further reducing the electricity consumption.

Another system that can be predisposed for roofs is the meteorological water recovery system. During the production, collection pipes are incorporated into the roof module, while tanks for rainwater collection are installed in the attic. This system allows the harvested rainwater to be used for specific purposes within the building, reducing the use of clean water and mitigating the risk of flooding by managing water runoff more effectively. In the image below the main features of the new roofing system are reported.

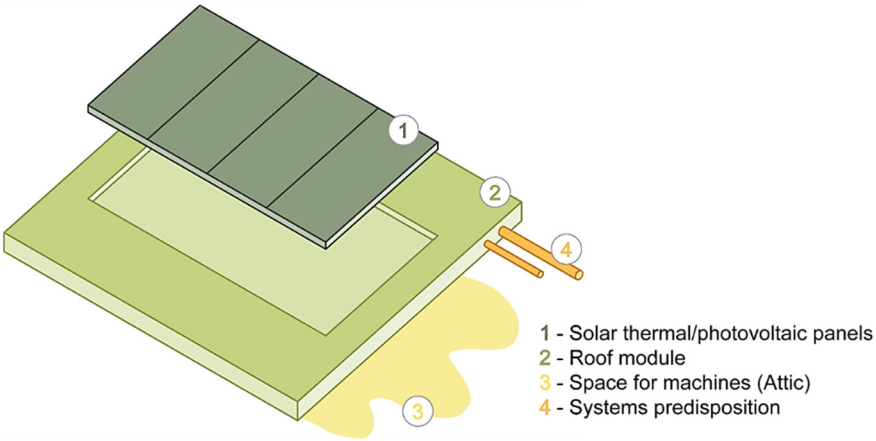

Figure 3.5 - Features and components of roof modules

3.3.3 Systems

After the increase of building's envelope thermal performances, it is fundamental to change old plants with new, more efficient, ones. Regarding the systems, different solutions are proposed, according to the specific needs of each case. However, the main objective is to integrate building systems within the new envelope components, in order to provide each new component of the building with the same prefabrication characteristics.

Centralised systems are preferred, with the use of existing distribution systems, by changing only generators and terminals. When it is not possible, the new distribution system is embedded into the façade modules, reducing time of realisation. In autonomous cases,

proposed solutions require small interventions in the internal spaces, integrating systems inside the false ceilings or floor.

Renewable production plants are mounted on the roof or façade modules, and their installation is crucial for increasing the needs covered by renewable sources: indeed, photovoltaic systems are sized to produce at least the required quantity of energy. Solar thermal systems, instead, are integrated with heat pumps to minimise consumptions to produce heat. Concurrently, the creation of energetic communities allows to exploit in the same district the overproduction of electricity, without installing electric storage systems.

Mechanical ventilation is required to maximise performances, for avoiding losses and ensuring indoor air quality. Cooling systems are often integrated with it, and it is usually coupled with heat recovery units, to reduce energy consumption for air conditioning. Machineries for autonomous systems, when it is possible, are installed in the prefabricated elements of the envelope, while for centralised configurations they are placed in the attic.

To optimise the prefabrication process and to reduce the time of realisation, aggregates of plants are created in factories. These solutions are designed for autonomous systems, where components such as heat pumps, hot sanitary water storage tanks, heat recovery units, control units, and others are integrated into a single compact box, which will be connected to systems on-site.

3.4 The Process

In order to optimize the entire construction process, by meeting client's requirements, deep renovation projects will be approached through different integrated systems that facilitate control. According to 4RinEU and EnergieSprong projects' methodology, the key player in this interaction is the BIM (Building Information Modeling) model [19]. It is not merely a digital and informational representation of a building's physical and functional characteristics. The use of BIM represents a «true working methodology that integrates digital models, information systems, and processes to optimize project delivery by improving the design and construction process»[12].

Although the application of this model may require greater efforts in the design phase compared to traditional solutions, there are several benefits that can be obtained in the subsequent project phases, including:

---

[12] 4RinEU Reliable Models for Deep Renovation, *4RinEU Management to Implement Deep Renovation,* op. cit page 43

- More efficient communication and collaboration among stakeholders, by trying to fulfil all their requests;
- Advanced model simulations, where the data collected is leveraged to improve the building system's efficiency;
- Organized and efficient planning, thanks to data collection that allows for future predictions and preventive measures regarding costs, timelines, and process quality. Indeed, thanks to the different monitoring systems provided by digital models, it is possible to immediately identify malfunctions or unforeseen failures in the system. In this way, extraordinary maintenance costs are reduced, and the potential inconvenience caused by these unexpected issues is avoided.
- Optimization through feedback to improve design, execution, and management. Indeed, through the immediate verification of data, it is possible to avoid subsequent design modifications during the construction phase, which would entail higher costs and lost time, or deviations from the initial budget estimate.

Therefore, it is possible to state that BIM ensures an integrated design process by involving various professional figures (architects, engineers, contractors) and investors throughout the entire life cycle (LCA) of a building, in line with the principles of a circular economy. Planning, design, construction, and management are no longer viewed as separate and independent phases, but rather as part of a fully interconnected process.

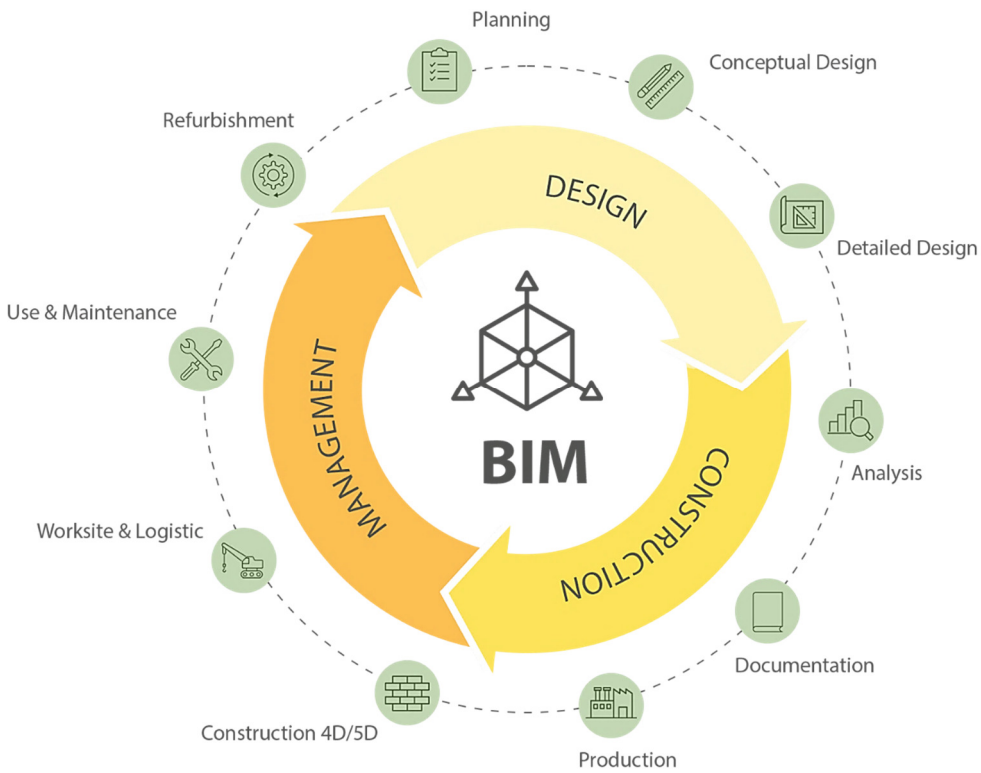

Figure 3.6 - BIM utilisation diagram

According to the Italian standard UNI 11337 part 6, the seven dimensions covered by the BIM process are as follows [20]:

- **1D**: Concept design;
- **2D**: Production of 2D drawings (such as plans, elevations, and sections)**;**
- **3D**: Three-dimensional representation of the building;
- **4D**: Analysis of duration or time (scheduling and planning);
- **5D**: Cost analysis (quantities, estimates, and economic evaluations);
- **6D**: Operation and management phase (use, maintenance, and decommissioning);
- **7D**: Sustainability assessment.

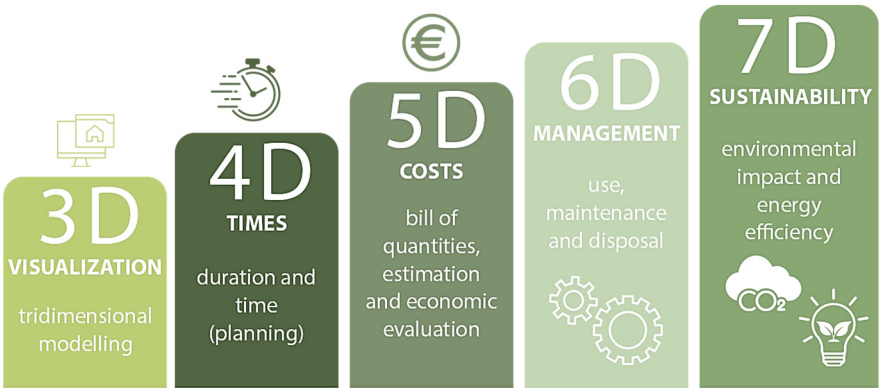

Figure 3.7 - Dimensions of BIM

However, this paragraph presents the different methods defined by companies for carrying out interventions, aiming to better understand the proposed standardized process. The entire realization is divided into main phases to provide a clear and well-defined framework to follow.

According to EnergieSprong project, this approach could be completed by accomplishing seven steps listed below and generally explained in the following subsections.

Figure 3.8 - Main phases of the prefabricated process

3.4.1 Analysis

The building analysis is a fundamental step to verify the feasibility of the intervention, by evaluating the possible solutions and the main achievable benefits. From the moment that, compared to traditional strategy, costs are slightly higher for the prefabricated modules and their installation, while they significantly decrease when it comes to worksite management, the cost-benefit assessment plays a crucial role. Thanks to available technologies, this phase is becoming more precise and faster, allowing to quickly define the effectiveness of the retrofit.

The preliminary analysis is the first step to be carried out during the analysis process. After defining a project budget, a series of digital surveys are conducted to determine the existing technical and geometric characteristics of the building. Photogrammetry and the use of drones enable the identification of point clouds, which are processed using algorithms and artificial intelligence to generate the most accurate three-dimensional model of the construction. These advanced tools allow the sampling of large built areas in short periods of time, creating a 3D database of the built environment and ensuring optimal accuracy in its reconstruction measures. The model is then used for a BIM approach, representing the building's digital twin throughout its entire life cycle, from the retrofit to the end of its life, for monitoring the building usage and maintenance. The described approach enables the integration of disciplines from the early stages of design, enhancing the subsequent phases' effectiveness.

Subsequently, an energy evaluation on building's consumptions before and after the planned requalification is performed, in order to verify the economic feasibility. In addition to the assessment of energy performances, the environmental impact of the building is analysed as well. Once the verification is completed and approved, the design can proceed, involving from the beginning all the technicians responsible for the retrofit implementation.

Figure 3.9 - Stages of the analysis phase

3.4.2 Project Design

The second phase concerns the design of the intervention, during which the participants in the process and the necessary steps to standardize the overall approach are defined. A fundamental aspect of this phase is the integration and multidisciplinary collaboration, made possible through the adoption of BIM model. This strategy increases the level of complexity,

requiring simultaneous and intensive coordination across different areas. Consequently, there will be an extension of the design time, as greater attention will be devoted to coordination management, along with an overall improvement in the subsequent stages. Indeed, BIM allows for planning all phases of project's lifecycle, simplifying data collection and information exchange. It can be applied at various levels of detail, adding new dimensions to the model, such as time and cost management, sustainability analysis, and energy efficiency.

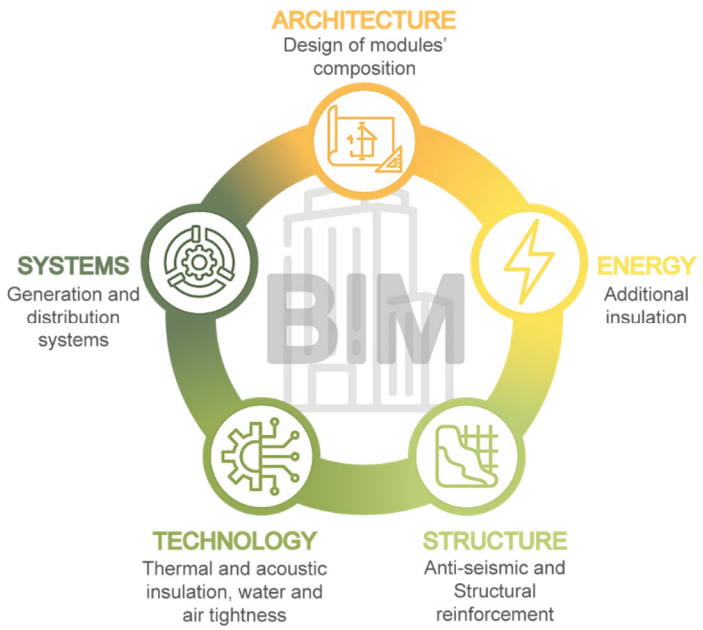

Figure 3.10 - Fields of the BIM approach

By considering both architectural design and technical systems simultaneously, it is possible to develop a highly defined intervention from the outset, yielding optimal results. The integration of the project is further enhanced through dialogue with manufacturers, who are the key players in the prefabrication of the elements, enabling the direct evaluation of solution feasibility and improving speed. Indeed, the final product is tested directly in the factory, allowing for the precise definition of the properties of the entire package, rather than relying on theoretical values obtained by combining the characteristics of individual components. For this reason, the created component can be adapted and used directly for the specific case.

Another important aspect is the architectural design: when using prefabricated elements, the final aesthetic may appear modular and repetitive. To avoid this, an architectural commission within the project team is necessary, responsible for evaluating the modules finishing and their overall combination to achieve a unique final composition.

At the end of the design development, analyses and simulations are carried out. Post-intervention energy simulations are performed to assess the building's performance, estimate

energy consumption, and make further considerations regarding the environmental impact of the structure.

Figure 3.11 - Stages of the design phase

3.4.3 Production

In the world of prefabricated solutions, the production phase can be defined as the heart of the entire process. Compared to the traditional approach, in this scenario, most of the production is shifted from worksite to factory, making it the new centre of the entire requalification model. The optimisation of factory production is the key point for a large-scale application of the retrofitting solution, obtained by replicating industrial processes across different structures and expanding this new technology to multiple projects. By following further development and implementation of this new solution, with the creation of several optimised and specialised facilities, production costs will be minimised, along with improvements of final products' characteristics.

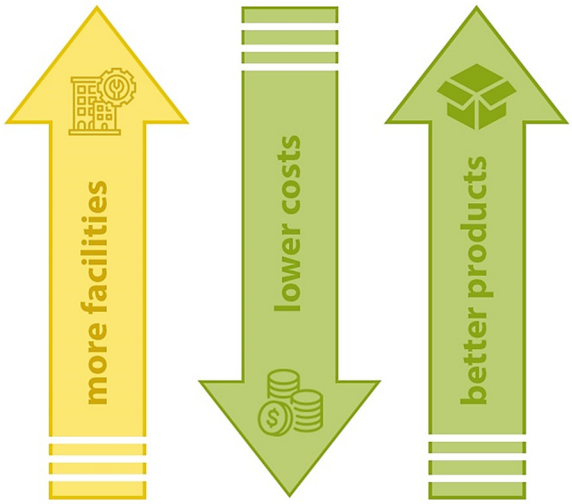

Figure 3.12 – Advantages for large scale production

During this phase, pre-sized materials and components arrive at the factory according to the design's specifications, where they are handled to be assembled to form the final product. The assembly processes could be either mechanized or manual, depending on their typology and

on the level of technological advancement in the factory for the specific task. A high level of automation consents to have benefits related to the precision of processes and workers' safety during operations. Thanks to the prefabrication of elements defined timing is respected during the production phase, allowing a precise planification of the timetable of the requalification.

Figure 3.13 - Stages of the production phase

3.4.4 Logistics

Buildings' construction represents a generally complex process that must take into account a variety of technical, economic, and social factors at its different stages. The complexity of the construction industry, due to the large quantity of materials, components, and equipment, can make it difficult to control quality throughout the entire process. For this reason, logistics plays a fundamental role in the entire building cycle, as it aims to clarify the project's timeline, costs, and objectives before the construction itself. It is a real organization with the final goal of reducing the energy demand of buildings, controlling impacts on costs and duration, while also providing an efficient communication platform with the client.

Since this study considers energy refurbishment with prefabricated solutions, greater attention is given to the worksite's logistics phase, as it differs significantly from the traditional approach. While in the latter construction takes place mostly on-site, with materials processed directly there, this is not entirely the case with prefabricated solutions. Indeed, the materials and construction components are sent to the factory, where they are produced, then transported and assembled on-site. Thus, this process requires careful planning to manage the arrival, storage, and assembly of specific components to minimize time. Additionally, refurbishment with prefabricated elements is much faster compared to traditional construction: once the components arrive on-site, assembly can be carried out quickly, reducing both time and inconvenience for the users.

When considering logistics for energy refurbishment, there is a strong focus on sustainability and efficiency, especially when talking about materials management. This may include the choice of environmentally friendly transportation methods, optimization of timelines to avoid unnecessary movement, and the management of material flow to minimize environmental impact. At the same time, the construction phase must be carefully planned, as these

prefabricated solutions are often integrated with advanced technologies. The installation and commissioning of these technologies require specialized skills and careful planning to avoid installation errors, but most importantly to ensure safety.

Figure 3.14 - Stages of the logistics phase

3.4.5 Worksite

As previously stated, the management of a construction site with prefabricated solutions is completely different from traditional approaches, not only in terms of logistics but also procedurally. Due to a completely new project realization, the prefabricated construction site offers several advantages over the traditional one. First of all, construction times are significantly reduced, as once the prefabricated components arrive on site, assembly takes place quickly, ensuring housing continuity and minimizing inconvenience for the users. This, in turn, leads to a reduction in the on-site work in terms of setup, as the use of scaffolding and its assembly is less required compared to traditional solutions. This results in an overall reduction in the environmental impact of energy refurbishments, also due to a decrease in noise, dust, and waste.

The construction phase is typically developed in three stages, divided into preparatory work, prefabricated elements installation, and finishing work. Depending on the level of prefabrication, the duration of these three stages may vary: by optimizing and increasing off-site production, the work required on-site is reduced, and consequently, the completion time is minimized. These three stages are:

3.4.5.1 Preparatory works

This phase includes all the operations that must be completed before the arrival of the prefabricated elements on site, such as setting up the construction site, removal and demolition of existing elements, preparing the systems, and installing the anchoring systems. Additionally, it involves assessing the existing structural conditions, cleaning the area, and identifying spaces for material storage. The preparatory phase thus falls within the logistics and design sector, which, when carefully planned, can subsequently overlap with factory production and potentially reduce the overall construction time.

3.4.5.2 Prefabricated elements installation

Once preparatory work is completed, the actual installation of the prefabricated elements begins. This phase is crucial to achieving the benefits associated with the analysed process: by optimizing transportation and the installation of the elements, time is managed and reduced efficiently. Once the prefabricated elements arrive on site from the factory, they are lifted using cranes or other specialized machinery, positioned, and secured to the appropriate pre-installed supports.

3.4.5.3 Finishing works

The construction site management final phase includes all the operations that must be carried out to complete the building, enhancing both its aesthetics and functionality. This phase is closely linked to the level of prefabrication achieved through factory production: indeed, with more refined and precise elements, the amount of work required for finishing is reduced. Additionally, the electrical, plumbing, heating, ventilation, and air conditioning systems (HVAC), as well as other technological systems integrated for energy efficiency, such as solar panels or heat pumps, are completed. Before dismantling the construction site, a final inspection of the installed elements is carried out to ensure quality and safety, through specific tests and inspections according to standards.

Figure 3.15 - Stages of the worksite phase

3.4.6 Building Usage and Management

Once the retrofit works are completed, the monitoring phase is crucial to ensure building's performance across all aspects and to guarantee its proper functioning. This phase involves continuously tracking and analysing key metrics, such as energy efficiency, structural integrity, and system performance, in order to detect potential issues before their evidence. Without effective monitoring, any latent problems after the refurbishment could go unnoticed, leading to higher maintenance costs and functional inefficiencies. For this reason, the integration of Building Information Modelling (BIM) enhanced the management phase, as it allowed for detailed tracking of building's operational parameters, facilitating quick identification of deviations from the anticipated performance.

The sixth dimension of BIM methodology, which is the maintenance phase, must be carefully planned during the design stage in order to ensure the building's expected performance throughout its entire life cycle. Having a defined plan of building usage and maintenance leads to full awareness of the total ownership cost, which is essential for comparing the studied methodology to a traditional retrofitting process. Another important aspect of prefabricated components is the dry assembly of elements: once a part of the system is damaged, it can be replaced without destroying the component, which is disassembled and reassembled after the replacement. This principle of Design for Disassembly is important not only for building maintenance, but also for the following phase, the end of life.

Figure 3.16 - Strategies of buildings usage and maintenance phases

3.4.7 End of Life

The end-of-life stage represents one of the key aspects of this new building refurbishment process, as it is closely linked to their ecological footprint. Indeed, the construction sector has long been criticized for its significant environmental impacts, particularly due to the large amounts of construction and demolition waste, which constitute one of the main categories of pollution. In order to ensure a more sustainable future, the construction industry must shift towards a circular system, a model in which the end of a building's life can mark the beginning of a new cycle for others. This means that the building components and materials, after disposal, can be recycled, adapted, and reused multiple times, beginning a new phase of life. For this reason, although the four main stages of a building (design, construction, use and operation, reuse, and demolition) have traditionally been conceived in a linear development process, the building ecosystem itself need not be. The foundation for achieving this goal lies in adopting this new circularity concept, which could lead to significant energy, economic, and environmental savings.

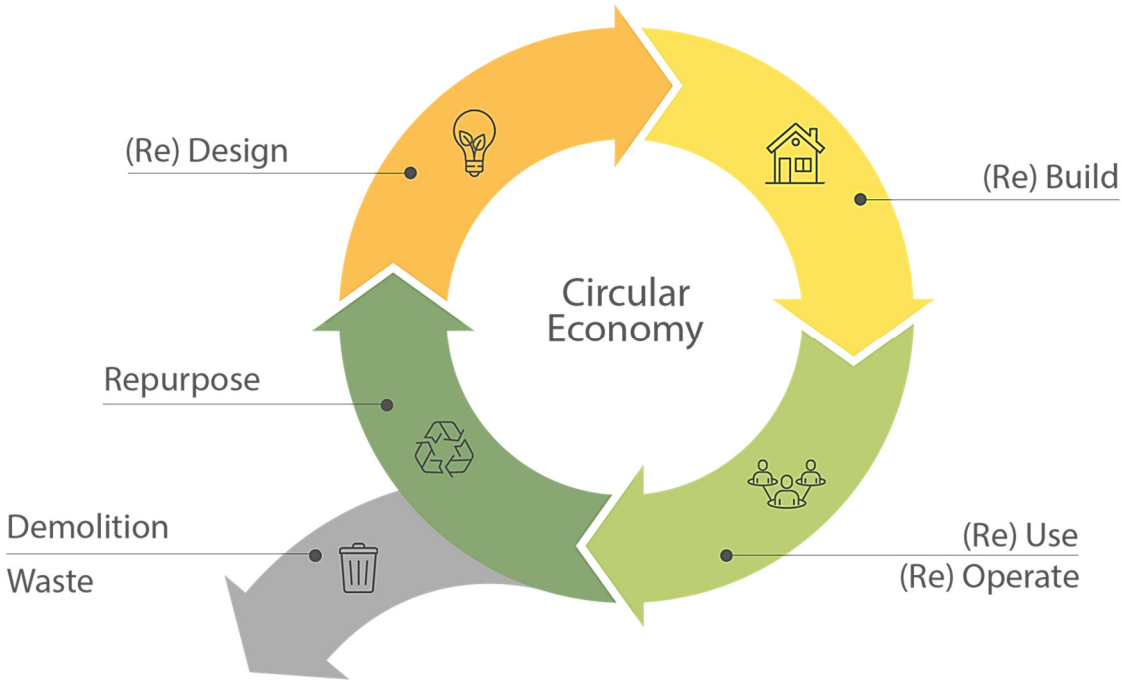

Figure 3.17 - Circular economy diagram

In the past, the Waste Framework Directive 2008/98 issued by the European Union, imposed on all Member States the need for better recycling of components. The main objective was to achieve a recovery rate of 70% for construction and demolition (C&D) waste by 2020. However, with the exception of a few EU countries, only about 50% of C&D waste is currently recycled, due to a lack of technology, inadequate product design, and insufficient economic incentives.

Nonetheless, the primary goal of this new circular economy lies in a series of procedural hierarchies aimed at promoting a more ecological approach both during the design phase and in subsequent processes. This is the waste hierarchy, imposed by the aforementioned EU Waste Framework Directive, which represents the guiding principle behind every decision or waste management system. Referring to one of the fundamental principles of the 4RinEU project, the end-of-life strategy for buildings must follow the priority scale shown in Figure 3.18 below. [21]

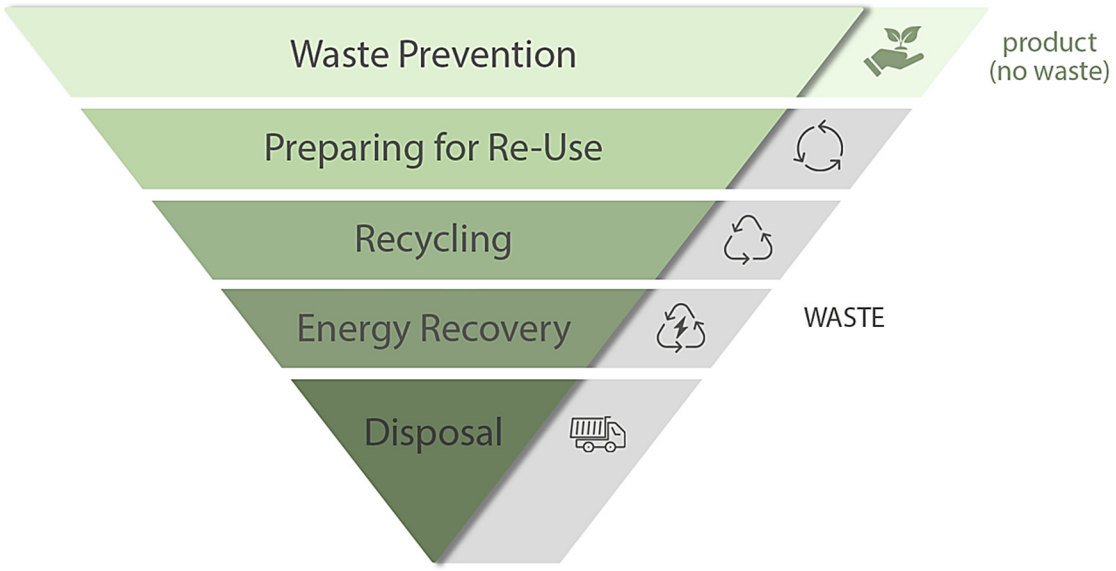

Figure 3.18 - 4RinEU End-of-Life strategy for buildings

3.4.7.1 Waste Prevention

Waste prevention is one of the key strategies for achieving a circular economy, as it would bring, if carried out correctly, a series of benefits both in the construction industry and at the environmental level. First of all, it could ensure a resources and raw materials reduction used in the construction process. This, in turn, implies a reduction in waste through their reuse, while simultaneously extending the useful life of various materials. Secondly, these preventive measures could lead to a decrease in negative impacts that demolition waste generates on the environment and human health. Indeed, by reducing waste through an organized management system, the well-being of individuals can significantly improve due to the reduction of harmful substances in materials and products.

Therefore, waste prevention can be defined as a set of measures adopted throughout the entire lifecycle of a construction process, not only at the end-of-life phase of a building. These actions can range from practical interventions on site, such as the use of reusable packaging systems to reduce waste material, to preliminary design choices, such as the use of materials that can be recycled or easily disassembled. One example is represented by the core of this energy retrofit: a façade made of prefabricated panels that can be easily dismantled allows for the recovery of materials and reduces the need for new resources.

3.4.7.2 Preparing for Re-Use and Re-Use

Reuse means that a product, its components, or entire building structures are used again for the same purpose, rather than being dismantled and sent for recycling, recovery, or disposal.

"Preparing for reuse" refers to performing inspection, cleaning, or repair operations that allow waste materials to be reused without the need for further preprocessing. Although recycling is also a recommended solution in the circular economy process, the benefits of reuse are even greater as it provides:

- A reduction in raw materials, leading to a lower environmental impact, as fewer resources are exploited;
- Lower energy consumption, which would otherwise be required in recycling processes, resulting in a decrease in greenhouse gas emissions and reduced acidification;
- An extension of the useful life of construction materials, allowing them to remain in their cycle for a longer period.

However, dismantling a building and the subsequent reuse of its components is not a straightforward or easy task, especially if the design and construction phases were not carried out with the intention of recovering the materials used. For this reason, another fundamental aspect of the circular economy is the Design for Disassembly (DfD): this is an approach to building design focused on creating structures in a way that allows them to be easily disassembled at the end of their lifecycle. Thanks to a series of cutting-edge techniques, it is possible to ensure the direct recovery of a limited percentage of products and materials after their disassembly, without causing damage to them.

Nonetheless, despite the progress made in the field of construction techniques and processes, the complete reuse of materials is still not fully achievable. In fact, there are several issues that can arise, starting with the degradation of components due to prolonged use and unfavourable weather conditions, which no longer meet the required safety standards. The lack of specialized labour, as well as the absence of specific transportation and storage systems, are also among the reasons why this technique has not yet been fully developed.

3.4.7.3 Recycling

Since the original, or "primary," production of materials requires significant amounts of energy and raw materials, recycling can represent one of the most eco-friendly solutions when it comes to waste disposal. It is, indeed, a process through which waste materials are transformed into new products, allowing them to have "a second life" as they would otherwise be destined for landfills. The positive aspects of this process are similar to those of reusing construction components, as it also involves:

- A reduction in the use of natural resources such as minerals, timber, water, and fossil fuels;

- A decrease in energy consumption compared to the production of new materials;
- A reduction in the amount of solid waste that ends up in landfills or is incinerated;
- A range of financial benefits.

Different materials are commonly recycled on construction sites, including concrete and stone materials (bricks, tiles, and ceramics), which are reused as coarse or fine aggregates in various roadworks or in the production of new concrete. Wood and metals are recycled too: the former is repurposed for chipboard, panels, or composite materials production, while the latter can be fully recycled, without losing quality, for bars, beams, structures, and reinforcements production.

Referring to the new concept of innovative design, prefabricated facades fall well within the category of recyclable, or even reusable building components. These technologies are made from durable and modular materials, which can be easily disassembled and separated at the end of the building's lifecycle. This characteristic makes them particularly suitable for recovery, as individual components such as metal, glass, wood, or insulation material can be extracted from the whole unit and reused for other construction cycles (Figure 3.17).

Figure 3.19 - Façade module installation

3.4.7.4 Energy Recovery

When recycling building components is not feasible, an alternative solution is the recovery of the intrinsic energy within waste materials. This approach can lead to significant environmental benefits, as certain high-calorific waste materials can be transformed into energy, such as electricity or alternative fuels (e.g., synthetic gas). There are several methods for energy recovery, including:

- Incineration, in which waste is burned at high temperatures, and the energy produced during the combustion process is converted into electricity or heat for urban heating. However, improper or incomplete combustion of waste materials can cause environmental and health damage through the release of harmful chemicals, including dioxins and acid gases.
- Gasification and pyrolysis, two methods that ensure the decomposition of waste such as wood, plastic, and rubber into combustible gases (synthetic gas, known as syngas) at high temperatures in an oxygen-free environment. This process occurs through advanced recycling technologies, referred to as waste-to-energy (WTE) plants.
- Methanization, a process that converts organic waste, such as wood and plant residues, into biogas, a renewable fuel, through composting or anaerobic digestion.

3.4.7.5 Disposal

At the base of this hierarchy lies the disposal of construction and demolition (C&D) waste, when re-use and recycling operations (both material and energy recovery) are not guaranteed. The term refers specifically to waste transport from worksite, its later treatment, and disposal in designated sites, such as landfills, incinerators, or treatment plants.

The waste hierarchy, within the concept of a circular economy, provides a simple tool to guide decision-making. As previously stated, these choices are made with the aim of minimizing waste generated from demolition, while simultaneously promoting a more environmentally friendly approach to design through recovery efforts.

3.5 Cost Analysis

As previously mentioned, the project cost analysis represents the fifth dimension considered by BIM methodology, adopted in this innovative energy retrofit process. Indeed, the economic variable has been integrated into the three-dimensional model with the ultimate goal of estimating project's construction costs, where the unit price of various materials and components is directly inserted into the 3D modelling, including supply and labour costs. In addition to being a leaner and faster process for the cost manager, this method allows for full operation control to be carried out and minimizes the risk of error. Several benefits are derived from the use of this 5D modelling compared to traditional methods, including enhanced cost control and quick, accurate quantity assessments, thanks to higher precision.

For this reason, companies have started to define economic models to compare an industrialized method with the traditional approach regarding the retrofitting process. For example, EnergieSprong has created its model using TCO (Total Cost of Ownership) to

analyse the costs and benefits of the building life cycle, which is 30 years. TCO considers not only the payback period but also the period following the breakeven point, when the revenues obtained are equal to the investments made in renovation (Figure 3.18). In this case, the focus shifts from revenues to savings for the investor, which includes savings in energy, maintenance, and management costs thanks to energy retrofitting.

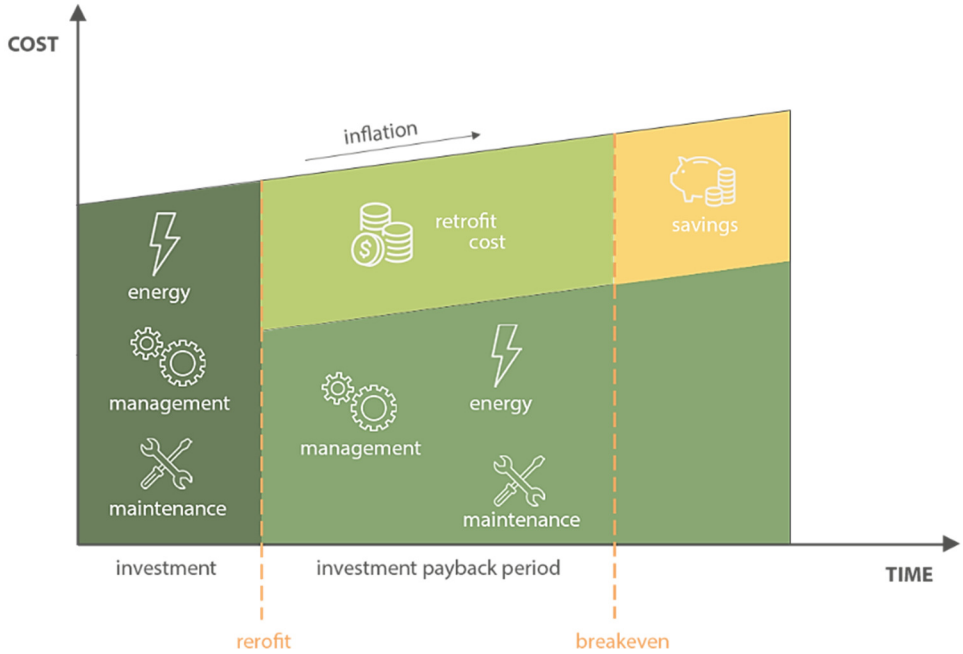

Figure 3.20 - TCO diagram, from Energiesprong

Thanks to these prefabricated technologies, several economic advantages in the short and medium term are guaranteed, primarily due to two main factors: higher quality and precision of components, leading to greater durability, and a reduction in errors during the construction phase. These benefits ensure that the savings generated throughout the building's life cycle are actually higher compared to those obtained through traditional solutions. According to the economic balance sheet conducted by EnergieSprong, illustrated in Figure 3.18, in addition to the savings guaranteed by energy retrofitting processes, there are two other key points to highlight:

- Costs decrease due to a factor called "economies of scale", resulting from an increase in production volumes and overall improvement in factory operations. This means that as the production of prefabricated elements increases, future component costs will decrease, a condition that cannot be guaranteed with traditional solutions.
- Benefits increase thanks to the indirect rise in property value, stemming from a reduction in social and environmental costs (such as CO2 emissions) and greater resilience provided by offsite technologies compared to traditional ones.

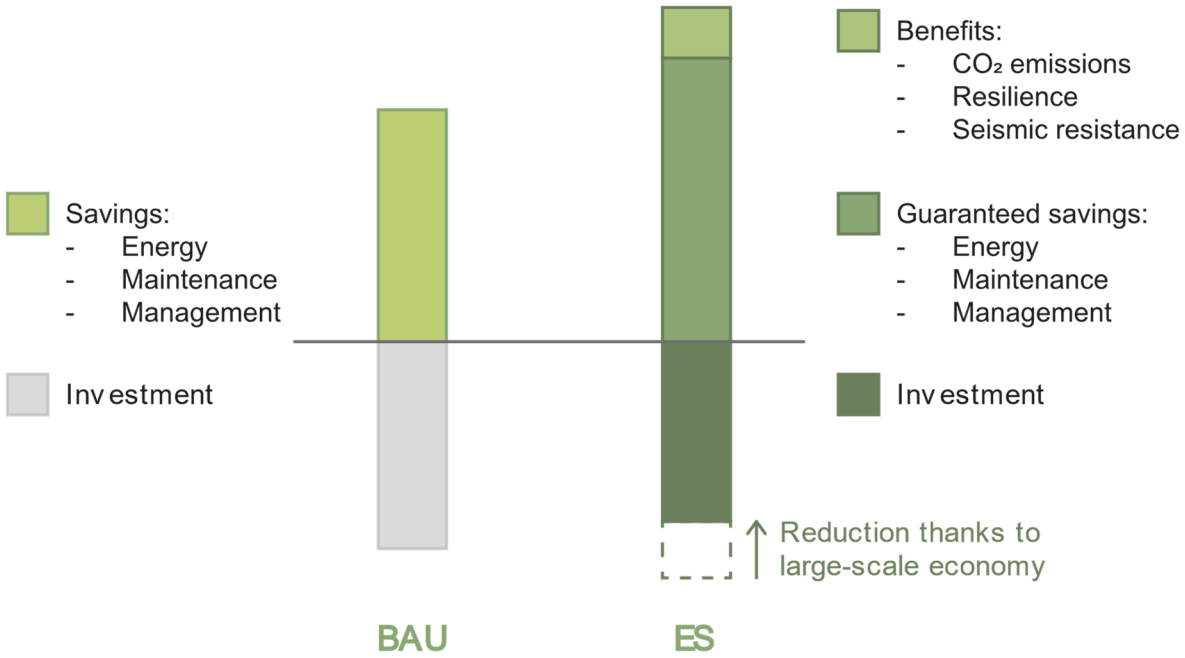

Figure 3.21 - Costs and benefits comparison of Building as Usual (BAU) and Energiesprong intervention (ES), from Energiesprong

Consequently, the TCO includes the purchase price of an asset along with its operational costs throughout its life cycle, in order to assess the long-term value of that particular purchase. This concept is applied to buildings using the Life Cycle Cost Analysis (LCCA) method, which considers the total costs associated with a building throughout its expected life. These are divided into the initial investment for design and construction, operational costs for the building's use, maintenance costs, and disposal costs at the end of its expected life.

The economic model provided by Energiesprong [22] aims at demonstrating how prefabricated intervention can be economically sustainable, comparing different scenarios of buildings' requalification. The cases examined are the non-refurbished building (As-Is), the traditional retrofit (BAU – Building As Usual) and the prefabricated solution (ES). During the evaluation on their TCO, several parameters are considered in order to deeply investigate benefits of different proposed solutions.

First of all, costs and revenues are identified and classified in different classes, listed in Table 3.1. They are divided into CAPEX, which is the initial investment for existing building's requalification, OPEX is related to usage and management of the building during its expected life, while revenues are the positive money fluxes for owners.

Table 3.1 - Costs and revenues of interventions

CAPEX	Cost of refurbishment
OPEX	Financial charges
	Maintenance
	Management
	Energy
Revenues	Incentives
	Rent

For what concerns the situation presented in this study, that is the prefabricated method, initial investments are slightly higher than the traditional ones, with an increase of 2-10% of costs. However, life cycle operational costs associated with the studied retrofit are 12% lower than the traditional retrofit and 43% lower than the existing building itself. On the final balance, at the end of 30 years, the prefabricated solution provides an increase of 2-5% respect the traditional, and 50-60% respect the existing conditions. In order to fully understand the benefits brought by this innovative solution, Figure 3.22 below plots CAPEX and OPEX costs values for the three scenarios. On the left side, regarding the CAPEX one, the traditional investment is considered as 100%, from the moment that it serves as the sole indicator for comparing the prefabricated solution. On the right, for OPEX costs, the predicted operative costs of the existing building are considered as 100%, as they represent the baseline for measuring the economic impact of the other two solutions. It is noticeable that the Energiesprong solution has slightly higher initial investment compared to the traditional one, while the operational costs are reduced by the percentages described before.

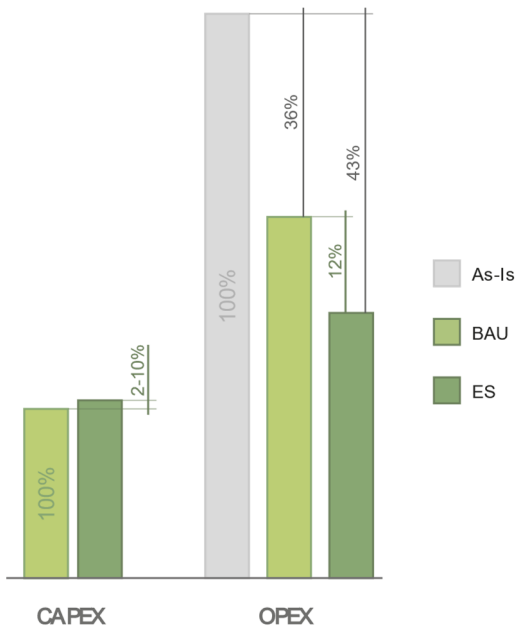

Figure 3.22 - CAPEX and OPEX comparison of As-Is, BAU and ES

To maximise the effectiveness of the solution, the analysis extends to future scenarios. Unlike traditional approaches, the prefabricated method benefits from principles similar to industrial production. Indeed, as production volumes increase, costs are expected to decrease, while the efficiency and quality of the entire supply chain improve due to the learning curve, driven by the repetition of standardized processes. This leads to a reduction in investment costs, potentially aligning them with those of traditional approaches, while operational costs remain similar to the current analysis. At the end, the final balance between these two costs shows an increase of 10-20% respect traditional solutions.

Alongside the effective impact on costs, potential costs are also identified. Those are related to benefits that now are not considered in the economical evaluation of designs, but they may become relevant in future analysis. They are listed below:

- Social costs: due to the reallocation of inhabitants during the refurbishment, the prefabricated approach guarantees the housing continuity during the works, reducing expenses related to alternative housing solutions.
- Safety costs: the reduction of construction site operations and the absence of scaffolding allows a reduction in insurance costs and unexpected costs due to delays resulting from accidents on construction sites.
- Environmental costs: the replacing of traditional systems with innovative technologies permits to access to incentives and tax breaks. Furthermore, failure to comply with standard requirements may result in financial penalties for owners.

To have a clear visualisation of possibilities and help with their selection, it is important to define a standardised comparison method. Based on the 4RinEU project, tools have been used to calculate the Return on Investment (ROI) in order to evaluate the profitability of an investment, as it calculates the return generated in relation to the invested capital, identifying any potential losses that may arise. The tool used for this analysis is defined as the Multicriteria Ranking Tool, which provides an overall picture and comparison of the results obtained from the use of different deep renovation packages. This can help investors understand the advantages (e.g., energy savings or a smoother process) and disadvantages (e.g., risks and costs) of various renovation interventions, comparing them and deciding which one may yield the greatest profit. As explained in the following chapters, an additional support will also come from the EU Taxonomy, whose aim is to encourage investors to direct their capital towards sustainable refurbishment projects, thereby yielding benefits on multiple fronts.

3.6 Examples: Traditional vs Prefabricated Solutions

As previously stated, the adoption of prefabricated solutions for buildings' energy requalification not only offers several benefits but also introduces a series of innovations that improve the overall efficiency of the construction process. One of the main advantages of offsite solutions compared to traditional ones lies in the reduction of on-site constructions times, by shifting a significant part of production from worksite to factory. The optimization of timelines is also made possible by a flawless project management system: construction site preparation, simplified by the absence of scaffolding and accessory structures (such as material lifts, canopy, etc.), can proceed simultaneously with the production of the prefabricated elements. Furthermore, it is important to highlight that the direct installation of these modules onto the building façades significantly speeds up the process compared to traditional thermal insulation's installation, with lower logistical impacts and more streamlined management of construction material and waste.

Figure 3.23 - Time reduction of off-site solutions

Another advantage of this new approach is the reduction in general costs. Although requiring a higher initial investment in the design and customization of prefabricated modules, the overall costs for construction phase are significantly reduced, thanks to the speed of execution and the decreased need for labour. Additionally, thanks to an accurate management process, which involves constant monitoring and inspections, the costs associated with unexpected maintenance are substantially minimized, thus increasing building's residual value. This leads to a reduction in management costs, making the construction more durable and resilient over time.

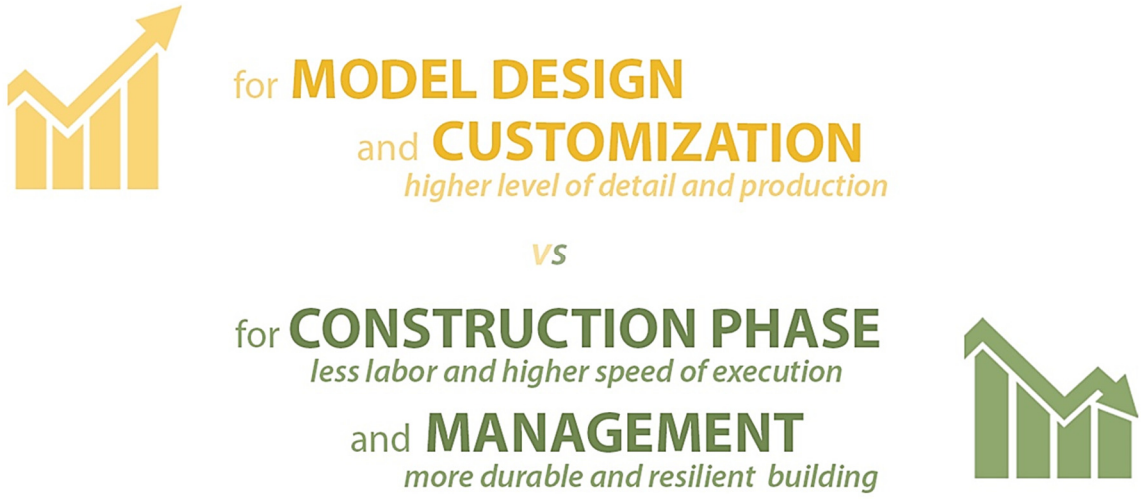

Figure 3.24 – Costs' distribution of the prefabricated approach

In order to concretely illustrate the benefits of this innovative approach, a renovation project promoted by Energiesprong, with the support of Eurac Research (the company managing the previously mentioned 4RinEU project), was analysed. The purpose of this paragraph is to compare, in terms of costs and timelines, the offsite approach with the traditional external insulation system, also defined as thermal coat, highlighting the advantages brought by the new renovation concept.

The case study considered concerns a building located in Povo, a small suburb of Trento, in Northern Italy. The construction, built in 1952, consists of three above-ground floors and is characterized by a load-bearing stone wall structure, hosting single-glazed window frames. Due to its poor energy performance, the main objective of the renovation was to improve the building envelope, particularly by addressing the thermal transmittance of perimeter walls, to reduce thermal losses initially present. Out of 800 m^2 of external surface, only two façades (130 m^2 in total) were the subject of intervention: instead of applying the traditional external thermal insulation, the modular Renew-Wall system was installed. The other retrofit interventions included the installation of a photovoltaic system on the building's roof, windows replacement and the installation of new autonomous boilers.

Figure 3.25 – Model of the case study, from Energiesprong

Table 3.2 – General information of the case study

Povo, Trento	
Construction year	1952
Number of units	9
Number of floors	3
Total facade surface [m2]	800
Facade surface retrofitted [m2]	130
Structure composition	Load-bearing stone wall

Renew-Wall is a new modular system designed for the integrated energy and architectural refurbishment of existing buildings. It is primarily made up of a wood-based panel, insulated and pre-integrated with windows, shading devices, mechanical ventilation with heat recovery, and a prefabricated finishing plaster. The finish used in Povo is plaster, the same as that used in the rest of the building, but with the key difference that it has been manufactured and finished in the factory. Table 3.3 below illustrates the main characteristics listed in the product's technical datasheet, which will be useful for developing the following analysis concerning production costs and installation timelines.

Table 3.3 - Characteristics of the module

Maximum dimension [mm]	Cost [€/m^2]	Installation time [m^2/day]
350x800	From 250 to 300	From 50 to 80

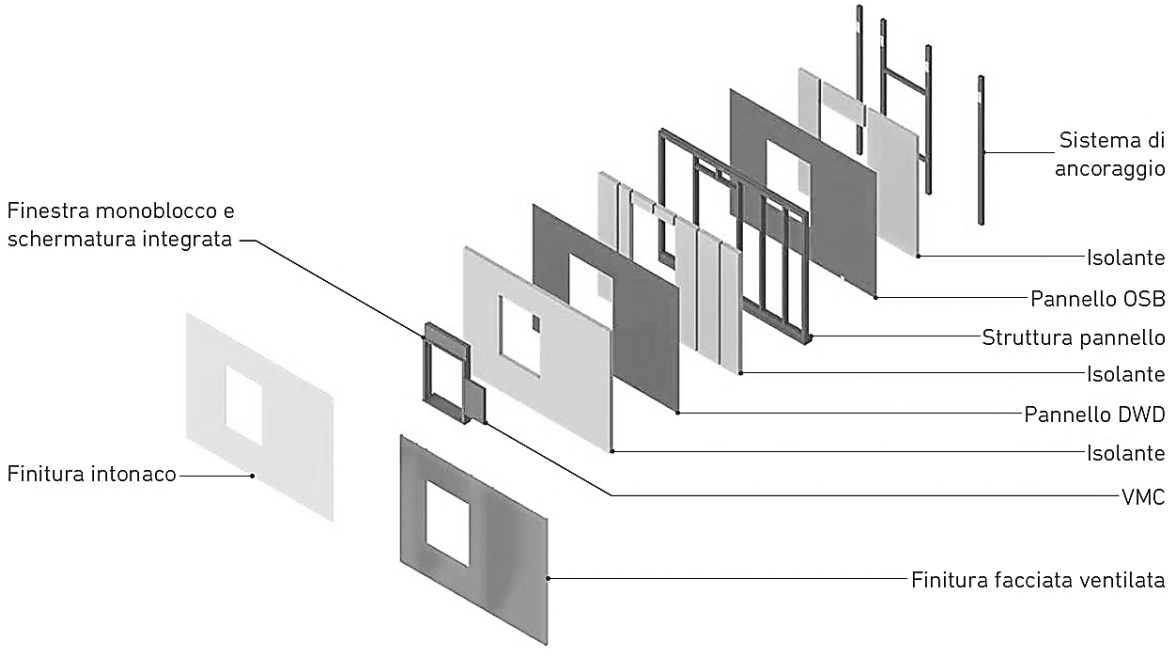

Figure 3.26 - Module composition, from Energiesprong catalogue

The first comparison between the traditional external insulation solution and the new prefabricated modules concerns the initial phase of the construction process, the worksite set-up. This step involves a series of activities necessary for building construction or renovation in order to ensure its proper functioning and safety. Generally, these activities include:

- The availability of a chemical toilet and a shed for changing rooms or storage;
- Fencing the construction area with fences, barriers, and warning tape, as well as the necessary signage to identify the work area;
- Possible public land occupation fees if scaffolding needs to be installed on public land or a road must be partially closed;
- The potential installation of scaffolding and its systems;
- The potential installation of an elevator for lifting heavy materials, if the building is high;
- The electrical system for the construction site, including a certified and CE-marked construction site distribution board, along with an earthing system with a declaration of conformity;

- Possible rental and transport to the worksite of a construction crane or similar lifting equipment required for moving specific elements.

By comparing the traditional solution with the prefabricated one, substantial differences in terms of costs and timelines can already be identified in this first step due to different operational methods. For instance, with the installation of traditional thermal coat, scaffolding must be mounted on both facades involved, along with the installation of a construction site electrical system. In contrast, with the use of prefabricated modules, scaffolding is not required, as the modules are directly applied to the façades through special anchors. In this case, lifting equipment, such as a construction crane, aerial work platform (AWP), or mobile crane, will be necessary, and the cost for them is already included in the total price proposed by Energiesprong (Table 3.3).

As shown in Table 3.4 below, the costs for a worksite set-up are significantly lower with the prefabricated solution, while also offering several advantages for the entire process. The rapid assembly of the modules helps reduce inconvenience for users and ensures housing continuity, as the work is less invasive. While with the traditional external insulation, scaffolding must be assembled and disassembled, requiring at least one or two days of work for each phase, the installation of the prefabricated modules takes place in significantly shorter times, without the need to maintain the support structures throughout the entire duration of the work.

Table 3.4 - Worksite costs comparison

Traditional Solution: Worksite set-up				
Type	**Unit Price**	**Unit of Measure**	**Quantity**	**Total Cost**
Scaffolding	31.35 €	m^2	130	4,075.50 €
Goods lift	4,100.00 €	cad	not required	0.00 €
Electrical system	151.55 €	cad	1	151.55 €
Security alarm system	876.25 €	cad	1	876.25 €
			Worksite Total Cost	**5,103.30 €**
Prefabricated Solution: Worksite set-up				
Type	**Unit Price**	**Unit of Measure**	**Quantity**	**Total Cost**
Scaffolding	31.35 €	m^2	0	0.00 €
Electrical system	151.55 €	cad	0	0.00 €
Security alarm system	876.25 €	cad	0	0.00 €
Areal Platform 21 m rental	350.00 €	gg	included	0.00 €
			Worksite Total Cost	**0.00 €**

The second term of comparison concerns the actual installation of both renovation proposals. As regards the traditional solution, several steps and processes are required before proceeding with the installation of the external thermal insulation. The first phase consists of analyzing the building's structural conditions, in order to ensure the external wall's ability to support the insulation system's additional weight. Secondly, the entire surface to be treated must be secured and restored, including:

1. Securing: control and demolition of the unsafe concrete parts carried out by manual tapping, followed by the removal of plaster that is detaching until the underlaying wall support is exposed;
2. Localized restoration: volumetric filling of the demolished plaster areas through application of bedding mortar;
3. Localized or complete smoothing: smoothing of the areas where the plaster has been restored, carried out on all surfaces involved, and applied manually in two or more coats;
4. Surface treatment: water-based paint with synthetic resins to prepare the final surface to be treated;

As regards the application phases of thermal coat, it is considered:

1. Starting profile and plinth installation, which allow the insulation to be lifted from the ground to avoid infiltrations;
2. Insulating panels installation, which are laid on the façade by using an adhesive (cement-based mortar) which must cover 40% of the surface. These have to be installed starting from the bottom, positioning the sheets staggered like bricks by at least 25 cm to avoid joints formation between the insulating panels;
3. Mechanical anchoring plugs displacement;
4. First smoothing of the insulating panels, which is generally carried out 3-10 days later, with prior elimination of any irregularities on the insulating sheets. This phase is carried out by applying base plaster inside which the fiberglass mesh is embedded;
5. Finishing coating layer application, which takes place after an appropriate curing time for the base plaster and the application of a primer.

Figure 3.27 – External insulation layer (thermal coat) application phases

In the case of the prefabricated solution, the modules are produced in the factory and sent directly to the construction site once completed. These components are later applied directly to the existing facade through an anchoring system, which allows for adjustments of module's position and accommodate the expansions of the load-bearing structure, both in façade plane and orthogonally. This installation method is considerably faster and involves less inconvenience than traditional one, with the advantage of reducing construction times and enhancing constant quality throughout the entire construction process.

Table 3.5 - Costs of construction works comparison

Traditional Solution: Construction Works				
Type	**Unit Price**	**Unit of Measure**	**Quantity**	**Total Cost**
Safety measures	11.45 €	m^2	130	1,488.50 €
Localized restoration	17.46 €	m^2	130	2,269.80 €
Localized plastering	46.94 €	m^2	130	6,102.20 €
Surface treatment	15.56 €	m^2	130	2,022.80 €
Thermal insulation system	100.15 €	m^2	130	13,019.50 €
			Partial Cost	**24,902.80 €**
Prefabricated Solution: Construction Works				
Type	**Unit Price**	**Unit of Measure**	**Quantity**	**Total Cost**
Renew-Wallsolution	250.00 €	m^2	130	32,500.00 €
Skilled labour for finishing work	39.28 €	h	included	0.00 €
			Total Cost	**32,500.00 €**

As previously mentioned, the prefabricated solution is slightly more expensive due to the higher level of detail required during the design phase. This increased cost is primarily associated with the need for careful planning and the customization of each module to fit specific needs of building's façade. However, it is important to underline that if this solution was expanded on a larger scale, with a focus on optimizing and further industrializing the production process, significant cost reduction could be achieved. Indeed, by standardizing the design and production of the prefabricated modules, manufacturers could take advantage of economies of scale, where the cost per unit decreased as the volume of production increases (Figure 3.28).

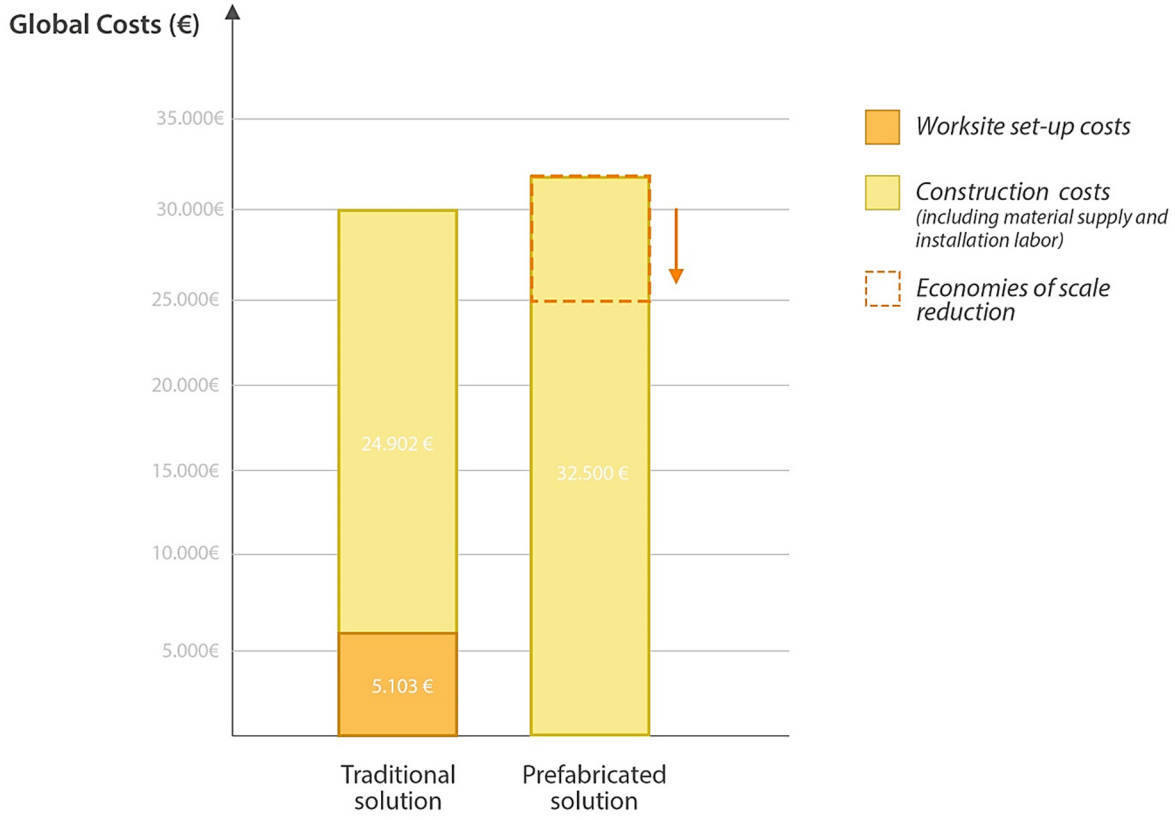

Figure 3.28 – Cost analysis and comparison between prefabricated and traditional solutions

Regarding timelines, the prefabricated solution offers a clear advantage. The installation of the Renew-Wall system took place in November 2023 without the use of scaffolding, requiring a total of just 3 days of work. This demonstrates the feasibility of achieving construction time reductions and minimizing disruptions for residents, ensuring housing continuity while guaranteeing the quality of the final result through the off-site production of the finished panels.

In contrast, the traditional thermal coat requires a significantly longer overall timeframe due to the multiple tasks involved on-site, including securing and restoring the façade, as well as the steps related to the installation of the insulation system. As shown in Table 3.6, the total estimated time for these processes is about 35 days, considering an additional one or two days for scaffolding installation. This extended timeline highlights the additional time and complexity required for traditional methods, underlining the efficiency of the prefabricated system in terms of both speed and minimizing disruption.

Table 3.6 - Timing comparison

Traditional Solution: Worksite set-up	
Type	**Average required time**
Scaffolding	1/2 days
Traditional Solution: Construction Works	
Type	**Unit Price**
Safety measures	from 10 to 15 days
Localized restoration	
Localized plastering	
Surface treatment	
Thermal insulation system	about 25 days
Prefabricated Solution: Worksite set-up	
Type	**Average required time**
Scaffolding	0 days
Prefabricated Solution: Construction Works	
Type	**Unit Price**
Renew-Wallsolution	3 days

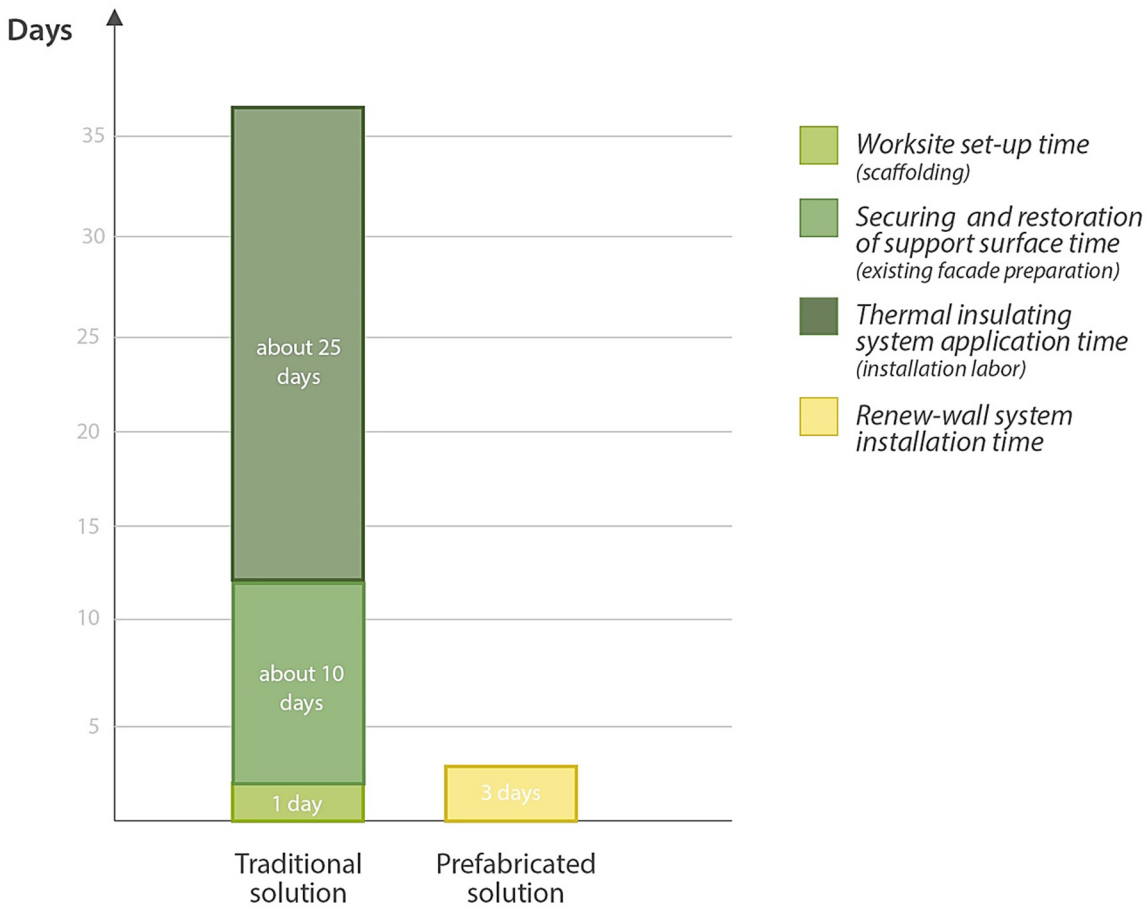

Figure 3.29 – Time analysis and comparison between prefabricated and traditional solutions

In conclusion, it is possible to state that the adoption of offsite prefabricated solutions not only offers significant time savings and almost equal construction costs, but also marks a crucial step toward more sustainable, durable, and energy-efficient architecture. This approach effectively addresses the modern challenges of sustainability and energy efficiency, paving the way for a greener and more resilient built environment.

3.7 Prefabricated Approach Considerations

According to the requalification rate for non-residential buildings in Italy, traditional methods for retrofitting process are not sufficient to meet the EPBD requirements. Prefabricated solutions offer a promising alternative that can accelerate the performance improvements needed in this sector, aligning with EU standards. Beyond time reduction, several benefits emerge from the adoption of this innovative approach, particularly in terms of sustainability, advanced design, and integration of more refined technologies that completely transform that way buildings are refurbished.

By embracing a well-defined approach, retrofit designs become easier to developed through standardised methodologies, ensuring a clear path to optimise time, costs and performances. The aim of the whole process is to industrialize the construction sector shifting a significant portion of the work from worksite to factory, which becomes the new heart of production. This transition enables the same production optimizations found in other industrial sectors, promoting efficiency, scalability and consistency across projects.

However, a crucial feature of this method is its strong consideration of building's entire life cycle. Not only does this focus help address environmental concerns, but it also enables more accurate economic evaluations, in particular through Life Cycle Cost Analysis (LCCA). Although prefabricated solutions involve slightly higher initial investment, they become more cost-effective over building's life cycle when compared to traditional retrofitting approaches. The long-term financial benefits, combined with reduced energy consumption and enhanced sustainability, make this solution more economically suitable in the future. Indeed, as production processes continue to be optimized and large-scale applications become more widespread, the upfront costs of prefabricated retrofitting will decrease, increasing the overall cost-effectiveness of these industrialized methods. Thus, by embracing these advanced technologies, buildings can be future-proofed, reducing at the same time construction-related disruptions and achieving a broader environmental and regulatory target.

Anyway, an intriguing question arises: why should investor choose to invest in this type of refurbishment? What makes this innovative approach stand out as a smart, forward-thinking choice for long-term returns?

4. Sustainable Financial Regulatory Frameworks

In order to align with the updated EPBD objectives, buildings undergoing refurbishment must achieve improved performance levels. Given the progressively stricter long-term requirements, it is advantageous to implement strategies that target Net Zero Carbon (NZC) configurations, which means aiming to achieve Net Zero-Emission Buildings (NZEB) for the European real estate. This approach minimises the need for multiple interventions between 2030 and 2050, ensuring cost efficiency and regulatory compliance.

The first step in achieving NZC status involves the identification of buildings at risk of non-compliance with present and future targets. Moreover, a methodology for risk assessment is explained in detail and a tool to facilitate evaluations is presented. By analysing energy performance, carbon emissions, and regulatory requirements, stakeholders can plan immediate or phased refurbishment. Once risks are determined, targeted refurbishment strategies can be devised and prioritised to meet EU climate and energy goals. The right balance between environmental and profitable activities is the key to plan a massive transition to the green requalification of the building stock. Indeed, achieving this equilibrium is crucial to accelerating the green transition of Europe's building stock.

A brief overview of the European sustainable finance framework is provided to contextualize how investors and owners could be encouraged to contribute to sustainability. The EU Taxonomy alignment plays a pivotal role in identifying environmentally friendly processes. Being aligned with it not only certifies that refurbished buildings are operationally green but also ensures that retrofit strategies minimise environmental impacts during implementation. Therefore, the EU Taxonomy is not simply a technical classification system but a strategic tool that is reshaping investment priorities across the real estate sector. By defining clear sustainability criteria, it enables stakeholders to identify activities that contribute to climate and energy goals. For investors, Taxonomy-aligned projects represent a compelling opportunity to allocate capital in ways that ensure regulatory compliance, reduce climate-related risks, and deliver long-term value. Developers, on the other hand, benefit from improved access to financial instruments such as green bonds, as well as from heightened market competitiveness.

Moreover, alignment with the Taxonomy provides a dual advantage: certifying that buildings meet the highest environmental standards while making these assets more attractive to institutional investors seeking to integrate ESG principles into their portfolios. This financial appeal is complemented by the operational benefits of reducing future costs associated with non-compliance, carbon taxes, or additional refurbishments required to meet future standards.

At the end, it is proposed a strategy that considers both the evaluation of operational emissions and the EU classification system, merging their strengths. This dual-focus approach allows to develop a standardised methodology to plan and verify energy retrofits in existing buildings. By addressing both immediate and long-term sustainability objectives, the proposed strategy could ensure alignment with regulatory milestones and promote the transition to NZC buildings, giving green strategies more relevance in the real estate sector.

4.1 ESG Strategies

From the perspective of real estate companies, investors, and developers, improving ESG (Environmental, Social, and Governance) performance in the building sector presents a significant opportunity. The construction field needs to adopt a revolutionary strategy based on advanced building and housing concepts rather than just fixing issues in the existing building stock. These principles should be focused on revolutionise energy management, minimise environmental impact, and align with broader sustainability goals.

To achieve this transformation, it is crucial to promote a culture based on ESG values. This requires integrating a practical, actionable approach from the beginning, offering stakeholders clear guidance on how to navigate the path toward global sustainability. [23] Each aspect of ESG has a key role in the focus on sustainable and ethical practices, and the three central ESG criteria are explained in Figure 4.1 below.

Figure 4.1 - ESG criteria

Assessing an ESG strategy is essential to meet evolving standards that place increasing emphasis on those principles. A well-structured ESG strategy provides a clear roadmap to understand and address these priorities effectively. Its proper development is crucial for organizations to navigate and respond to growing regulatory, ethical, social, and financial pressures.

In the figure below, it is explained how an ESG strategy can face the four challenges. [24]

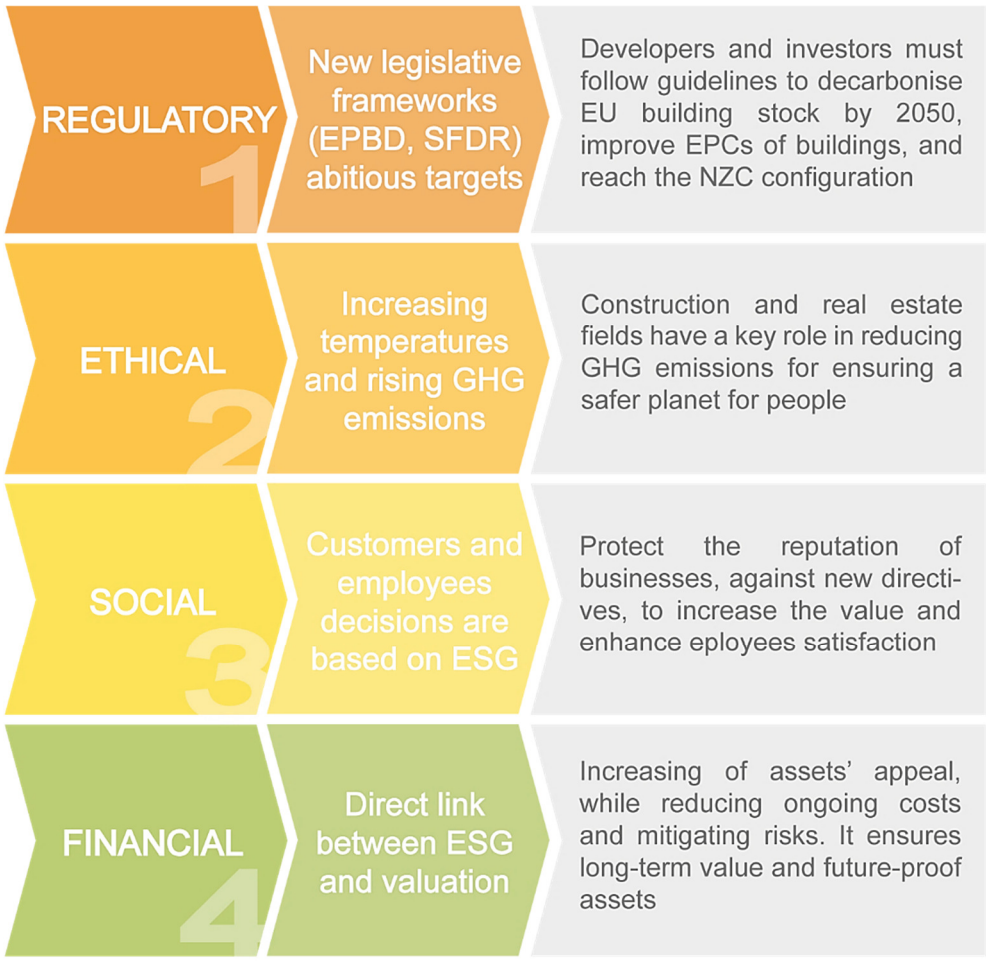

Figure 4.2 - Challenges of ESG strategies

4.2 Net Zero-Carbon Transition

The transition to Net Zero-Carbon Buildings has many benefits, not only for the compliance with deadlines and values defined by regulations, but it may enhance investors financial possibilities. The selection of sustainable designs aimed at reaching Net Zero-Emission condition is more likable subjected to green financings, since financial institutions make the accessibility to capital easier for those initiatives, thanks to an increase in interest to

sustainability. The market demand of green buildings is rising, making net zero properties more desirable and increasing therefore their value. Alongside the monetary value of the construction, operational costs are reduced, and incomes are maximised, increasing the buildings' long-term value.

To encourage the transition of capital towards activities with a more sustainable economy, the European Union has drafted regulations aimed at providing investors information for the evaluation and comparison of green investment options.

4.2.1 Pathway to NZC

For accomplishing the transition of buildings to Net Zero-Carbon, a pathway to follow for the assessment and implementation is determined. The main steps are listed and described below [25]:

- **Baseline establishment**: starting from the existent conditions, energy consumption data and documentation are collected to calculate the baseline energy use and greenhouse gas emissions, identifying the possible improvement areas.
- **Emissions management**: engaging with inhabitants for reducing energy consumptions and therefore the related GHG emissions.
- **Opportunities identification**: evaluation of different options to promote energy-saving measures.
- **Impact analysis**: assessment of energy consumptions, emissions and financial impact of the proposed solutions.
- **NZC implementation plan**: development of an implementation plan with phases aimed at reducing energy consumption and carbon emissions, defined with actions, timelines, and milestones. In addition, the alignment with regulatory and non-regulatory frameworks must be ensured.
- **NZC roadmap**: identification of a clear pathway to reach the net zero carbon condition, following steps, and setting deadlines.
- **Governance**: tracking of energy uses and carbon emissions to have a constant monitoring and to continuously develop performance optimisations.

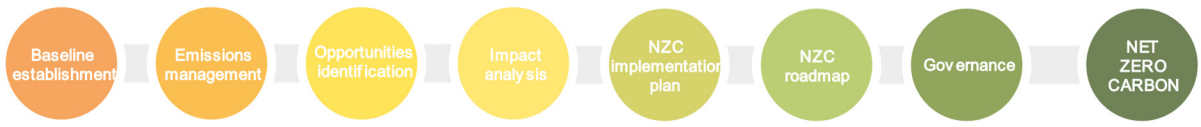

Figure 4.3 - Pathway to NZC

In the first stages of the process, it is fundamental to understand the current conditions of existing buildings compared to regulations' limitation and requirements, for this reason in the following paragraph the methodology of risk assessment is explained.

4.3 Assets Stranding and Transition Risk

During the evaluation on existing buildings, it is pivotal to assess the possibility of transition risks or stranding. Their identification allows to develop strategies for avoiding them and to protect owners from related drawbacks.

Transition risk arises during the market's shift toward a low-carbon economy. The implementation of stricter standards on emissions and energy efficiency can lead to higher operational costs or potential fines for property owners. Additionally, the market value and appeal of a property may decline if its technologies and sustainability features are not adequately aligned with the latest innovations and environmental regulations. If this risk occurs, the asset may fall in a situation of stranding. [26]

The assets stranding regards properties exposed to the risk of obsolescence, due to more restrictive future standards. In this scenario the asset loses its value, having parameters that do not respect certain efficiency thresholds, set for environmental purposes. When the risk of future stranding is identified, buildings become less marketable and may require retrofitting strategies to comply with future regulations. [27]

To maintain short and long-term value of assets, it is fundamental that investors must be aware of the risk of stranding, in order to stay aligned with standards, and contribute to climate goals at the same time. First of all, the risk of stranding must be assessed, to understand how the building performs in comparison with current and future regulations.

4.3.1 CRREM

Carbon Risk Real Estate Monitor (CRREM) is a project aimed at establishing targets for operational carbon emissions, allowing real estate investments to stay consistent with goals of Paris agreement. This will contribute to an increase in sustainable retrofits and so the reduction of carbon emissions of the building sector. By using this tool, users are able to monitor energy performances of buildings and assess the risk of stranding. [28]

4.3.1.1 Methodology

Following the methodology, it is possible to generate a graph to understand the situation of properties, compared to future limitations on carbon emission values. In the following image

the asset stranding level diagram is reported, which is one of the outputs of CRREM analysis. The orange curve represents the decarbonisation pathway that GHG emissions must follow for accomplishing 2050 goals of the Paris Agreement, and it is related to a specific building type, in a specific location. The black line indicates the property, direct and indirect, GHG emissions: they can slightly slope according to the grid decarbonisation in time, decreasing indirect emissions, while the increase of direct emissions is related to increased energy use for balancing climate change effects. The intersection between them, highlighted in green, shows the moment in which occurs the asset stranding. The shifted line shows the new intensity of emissions, after a possible retrofit, to be aligned with the threshold.

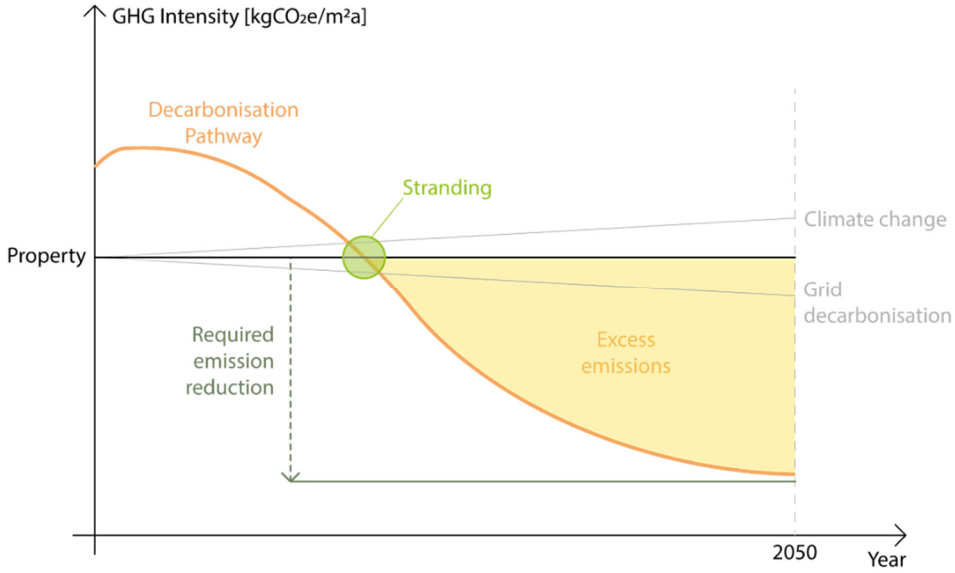

Figure 4.4 - Stranding Chart

Defining the position of an asset respect to the decarbonisation curve determines if the property is at risk, as well as its value. As shown in Figure 4.5, buildings, depending on their position on the chart, are classified as “green premium” or “brown discount”.

Green premium properties are buildings that have or overcome sustainability requirements, they are built or refurbished following high energy standards. Their market values are higher than the average one, allowing investors to increase their incomes [29]. Brown discount assets have poor energy ratings, since they are neither sustainable nor energy efficient. Nowadays, these types of building are more widespread than green premium ones, around 75% of the European building stock belongs to this category. For investors, older or obsolete buildings that exhibit signs of obsolescence or neglected maintenance represent a serious financial risk and might need more funding for upgrades [30].

There are three possibilities:

- (A) The asset is below the curve: the emissions are lower than the requested ones, denoting high sustainability performance which increases the value of the asset.
- (B) The asset is on the curve: the property is in a condition of stranding, in which emissions and requirements are equal, measures must be quickly applied to solve issues and to avoid future risk of stranding.
- (C) The asset is above the curve: the emissions do not meet the requirements, the asset is losing value, due to poor performances.

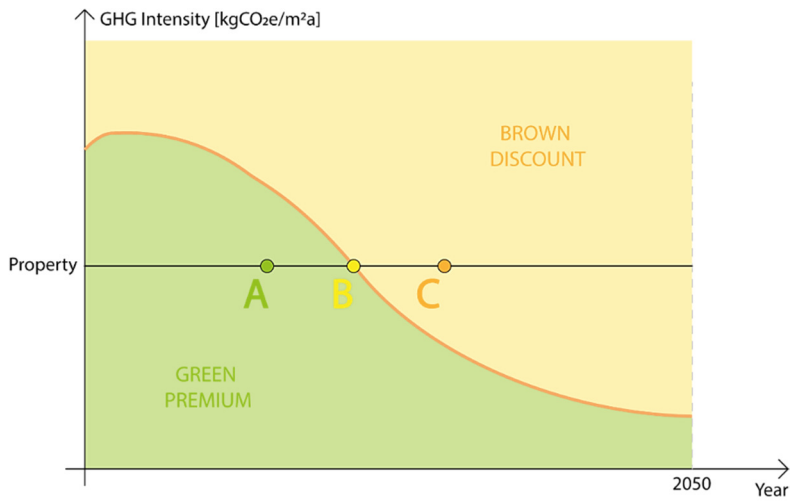

Figure 4.5 - Stranding Chart: Green Premium VS Brown Discount

4.3.1.2 CRREM Risk Assessment Tool

To generate the final stranding chart and other important diagrams, useful to determine the actual and future conditions of existing buildings, a tool is provided by CRREM project. The tool requires inputs that must be defined for each asset, from the manual of CRREM Risk Assessment Tool [31] the main input parameters are listed below:

- General information: name, GAV (Gross Asset Value), reporting year, entity allocation, and period of data reporting.
- Characteristics: location, size, building typology, floor areas, use of air conditioning, and average annual vacant area.
- Total energy procurement: whole building procured energy data, to calculate carbon emissions.
- Renewable energy: on-site and off-site generated renewable energy, divided into used on-site and exported.

According to different fields the tool generates different output, with results collected in diagrams and analysis:

- Stranding diagram: the decarbonisation pathway is created according to the location and the building's destination of use. The asset carbon intensity is given by the building surface and operational energy consumptions, and its performances are analysed per year.
- Energy reduction pathway: energy intensity per year of the asset, compared to the energy target related to the building type and the country.
- Excess emissions: overview of the excess emissions per surface, according to reduction targets.
- Cost of energy and carbon emissions: annual energy costs divided into type of emission.
- Total net energy per floor area: produced energy as percentage of consumed energy and the share of renewable energy on consumption.
- Carbon costs of excess emissions: annual costs of emissions above or below the decarbonisation target.
- Individual scenarios and payback: energy intensity after the retrofit and payback diagram with the break-even point.
- Economic payback: investment for the retrofit compared to savings from the refurbishment.
- Energy and carbon intensity with and without retrofit measures: individual retrofit scenarios including payback and stranding after the retrofit.

After conducting the analysis using the CRREM tool, it becomes possible to develop a strategy to comply with regulatory limits. Once the asset's position on the stranding chart is identified, specific years for interventions can be determined. The refurbishment process can also be divided into multiple steps, considering various factors, such as limited capital availability. An example of strategy with two retrofit is presented in Figure 4.6. Starting from the baseline emissions intensity, it is possible to determine the first stranding point, before which the first intervention is programmed. After retrofit 1, emissions intensity is reduced to the yellow curve, which is still not sufficient to align with 2050 target. It is determined the second stranding point and, as before, it is identified the second intervention, to bring the final intensity, the green curve, below the decarbonisation pathway.

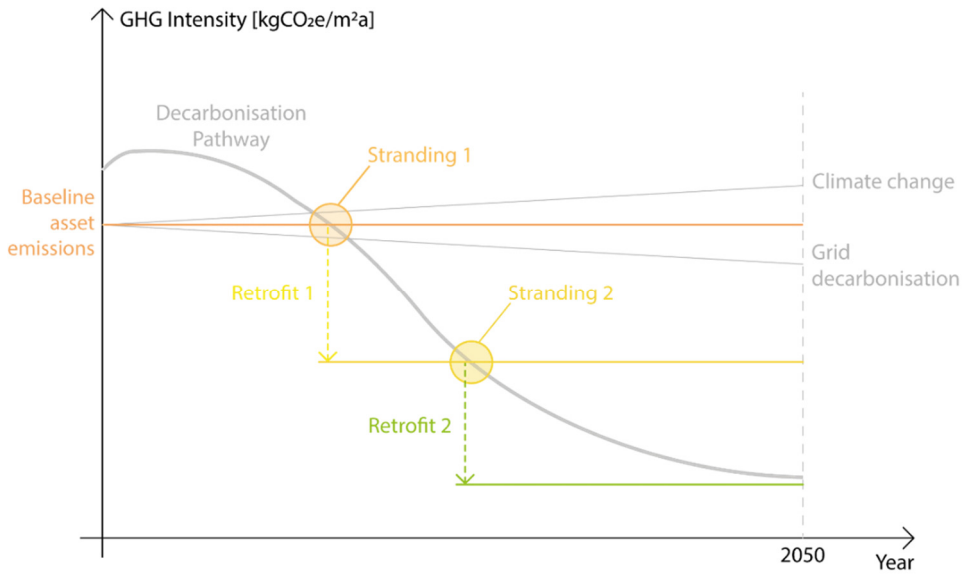

Figure 4.6 - Stranding Chart: multi-retrofit strategy

4.3.1.3 Limitations

Although the CRREM methodology follows clear guidelines and makes it straightforward to develop strategies to keep assets in the green premium category, the approach above described has limitations. It focuses solely on operational carbon, which depends on the behaviour of the building's inhabitants rather than its characteristics. As a result, the outcome may not provide a precise or complete representation of the asset's condition.

For this reason, the EU Taxonomy defines a more structured method to assess the buildings' sustainable features. Its guidelines are more comprehensive and as result an ac can be aligned or not with the Taxonomy, denoting its sustainability achievements.

4.4 EU Taxonomy

EU Taxonomy is a European Union classification system, which allows to determine environmentally friendly economic activities. It guides investments towards green activities, aligned with sustainable goals set by the Union, aimed at the reduction of GHG emissions and promoting the transition to low carbon emissions economy. For what concerns the construction field, the system defines specific criteria to assess the sustainability of buildings, based on six main objectives [32]:

- **Climate change mitigation**: reduction of GHG emissions during buildings' life cycle
- **Climate change adaptation**: improve the resilience of buildings to extreme climate conditions.
- **Water management**: optimise buildings' water consumption.

- **Circular economy**: enhance reuse and recycling of construction materials.
- **Pollution prevention and control**: reduce the environmental impact of buildings.
- **Ecosystems protection**: minimise the impact on ecosystems during construction activities.

Figure 4.7 - Six environmental objectives of EU Taxonomy

In general, for buildings different criteria are defined, depending on the economic activities. They are reported in the following table [33].

Table 4.1 - General criteria of Taxonomy alignment for building sector's activities

Economic activity	Criteria
New construction	• Reduction of at least 10% of primary energy demand, compared to NZEB standard requirements. • Energy performance certified by EPC.
Renovations	• Compliance with criteria related to major renovation, given by the EPBD. • Reduction of primary energy demand of at least 30%.
Building ownership	• Construction year before 2021: at least inside the 15% of buildings with highest performances • Construction year after 2021: compliance with the EPBD criteria of NZEB

The alignment of economic activities with Taxonomy is verified when they make a substantial contribution to one of the six objectives described, it is accomplished the principle of DNSH (Do No Significant Harm) to any of the other five goals, and they comply with the Minimum Social Safeguards.

The Substantial Contribution (SC) of an activity refers to its positive environmental impact in relation to one of the six objectives outlined in the EU Taxonomy. This contribution is assessed through specific Technical Screening Criteria (TSC). The TSC for the objectives of Climate Change Mitigation and Adaptation were established in the Taxonomy Regulation (EU 2020/852), while the criteria for the remaining objectives were introduced in the Environmental Delegated Act (EU 2023/2486) [34].

Minimum Social Safeguards ensure compliance with fundamental standards on human rights, social responsibility, labour rights, and anti-corruption measures. Verification requires alignment with the OECD Guidelines for Multinational Enterprises and the UN Guiding Principles on Business and Human Rights, alongside adherence to the International Labour Organisation's (ILO) Declaration on Fundamental Principles and Rights at Work and the International Bill of Human Rights [35].

Figure 4.8 - Taxonomy alignment, principal steps

4.4.1 Regulatory Context

The European Union sustainable finance framework includes the EU Taxonomy, the Corporate Sustainability Reporting Directive (CSRD), and the Sustainable Finance Disclosure Regulation (SFDR). They are closely interconnected, whose collectively aim is to enhance investments in activities aligned with the EU Taxonomy. Their primary objective is to address environmental challenges by fostering sustainable solutions, supported by reliable and comparable ESG (Environmental, Social and Governance) data. By providing a transparent and standardized framework, they establish a common language that enables stakeholders to make well-informed decisions.

Figure 4.9 - EU sustainable finance framework

In the EU Regulation 2020/852 [36] the framework of the EU Taxonomy is set, which contains its main objectives and how it will be applied in practice. It defines a clear methodology to promote sustainable investments within the Union, aimed at creating a universal way to

classify sustainable economic activities. Another goal is the alignment with environmental and climatic purposes, defined in previous regulations.

The Taxonomy is comprehensive and closely interconnected with the EU Regulation 2019/2088 [37], known as the Sustainable Finance Disclosure Regulation (SFDR). The SFDR establishes standards to enhance transparency on sustainability-related information within the financial sector. Together, they provide investors an instrument to promote activities aligned with the EU Taxonomy principles.Three main goals of the SFDR are:

- Improve transparency: thanks to clear and reliable information, comparable on investments' sustainability.
- Avoid greenwashing: to prevent misleading promotion of sustainable products, when they are not.
- Promote sustainable investments: to encourage responsible use of capitals, following guidelines regarding EU sustainable goals.

The regulation provides, in three articles, the classification of different investment funds, reported in Figure 4.10.

Figure 4.10 - Investment funds classification and definitions, from SFDR

The last regulation is the Corporate Sustainability Reporting Directive (CSRD), EU Regulation 2022/2464 [38], to reinforce and to modernise standards regarding social and environmental information that companies must report. It enhances coherence and harmonizes the way companies draft ESG impacts disclosures. The main objectives of the CSRD are listed below [39]:

- Standardisation: to reduce inconsistency and information gaps of ESG disclosures, improving the assessment of comparison between sustainability performance of different companies.
- Transparency: thanks to comprehensive disclosures, it increases the ESG activities transparency, allowing a more informed decision-making process.
- Alignment with other regulations: it is linked to other EU standards, such as the SFDR and The EU Taxonomy, improving the efficiency of the European sustainability framework.

The Taxonomy, SFDR, and CSRD are regulations bonded to simplify and promote sustainable investing practices. The EU Taxonomy is the basis of sustainable activities, adding the coherent disclosure requirements of SFDR and CSRD. They use Taxonomy metrics, SFDR ensures transparency and CSRD improves the comprehensiveness of company reporting. In Table 4.2 main scopes of the three regulations and their relationships are summarised. [40]

Table 4.2 - Scopes and connections of EU Taxonomy, CSRD, and SFDR

	Level	Scope	Relationship with others
EU Taxonomy	Asset level	Classification system for sustainable economic activities	Criteria to identify sustainable activities, used for reporting under CSRD and SFDR
CSRD	Organisation level	To enhance the quality and scope of companies' sustainability reporting	Complements SFDR with pivotal data for reporting
SFDR	Fund level	To improve transparency of ESG disclosures and investment practices	Data from CSRD to enrich reporting and integrate it for a more comprehensive view

4.4.2 Benefits

The alignment of assets with the EU Taxonomy improves their features and expands possibilities for sustainable development. Four key benefits of aligning retrofit activities with EU guidelines are outlined below. [41]

- **Commitment to sustainability**

The criteria for alignment are grounded in environmental and climate objectives outlined in the Paris Agreement. To be aligned with them, buildings must comply with a set of rigorous rules, defining important steps towards reduction of environmental impacts. Those steps contribute to reduce emissions, and the carbon footprint of the construction, simultaneously increasing

energy efficiency and water management. As side benefit of the green commitment, sustainability perspective is an added value to businesses, resulting in higher competitivity in the market.

- **Assets' risks reduction**

Investment opportunities linked to green initiatives represent a safer financial choice, as they present lower risks thanks to their strategies against future climate change issues. Alignment with the taxonomy is a sure way to ensure compliance with the most stringent environmental objectives, ensuring the sustainability and future proofing of assets.

- **Increased access to capital**

Sustainable activities have become a pivotal criterion in the selection of loan recipients, driven by the European Union's growing emphasis on green initiatives, such as having the access to European Green Deal funds. In response to directives and regulations, banks and financial institutions are prioritizing the allocation of capital to projects that align with sustainable development goals, fostering innovation and environmental responsibility across sectors.

- **Reduction of emissions**

Building stock refurbishment has a key role in the European emission reduction, since around 40% of emissions is related to the building sector. The assessment of Taxonomy-aligned retrofits guarantees the contribution to EU climate goals, ensuring the reduction of emissions for interventions and during the operational stage of the building lifecycle.

- **Operational costs reduction**

Operational expenses are reduced through adherence to guidelines, which ensures consistent performance and enhances the energy efficiency of assets. This alignment not only increases the intrinsic value of the property but also lowers ongoing costs, thereby improving economic returns on investments. Alongside the operational costs' reduction, the indoor comfort and life quality are enhanced, improving social conditions of inhabitants.

4.4.3 Taxonomy and EPBD requirements

To meet European's climate and energy targets, described in the European Green Deal, it is crucial mobilising investments towards sustainable projects. To achieve this, the common and defined language of EU Taxonomy is needed for defining sustainable activities. [42]

Although the EPBD continues to be the primary legal framework behind evolution in the construction field, the EU sustainable finance policy package, particularly through EU Taxonomy, is pivotal in directing funds into the transformation. In order to distinguish green investments from those that only adhere to the minimal performance requirements that will be regulated for all buildings, the EU Taxonomy must be more ambitious than the EPBD as a piece of legislation that specifies green economic activity. [43]

Meeting the EPBD objectives does not guarantee compliance with the Taxonomy requirements, highlighting the added importance of this rating system for the construction field. Taxonomy's comprehensive approach ensures that investors gain access to green funds to perform these activities, fostering transparency and promoting their environmental commitment. Compliance with the Taxonomy guidelines is critical for achieving international recognition, enhancing a company's reputation and access to global markets, ultimately boosting competitiveness. Although the EPBD aims at improving energy efficiency within the European building stock, Taxonomy provides a more ambitious framework, addressing additional aspects such as biodiversity, resource efficiency, and the circular economy. This broader perspective maximizes both the value and the environmental impact of a refurbishment strategy.

4.5 CRREM and EU Taxonomy

During the evaluation of sustainable finance activities, CRREM and the EU Taxonomy offer distinct but complementary approaches. This section compares their purposes, fields, and applications, highlighting their strengths and how their integration can provide a comprehensive strategy for sustainable building refurbishment.

In the following table the two are compared and the main differences are outlined. CRREM analyses the carbon emissions of construction field, and it assesses the risk of stranding for assets, with quantitative values. The Taxonomy defines criteria to identify sustainable activities in different economic fields, covering more aspects, such as the environment and society.

Table 4.3 - Main features of CRREM and EU Taxonomy

	CRREM	EU Taxonomy
Purpose	To measure and reduce CO_2 emissions of buildings	To standardise and classify sustainable activities
Field	Building sector	All economic sectors
Objectives	Carbon emissions reduction	Contribution to EU environmental goals
Application	Assets' transition risk assessment	Guide for sustainable investments and reporting
Method	Quantitative assessment of emissions	Alignment with environmental criteria
Scope	Operational emissions	Environmental and social aspects

By merging them it would be possible to perform a better consideration on building stock refurbishment process, setting a method that considers more aspect, reported in Figure 4.11.

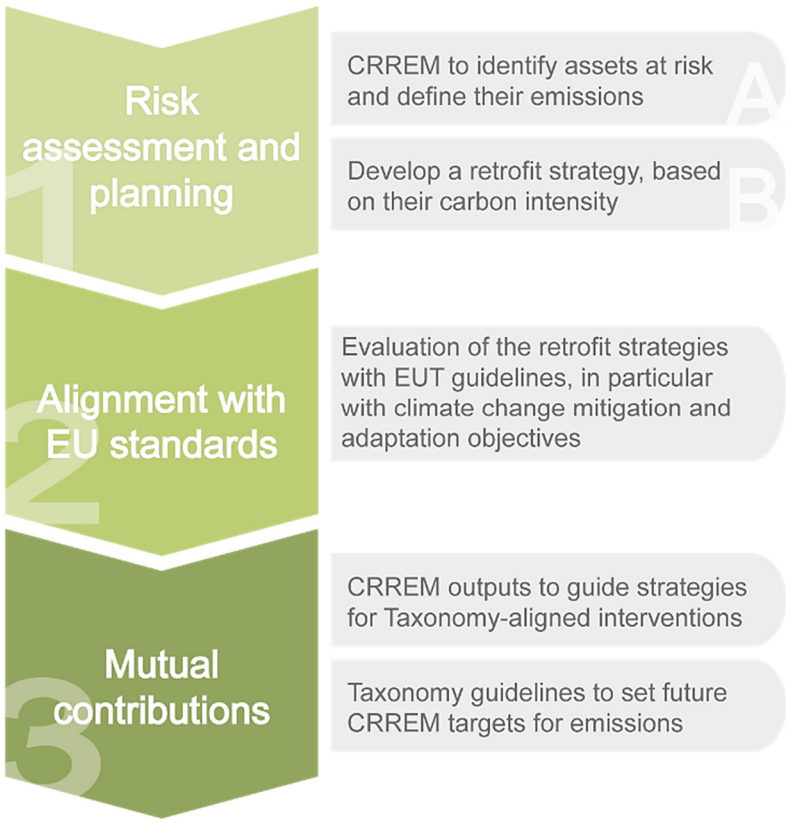

Figure 4.11 - CRREM + EU Taxonomy strategy

4.6 Considerations

The transition to Net Zero-Carbon Buildings, consisting of an overall greenhouse gas emissions reduction, is a fundamental step to accomplish for complying with 2050 environmental goals. During the implementation of existing building refurbishment strategies, many aspects must be considered to develop them in a meaningful way. The considerations made in this chapter aim at having a perspective that considers not only the environmental impact, but also the interest in promoting green financial activities that offer incomes and constitute a valid option for investors and companies. First of all, the individuation of the starting point for assets is a key role to plan next phases. Thanks to the CRREM assessment, risks for assets are quantified and localized in time, developing subsequent stages for aligning them with actual and future targets. The EU Taxonomy and its regulatory framework is explained to understand how activities must be selected, in order to comply with requirements, as well as sustainability features. At the end, it is presented an approach that considers different benefits from both the methodologies. It could be used for developing a wider strategy that follows several steps: identification of the building stock that must be refurbished, planification of retrofit activities, verification of their alignment with Taxonomy and their realisation. Alongside the assessment of those phases, financial benefits for companies are identified to promote a transition of the market to more sustainable and eco-friendly activities.

5. Case Study: An Office Building in Milan

By reaching the end of this research journey, the following chapter aims to summarize the new Energy Performance of Buildings Directive key principles, providing a concrete and tangible proof that change is possible, yet complex. Indeed, the ambition to reduce carbon emissions, aiming for Net Zero-Emission Buildings by 2050, is based on following a gradual approach able to transform a more sustainable future into reality. In this context, it is essential to initially focus on the requalification of a small but significant portion of the European building stock, corresponding to 16% of the non-residential sector, which must be improved by 2030.

The case study selected fully falls within the category of non-residential buildings targeted for retrofitting, with nearly all the information in line with the “typical building” characteristics, outlined at the end of Chapter 2. Indeed, the selected office complex could be classified as one of the worst energy performers, characterized by high envelope’s thermal transmittance values, as well as outdated and obsolete conditioning systems. For this reason, an intensive energy retrofit project has been necessary to improve its thermal performance, enhancing its environmental impact, and increasing at the same time its market value. Indeed, thanks to the planned requalification, this building will be able to meet the criteria for Net Zero-Emission Building (NZEB) by 2050, fully complying with the energy efficiency and sustainability requirements established by the new EPBD. This condition was ensured through the CRREM framework, which confirmed that this retrofit could lead to significant reductions in emissions, aligning with the targets set by the Paris Agreement. Thus, this turned out to be a project that not only deliver several energy-related benefits but also complies with the EU Taxonomy. This alignment has not only certified the retrofit sustainability but also guided and facilitated potential investments by demonstrating its contribution to climate and energy goals, enhancing the project’s credibility and appeal.

In any case, the following chapter does not aim to present the actual renovation carried out, by explaining the interventions designed and implemented by construction companies. Indeed, since property data is not available to public and many owners choose not to share information about their buildings, for privacy reasons it will not be possible to disclose certain confidential details, such as the location or the exact building considered. Therefore, an alternative solution for renovation with prefabricated elements on the façade and on the roof was proposed, by following the guidelines set by the 4RinEU and EnergieSprong projects. In this way, the goal was to demonstrate how prefabrication can offer significant advantages in the construction process, achieving the same energy performance results as the adopted renovation, while optimizing construction time and cost.

5.1 Office Building Selection

Although three categories of non-residential buildings with poor energy performance have been identified, including offices (E2), commercial activities (E5), and industries (E8), only one was chosen as the reference. By following a series of considerations and evaluations, offices turned out to be the most suitable choice for the analysis for several reasons.

A preliminary consideration was made regarding the energy performance of the three buildings' categories in order to understand which of them had the greatest impact in terms of energy consumption. The parameter used for this analysis is the non-renewable component of the Global Energy Performance Index, as it directly provides information about buildings' energy efficiency and primary energy consumption. The latter represents the energy that has not undergone any transformation processes, such as the one derived from fossil, and it is a crucial measure for understanding the ecological impact of a structure. Unlike the previous analysis conducted on the Italian building stock (Chapter 2.3), in this case, the renewable component of the Global Energy Performance Index is temporarily excluded. The reason is that, in order to simplify the understanding of buildings' environmental impact, the non-renewable component provides a more significant assessment in terms of ecological footprint, both in terms of emissions and consumption of natural resources.

Based on SIAPE data, Table 5.1 below illustrates the number of Energy Performance Certificates (EPC) in class F and G issued for each of the three categories from 2022 to 2024, alongside the corresponding Average Value of Non-Renewable Global Energy Performance Index ($EP_{gl,nren,average}$). In the following Figure 5.1, the total values are presented, by summing the data regarding the number of certificates in class F and G and calculating an average of the indices, highlighting their evolution over time.

Table 5.1 - EPCs number and Non-renewable Global Energy Performance

		Class F		Class G	
Intended Use	**EPC Emission Year**	**n. EPC**	**$EP_{gl,nren}$ average [kWh/m² per year]**	**n. EPC**	**$EP_{gl,nren}$ average [kWh/m² per year]**
Offices E2	2022	4133	288.1	4415	285.1
	2023	4652	290.6	4734	280
	2024	3407	282.2	3337	267.7
Commercial Buildings E5	2022	6814	318.6	7910	300
	2023	7411	312.4	8177	302.3
	2024	6261	304.4	6602	287.6
Industrial Buildings E8	2022	3311	288.7	7172	299.3
	2023	3558	273.3	7588	300.2
	2024	3887	300.8	5065	296.7

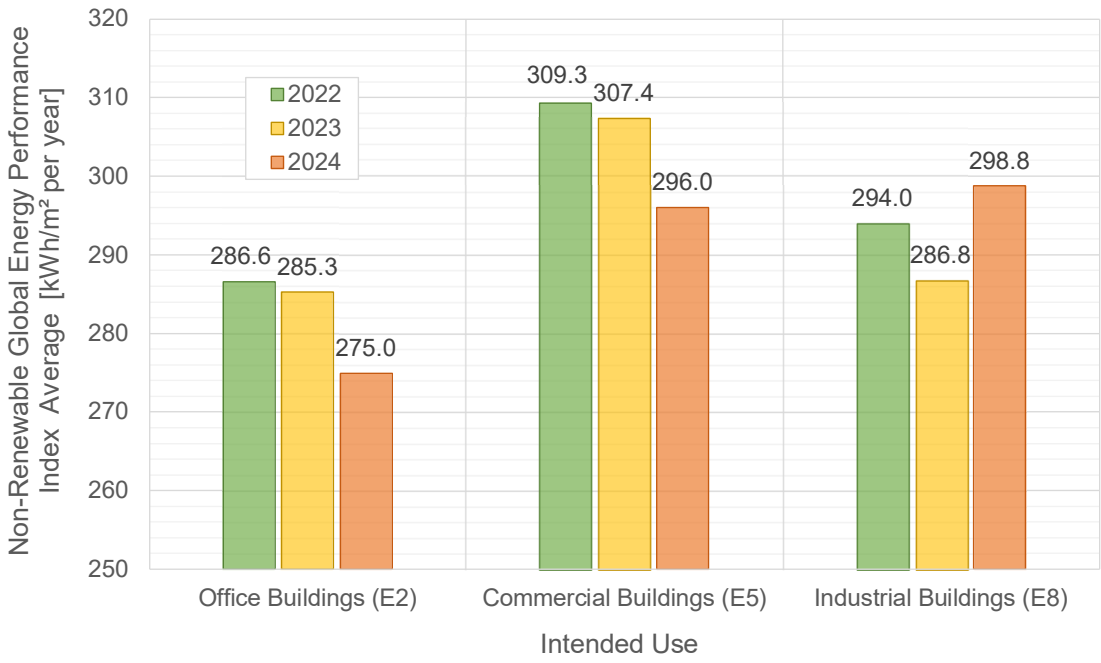

Figure 5.1 - Yearly values of average Non-renewable Global Energy Performance

It can be observed that the energy consumption for commercial activities is higher compared to the other two categories, due to a higher Average Vale of Non-Renewable Global Energy Performance Index. At the same time, a consistent decrease in demand has been recorded over time, with a significant drop in 2024, a trend also registered for category E2. Indeed, in recent years, many commercial activities and offices have invested in more energy-efficient technologies, such as LED lighting systems, more efficient HVAC systems, and the adoption of more sustainable energy management practices. These changes may have led to an energy use reduction, although there is still a long way to go to achieve energy neutrality. On the other hand, industries show lower requirements in 2023, with an increase in the following year.

Although the average consumption of categories E5 and E8 is slightly higher than that of offices, the latter were still selected as the focus of the energy retrofit. Several reasons led to this choice, with the key factor being the case study central to the analysis. As explained in the following section, available data of the case study concerns the energy retrofit of a building within category E2, which subsequently allowed for an in-depth analysis of costs and timelines.

Among the more theoretical reasons behind the choice of offices is their working process. Indeed, these buildings are high-energy-use environments, with extended operating hours and a large number of electronic devices in use, as well as artificial lighting. This makes them, on the one hand, significant consumers, but on the other particularly suitable for improvement interventions. Adapting the structures to more modern standards, such as installing efficient

HVAC systems, using temperature control technologies, and enhancing insulation, not only reduces energy consumption but also lowers operational costs for businesses. Improving the energy efficiency of offices is therefore a crucial step not only to comply with regulatory obligations (EPBD) but also to make buildings more competitive in the market and increase property value.

Another factor justifying the choice of this building category is the growing focus on occupant well-being: designing healthier work environments and meeting the thermal comfort levels required by regulations are two parameters that must be considered. This does not mean that commercial activities and industries do not need or deserve improved working conditions, but offices are more occupied and people permanence during working hours is much longer than for the other categories. Therefore, the adoption of green solutions that reduce environmental impact and improve air quality contributes to a healthier work environment, with positive effects on employee productivity and satisfaction.

5.2 Pre-Refurbishment Conditions

The case study analysed represents a building complex for office use, located in an area of Milan that has been subjected to redevelopment interventions for many years. Indeed, the entire neighbourhood to which the construction belongs has undergone a series of changes, with the aim of giving the city a new light towards sustainability. It will be occupied by 39,500 square meters of new construction, of which 17,000 sqm will be used for apartments (including 150 social housing units), 5,000 sqm for commercial and retail spaces, and 17,000 sqm for offices. The remaining 43,000 square meters will be occupied by new green areas, in order to create a new connection between humans and nature for the well-being of citizens.

As previously mentioned, due to corporate privacy reasons, it will not be possible to provide detailed and specific information regarding the building in question, although a comparison of the results obtained before and after the interventions will still be presented. Therefore, the focus of this analysis is not so much on the types of technologies used for the retrofit project, but rather on presenting a valid solution with prefabricated elements, confirming what has been discussed in the previous chapters. In this way, the importance of these advanced technologies is highlighted, both for the environment, thanks to the reduction of construction waste and raw resources, and for the optimization of the work itself. Therefore, this consists of a demonstration that change toward a more sustainable future is possible, though being difficult to achieve.

5.2.1 Structural and Architectural Description

The building was originally built in 1982 by a team of engineers and architects, being designed as a classic period construction. It was a complex consisting of a reinforced concrete load-bearing structure, crowned by glass panel facades. Although there is limited information regarding the original composition, it is important to note that it was not a modern curtain wall: an exposed reinforced concrete wall housed a row of openable windows on each floor throughout the entire development of the building. In this way, as explained later, natural ventilation was guaranteed to achieve a satisfactory level of indoor air quality. In any case, the ratio between the glass surface and the opaque complies with the specific characteristics outlined in Chapter 2, namely those characteristics that the "typical building" must have.

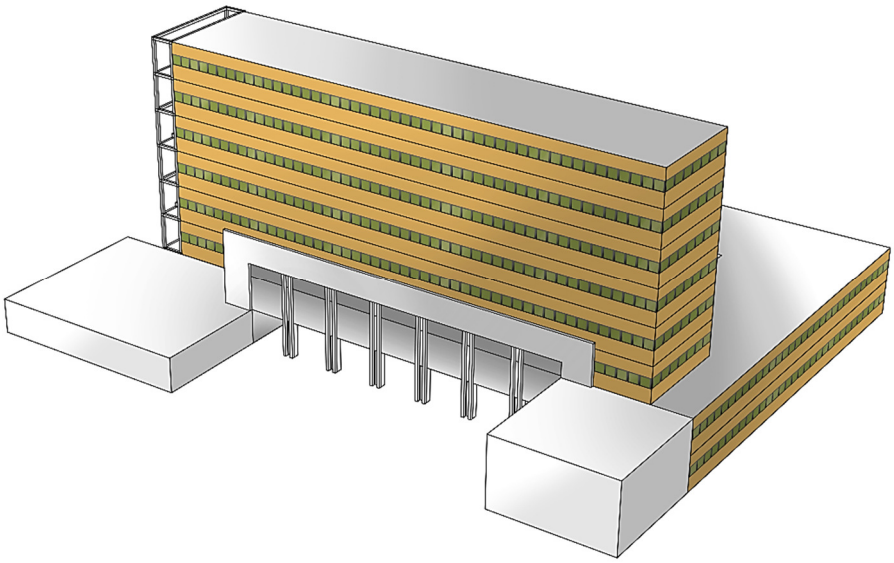

Figure 5.2 - Schematic representation of the building's façade

The building was mainly intended for office use, considering a small portion of common areas and customer reception. In addition to the above-ground floors indicated below, the complex also included a basement, equipped with storage rooms and others serving as technical rooms, in addition to parking spaces. As represented in Figure 5.3 and Figure 5.4 below, the complex was characterized by four main bodies:

- “Body A”, also called “pavilion”, which represents the distinctive feature of the entire complex as it consists of 8 floors above ground. The peculiarity of this building section is the raised ground floor (column-supported, known as “pilotis”), which connects the main entrance to the inner courtyard. This design allows direct access to “Body B” from the main entrance, rather than through internal side corridors.
- Body B, made up of 3 floors above ground;

- Body C, consisting of 2 floors above ground, is characterized by an additional volume that faces the street, corresponding to the main entrance of the building.
- Body D, consisting of only 1 floor above ground, also characterized by an additional rectangular volume on the main roadside.

The useful surface area of the building complex before the renovation was 8952 m^2, with a total length of approximately 80 meters (calculated considering the length of Body A) and a width of approximately 65 m (calculated considering the length of Body B).

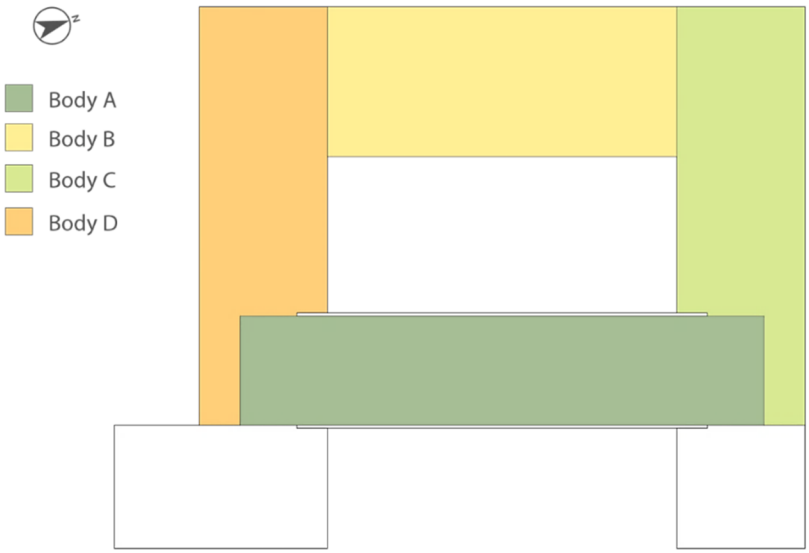

Figure 5.3 - Bodies in which the building is divided

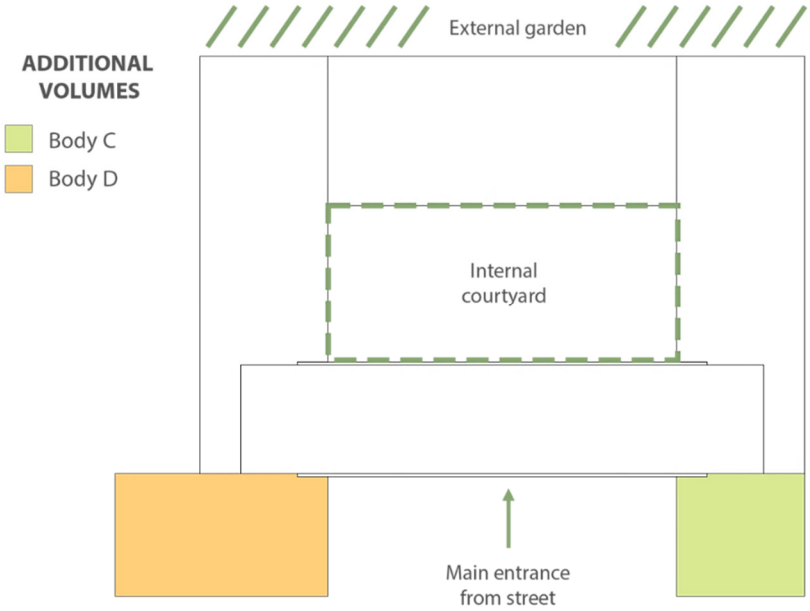

Figure 5.4 - Additional blocks added to the existing structure

5.2.2 Building Services Description

The central component of the original heating system in the building is a non-condensing boiler. This device is a closed vessel in which water is heated to produce steam or hot water for different purposes, with heat generated through the combustion of a fuel, such as natural gas. However, this type of boiler has a generally lower efficiency, being less performing, from the moment that it is not able to capture and use the latent heat released during water vapor condensation process. Instead, it releases the flue gases directly into the atmosphere after combustion, without allowing them to cool down and condense.

Once the water is heated, it is pumped through a network of pipes that runs throughout the entire building, considering all bodies previously describes. These pipes, typically made of copper or heat-resistant plastic materials, are places along the walls or on the floors to evenly convey heat across the different areas. Thus, the distribution system consists of a series of radiators, placed throughout the building in necessary quantities, which emit heat through thermal radiation. However, it is possible to state that these components result inefficient in achieving the required level of thermal comfort, as they do not manage to evenly spread heat across all areas. This inefficiency is even more apparent during summer month, as the building lacks an appropriate cooling system. Without air conditioning, the construction cannot effectively reduce the impact of heat gains, as solar, people and equipment gains, leading to a greater discomfort.

Moreover, the situation is made worse by the absence of a proper mechanical ventilation system. The building relies entirely on natural ventilation, which means air circulation is dependent on the opening of windows or other passive means. In a large, eight-story building like this, natural ventilation is not the ideal system to ensure proper air quality and distribution. Indeed, without mechanical ventilation, it is harder to maintain the necessary airflow, in particular in such a big space, making it challenging to provide consistent comfort throughout the building.

Therefore, in a structure of this scale, with multiple floors and office spaces, it is essential for heating, cooling and ventilation system to operate in an integrated and efficient way. Upgrading to a more modern, high-efficiency generator, by incorporating cooling and mechanical ventilation systems, would address these challenges effectively. Indeed, such improvements would optimize the overall energy consumption, enhancing indoor thermal comfort of occupants, and ensure compliance with relevant regulatory standards.

5.3 Real Energy Refurbishment

The following paragraph aims to illustrate the actual renovation project carried out, which has contributed to giving new life and functionality to this building complex. With the goal of achieving climate neutrality by 2050, reducing consumption levels and environmental impact, the building has become a new face of Milan's future: an open space, filled with light, ideas and above all, people. It is a dynamic and versatile environment, conceived with the idea of harmoniously integrating the construction world with the surrounding urban context.

The restoration involved, on the one hand, an architectural and structural resizing, in order to improve the functionality of the spaces and create new connecting environments, such as the common areas and the welcome area. Moreover, the façade has been completely restored through its demolition and reconstruction with technological solutions, known as curtain wall system. On the other hand, the building's services have been completely demolished and rebuilt: a new heating and cooling system was installed, as well as the electrical one through the adoption of PV panels. The final aim was to minimize the overall energy consumption, enhanced thanks to the use of advanced control and monitoring systems.

Therefore, it is possible to say that sustainability is the central focus of this project, not only through passive systems (such as the new photovoltaic components, water and energy consumption management), but also through active ones. Among these, indeed, there is the reconstruction of green oases to promote biodiversity and improve the internal well-being of employees.

5.3.1 Structural and Architectural Intervention

From an architectural and structural point of view, the building has undergone a series of interventions to ensure the optimization of public and private spaces, resulting in the creation of a new social ecosystem. This inevitably led to an increase in the overall heated useful area, which raised to 19% compared to the original situation. Indeed, following an expansion of the four main bodies of the office complex and the establishment of two commercial areas, as described later, the final usable area amounted to 10,648 m^2.

Table 5.2 - Increment of floor area after the intervention

	Before Renovation	After Renovation	Variation Retrofit	Increment [%]
Usable Floor Area [m2]	8952	10648	1696	19%

Among the structural interventions carried out, the following stand out:

- "Body A" was raised by two floors, thus reaching 10 floors above ground, while first floor has been demolished to be rebuilt with a higher height: this floor took the function of lobby and client welcoming area. At the same time, the existing stairwell, located centrally in the building, as well as the external emergency staircase on the side, were demolished. This means that the latter will no longer be visible, external to the complex, but will be redesigned internally to guarantee façade continuity. Furthermore, new terraces will be created on each floor at the left end of "Body A" (south-west position of the facade), to provide an outward-facing view.
- "Body B" was not raised, but the ground floor was removed to connect the existing internal courtyard with the garden behind the building. In this area, as in other portions, a relaxation and break area has been set up for company employees.
- "Body C" was raised by one floor in order to reach the same level as "Body B", i.e., 3 above-ground floors. As with "Body D", the two volumes facing the main street, corresponding to the entrance to the complex, were developed over 2 total floors above ground. They have been converted into commercial use on the basement, ground and first floors.
- “Body D” has not undergone any particular expansion interventions, with the exception of the upper covering to shade the existing terrace.

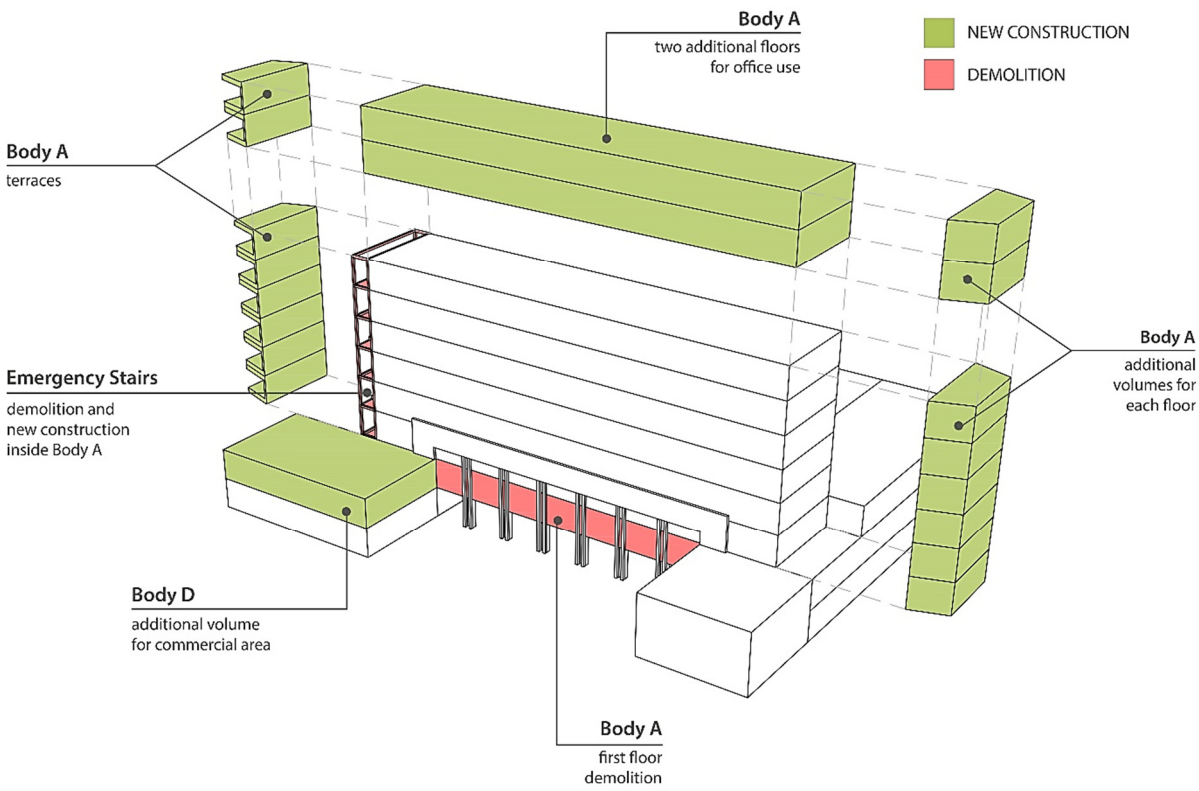

Figure 5.5 - Demolition and construction of volumes, front view

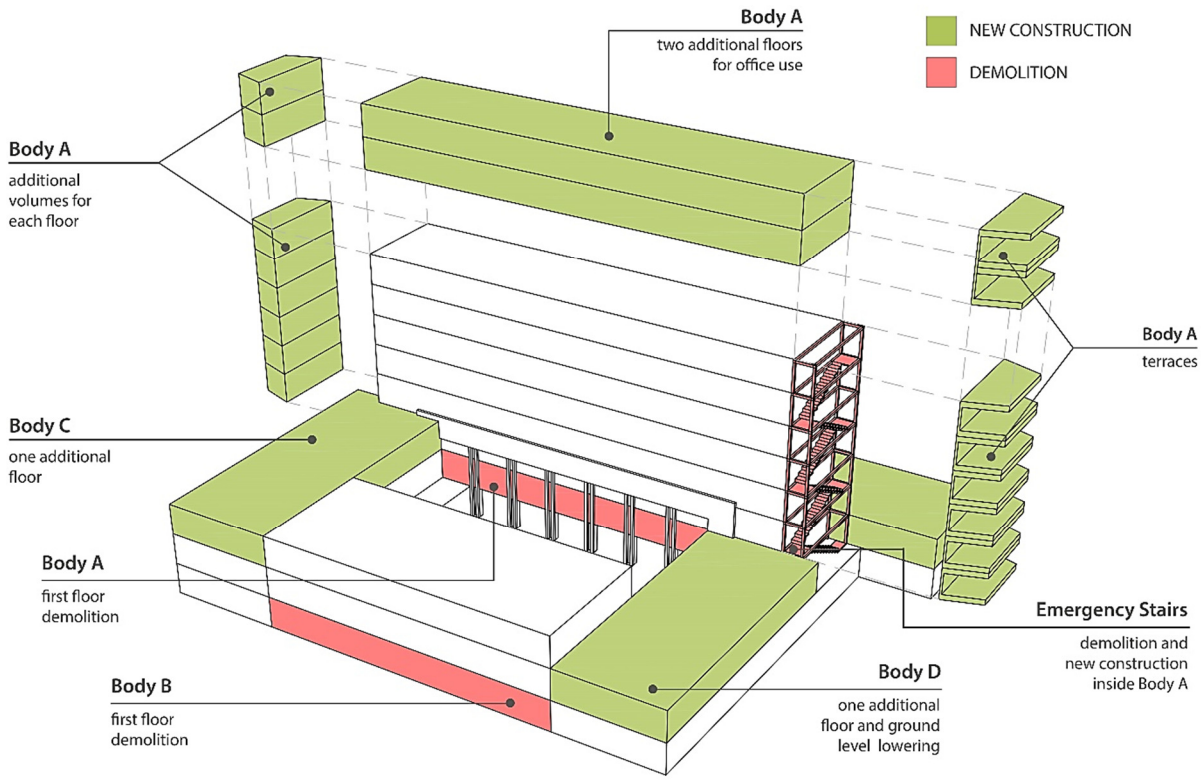

Figure 5.6 - Demolition and construction of volumes, back view

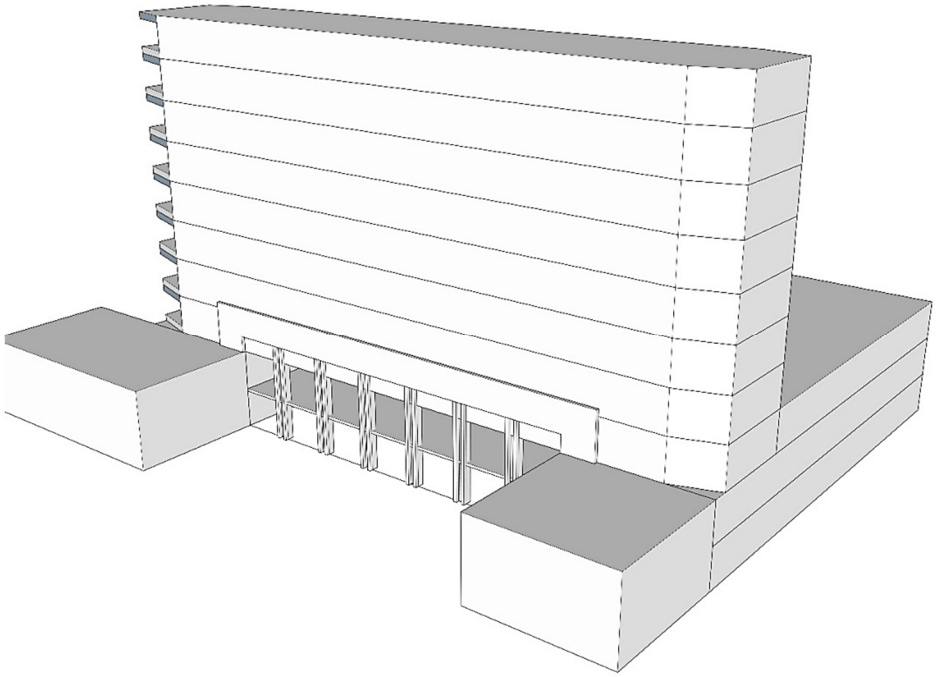

Figure 5.7 - Final volumes, front view

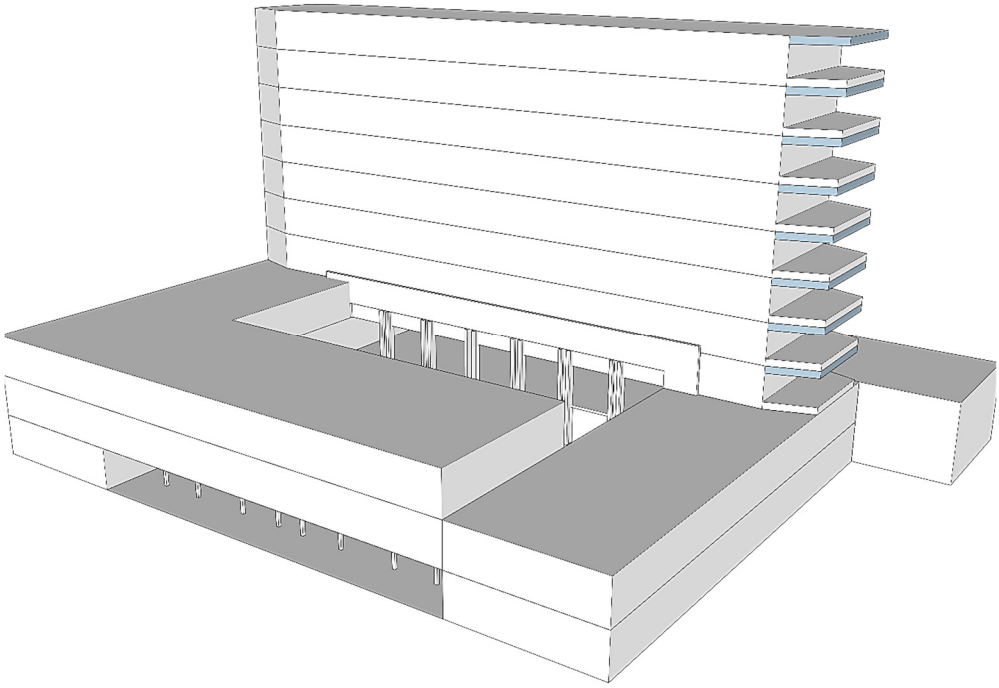

Figure 5.8 - Final volumes, back view

Following the structural restoration works, most of the building's spaces have been mainly designed for office use, as in the past. The exception is presented by the ground floor, which now serves as a reception and connection area: on either side of the main entrance, two large lobbies have been set up as a reception and information point for customers, while near "Body B" there is a relaxation and break area for the staff. The basement, currently used as a warehouse and garage, has undergone a series of changes too: the ground level has been lowered in the southwest corner to allow part of the basement to be used for a new tertiary function. Indeed, this area has been rehabilitated in accordance with the Regional Law. n. 7/2017 and will be transformed into office space (coworking), while the other functions of garage, warehouse and technical rooms remained unchanged.

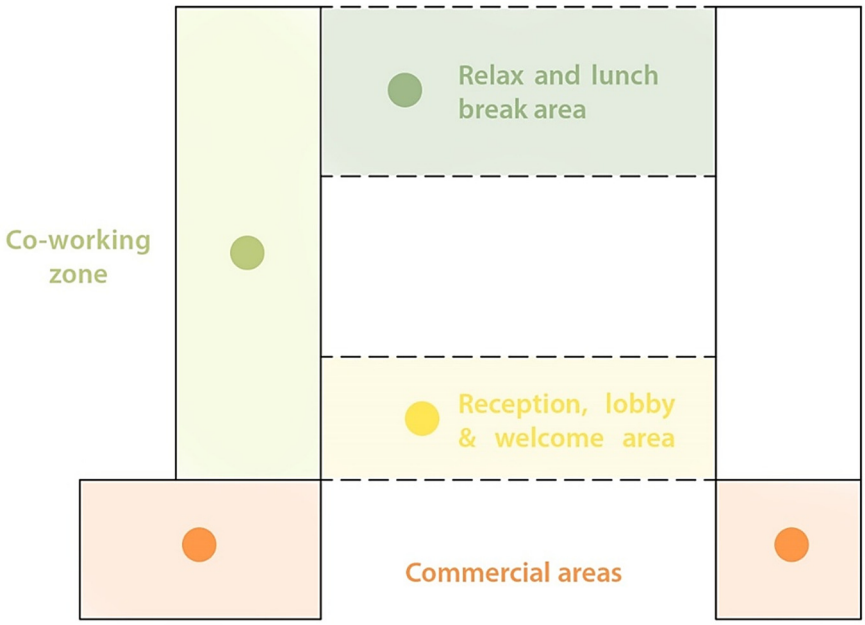

Figure 5.9 - Spaces destination of use, ground floor

From an architectural point of view, the renovation works involved the creation of a new facade for the entire complex: the previous exposed reinforced concrete wall, hosting a row of windows on each floor of the building, was demolished, with only the load-bearing columns being retained. The new external envelope takes on the function of a curtain wall system, made with Schüco aluminium windows frame and solar control glazing. This new technology was designed to guarantee high internal comfort, since it has very low thermal transmittance values, and an incredible ratio between natural light and sun protection. Indeed, insulating

glass brings light inside the building, offering 70% light transmission, while blocking two thirds of solar heat.

Although this type of unitized façade system can also be considered prefabricated, as the various glazed modules are produced directly in the factory and later anchored on worksite, it slightly differs from the concept of prefabrication described in Chapter 3. The difference lies not so much in the type of component manufactured in the factory, but in the application methods on the existing building envelope. Indeed, in this case, the entire external facade of the complex has been demolished and replaced by these glass modules. On the contrary, the innovative prefabricated components are directly applied to the existing facade, like a real coat, without removing the original structure. For this reason, in the following paragraphs, a new type of envelope will be proposed which does not include any demolition process, except for the row of windows.

5.3.2 Building Services Interventions

The renovation process also included a complete renewal of the building's systems, in order to both achieve suitable indoor thermal comfort, according to normative levels, and energy efficiency.

The approach adopted for these new facilities' design is based on the concept of multi-tenant building, which represents a type of construction intended to host multiple "tenants", each with separate and independent spaces. Therefore, it must offer maximum flexibility in space use, with each area being carefully designed from a structural point of view, in terms of network distribution, and appropriately sized according to technical specifications of the systems themselves. This will be necessary in order to allow future customization by the tenants, as each of them will have to be considered as a single independent unit.

For this reason, the technical systems will ensure the separation and accounting of the main utilities (such as electricity, water, heating/cooling) for each "macro-zone". This means that each floor or block of the building will be equipped with its own consumption measurement system, allowing for precise monitoring of resource usage. This approach facilitates management and gives the possibility of charging costs separately to the various tenants who occupy building zones, as, being a very large complex, it could accommodate several companies inside. Therefore, the main distribution will take place on all building's floors through different cavities, starting from the technical rooms located in the basement, which serves as central points for energy arrival and distribution. For each macro-zone a technical room will be provided where control and management devices, such as electrical panels and other equipment, will be placed.

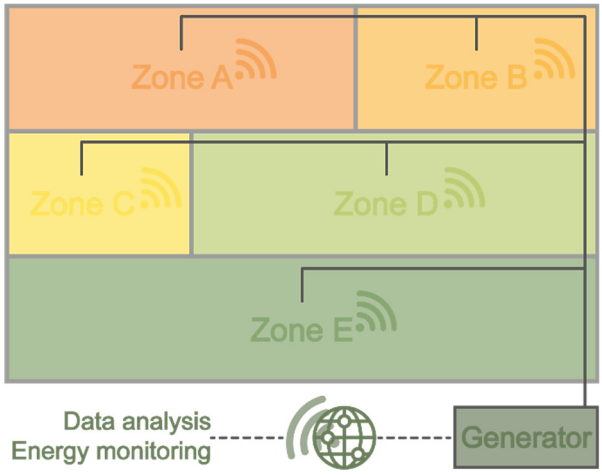

Figure 5.10 - Schematic representation of the control system

However, the other systems serving the building, such as the fire detection system and emergency lighting, are centralized. This means that they are no longer separate and independent for each macro-zone, but are managed from a single area, the control room, located near the building's reception area on the ground floor.

5.3.2.1 Air Conditioning System: Heating and Cooling

The first system to have undergone significant renovation works is the air conditioning system, which includes both heating and cooling, as well as the air quality management and domestic hot water. Indeed, its main functions are two: on the one hand, the maintenance of internal temperature and relative humidity within specific ranges (between 20° and 26° for the former and 46% for the latter), in order to ensure adequate thermal comfort; on the other, the reduction of pollutants' concentration within workspaces, which must remain within certain limits to safeguard the well-being of the occupants. Thanks to its optimization, this system will have a significant impact on the building's energy needs, resulting in a reduction in consumption.

The heart of the air conditioning system is represented by a heat pump with 3 multifunctional units (one of which serves as a backup), capable of producing both refrigeration and thermal energy, thereby ensuring the cooling and heating of the spaces respectively, as well as the generation of domestic hot water. The air distribution system is mixed, consisting of a combination of four-pipe fan coils and primary air systems, represented by the Air Handling Units (AHU) distributed across the various floors of the building. Therefore, it follows that:

- The 5 AHUs, set up in different areas of the building, have the function of treating only the external air, which will be heated and cooled according to needs, and distributed to all rooms. Four heat recovery units (REC) have been installed associated with them,

which are devices used to recover heat from environments where air flows are lower, such as in commercial areas, in the lobby/reception and in the pavilion. RECs work together with AHUs to optimize energy efficiency, reducing consumption, as they use residual heat to heat or pre-heat the air that is introduced into the building. Together, they represent the building's primary air system, with flow rates calculated based on the number of occupants on each floor, satisfying the requirements of LEED IEQc 2 of the LEED V4 CORE AND SHELL protocol index (see 6.1.1). The following have been prepared:

  - AHU 1 - serving the restaurant area - Flow rate 7,000 m³/h
  - AHU 2 - serving the coworking area - Flow rate 6,500 m³/h
  - AHU 3 - serving the open space office area - Flow rate 3,000 m³/h
  - AHU 4 - serving the office area - Flow rate 12,000 m³/h
  - AHU 5 - serving the tower area - Flow rate 30,000 m³/h
  - REC 1 - serving the commercial area - Flow rate 1,000 m³/h
  - REC 2 - serving the lobby area - Flow rate 800 m³/h
  - REC 3 - serving the pavilion area - Flow rate 800 m³/h
  - REC 4 - serving the "cyclists" changing rooms with hot coil only.

- The fan coils, in turn, are responsible for further treating the internal air previously supplied by the AHUs, by cooling or heating it in order to regulate the temperature independently, depending on the needs of each zone. Indoor air enters the component passing through a filter, in order to remove any pollutants before being released back into the environment. This process is managed by a fan, whose function is to ensure the circulation of incoming and outgoing air: for this reason, the work spent by the component is only electrical. Afterwards, before being released back into the indoor environment, the air will pass through a heat exchanger to be heated or cooled. In this system, the heat exchanger is powered and directly connected to the heat pump, where the energy carrier for air conditioning is represented by water.
  The fan coils used are units that work using two separate circuits, one for heating and one for cooling, each defined by a water delivery and return pipe.

Regarding the two commercial areas on the ground floor, a fan coil and primary air system has been provided too, connected to the main system for operation but independent in terms of regulation.

In any case, the air is introduced into the environment through a system of ducts passing through the ceiling, which conveys the air treated by the AHUs (heated, cooled or filtered) through the supply diffusers. These have an inductive effect, which means that the outgoing air is mixed with the indoor air, thereby helping to distribute it uniformly throughout the

environment. Due to the low ceiling height of the spaces, it was not possible to install a return air duct parallel to the supply one. For this reason, during the renovation process, suspended ceilings have been created: these serve as a return plenum as they collect the air to be expelled from space and re-treated. In this way, the exhausted air will pass through 3 to 4 return grilles, by generating negative pressure (plenum pressure is lower than the ambient one), installed in the ceiling itself, to be subsequently supplied to the AHUs via sheet metal ducts. Part of the return air will pass through the bathrooms, which are always in extraction and therefore in depression compared to the surrounding environment and are thus "cleaned" by a flow rate of 10 V/h, as required by the Municipal Hygiene Regulation for intermittent extractions operation.

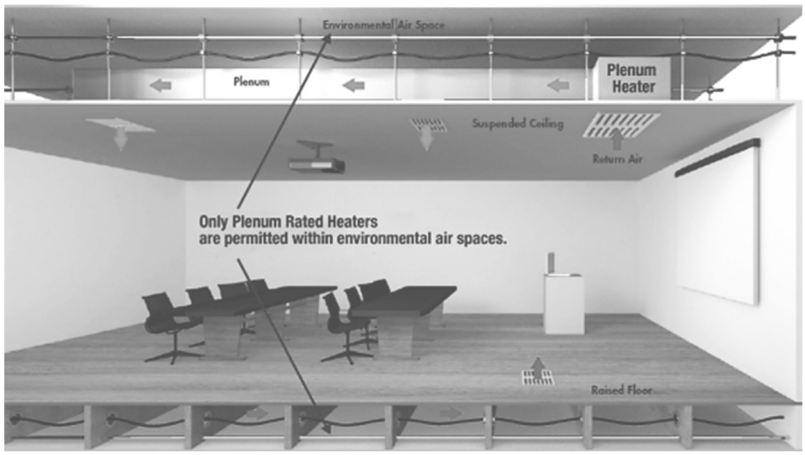

Figure 5.11 - Typical system layout for internal spaces

The additional components that have been planned for this air conditioning system are:

- two thermal substations for thermal fluid's exchange and pumping and the domestic hot water production system by using heat pumps;
- piping and distribution headers for the thermal fluid within the building;
- air extraction systems for bathrooms, disposal rooms and, possibly, kitchen areas

A key aspect for the efficient energy management of the building is the centralized supervision system using the Modbus/Knx/Bacnet protocol, which allows the monitoring and control of all operating parameters. In line with the concept of multi-tenant building, each floor of the building will be equipped with a technical room aimed at the independent management and regulation of the technological systems, resulting in varying the energy consumption based on usage. Therefore, each tenant will be provided with a heat meter, which serves to quantify the actual heat consumption used for heating and cooling in real time for each "macro-zone" considered. These heat meters are integrated into a communication network called Meter Bus, allowing them to communicate and exchange information with a concentrator located on each floor. The latter represents a device that collects data from the different meters and sends it

to the central supervision system, guaranteeing remote monitoring as well. Indeed, one of the key features of this system is the ability to monitor and manage consumption and operations in real time remotely: this means that building administrators can access the data and intervene, if necessary, even when not physically on-site, improving efficiency and responsiveness in managing utilities.

In addition to heat meters, the main water and heat utilities (such as drinking water and heating lines) are monitored via electricity meters too. These meters are equipped with communication systems that connect them to the central supervision system via standardized communication protocols such as Modbus and BACnet. Moreover, each fan coil will be equipped with a 230 V controller linked to a room sensor (multifunction panel) with a speed regulator.

5.3.2.2 Water System: Hot Sanitary Water

As previously expressed, the heating system includes a heat pump system that provides heating and cooling through four-pipe fan coils installed in each “macro-zone” of the building, complemented by primary air treatment units for air conditioning. The system is further integrated by thermal substations for the exchange and pumping of the heat transfer fluid, as well as the system for domestic hot water production.

The water networks include a filtration, treatment, pressurization and distribution system, as well as the connection to the sewage collector for wastewater. This system ensures the supply of potable water, starting from the delivery meter up to the Central Unit, subsequently distributed to user terminals.

In addition to the domestic hot water supply system, the overall water installation include:

- A system for the collection and drainage of rainwater, consisting of downpipes and horizontal drain collectors leading to the drainage pits, with oil separators for the water coming from parking area;
- A fire safety system through hydrant and sprinkler systems to ensure safety in garages;
- A system for managing the condensed water produced by air conditioning systems (drainage networks) and wastewater disposal through the connection to the municipal sewer collector;

In order to house the hot and chilled water distribution network, the drainage system and the remaining electrical distribution, each floor have been composed of floating floors. The raised floors, made of 60x60cm tiles, will be encapsulated in pre-bent galvanized steel with structural reinforcement at the perimeter, both recessed and vertical.

5.3.2.3 Electrical System & PV Panels

Following the renovation process, the building's electrical system was completely redesigned with the aim of minimizing energy consumption, resulting in a highly efficient and sustainable system. In addition to the introduction of low-consumption technologies, energy efficiency has been improved thanks to the installation of a photovoltaic system, which helps reduce the environmental impact through the production of energy from renewable sources.

The project involves the construction of a photovoltaic system consisting of 192 monocrystalline silicon modules, arranged over a total surface area of 313 m^2 corresponding to "Body A" roof. This system has a total nominal power of 64 kWp, with each panel capable of generating 333 Wp: given the high capacity, this system can cover a significant part of building's energy needs. According to simulations carried out with calculation software, the plant will be able to produce approximately 66,200 kWh/year, assuming no interruptions in service.

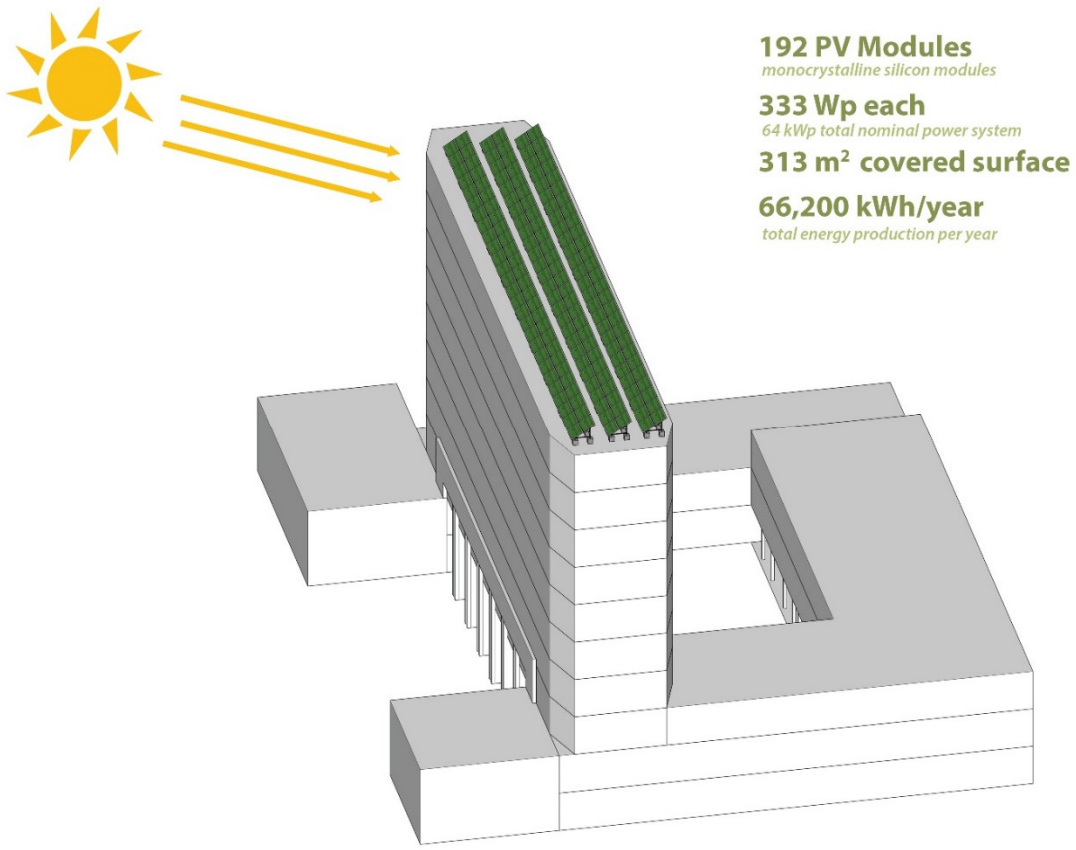

Figure 5.12 - Schematic drawing of PV modules on the roof

The energy produced by the photovoltaic system will be fed into the electricity grid when in excess of the building's needs or will be completely self-consumed. The characteristics of the

system, as well as all its components, must comply with applicable laws and regulations and comply with:

- local authorities' requirements, including the requirements of the Fire Brigade
- requirements and indications of the Electricity Distribution Companies CEI 0-16 and others
- CEI (Italian Electrotechnical Committee) regulations.
- the renewable energy producibility values envisaged by Legislative Decree 28/11

However, the Energy Performance Certificate (EPC) performed after the renovation process shows that the annual energy production of the photovoltaic system is equal to 78,093 kWh/year, higher than the energy production previously evaluated in the project.

Regarding lighting, both internal and external, the requirements set forth by the LEED v4 Protocol and ASHRAE 90.1 standard of 2010 have been met. To determine the necessary Lighting Power Density (LPD) values for the building's dynamic simulation, as required by LEED, the complete lighting design for a typical floor was developed using highly efficient fixtures (LED light sources with DALI control). This design serves as both a reference for comparison and an ideal solution for those without specific lighting needs.

5.4 Energy Refurbishment with Prefabricated Solutions

As previously stated in the earlier chapters, this new version of the EPBD Directive has introduced a series of measures that all EU Member States must adopt, to achieve the goal of climate neutrality by 2050. Since several interventions need to be carried out and the timelines for action are limited, it is necessary to find alternative retrofitting solutions that can meet both requirements.

The energy retrofit process previously described has been successfully completed with excellent results, both in terms of the technological solutions adopted and the improvement of building's thermal performance. Indeed, as explained later, this building complex meets all the requirements to be defined as a Net Zero-Energy Building (nZEB) by 2050, showing a clear improvement in energy consumption. Nevertheless, it was a major renovation process, as the works required high attention to detail and extended timelines, starting at the end of 2021 and finishing in April 2023.

For this reason, the following paragraph aims to propose an alternative strategy that could further enhance the retrofit completed, with a primary focus on the timelines and costs involved, in order to comply with the European EPBD directive's principles. This proposal outlines an energy requalification plan through the adoption of innovative prefabricated

solutions for the entire building's façade and roof, while other interventions carried out remained unchanged. Indeed, since the energy performance results obtained, together with the subsequent comparison between the pre- and post-intervention states, are expressed per square meter, the volumes and additional spaces previously described have been preserved. Similarly, the upper floors maintained the same composition as the others, extending, in this case, the portion of the load-bearing structure in reinforced concrete.

However, this proposed alternative solution is not limited solely to illustrating the prefabricated solutions discussed in Chapter 3 but is also intended to suggest possible improvements that could be adopted throughout the construction process.

5.4.1 Design Approach

By following the design approach outlined in Chapter 3, the best ally for optimal organization and planning of a prefabricated retrofit project is the BIM model. Due to the high building complexity, it was necessary to create a three-dimensional architectural model of the existing structure, through a combination of laser scanning and manual control. This approach made it possible to carry out an accurate survey of the building, which could then be digitally reconstructed: the so-called "point cloud" was transformed into a line model precise enough to be used as the digital basis for the production process.

Figure 5.13 - Phases of the BIM model creation

Once the architectural model from the existing survey was obtained, the overall design and aesthetics of the new building were defined down to the smallest details, with each component having all the necessary properties and characteristics for its realization. Indeed, this three-dimensional model was later transformed into a BIM for digital production.

Digital Fabrication is an innovative manufacturing process that uses computerized procedures to create three-dimensional solid objects, starting from digital models and drawings. In this case, the four bodies of the building, characterized by the new proposed prefabricated

components for façade and roof, have been divided into separate blocks, designed to be easily produced, transported and installed. Building's perimetral walls have been divided into precise modules, which represent the prefabricated components that will be directly manufactured in the factory.

Figure 5.14 presents a general division of façade modules, according to their block. For each building section, façades are divided into corner parts and inner parts, with modules designed depending on their position. In each section, modules must be differentiated to avoid the repetitiveness of the elevation. The remaining parts of the building façades, related to the two small blocks, are composed of unitised systems of glass and aluminium.

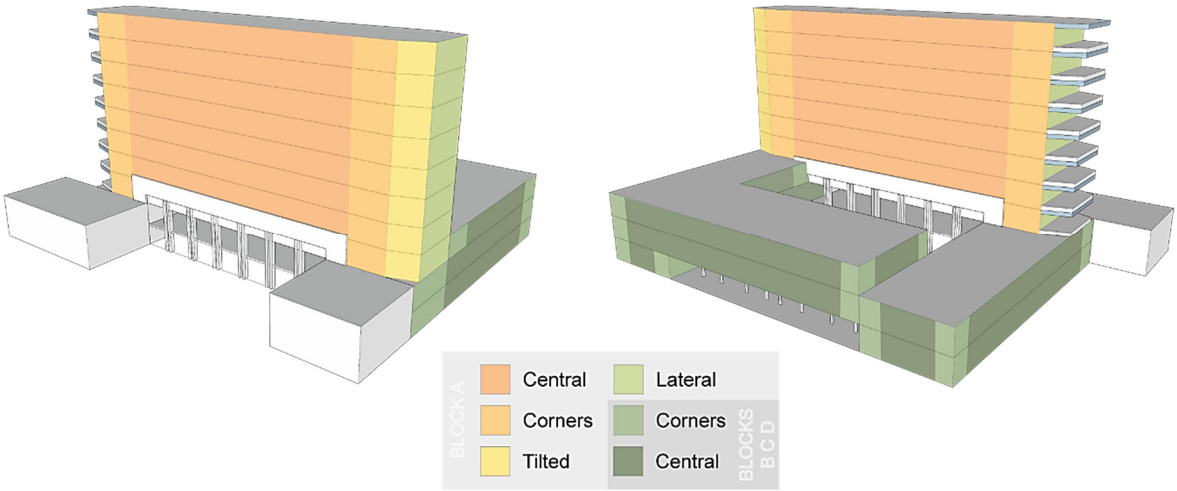

Figure 5.14 - Differentiation of façade modules, front and back views

Once the design was completed by using appropriate software, the BIM objects for the facade and roof elements were directly used in the factory production line through different technologies. In this way, the precision achieved with modelling software was transmitted to a series of digitized tools, such as CNC machines, 3D printers, laser engraving machines and others, which automated some production phases. This approach optimized the use of raw materials required for the creation of prefabricated panels, which, as explained later, consist of the alternation of opaque and glazed components. Even before being transported to the construction site, where only the anchoring process on the relevant surfaces and the finishing work will take place, the final assembly of each element was performed manually still in the factory.

5.4.2 Prefabricated Components for Façade and Roof

5.4.2.1 Products selection

The selection of modules is based on the Energiesprong catalogue [44], which lists products from various companies to assist in choosing the most suitable layout. The solutions and their characteristics are compared according to the specific features of the analysed building.

Firstly, the dimensions of the modules are considered, such as the height of the storeys, as companies specify maximum allowable dimensions for each element. Another key consideration is the maximum number of floors the product can accommodate. Given that the highest body of the office building is characterized by ten floors, the chosen product must support at least this application. Additionally, the integration of windows and systems plays a critical role in the selection process, as the design includes the incorporation of windows directly into the modules.

Based on these considerations, the selected company is Ricehouse, which not only meets the specific requirements of the case study but also enhances the circularity of construction elements through its innovative use of materials. Their approach begins with the recovery of industrial waste from rice production, which is then used to create new biomaterials for modules' assembly. They are off-site elements produced by combining layers of different biobased materials, as shown in Figure 5.15. It is possible to notice how the composition of the module is relying primarily on those materials, main insulation layers and elements are produced from the rice waste. Framing elements are made of wood, while membranes used are similar to the ones used in traditional construction.

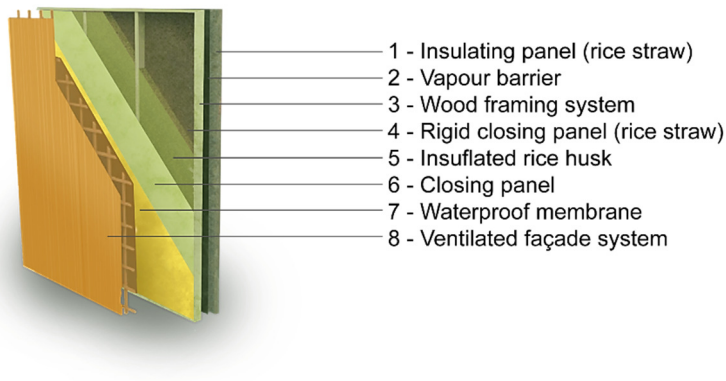

Figure 5.15 - Façade modules' composition, from Energiesprong catalogue

This system application does not require any scaffolding, while needing only a crane to lift modules to their final position, since they are fixed to the façade with a quick anchoring system.

The anchoring is provided by punctual elements, installed on the existing concrete walls, and once modules arrive to the construction site, they are directly attached to those brackets.

Figure 5.16 - Anchoring phase of modules to the existing façade, from Energiesprong catalogue

The characteristics of this type of modules are reported in the table below. The thermal transmittance is related to the modules, without considering the existing wall. The cost per square meter considers the supply and installation of finished elements, done by the company's specialists. Alongside them, elements are tested and certified for the following characteristics: waterproofing, airtightness, fire reaction and fire resistance.

Table 5.3 - Module's characteristics, from manufacturer

Characteristics	
Thickness [cm]	31
Weight [kg/m^2]	83
Thermal transmittance [W/m^{2}k]	0.215
Installation [m^2/day]	140
Cost [€/m^2]	475

Since the catalogue does not provide a specific composition for the roof modules, it is assumed that materials are the same as the façade ones, following the right stratification for inaccessible roofs.

5.4.2.2 Modules description

Since the elements design is not the focus of this study, this phase is briefly explained, and a general description is presented. The façade subdivision presents the composition described in the previous section, with specific dimensions calculated for the analysed building.

Figure 5.17 below illustrates a general layout of a single module, whose composition is represented through a simplified scheme, in order to illustrate the alternation of opaque and transparent components. Since the urban aesthetic requalification is one of the goals associated to prefabricated solution, the architectonic composition of elevations should be designed to generate interesting shapes, avoiding the modularity repetition.

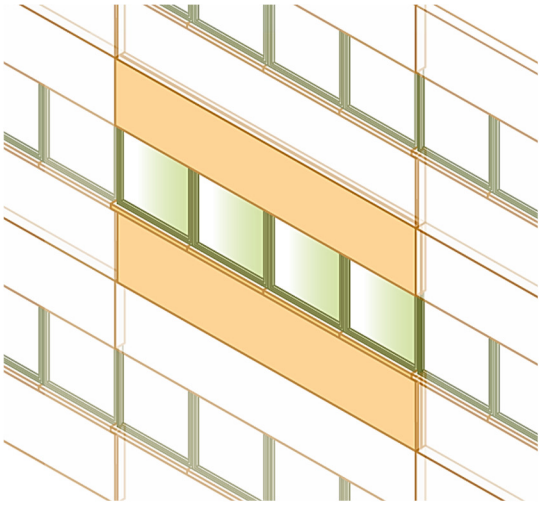

Figure 5.17 - Schematic representation of the façade module

The roof is also covered with the new prefabricated package, which is lifted by a crane and directly attached to the existing structure, following structural verification. In this case, the prefabricated module systems incorporate several features: solar thermal and photovoltaic panels are places on top of the new stratigraphy, while pipes for rainwater collection are embedded within the component. The number of modules is calculated based on the maximum dimensions for standard transportation to the construction site: 12 meters by 2.5-3 meters. The following image shows a generale scheme of roof modules according to the four roof blocks, categorized by different heights. Four distinct shapes have been determined to optimize production, in line with the roofing system layout.

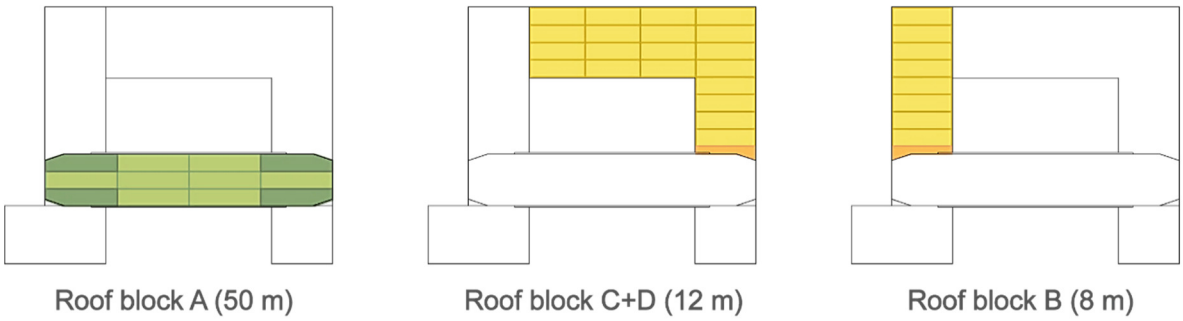

Figure 5.18 - Roofs' modules schematic configuration

5.4.3 Comparison Real Retrofit, Traditional Solution and Off-site Solution

In this section, three strategies for the case study requalification are evaluated: the real retrofit consisting of a complete recladding of the building with a curtain wall system, which has been already completed, a traditional intervention with external thermal insulation system and the prefabricated solution described in previous chapters. The unitised system is a completely different technology, and its consideration is only made to highlight how the others differ from the real intervention. Analyses are made to compare different aspects of the three methods, to verify if the prefabricated strategy could be an effective solution respect to the other ones.

5.4.3.1 Demolition phase

The main difference between the three interventions concerns the type of facade for the new building or, rather, the way it was designed and built. Compared to the traditional and prefabricated solutions, in the real retrofit the existing façades belonging to the various building's bodies have been partially demolished. Indeed, the exposed reinforced concrete portion was removed, as well as the existing window bands, while the load-bearing structure was kept intact. To better understand the works, Figure 5.19, showing the south elevation of building's Body A, illustrates the sections of the perimeter wall that were demolished (represented in orange) and the window rows (indicated in green) that were simply disassembled. Following these works, as explained previously, a new curtain wall facade was created, replacing all the previously demolished surfaces.

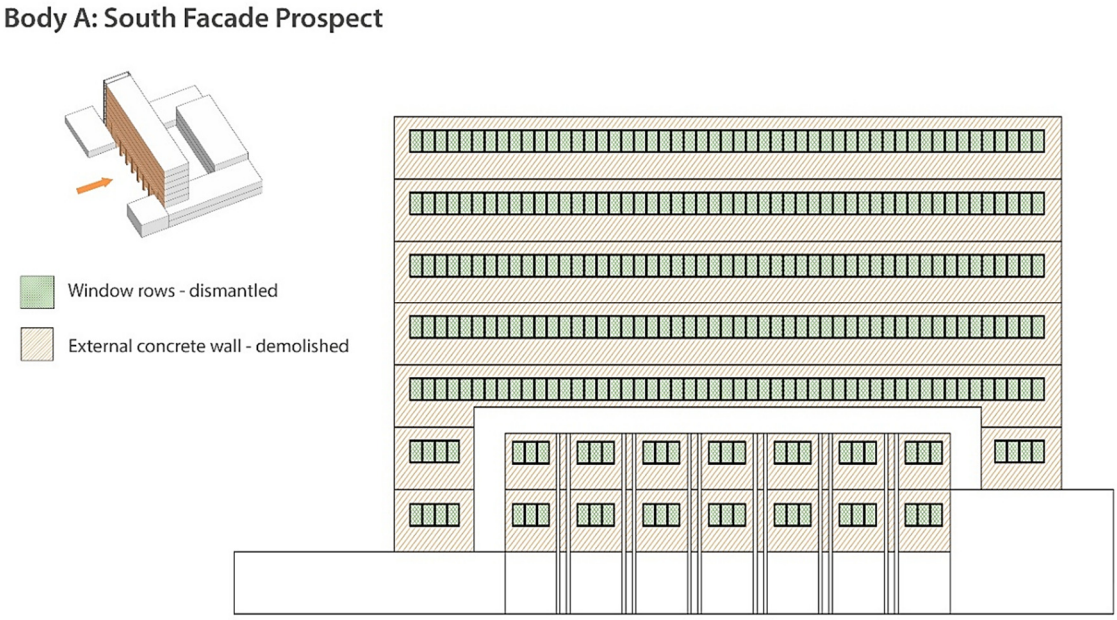

Figure 5.19 – Real Intervention: Demolition of walls and dismantling of windows, south elevation

On the other hand, the traditional and prefabricated proposals involve the recovery of the existing external walls, with the installation of insulation, without their demolition. The cement masonry is kept as the original one and only the existing windows will be dismantled for their subsequent replacement with new ones. It is important to notice that for the off-site solutions these glazed components will be directly integrated into the façade modules.

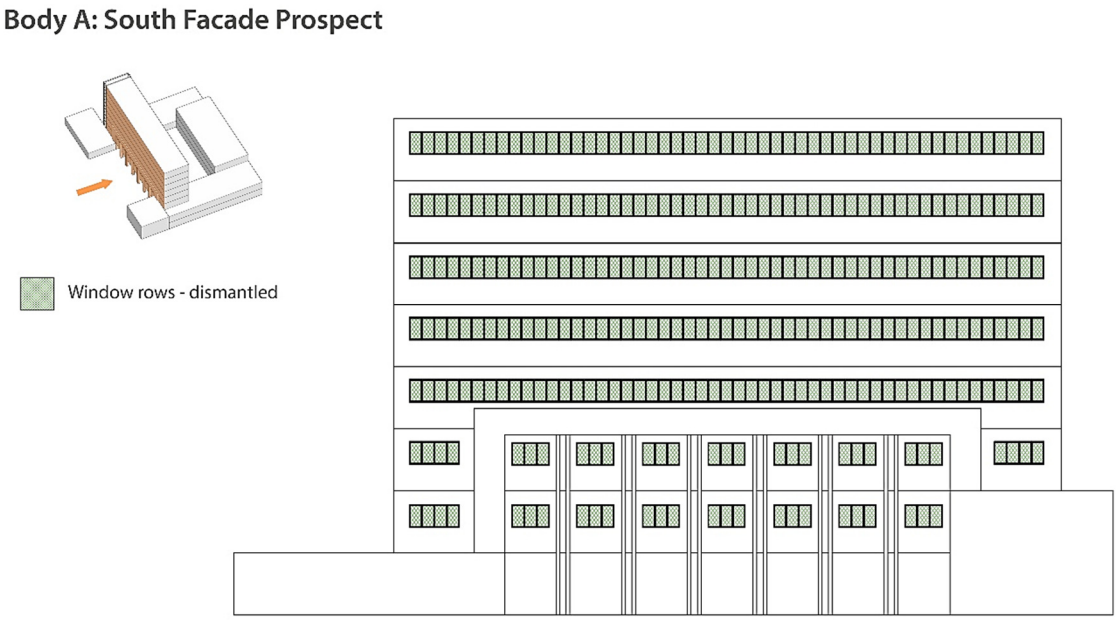

Figure 5.20 - Prefabricated Solution: Dismantling of windows and new façade module, south elevation

Therefore, it is possible to state that the main advantage of those alternative solutions lies in the elimination of the demolition phase, bringing several benefits in terms of cost, time and environmental impact. Indeed, demolition is a complex and demanding process, which has a greater impact in terms of time and resources, requiring several steps:

1. Before starting the works, it is mandatory to verify the conservation and stability conditions of the building subject to intervention, followed by the structural components' consolidation. Furthermore, the entire investigation must be supported by the execution of destructive and non-destructive tests on existing materials, to guarantee their efficiency.
2. Within the demolition area, parking and transit must be prohibited in the demolition area with appropriate barriers, to limit access to authorized workers only. Furthermore, in order to minimize the vibrations caused by the movement of mechanical equipment, a sand layer will be laid in the area where the excavator will operate.

3. The demolition phase began using several excavators due to the large size of the building complex, which were placed alongside the structure and kept at a safe distance to remain outside the fall zone. Subsequently, the façade components are gradually and sequentially removed, by following a reverse path from that used during the construction of the building, to avoid problems of instability and unexpected collapses in the work area or elsewhere in the building. Additionally, during demolition work, dust lifting must be minimized by spraying water on the walls and debris materials.
4. The second phase of the demolition was carried out manually, using service bridges independent from the structure: this means that working on the walls being demolished or on partitions connected to them is prohibited. The demolition material must not be thrown from above but must be transported or conveyed into special channels. Where the material consists of heavy or bulky items, it must be lowered to the ground using appropriate equipment.
5. The demolition process ends with the transport of debris to landfills, analysing those that may potentially be recycled or reused.

Figure 5.21 - Typical demolition's phases

In order to compare the three solutions and illustrate the potential economic savings with other renovation proposals, as well as the time spent or saved, an approximate analysis of demolition costs is presented. To begin, the approximate dimensions of Body A, B, C and D are provided in Table 5.4 below, including:

- the glazed surface to be removed, which has to be considered within the traditional and prefabricated solution too, from the moment that also in these cases more efficient and performing components will be provided.
- the opaque surface to be demolished, which is considered only for the renovation process that actually took place. The item related to the perimeter concrete walls' volume have been quantified assuming an indicative thickness of 40 cm, as defined in Chapter 3, assuming the typical construction technology of the specific construction period.

Table 5.4 – Quantity definition of external walls and windows to be demolished

	Opaque Part Surface [m²]	Opaque Part Volume [m³]	Transparent Part [m²]	Total Façade surfaces [m²]
Body A	1790	716	550	2340
Body B	552	220.8	175	727
Body C	221	88.4	101	322
Body D	105	42	49	154
Total	**2668**	**1067.2**	**875**	**3543**

The estimated surface area of the external concrete wall to be demolished has been expressed and calculated as the sum of the surfaces of each façade, corresponding to the four bodies of the building. While for Body A and Body B the surfaces to be demolished correspond to the four façades exposed to the South, East, West and North directions, for the two lateral bodies (Body C and D), the South façade is not included in the demolition works, as it coincides with the additional volumes previously indicated.

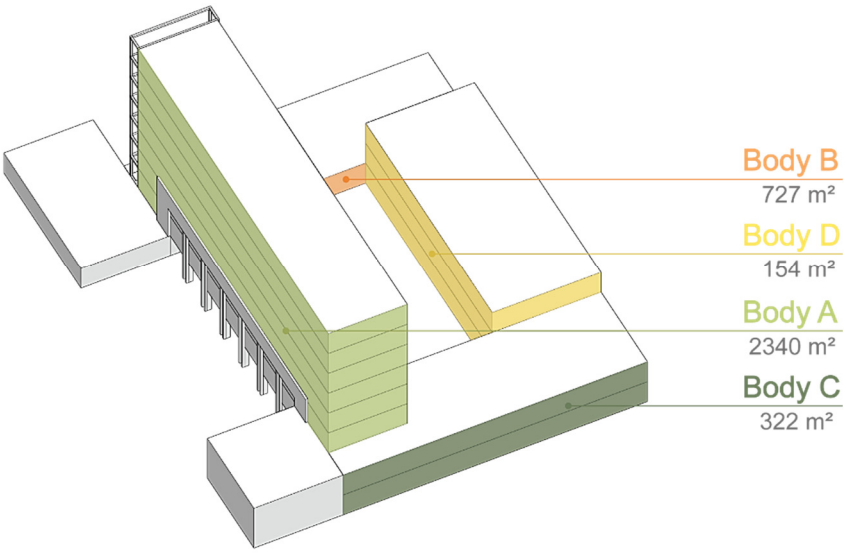

Figure 5.22 - Surfaces of façades to be demolished

Based on Italian price lists, Table 5.5 provides an approximate cost estimation for the demolition of all façades of building's volume, considering an additional percentage for structural reinforcement necessary for building consolidation. However, since this data is not available and the surface area requiring such intervention has not been quantified, the cost per square meter has been indicated for now. Furthermore, the item for window removal has been included in order to give a general idea of the cost, although it is important to note that this intervention will also be required in the other retrofit proposals.

In detail, the costs associated with the demolition work include:

- Charges for the installation of channels necessary for transporting waste materials;
- Any shoring, both mandatory and recommended, to ensure safety during operations;
- Watering the surfaces to be demolished, to minimize dust dispersion;
- Washing the walls from which the plaster will be removed;
- The supply and use of the necessary machinery (excavators, demolition shears, crushers);
- The handling of materials within the construction site area;
- The transportation of debris, including loading, unloading and levelling operations.

Table 5.5 - Estimation of demolitions costs of façades

Type of Intervention	Work	Unit of Measure	Cost	% Labor	Quantity	Total Cost
Concrete Wall Demolition	Partial demolition of above-ground building structures, using mechanical machines, assessed based on the actual volume, including lowering, loading, and transportation to an authorized treatment facility.					
	Body A- Concrete external wall	m³	463.94 €	73.20%	716.0	332,181.04 €
	Body B- Concrete external wall	m³	463.94 €	73.20%	220.8	102,437.95 €
	Body C- Concrete external wall	m³	463.94 €	73.20%	88.4	41,012.30 €
	Body D- Concrete external wall	m³	463.94 €	73.20%	42.0	19,485.48 €
Total						**495,116.77 €**
Structural Reinforcement	Supply and installation of a reinforcement system in micro-reinforced concrete using high-performance cementitious grout with elevated mechanical properties, compensated shrinkage, and high ductility reinforced with steel fibres (HPFRC) for the encasement of columns, beams, and beam-column joints in reinforced concrete. The application is carried out on a clean, water-saturated substrate by pouring in the prepared on-site formwork, without contrast reinforcement.					
	For an average width of 4 cm		m²	211.70 €	9.01%	-
Window Rows Removal	Removal of any kind of furniture, on any floor of the building, including the lowering or raising of materials, debris clearance, transportation of the debris to an authorized treatment facility, including the removal and stacking of glass in the case of windows, with the areas to be calculated before demolition.					
	Body A- Window rows	m²	13.81 €	99.89%	550	7,595.50 €
	Body B- Window rows	m²	13.81 €	99.89%	175	2,416.75 €
	Body C- Window rows	m²	13.81 €	99.89%	101	1,394.81 €
	Body D- Window rows	m²	13.81 €	99.89%	49	676.69 €
Total						**12,083.75 €**

These costs clearly highlight the economic extent of the demolition intervention and the potential savings that could be achieved by adopting the other renovation proposals, both considering the prefabricated solution and the traditional external insulation system. Indeed, during this first phase of the restoration process alone, approximately €500,000 have been invested for the demolition of the reinforced concrete façades of all the building's volumes. This represents, for sure, an estimated cost based on quantities indicated in Table 5.4, which will need to be adjusted according to the prices requested by the companies involved and the work's impact itself. In any case, attempting to go beyond the dismantling of these surfaces would result in other benefits, as significant time savings, which could be achieved through the application of the prefabricated solution or the thermal insulation system. Indeed, this demolition process, including structural checks and consolidation, could require up to 3 months of work. As for the costs, this represents an approximate estimate of timelines, as this factor depends on a number of variables that cannot be established in advance, such as the number of workers involved, the availability and number of machines required, permits, and weather conditions.

Therefore, the approach using traditional retrofitting or prefabricated modules allows for a significant reduction both in terms of costs and intervention times even before the actual renovation process begins. In this way, it is possible to save part of the time spent on demolition for more detailed planning and production of prefabricated modules, while for the traditional solution this will be invested in more time required for insulating panels installation. At the same time, they are considered more sustainable solutions as they aim at limiting environmental impacts, by minimising the disposal of demolished materials and the emissions caused by their transport to landfill. Additionally, the proposed off-site intervention is less invasive from a logistical standpoint: thanks to a carefully planned and well-organised process, starting from the design phase up to the preparation of the construction site, project implementation times can be drastically reduced.

5.4.3.2 Worksite Differences

To compare the construction periods and costs of the three solutions, the main differences in worksite layouts are outlined. This differentiation is based on the typical construction phases commonly associated with each methodology. During the evaluation, common worksite elements and stages are excluded, as they do not contribute to significant cost or time variation. For instance, elements such as cranes, site offices, fences, protective canopies, and similar infrastructure are present in all three worksites.

On the other hand, some differences can be defined for each solution proposed, which will result in significant changes on an economic and timeline perspective, as quantified in the following paragraphs. The unitised and prefabricated systems require loading platforms to deliver the modules to each floor. Additionally, the unitised solution necessitates protective measures to prevent falls from exposed floors, as external partitions are demolished in earlier stages. These measures include safety guardrails, debris netting, and metal sheets to cover exposed slabs. In contrast, the traditional solution relies on scaffolding, which significantly contributes to both costs and time requirements.

These considerations are general. A detailed evaluation of the composition of each construction worksite would require a comprehensive design of the labour processes and the specific components used in the implementation of the three solutions. Additionally, optimising the project timeline would be pivotal to reach the best possible cost-time balance.

5.4.3.3 Worksite Set-Up and Installation Costs Differences

In this section, the three interventions have been compared in terms of supply and installation costs, as well as of worksite set-up expenses, providing a comprehensive evaluation of the initial investment for improving the building's façades thermal performances. The main objective of this study is to analyse the differences in costs associated with the installation of new external partitions, respect to the one already used. Indeed, the case study has already been refurbished with an effective solution, consisting of a curtain wall system for all façades, which has brought significant benefits to the overall building's energy consumption. However, the following brief comparison aims to assess whether the alternative approaches are equally valid or even better to the real implemented intervention. For this reason, an initial comparison is made between the cost estimates for the three proposed technologies.

First of all, in order to provide a rough comparison with the actual intervention applied, the average costs for the unitised curtain wall systems have been investigated. Based on the considerations previously made, the worksite set-up costs for the real retrofit project should include the following items:

- the platform loading, one of which has been considered for each floor of Body B, C and D, while for Body A, due to its significant size, two loading platforms have been allocated for each floor. In all four cases, the counting started from the first storey up to the top of the building. Therefore, 7 loading platforms were counted for Body A (one for each of the seven floors), 2 for Body B, 1 for Body C (which consists of only two above-ground floors), and none for Body D, as it is characterized by a single floor.

- the safety guardrails, debris netting and metal sheets, which has been calculated based on the total perimeter length of each floor of the building's bodies, as illustrated in Table 5.6 below. Also in this case, the quantification started from the first floor and continued up to the total hight.

Figure 5.23 below illustrates the arrangement of both loading platforms and safety guardrails to be installed on a typical façade, a method that has been also considered for the following case study. It is possible to observe that the loading platforms are staggered for each floor in order to approximately cover the entire length of the building.

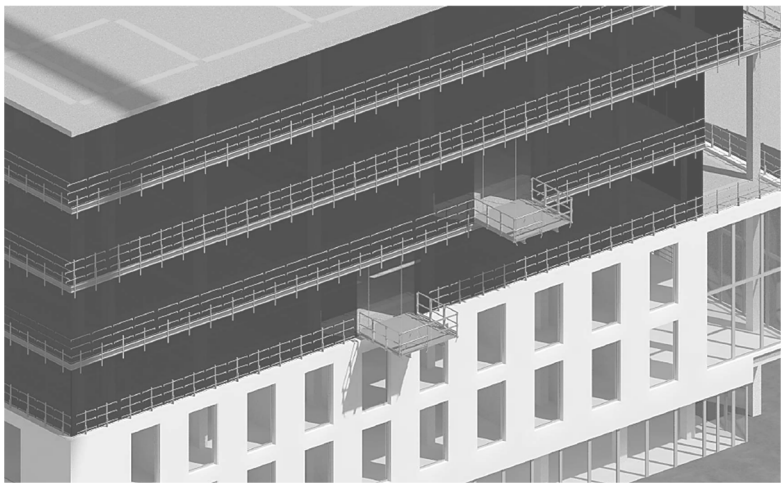

Figure 5.23 – Loading platforms and safety guardrails disposition on building's façade

Table 5.6 – Body A, B, C and D perimeter length quantification

	Safety Guardrails and Debris Netting			
	Floor Dimensions [m]	**Total Floor Length [m]**	**Number of Floors Requiring Safety Guardrails**	**Total Floor Length [m]**
Body A	43x9 m	104	7	728
Body B	28x12 m	80	3	240
Body C	34x10 m	57	3	171
Body D	34x10 m	57	not required	not required
			Total Length	**1139**

For these elements, a unit price was established based on market survey and Italian price lists. The total cost for the construction site set-up and the necessary safety elements for the work is shown in Table 5.7 below. Also in this case, this represents an approximate estimate based on the general building's dimensions and the necessary measure for the unitized curtain wall system installation.

Table 5.7 – Unitized curtain wall solution worksite set-up total cost

Unitized System: Worksite Set-Up Cost					
Body	**Type**	**Unit Price**	**Unit of Measure**	**Quantity**	**Total Cost**
BODY A	Loading platform	1,500.00 €	cad	7	10,500.00 €
	Safety guardrails and debris net	50.00 €	m	728	36,400.00 €
				Partial Body A	**46,900.00 €**
BODY B	Loading platform	1,500.00 €	cad	2	3,000.00 €
	Safety guardrails and debris net	50.00 €	m	240	12,000.00 €
				Partial Body B	**15,000.00 €**
BODY C	Loading platform	1,500.00 €	cad	1	1,500.00 €
	Safety guardrails and debris net	50.00 €	m	171	8,550.00 €
				Partial Body C	**10,050.00 €**
BODY D	Loading platform	1,500.00 €	cad	0	0.00 €
	Safety guardrails and debris net	50.00 €	m	0	0.00 €
				Partial Body D	**0.00 €**
				Total Worksite Set-Up Cost	**71,950.00 €**

In addition to the construction site expenses, the cost for the installation of the glazed modules on the façades has been quantified too, including both supply and labour. Generally, for this type of systems, the average price ranges from € 600 to € 1,500 per square meter, depending on glazing and framing systems configuration. From the moment that the information regarding the specific glazed modules considered for the actual renovation project cannot be provided for owner's privacy reason, the following analysis considers an approximate cost from the market related to these components. For this reason, an average cost of € 1,000 have been considered to have an indicative comparison with other solutions, taking into account both the glazing and framing elements, as well as the anchoring system required for the installation. By considering the total façade surface for each building's body, based on the quantification reported in Table 5.4, the total installation cost for the unitized curtain wall system turns out to be quite high, accounting for about € 3,543,000.00.

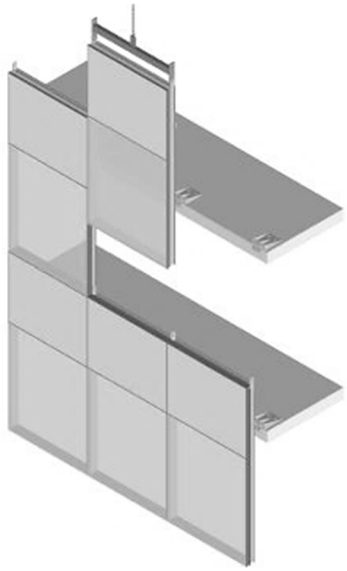

Figure 5.24- Unitised curtain wall system

Table 5.8 - Unitized curtain wall solution supply and installation total cost

	Unitized System: Installation Cost	
	Total Façade surfaces [m^2]	**Total Cost**
Body A	2340	2,340,000.00 €
Body B	727	727,000.00 €
Body C	322	322,000.00 €
Body D	154	154,000.00 €
Total	**3543**	**3,543,000.00 €**

On the other hand, in order to illustrate the necessary and approximative investment required for this unitized curtain wall system applied and to be compared with the other two solutions, the overall cost has been quantified. Table 5.9 below illustrates the total cost for both supply and installation works, increased by the amount of money required for worksite set-up.

Table 5.9 - Unitized curtain wall solution total cost

	Unitized System: Installation and Worksite set-up Total Cost		
	Installation Cost	**Worksite Set-Up Cost**	**Total Cost**
Body A	2,340,000.00 €	46,900.00 €	2,386,900.00 €
Body B	727,000.00 €	15,000.00 €	742,000.00 €
Body C	322,000.00 €	10,050.00 €	332,050.00 €
Body D	154,000.00 €	0.00 €	154,000.00 €
Total	**3,543,000.00 €**	**71,950.00 €**	**3,614,950.00 €**

The second solution analysed is the traditional one, necessary to provide a broader comparison of the properties and benefits characteristic of different energy retrofitting technologies. Indeed, simply comparing the prefabricated proposal with the technology used for the building's refurbishment, to which it was subjected, was not able to highlight the efficiency of these innovative solutions. For this reason, as explained at the end of Chapter 3, it was necessary to introduce an additional comparison term through a traditional solution, consisting of a classic thermal insulation cladding on the façade, made of 14 cm wood wool panels. The choice of these elements aims to provide a more truthful, similar, and significant comparison with the prefabricated product described earlier. Indeed, this type of insulation is generally obtained through the use and processing of waste materials derived from wood production, a concept similar to the principle used for the prefabricated Ricehouse module. At the same time, not only the concept of sustainability and recycling can be integrated into both solutions, promoting the idea of a circular economy for materials' life cycle, but their thermal properties can also be compared.

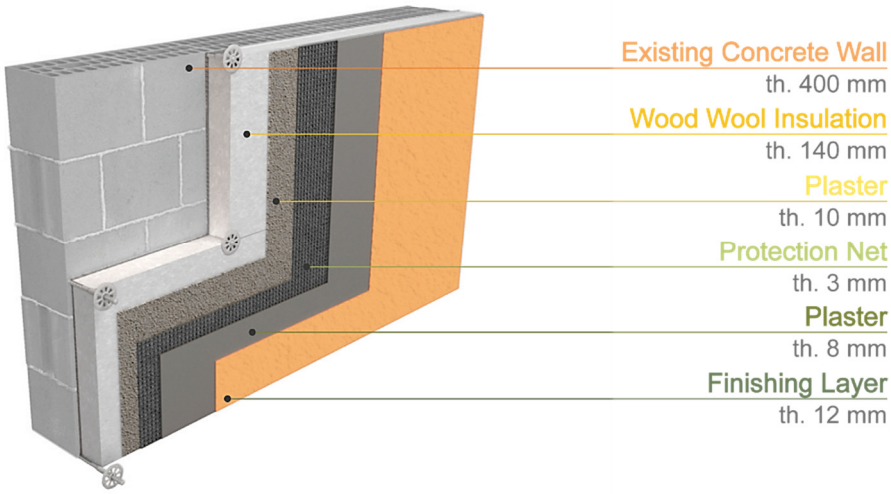

Figure 5.25 – Thermal insulation system

Before defining the overall costs determined for the four building's bodies, considering both the supply and installation of the thermal insulation system and the windows, a third key component of the traditional solutions must be taken into account: the construction site costs. As stated in Chapter 3.6, the main difference between this technology and the prefabricated modules later analysed lies in worksite management, including both the costs and the preparation timelines. Indeed, while specific machinery will be required for the installation of the prefabricated solutions, the traditional insulation system will need scaffolding for the entire façade surface. Table 5.10 below lists the main elements to be considered during the construction site preparation phase, excluding common elements between the two solutions.

The corresponding prices for each section of the building, defined as the sum of the various façades, are also provided.

Table 5.10 - Traditional solution worksite set-up total cost, considering scaffolding

	Traditional Solution: Worksite Set-Up Cost (Scaffolding)			
	Unit Price	**Unit of Measure**	**Quantity**	**Total Cost**
Body A	31.35 €	m²	2340	73,359.00 €
Body B	31.35 €	m²	727	22,791.45 €
Body C	31.35 €	m²	322	10,094.70 €
Body D	31.35 €	m²	154	4,827.90 €
			Total Worksite Set-Up Cost	**111,073.05 €**

According to a market survey, the approximate cost for the thermal insulation system application on all façades has been calculated per square meter, as shown in Table 5.11. This cost includes all the works previously outlined in Chapter 3.6, covering the supply of necessary materials and the labor costs for installation. It is important to note that, in this case, the cost per square meter is higher than the one mentioned in the referenced chapter, as a new insulating material has been considered. Indeed, the market price for woodwool panels is higher compared to the expanded polystyrene (EPS) ones, which are also of a smaller thickness, measuring only 10 cm.

Table 5.11 – Cost per square meter for traditional thermal insulation system

Labour work	**Cost**	**Unit of Measure**
Supply and installation of thermal insulating cladding, applied as an external "thermal coat" on vertical surfaces, consisting of: a) Flexible wood fibre insulation panels, low density and thermal conductivity, suitable for compression. These panels are glued with an appropriate bonding compound or special adhesives, including fixing with expandable screw anchors (mushroom fixings) of 130/150 mm length. b) Reinforced plastering with bonding compound and fiberglass mesh with a 5x5 mm grid, weighing 150 g/m², applied over the wood fibre panels. c) Application of a finishing layer with a minimum thickness of 1.5 mm in a specific colour, following the application of a primer.	113.15	m²

Regarding the traditional solution, the installation of new windows must also be considered. The selection was made based on the configuration that most closely resembles the windows integrated into the prefabricated modules. Therefore, based on the average prices per square meter available on the market, the costs for the supply of these glazing elements and their installation, including labour, has been calculated. An approximate average of € 500.00 per square meter was considered.

Table 5.12 below shows the total installation cost associated with the traditional solution considered, accounting for the thermal insulation panels and new windows application. By comparing this traditional technology with the one previously explained, it is evident that the total installation cost is significantly lower, resulting in an economic saving of approximately 73% compared to the unitized system.

Table 5.12 – Traditional solution supply and installation total cost

	Traditional Solution: Installation Cost		
	Insulation System Cost	**Windows Cost**	**Total Cost**
Body A	366,162.40 €	275,000.00 €	641,162.40 €
Body B	77,732.80 €	87,500.00 €	165,232.80 €
Body C	45,207.76 €	50,500.00 €	95,707.76 €
Body D	21,478.80 €	24,500.00 €	45,978.80 €
Total	**510,581.76 €**	**437,500.00 €**	**948,081.76 €**

Table 5.13 below, instead, takes into account both the installation and worksite set-up cost, accounting for an overall approximate € 1,059,000.00 of initial investment for this solution.

Table 5.13 - Traditional solution total cost

	Traditional Solution: Installation and Worksite Set-Up Total Cost		
	Installation Cost	**Worksite Set-Up Cost**	**Total Cost**
Body A	641,162.40 €	73,359.00 €	714,521.40 €
Body B	165,232.80 €	22,791.45 €	188,024.25 €
Body C	95,707.76 €	10,094.70 €	105,802.46 €
Body D	45,978.80 €	4,827.90 €	50,806.70 €
Total	**948,081.76 €**	**111,073.05 €**	**1,059,154.81 €**

The last evaluated strategy is the prefabricated solution, consisting of the adoption of the Ricehouse modules described in Chapter 5.4.2.2, both for the façades and the roof surfaces. By considering the overall construction set-up costs, the loading platforms have also been considered for the following technology, calculated in the same way as for the unitized curtain wall system. On the other hand, neither scaffolding nor safety guardrails and debris nets are required for this type of renovation, as illustrated in Table 5.14 below. This further highlights the efficiency of these prefabricated solutions in managing the construction site, as costs and time are significantly reduced due to a careful work organization.

Table 5.14 – Prefabricated solution worksite set-up total cost

	Prefabricated Solution: Worksite Set-Up (Loading platform)			
	Unit Price	**Unit of Measure**	**Quantity**	**Total Cost**
Body A	1,500.00 €	cad	7	10,500.00 €
Body B	1,500.00 €	cad	2	3,000.00 €
Body C	1,500.00 €	cad	1	1,500.00 €
Body D	1,500.00 €	cad	0	0.00 €
			Total Worksite Set-Up Cost	**15,000.00 €**

Unlike the traditional solution, where the costs for the supply and installation of the thermal insulation and windows have been calculated separately, as they represent two distinct and unrelated components, in the case of the prefabricated solution, this barrier is removed. Indeed, the calculated values are based on a typical module layout, where the integrated windows are already included in values indicated in Table 5.3. This price, therefore, includes both the supply of necessary materials for components' production and their installation on the façades by using specialized machinery, as well as the required finishing work. Any changes to the module components or project scale could result in variations in the cost per square meter. Since this information is unknown, a price of €475, as specified in the catalogue, has been considered for calculating the overall cost of the façade modules, based on the price per square meter provided by the manufacturers.

Table 5.15 - Prefabricated solution supply and installation total cost

	Prefabricated Solution: Installation Cost	
	Total Façade Surfaces [m^2]	**Total Cost**
Body A	2340	1,111,500.00 €
Body B	727	345,325.00 €
Body C	322	152,950.00 €
Body D	154	73,150.00 €
Total	**3543**	**1,682,925.00 €**

Table 5.16 takes into account both the installation and worksite set-up cost, accounting for an overall approximate € 1,683,000.00 of initial investment for this solution. As it is possible to state, this investment required is slightly higher respect to the traditional thermal coat application, while being much lower compared to the unitized curtain wall system.

Table 5.16 – Prefabricated solution total cost

	Prefabricated Solution: Installation and Worksite Set-Up Total Cost		
	Installation Cost	**Worksite Set-Up Cost**	**Total Cost**
Body A	1,111,500.00 €	10,500.00 €	1,122,000.00 €
Body B	345,325.00 €	3,000.00 €	348,325.00 €
Body C	152,950.00 €	1,500.00 €	154,450.00 €
Body D	73,150.00 €	0.00 €	73,150.00 €
Total	**1,682,925.00 €**	**15,000.00 €**	**1,697,925.00 €**

The ultimate goal of this analysis is to compare the three solutions in terms of initial investments, in order to determine which of them might be more economically attractive. Naturally, this analysis is not a single evaluation, as other parameters and factors will be considered in the following sections, such as the required execution timelines and the energy benefits provided. Therefore, Table 5.17 summarizes the estimated costs for each building's body for the three adopted technologies, representing the sum of the construction and installation costs of the included elements. In terms of costs, the unitized curtain wall system is more expensive compared to the other two solutions, although the costs for the prefabricated modules, as well as for the traditional solution, may increase with the addition of different windows, depending on the required thermal transmittance. Of all the solutions, it can be stated that the thermal insulation system is the most economical: despite the higher cost related to the construction site set-up, the installation of these elements requires a lower investment compared to the other two solutions. Indeed, this technology guarantees a saving of approximately 71% of the initial costs compared to the unitized system, and about 38% compared to the prefabricated solution. However, it is important to note that the cost of the prefabricated modules could be reduced through their large-scale implementation: by increasing the demand and production volume, the overall cost per square meter would decrease.

Table 5.17 - Costs estimation comparison between the three retrofit solutions

	Real Retrofit	**Traditional Solution**	**Prefabricated Solution**
Body A	2,386,900 €	714,521.40 €	1,122,000 €
Body B	742,000 €	188,024.25 €	348,325 €
Body C	332,050 €	105,802.46 €	154,450 €
Body D	154,000 €	50,806.70 €	73,150 €
Total	**3,614,950 €**	**1,059,154.81 €**	**1,697,925 €**

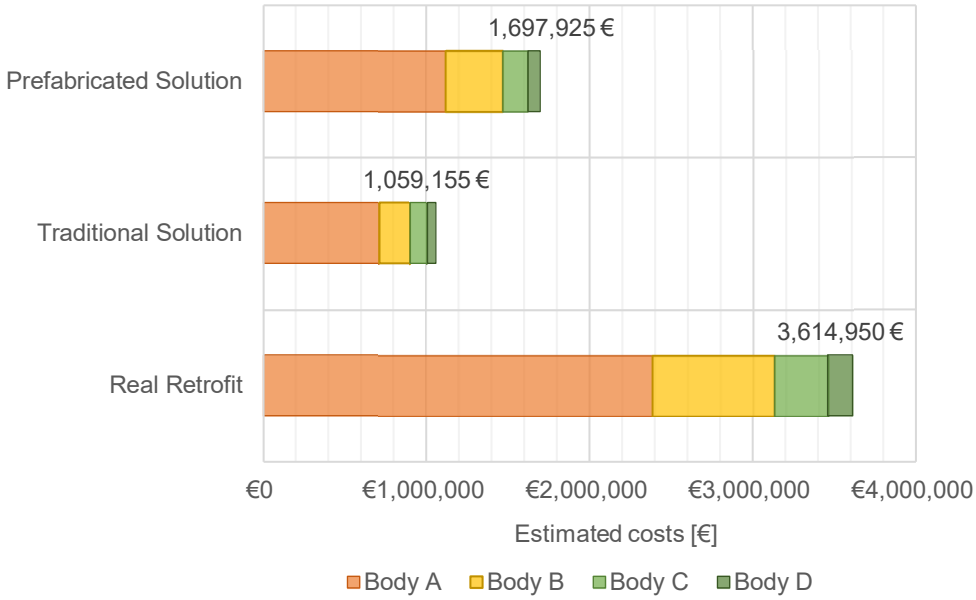

Figure 5.26 – Cost estimation comparison between the three retrofit solutions

However, as previously explained, the timeline represents the main point of comparison to highlight the efficiency and benefits derived from prefabrication. For this reason, an analysis of the construction site setup and installation timelines for the three technologies is provided for both strategies in the following paragraph.

5.4.3.4 Construction Period Comparison

Another key aspect for comparing the three retrofit solutions is time, which includes both the duration required for worksite set-up and the time needed for the application of these technologies. This comparative parameter is important in relation to the strict deadlines imposed by the new version of the Energy Performance of Buildings Directive. Indeed, specific year deadlines have been set by which energy improvement interventions on the European building stock must be completed, drastically reducing intervention times. As already emphasized, it is crucial to identify the retrofit solution that can effectively meet these requirements, addressing all economic, energy, and time aspects. For this reason, a comparison was made between the time needed to implement each of the three solutions, with the aim of identifying the one that turns out to be the most efficient, requiring the least number of days on site and for the actual work. At the same time, this helps to understand the impact of each solution on the period after which the initial investment could generate profits. By reducing this gap, it is possible to enhance the economic paybacks of the intervention, making the investment more attractive and viable in the long term. Quicker payback can lead to better cash flow for stakeholders, allowing for reinvestment in other areas of the project

considered. Additionally, reducing the timeframe for achieving profitability often improves the final sustainability of the intervention.

Starting with the unitized curtain wall system actually applied, the overall timelines for each activity has been defined in Table 5.18. Both the average construction site set-up and the unitized curtain wall system installation has been defined based on market installation timelines provided by companies, which depends on several factors, such the number of worker teams involved and construction conditions. Since worksite set-up includes both the installation of loading platforms and safety guardrails, as well as debris nets, an overall 17 days has been considered. On the other hand, the glazed module installation, including both the application with specific machinery and finishing works, has been approximated 40 m^2 per day considering three worker teams involved. Based on these considerations, it turned out to be 29 days of work for the installation, accounting for a total 46 days, considering for both worksite set-up and installation phases 3 worker teams.

Table 5.18 – Unitized curtain wall system timelines

Unitized System: Worksite Set-Up Timeline		
Type	**Average required time**	**N. Worker Teams**
Loading platform	about 2 days	3
Safety guardrails and debris net	about 15 days	3
Unitized System: Installation Timeline		
Unitized system	about 29 days	3

For what concerns the prefabricated solution, the installation and construction site set-up timeline are comparable to the unitized system, as both are anchored to the structure in a similar way. However, regarding the worksite setup, since there is no need to install safety guardrails, the required time is reduced to 3 days, considering only the loading platforms. On the other hand, the installation speed of the selected modules is provided in the technical data sheets of the Ricehouse system used, which is equal to 140 m^2 per day. Therefore, the installation period of this module technology, as provided by the manufacturer, is used to estimate the total period in which they are attached to the existing structure (Table 5.19).

Table 5.19 – Prefabricated solution timelines

Prefabricated Solution: Worksite Set-Up Timeline		
Type	**Average required time**	**N. Worker Teams**
Loading platform	about 2 days	3
Prefabricated Solution: Installation Timeline		
Ricehouse modules	about 25 days	-

However, the primary difference between this prefabricated solution and the unitized system lies in the demolition phase: since the former does not require the complete removal of the existing concrete walls, the overall period is reduced by almost 3 months, as calculated in the previous section. Another important consideration is the continuity of use: the prefabricated solution involves less invasive operations, minimizing the discomfort caused by the intervention. This allows for minimal disruption to the building's use during the façade renovation.

This benefit reported by prefabrication can be compared to the traditional thermal insultation system, since it requires much higher timelines. Even though also in this case no demolition of existing external partitions is required, the use of scaffolding for the entire construction period could result in some inconvenience for the building's occupants. Considering market-based timelines, the total number of days required by scaffolders to install the framework across the entire surface of the building has been estimated to be 14 days, counting for 6 worker teams. On the other hand, the entire process related to the thermal insulation system's installation requires significantly longer times compared to the other two solutions. Indeed, by consulting companies involved in the renovation sector, it was estimated that approximately 40 days are needed for securing and restoring the existing façade, 85 days for the application of the insulation system on all surfaces, and 26 days for the installation of the new windows (Table 5.20). Both for worksite set-up timelines and thermal coat and windows installation a number of six worker teams has been considered. It is important to note that these estimated values could be reduced considering higher numbers of workers involved, but this represents a variable that cannot be controlled within this analysis.

Table 5.20- Traditional solution timelines

Traditional Solution: Worksite Set-Up Timeline		
Type	**Average required time**	**N. Worker Teams**
Scaffolding	about 14 days	6
Traditional Solution: Installation Timeline		
Safety measures	about 40 days	6
Localized restoration		
Localized plastering		
Surface treatment		
Thermal insulation system	about 85 days	6
Window installation	about 26 days	6

In conclusion, Table 5.21 compares the total period of façade renovation for the three strategies. It is clear that the prefabricated technology is the most efficient in terms of time compared to the unitized system, and especially when compared to the traditional external thermal insulation system. Indeed, by using this new technology, it is possible to reduce the work duration by approximately 80% compared to the traditional solution, and by 70% in relation with the unitized curtain wall system, where demolition is considered. This is due to the high level of details and organization for planning and production phases of these prefabricated modules, making it a highly valid alternative to meet the tight deadlines set by the EPBD.

Table 5.21 – Timelines comparison between the three retrofit solutions

	Traditional solution	**Prefabricated solution**	**Real retrofit solution**
Walls demolition	-	-	50 days
Windows dismantling	10 days	10 days	10 days
Worksite set-up	14 days	2 days	46 days
Supply and installation	165 days	25 days	29 days
Total	**189 days** **about 9.5 months**	**37 days** **about 2 months**	**135 days** **about 7 months**

Figure 5.27 – Timelines comparison between the three retrofit solutions

5.4.3.5 Energy Features

Lastly, the thermal characteristics of the envelopes for the solutions are briefly evaluated. While energy analysis is not the primary focus of this study, a comparison between the proposed solution, the traditional approach, and the real intervention has been performed to validate the energy performance effectiveness of the proposals.

At first, the building services are considered the same of the actual building, because they are aligned with what has been said regarding the best solutions in terms of efficiency and performances. To estimate the envelope performances, the thermal transmittances of both the unitised systems and the external walls, after the installation of insulation, have been approximately calculated.

According to standards, for a NZEB building in Milan, the maximum allowable average thermal transmittance for the curtain wall system is equal to 1.2 W/m^{2}K, with the goal of achieving a lower value. For this reason, it has been hypothesised a unitised system's thermal transmittance of 1.0 W/m^{2}K.

The thermal transmittance of the external walls with the application of the module and traditional insulation is influenced by the existing partition, which is composed of the opaque part of the module and the integrated windows. The picture below illustrates a graphical and numerical schematic representation of the two solutions, including their associated values and the general layout. For the existing structure, a thermal transmittance of 1.317 W/m^{2}K has been considered, as defined in Chapter 3 in the typical construction technology.

Figure 5.28 – Envelope components' thermal transmittance, Traditional VS Prefabricated Solutions

The thermal transmittance of the opaque part, knowing properties of the two layers, is calculated using the following formula:

$$U = \frac{1}{R_{tot}} = \frac{1}{R_1 + R_2}$$

Where:

- U is the thermal transmittance of the opaque part, in W/m2K
- Rtot is the thermal total resistance of the opaque part, in m2K/W
- R1 and R2 are thermal resistances of the existing structure and the additional layers of insulation and finishings, calculated as $\frac{1}{U}$

After the calculation, opaque parts' thermal transmittances of the two solutions are: 0.204 W/m^{2}K for the traditional solution and 0.185 W/m^{2}K for the prefabricated solution.

To calculate the average thermal transmittance of the façade, the share of opaque and transparent parts has been used for considering their influence. According to surfaces used for previous analyses, the percentage of transparent envelope is 33%. The average value is calculated as a weighted average of thermal transmittances, based on elements' surfaces, following the formula:

$$U_{avg} = \frac{U_o * S_o + U_t * S_t}{S_{tot}} = U_o * \%_o + U_t * \%_t$$

Where:

- U_{avg} is the average thermal transmittance of the envelope, in W/m^{2}K
- U_o is the thermal transmittance of the opacity of the opaque part, in W/m^{2}K
- U_t is the thermal transmittance of the windows, considered equal to 1.0 W/m^{2}K
- S_o is the surface of the opaque part, in m^2
- S_t is the surface of the windows, in m^2

At the end of calculations, the average thermal transmittances are 0.467 W/m^{2}K for the traditional solution and 0.454 W/m^{2}K for the Off-site solution. For the traditional solution is calculated an additional 10% to evaluate the possibility of thermal bridges due to incorrect positioning of interfaces, resulting in a final value of 0.514 W/m^{2}K.

Table 5.22 compares the average values of thermal transmittances for the three solutions. It is possible to notice that this estimated average values of thermal transmittance for the proposed solutions are lower than the actual retrofit one, suggesting that these techniques provide more insulation to the building envelope. The prefabricated solution shows a lower value respect the traditional, highlighting its optimised realisation. This means that, following

a more detailed analysis, the prefabricated approach could lead to better performance and reduced energy consumption, enhancing overall energy efficiency.

Table 5.22 – Thermal transmittance values comparison between the three solutions

	Real Retrofit	Traditional Solution	Prefabricated Solution
U_{avg} [W/m²K]	1.000	0.514	**0.454**

5.4.3.6 Results of Comparisons

Figure 5.29 summarizes the outcomes obtained from of the previous comparisons, to quickly highlight the main differences in terms of costs, construction and energy features of the three solutions.

Regarding the costs of the renovation process, a clear reduction can be observed with the traditional and prefabricated solutions compared to the unitized curtain wall system. This is not only due to the elimination of the demolition process required for the real retrofit, but also the lower cost of the components considered. Among the three solutions, the most cost-effective is the traditional thermal insulation system, resulting in a reduction of approximately 71% compared to the unitized system and 38% compared to the prefabricated solution. Although the initial investment for the traditional thermal insulation system is more appealing to investors, given the significant energy benefits it provides, based on the considerations presented in this thesis, it cannot be defined as the best solution. This is due to the fact that the time required to implement the thermal insulation on the façade and replace the windows is very high, approximately 165 days. For this reason, the effectiveness of applying prefabricated solutions to accelerate the transition of the building stock has been assessed.

Figure 5.29 – Cost, time and energy features comparison between the three solutions

5.5 CRREM and EU Taxonomy

The case study building has been analysed by following the methodology presented in Chapter 4.8. The aim was to assess the risk of stranding of the construction, in order to define the year in which it becomes necessary to apply retrofit strategies. With the application of principles of EU Taxonomy, it has been checked the compliance of the proposed strategy with EU sustainability goals, to verify if the solution is effective not only in terms of energy efficiency but also in terms of economic sustainability for real estate owners and investors.

5.5.1 CRREM

By using the Carbon Risk Real Estate Monitor Risk Assessment Tool, analyses on the pre-refurbishment conditions have been performed. For the implementation of the analysis, it has been used the version 2.5 of the tool, available on the CRREM Project website [45]. As explained in the previous chapter, the tool requires information regarding the building, collected in the following table. For the reporting year the period before the real requalification has been taken into account, to have the exact values of consumptions. The following inserted data have been used to generate the stranding chart, plotting the decarbonisation curve and the property emission intensity.

Table 5.23 - Input used for the CRREM software

Required input	Value
Reporting year	2022
Country	Italy
City	Milan
Zip-code	20121
Property type	Office building

Table 5.24 below lists the energy characteristics of the building pre-intervention. Based on the analysis, the electricity and natural gas consumption have been estimated, while, since no renewable generation system are present, the associated values are equal to zero.

Table 5.24 - Pre-intervention inputs

Required input	Value
Total floor area	8,952 m^2
Electricity usage	468,862 kWh/year
Natural gas usage	425,302 kWh/year
On-site renewable	0 kWh/year

The tool outputs different charts, according to the type of evaluation required for the analysis. Below, two graphs are presented and discussed as being relevant to this study.

At first, the stranding chart is plotted to evaluate the stranding year and required reduction of emissions to comply with regulations. The orange curve represents the decarbonisation pathway, while the green curve is related to the building emissions, already corrected according to climate change and grid decarbonisation. The green dashed line, instead, is linked to the baseline performances without corrections, which remains constant throughout the years. Since 2022 is considered as reporting year, it is highlighted the current year, 2025. Starting from an initial GHG intensity of 25.2 $kgCO_{2eq}/m^2year$, the asset stranding occurs in 2031, which means that an intervention strategy must be implemented and realised in less than six years. To align with targets, emissions intensity must be reduced to zero before 2050, so implemented interventions should decrease GHG intensity of around 25 $kgCO_{2eq}/m^2year$.

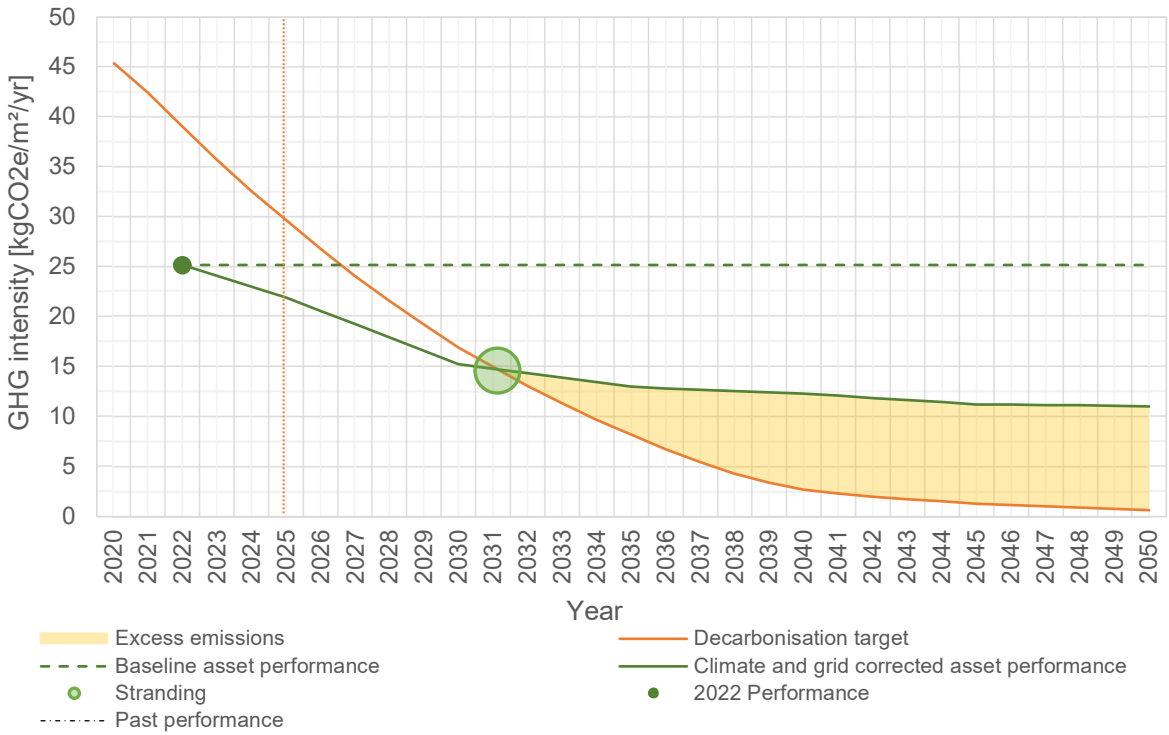

Figure 5.30 - Stranding chart of the case study – Pre-intervention

The second chart is the energy intensity diagram, still generated by the tool. It represents the yearly energy intensity per square meter of the building, compared to the required value for standards' compliance. The green curve represents the intensity of the analysed asset, while the orange curve shows the target for the specific building type, calculated according to regulations of the country in which is located the building. When the intensity of energy of the asset overcomes the limits, the building is not aligned with standards. The starting value of

intensity is 100.3 kWh/m^{2}year. In this scenario, the case study has higher energy intensity after 2031, the same year in which was found the stranding condition for GHG emissions.

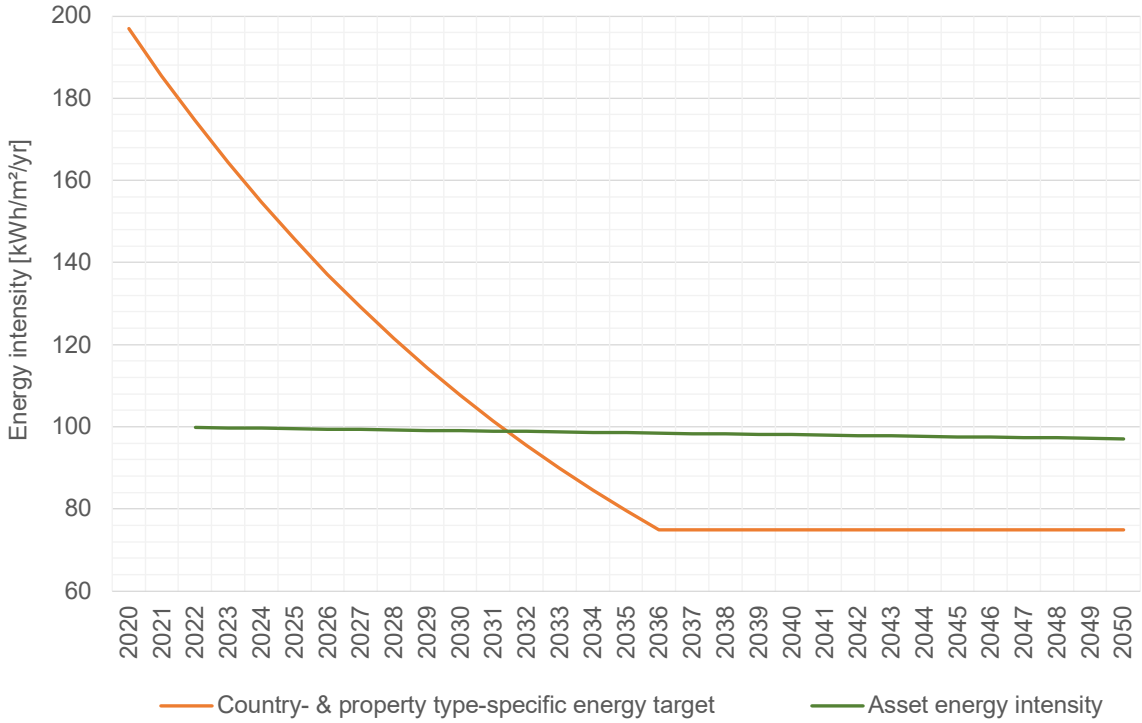

Figure 5.31 - Energy intensity diagram of the case study – Pre-intervention

According to results from the CRREM tool, the retrofit strategy must be performed before 2031 to comply with European standards. The real intervention is already completed, resulting in a transition to NZC building, with emissions that, after the correction of the curve, are below the decarbonisation pathway concerning EU environmental goals.

As for the previous CRREM evaluation, in the table below are listed inputs related to the new useful heated surface, the yearly electricity and natural gas usage. The electrification of systems provokes a complete removal of natural gas consumption from the analysis. Photovoltaic panels are installed during the retrofit, as explained in the previous section, generating electricity for the building needs.

Table 5.25 - Post-intervention inputs

Required input	Value
Total floor area	10,648 m^2
Electricity usage	167,731 kWh/year
Natural gas usage	0 kWh/year
On-site renewable	66,200 kWh/year

As before, the stranding diagram is plotted to see future positioning of the building respect to the decarbonisation curve. Figure 5.32 shows the trend of the decarbonisation pathway, in orange, and the asset's emission intensity, in green. It has been corrected according to climate change effects and future grid's decarbonisation. As starting point is considered 2023, the date in which the real intervention was completed, to ensure a precise input of data. After the intervention, the GHG intensity is 3.02 $kgCO_{2eq}/m^2year$, given by the improvement of envelope's performance, system efficiency, and electricity production. It is possible to notice how the asset's curve remains below the decarbonisation line, ensuring that the building will remain in compliance with emission targets at least until 2050. In fact, no stranding point is identified during the development of the CRREM risk assessment.

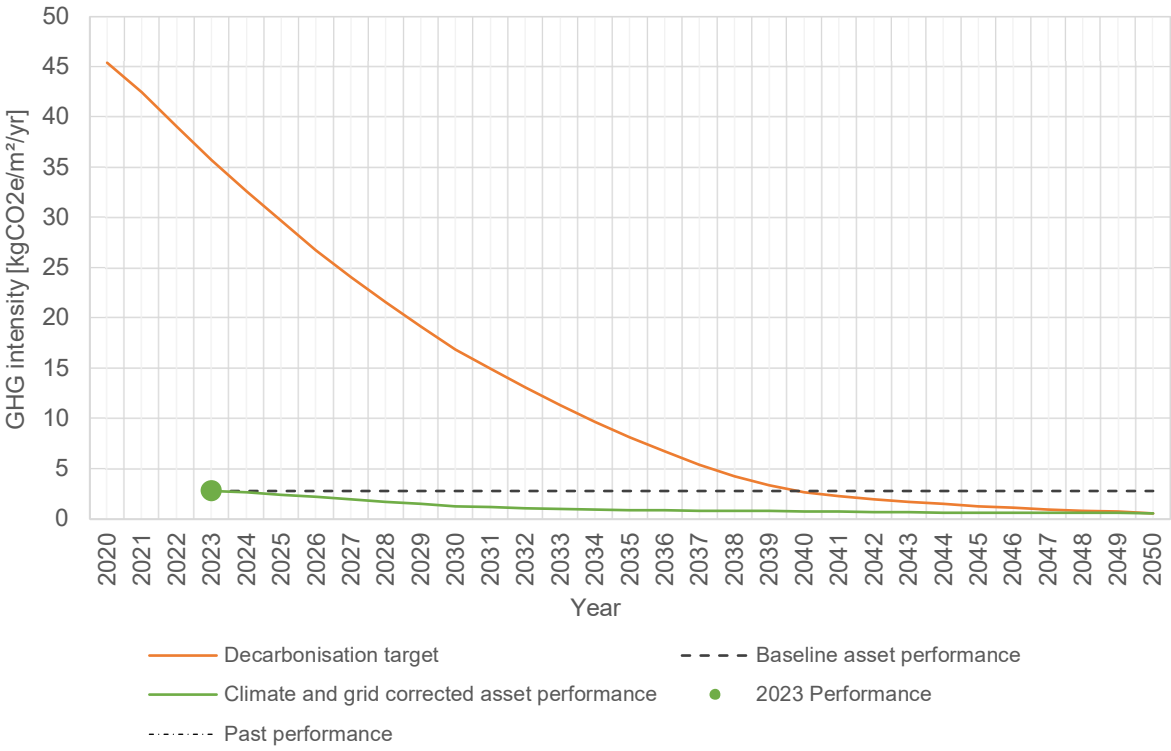

Figure 5.32 - Stranding chart of the case study – Post-intervention

The second output chart, reported in Figure 5.33, is the evaluation of energy intensity of the analysed building. In orange is plotted the target given by regulations, while in green is traced the energy intensity of the analysed asset, from the intervention to 2050. Results are in accordance with the previous diagram, as the building's curve is always below the threshold line. The asset shows no risk of stranding in the next 27 years, positioning in a favourable condition for owners and investors. The energy intensity after the retrofit is 22.40 kWh/m^2year,

its trend has a smaller slope compared to the pre-intervention curve, denoting a less dependence from the grid, which causes a decrease in the energy intensity in future years.

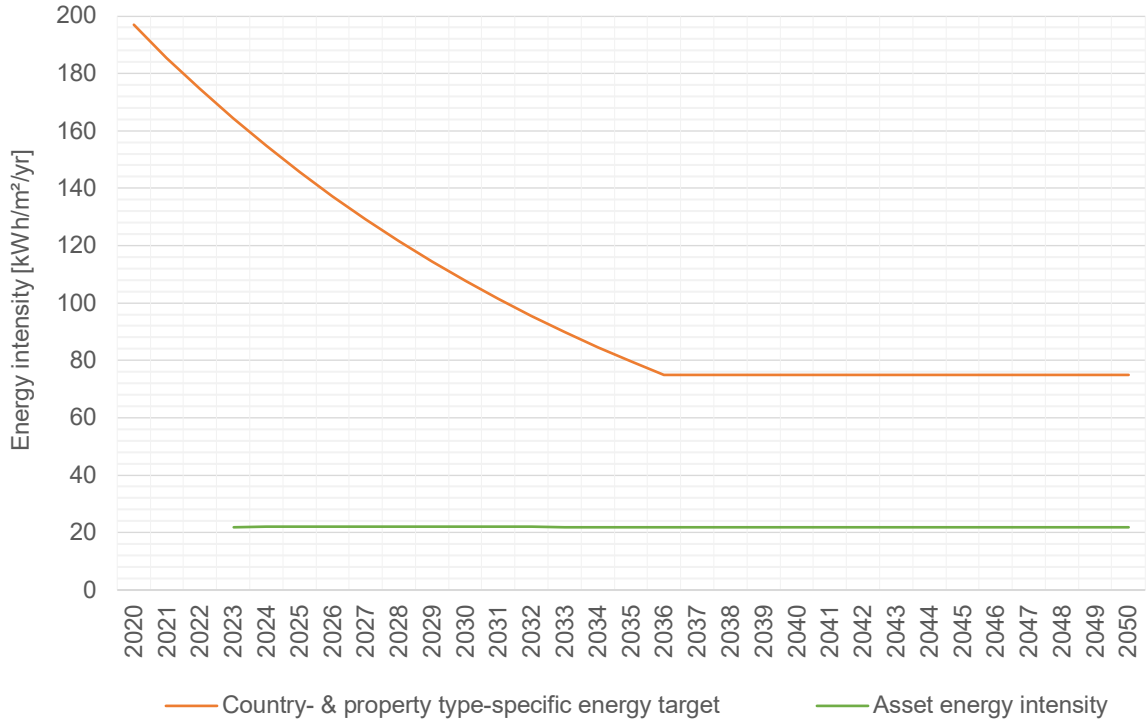

Figure 5.33 – Energy intensity diagram of the case study – Pre-intervention

At the end of the CRREM analyses a comparison between main inputs and results has been computed, in order to evaluate main differences and reduction of energy usage and emission production. In Table 5.26 the values are compared, with percentages of increase or reduction after the refurbishment. The intervention allows to have evident results, in terms of energy usage, GHG emission and energy intensity.

Table 5.26 - Pre and post-intervention CRREM data comparison

		Pre	Post	
Inputs	**Total floor area**	8,952 m^2	10,648 m^2	+18.9%
	Electricity usage	468,862 kWh/year	167,731 kWh/year	-64.2%
	Natural gas usage	425,302 kWh/year	0 kWh/year	-100.0%
	On-site renewable	0 kWh/year	66,200 kWh/year	
Outputs	**Stranding year**	2031	-	
	Emission intensity	25.20 $kgCO_{2eq}/m^2year$	3.02 $kgCO_{2eq}/m^2year$	-88.0%
	Energy intensity	100.30 kWh/m^2year	20.40 kWh/m^2year	-79.7%

5.5.2 EU Taxonomy

To highlight the commitment to sustainability and promote this type of economic activity to investors, the alignment with the EU Taxonomy has been checked by following the steps described in the previous chapter. This analysis is qualitative and main features of the retrofit strategy are used for the verification.

5.5.2.1 Economic activity

At first, the economic activity of interest has been determined. For the construction field in the Taxonomy three principal activities are identified: construction of new buildings, refurbishment of existing buildings, and ownership of buildings. In this case, the intervention is related to the second economic activity, since it consists of the requalification of an existing construction.

Figure 5.34 - Definition of economic activity for the construction field

5.5.2.2 SC to One of the Six Taxonomy Objectives

For the buildings' retrofitting the most relevant objective is the Climate Change Mitigation. To contribute to this parameter, the renovated building must comply with the EPBD requirements or improve the energy efficiency of 30% respect to initial conditions, as defined in the Taxonomy. The criterion has been verified, and the solution results aligned with both requirements. Following the EPBD, the opaque part of building's envelope is insulated, and windows are replaced, systems are substituted with more efficient and renewable energy production is ensured by solar and photovoltaic panels. Consequently, the overall energy efficiency of the building is improved. This ensures a SC to Climate Change Mitigation.

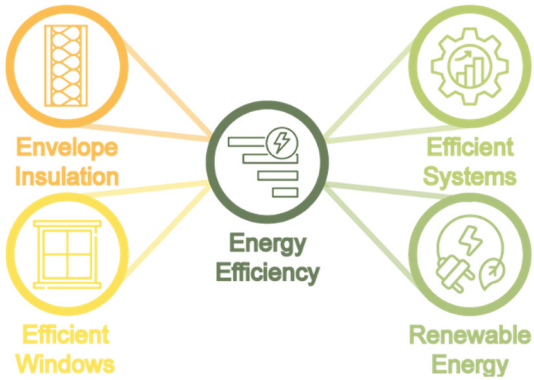

Figure 5.35 - Interventions to improve energy efficiency

Table 5.27 below reports the comparison between values before and after the renovation of the case study. Values of GHG intensity, electricity and natural gas of one year are shown to understand the impact of the retrofit on consumption and emissions. The Natural gas usage is completely removed by changing generators from combustion devices to electrically driven machines, avoiding the combustion of fuel for heating purposes. The electricity from the grid is minimised thanks to the installation of PV panels on the roof, promoting the production and self-consumption of electricity the initial value is decreased of around 60%. Avoiding the combustion and decreasing the energy needs of the building allows to reduce the GHG intensity of 88% compared to the before renovation value. Those results confirm the contribution of the building to the first objective of the EU Taxonomy, since they follow the requirements provided by standards.

Table 5.27 - Pre and Post intervention values

	Before	After	Variation
Grid Electricity [kWh/yr]	468,862	167,731	-64.2%
Natural Gas [kWh/yr]	425,302	0	-100.0%
GHG emissions [$kgCO_{2eq}/m^2yr$]	25.30	3.02	-88.0%

5.5.2.3 DNSH to the Other Objectives

The second principle to verify is the Do No Significant Harm to any of the other five objectives. Each of them has been controlled and ensured, as listed below.

- Climate Change Adaptation: the building is renovated considering future effects of the climate change, such as the temperatures rise. In the interventions are implemented technologies and solutions ensuring inhabitants resilience to those unpleasant effects.
- Water Management: in the prefabricated modules for the roof, as described in Chapter 3, a water recovery system can be directly integrated. This typology of system recovers rainwaters and uses them inside the building, allowing a reduction in drinkable water usage and improving the overall water management of the construction.
- Circular Economy: the selection of materials for the retrofit is made considering their sustainability, and their environmental impact, promoting, when it is possible, reuse or recycling of existing elements. The façade modules are selected for their innovative materials, coming from the industrial production of rice they ensure the circularity of the intervention. In addition, the proposed solution avoids the complete demolition of the envelope, recovering most of its opaque part, this reduces the need for materials and the production of construction waste.

- Pollution Prevention: the offsite strategy does not produce dust or other particles in the building site, avoiding the spread of pollutants to near areas. In factory, thanks to filtering systems and controlled production environments, the pollution production is kept under certain thresholds.
- Ecosystems protection: a faster worksite, with less on-site works reduces risks of negative impacts on local ecosystems.

Figure 5.36 - DNSH principle to the other five objectives

5.5.2.4 Minimum Social Safeguards

The third principle to accomplish is related to fundamental safeguards on human rights, social responsibility, labour rights, and anti-corruption measures. The implementation of off-site strategies allows to improve the safety of workers both in worksite and in factory, with more strict rules to follow during the realisation of the retrofit. Companies responsible for the refurbishment must align with European guidelines for social safeguards.

5.5.2.5 Documentation, Reporting and Transparency

Once the previous principles are respected, detailed analyses of the parameters must be drafted to prove the achievement of goals. To ensure significant contribution to climate change mitigation, the technical documentation related to the energy efficiency before and after the refurbishment have been conducted and reported, to ensure that performance requirements are achieved. The DNSH principle must be verified for each objective, providing detailed and technical documentations regarding social and environmental risks, with strategies for their reduction. For example, for the circularity of used construction materials, datasheets and certification are pivotal to guarantee their alignment with environmental requirements. For companies, as defined in the CSRD, reporting the EU Taxonomy alignment is mandatory and it must include the percentage of aligned activities, and all the information collected during the process of alignment.

5.5.2.6 Alignment with the Taxonomy

According to guidelines and procedures for the alignment verification, the proposed intervention meets requirements, and it can be considered Taxonomy-aligned. In the following table are reported the verifications made in order to define the compliance.

Table 5.28 - EU Taxonomy alignment verification

Economic activity definition		
SC to one objective		
DNSH to the others		
Minimum Social Safeguards		

5.6 Considerations

The presented case study integrates many of the topics discussed in earlier sections of this research, offering a practical application of more theoretical concepts. The selected building aligns with the definition of a typical building, as identified through the analysis of the Italian non-residential building stock. Indeed, it is characterized by low levels of thermal transmittance for the external envelope, as it was built in the early 1980s, and it feature an outdated heating system powered by a natural gas non-condensing boiler. Moreover, the absence of an appropriate ventilation and cooling system further worsens its efficiency, in addition to the lack of energy production from renewable sources. In developing an alternative strategy, the knowledge of prefabricated solutions has been applied to evaluate their feasibility in the context of a realistic and effective intervention. The CRREM method has been used to identify future issues of the existing building and to check if the designed solution could futureproof the building. Furthermore, incorporating green finance principles, such as verifying the alignment with EU Taxonomy guidelines, underscores the commitment to sustainability goals. This approach not only ensures environmental alignment but also highlights the solution's competitiveness for potential adoption within the real estate sector.

However, the analysed strategy has certain limitations, as some aspects has been excluded to maintain focus on the primary principles being demonstrated. One notable consideration is the detailed design of prefabricated modules from both architectural and technological perspectives. While this report does not emphasize module layout development, in a complete application of the methodology, the design phase should serve as the core of the intervention. Indeed, factory workflows should be meticulously planned and optimized to enhance the performance of the final product. Additionally, the technological layout must be tailored to achieve the highest possible energy efficiency, evaluated through detailed simulations. Future analyses could incorporate advanced modelling tools to simulate the building's energy performance, enabling more precise predictions of consumption and operational outcomes.

6. Conclusions

The research focuses on addressing the challenges presented by the fourth edition of the Energy Performance of Buildings Directive (EPBD), with the final goal of accelerating the transition of the European building stock towards climate neutrality by 2050. Achieving zero-emission buildings is a formidable task, not only in terms of technical implementation but also in meeting the critical milestones established for each EU Member State on the path to sustainability. Specifically, for the non-residential building stock, being the focus of this investigation, 16% of buildings with the poorest energy performance must be retrofitted by 2030, increasing to 26% by 2033. Given these strict timelines, the urgency of intervention becomes ever more apparent, as the climate emergency calls for immediate action to preserve both society and the environment is growing every day.

The primary questions driving this reflection are raised by three central pillars of the retrofitting process: the efficiency of interventions and achievable results, implementation timelines, and the associated costs, along with the necessary initial investments. The study sought to understand how the building sector, particularly non-residential buildings, could respond to the energy efficiency requirements within the ambitious and challenging deadlines set by the Directive. For this reason, it was necessary to explore and gather information about alternative, more sustainable and time-efficient solutions that could facilitate achieving these objectives. Indeed, while traditionally adopted technologies, such as conventional insulation systems, are energy-efficient, they tend to be time-consuming, labour-intensive and challenging to manage efficiently, significantly delaying the retrofitting process. This emphasizes the need for a new, more dynamic approach able to meet the EPBD's objectives within the given timeframe.

At the same time, a key element of this study was identifying how to overcome economical and structural barriers by adopting innovative approaches, such as prefabrication, which offer several advantages due to the integration of advanced technologies. However, these strategies require slightly higher initial investments, presenting a challenge for property owners and investors, who often prioritize more immediately profitable projects, regardless of their sustainability compliance. The primary aim, therefore, was to outline a viable alternative that combines environmental responsibility with economic incentives for stakeholders, supported by new regulatory frameworks, designed to promote the green transition in the real estate sector.

- **Structure of the Thesis**

The study began with an empirical analysis and comparison of the Italian building stock, with the goal of identifying the 16% of non-residential buildings showing the poorest energy performance. According to the European Directive, these structures will be the first targets for retrofitting, as being the primary contributors to emissions and energy consumption. By conducting a careful assessment of the national and regional building stock, according to information provided respectively by SIAPE and CENED databases, the research refined its focus on a smaller and more homogeneous building cluster. Offices (E2), commercial activities (E5) and industries (E8) have been classified as the worst energy performers in the entire real estate, making them the primary targets for renovation. Therefore, this approach enabled the identification of the most critical constructions for intervention, through the definition of the "typical building", making it possible to achieve the percentage required by the Directive.

In order to accelerate the retrofitting process and meet the tight deadlines, the research explored alternative solutions, particularly focusing on prefabrication, which proved to be a faster, more efficient method compared to traditional construction techniques. The industrialized process and the standardization of modular design presented several benefits, including reduced construction times and cost efficiency, fundamental for completing the required European's real estate renewal.

The economic issue still remains a crucial variable when discussing renovation projects that require significant capital investments. Large-scale retrofitting initiatives often demand substantial upfront cost, and for such projects to succeed, they need to be financially feasible, offering a balance between initial investment and long-term returns. Therefore, the transparency of economic activities and companies in the building sector ensures a potential ecological transition, which becomes a cornerstone for investments and not just a moral commitment. For this reason, the basic concepts of sustainable finance have been outlined to offer solutions that ensure a good economic return in addition to other benefits for investors. Sustainability assessment systems for companies and economic activities, such as the EU Taxonomy, incentivize the green transition process of the real estate sector, thereby discouraging unsustainable practices.

In the final phase of the research, the proposed solutions and methodologies have been applied to a real case study, highlighting their key strengths and uncovering potential limitations of the developed approach. This practical application allowed for a deeper understanding of how the developed strategies perform in a real-world setting, demonstrating that the topic is not addressed solely from a theoretical perspective. The solutions implemented successfully validated many of the objectives outlines as a starting point,

confirming that prefabrication is a viable alternative to traditional building retrofitting method in meeting stringent requirements.

- **Interpretation of Results**

The results demonstrated that the building sector, particularly the non-residential segment, offers significant opportunities for improvement in terms of energy efficiency. Data analysis confirmed that a substantial portion of non-residential buildings fall into the lowest energy performance classes, highlighting the urgent need for retrofitting interventions. For the three categories of non-residential buildings with the worst energy performance, which include offices (E2), commercial activities (E5), and industries (E8), a typical building has been identified for each category. Among these, common characteristics in terms of building envelope and systems have been defined in order to outline a type of non-residential buildings that, following energy retrofitting, could provide sufficient environmental benefits. It has been established that the typical buildings belonging to these three categories represent about 21.5% of all buildings in the Italian non-residential sector. This means that retrofitting this group would ensure an improvement of 16% of non-residential buildings with the worst energy performance, as required by the EPBD.

However, although the categories of buildings to be retrofitted have been identified according with the requirements of the Directive, efforts were also made to meet the stipulated timelines. Indeed, the restoration of that 16% must be completed by 2030, a challenging deadline as it entails the renovation of approximately 170,000 constructions. Therefore, the adoption of prefabricated solutions demonstrated considerable promise, allowing for a significant reduction in construction timelines and costs, while simultaneously enhancing energy efficiency and ensuring compliance with European regulations.

As later explained, the study of these prefabricated components does not aim to fully ensure the compliance with the established deadlines, but it has been demonstrated how they can facilitate the transition of the European building stock towards climate neutrality, by encouraging faster intervention times. Thanks to the comparison of the three retrofit solutions for the analysed case study – the unitized curtain wall system, the prefabricated modules, and the traditional thermal insulation – it has been possible to quantitatively assess the benefits brought by the technology proposed in this research. Compared to traditional thermal insulation methods, prefabricated solutions have allowed for more efficient resource management, faster construction processes, and a reduction in material waste, without compromising quality and sustainability. Although these solutions require a higher initial investment than traditional façade insulation, about 38%, the greatest benefits can be observed in the significant reduction in both timelines and the disruptions caused.

First, since the use of prefabrication eliminates the need for scaffolding, housing continuity is fully ensured, minimizing any issues faced by users. Secondly, it has been roughly verified that these innovative solutions can reduce intervention times by approximately 80%. On the one hand, the 14 days required for scaffolding installation when considering the traditional thermal insultation system are no longer necessary, with only a minimal percentage allocated for the arrangement of work platforms on each floor. However, the significant difference becomes evident in the application of the two technologies: the 165 days (around 8 months) required to apply the thermal coat on all building's façades is drastically reduced to just 25 days for the installation of prefabricated modules. This results in a reduction of around 85% in the work time alone.

In the analyzed case study, these prefabricated modules were also compared with the actual energy renovation project of the façade, which consists of a unitized curtain wall system. Although this technology has brought significant improvements in terms of efficiency and energy consumption to the building, a new proposal was also compared to see what additional benefits it could provide. First, since the actual retrofit comported the demolition of all building complex façades, the use of the new prefabricated modules saved the approximately 2 months dedicated to this process. As for the components installation, the required timelines are very similar due to the same façade application methodology, with prefabrication resulting in a reduction of approximately 24%.

It can, therefore, be stated that these prefabricated solutions can represent a valid alternative to the traditional insulation technologies currently adopted, enabling compliance with the deadlines set by regulations. Additionally, the adoption of tools such as the CRREM model and the EU Taxonomy helped the identification of retrofit solutions that align with long-term climate neutrality objectives, enhancing the attractiveness of investments in the sector.

- **Limitations of the Research**

Despite the significant contribution of this research, some inherent limitations in its application can be highlighted. Firstly, this study does not claim to definitively establish the widespread effectiveness or applicability of prefabricated solutions across all contexts. Consequently, it has not been possible to verify if the adoption of these new technologies can ensure the achievement of climate neutrality by 2050 or even the retrofit of 16% of non-residential buildings in the next five years.

Indeed, the implementation of prefabricated elements is influenced by several factors, including territorial specificities, building structural characteristics, and varying regulations across different EU Member States. As retrofitting conditions differ, each project requires a

tailored approach in terms of design details, module characteristics, as well as differing levels of labour. Additionally, variables like material availability, local laws, and climate conditions make it difficult to apply a standardized approach on a national scale, let alone at the European level. For this reason, further research, including multiple case studies across diverse urban contexts, is needed to assess and validate the benefits of prefabrication, comparing its impact on execution times and outcomes against traditional retrofitting methods.

During the implementation of the solution for the case study, some fundamental yet secondary aspects of this research have been addressed only superficially. For instance, a more detailed energy analysis could further validate the proposed solutions in terms of actual energy consumption and the overall performance of the retrofitted buildings. Additionally, a more in-depth investigation into the specific design of the renovation components could identify new dimensions for integrated design.

Although a clear direction toward sustainability through retrofitting has been outlined, many policy decisions and necessary investments remain uncertain and beyond designers and investors' control. Therefore, further research should address the economic-financial aspect dimension of these projects: while the initial investment costs and potential economic returns have been explored, it was not possible to thoroughly investigate the entire economic life cycle of buildings under consideration. Indeed, such an analysis would include long-term operating costs and the economic sustainability of the solutions over time, as well as their potential to provide financial benefits through energy savings and increased building value.

Moreover, the comparison between traditional and innovative retrofitting solutions was conducted for a single case study, limiting the generalizability of the results obtained. Additional variables, such as structural differences, diverse geographic contexts, and varied uses, must be considered, as they significantly influence the performance of each intervention.

- **Recommendations for Future Developments**

As previously explained, further investigation could prove useful to better validate the benefits of prefabrication, helping to understand its applicability in real-world scenarios. An interesting area of research would be the examination of multiple case studies across different urban contexts, in order to assess the effectiveness and adaptability of these retrofitting solutions in heterogeneous situations. A key avenue for exploration would be the analysis of impacts comported by various factors – such as the production requirements of prefabricated modules, building types and sizes, and labour times – on final outcomes. The examination of different scenarios would help verify whether prefabrication is the most suitable choice for achieving the goals set by the EPBD in terms of sustainability and energy performance. Indeed, such

research would enable a more detailed quantification of benefits in terms of times and cost effectiveness that prefabricated solutions are able to comport respect to traditional retrofitting methods. Additionally, it would be useful to investigate the development of new economic models that not only consider immediate costs but also address the total life-cycle of buildings, accounting for long-term energy savings and operational cost reductions.

Another step could involve integrating advanced digital technologies, such as artificial intelligence (AI) and Building Information Modelling (BIM), to further optimize the design and construction process. The incorporation of emerging innovations, such as low-impact materials or smart building technologies that optimize energy consumption in real time, could also significantly enhance the eco-friendly aspect of retrofitting projects.

In conclusion, this research serves as a meaningful contribution to the ongoing transition of the European building stock towards net zero-emissions concepts. Although prefabricated solutions are still in development and not yet widely adopted, they demonstrate significant potential to reduce construction timelines and facilitate a faster, more efficient retrofitting. While it is impossible to guarantee that all objectives will be completely realized, the findings suggest that, with a commitment to high-performing solutions and policies aligned with the EPBD, substantial progress can be make. By embracing innovative solutions and fostering collaboration between stakeholders, with the right combination of determination, support and financial investments, the path towards a greener, sustainable and low-carbon future can become reality sooner than expected.

7. References

[1] EPB Center: Consultancy and Services on the Energy Performance of Buildings, "The Energy Performance of Buildings Directive (EPBD)", doi: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

[2] IEA International Energy Agency, "Energy Performance of Buildings Directive – EPBD (2002/91/EC)", (last updated October 10, 2019), doi: https://www.iea.org/policies/868-energy-performance-of-buildings-directive-epbd-200291ec

[3] European Parliament Research Service (EPRS), Alex Wilson & Members' Research Service, "Energy Performance of Buildings Directive" (March 2023), doi: https://www.europarl.europa.eu/RegData/etudes/ATAG/2023/739377/EPRS_ATA(2023)739377_EN.pdf

[4] IEA International Energy Agency, "Directive (EU) 2018/844 on the Energy Performance of Buildings Directive (EPBD)", (last updated September 12, 2024), doi:https://www.iea.org/policies/3296-directive-eu-2018844-on-the-energy-performance-of-buildings-directive-epbd

[5] Paolo Maria Congedo, Crisina Baglivo, Delia D'agostino, Ilaria Zacà, Department of Engineering for Innovation, "Cost-Optimal Design for Nearly Zero Energy Office Buildings Located in Warm Climates" (September 24, 2015), p.2

[6] Official Website of the European Union, Directorate-General for Energy "Nearly-Zero Energy and Zero-Emission Buildings" https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-and-zero-emission-buildings_en

[7] ENEA Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Ecosostenibile: Dipartimento unità per l'Efficienza Energetica, Ing. Ilaria Bertini "*Direttiva EPBD*" (June 22, 2023) doi: https://www.efficienzaenergetica.enea.it/glossario-efficienza-energetica/lettera-d/direttiva-epdb.html

[8] ENEA, Supervisor Ilaria Bertini e Alessandro Federici, Comitato di Redazione Francesca Pagliaro, Nicola Labia, Enrico Cosimi, Maria Salvato, a coordinamento di Giovanni Addamo, "Rapporto Annuale sulla Certificazione Energetica degli Edifici: Annualità 2024" (July 21, 2024)

[9] Regione Campania, Assessore Antonio Marchiello "Certificazione Energetica degli Edifici (APE)" doi: https://www.regione.campania.it/regione/it/tematiche/certificazione-energetica-edifici-ape/certificazione-energetica-degli-edifici-ape?page=1

[10] Horizon 2020 European union Funding for Research & Innovation, Green Building Council Italia, "Energy Efficiency of Buildings in Italy", Rev 00, (August 29, 2019) doi: https://gbcitalia.org/wp-content/uploads/2022/12/SMARTER-Energy-Efficency-in-Italy-GBC-Italia-ENG-2019_08_29.pdf

[11] Italian Government: Ministry of Enterprises and Made in Italy, “Interministerial Decree of June 26, 2015 - Adjustment of National Guidelines for the Energy Certification of Buildings” (June 26, 2015)

[12] Sester S.r.l, “Energy Efficiency Classes of Buildings: What are They and How to Evaluate Them” (February 11, 2021) doi: https://www.sester.it/classi-efficienza-energetica-edifici-quali-sono-e-come-valutarle/

[13] Decree of the President of the Republic (D.P.R), n. 412, “Heating Systems: Design, Installation, Operation, Maintenance” (August 26, 1993)

[14] ARIA Regional Agency for Innovation and Procurement, “Cened – Energy Certification: A New Way of Designing, Constructing and Living in Buildings” (2007) doi: https://www.ariaspa.it/wps/portal/Aria/Home/cosa-facciamo/energia/cened-certificazione-energetica

[15] CENED Building Energy Certification “Digital Information Hub and Cened: New Project for Data Visualization of Certified Buildings in Lombardy” (June 26, 2023) doi: https://www.cened.it

[16] Ecoworks, “Innovator in Serial Renovation: About Ecoworks”, doi: https://www.ecoworks.tech/en/ueber-uns

[17] Edilportale, “Innovative Energy Retrofit: the EnergieSprong Method” (December 11, 2024), doi: https://www.edilportale.com/news/2024/12/focus/energiesprong-riqualificazione-energetica-degli-edifici_102677_67.html

[18] Ecoworks, “Standardised Renovation Solutions” https://www.ecoworks.tech/en#loesungen

[19] 4RinEU Reliable Models for Deep Renovation, “4RinEU Management to Implement Deep Renovation”, doi: http://www.4rineu.eu/wp-content/uploads/2020/04/4RinEU_WP3_20190930_D3.6_4RinEU-management-to-implement-deep-renovation.pdf?utm_source=website&utm_medium=button&utm_campaign=D3.6_4RinEU-management-to-implement-deep-renovation

[20] InfoBuild, Arch. Emanuele Meloni, “The Digital Revolution in Construction: BIM or Building Information Modelling” (March 5, 2021), doi: https://www.infobuild.it/approfondimenti/bim-rivoluzione-digitale-edilizia-building-information-modeling/

[21] 4RinEU Reliable Models for Deep Renovation, “Guidelines and Technology Concepts for Managing Building End of Life” doi: http://www.4rineu.eu/wp-content/uploads/2020/04/4RinEU_WP2_20190930_D2.7_Guidelines-for-managing-end-of-life.pdf?utm_source=website&utm_medium=button&utm_campaign=D2.7_Guidelines-for-managing-end-of-life

[22] Energiesprong, “Modello Economico v.1.0” (2024)

[23] Francesco Rossi, “ESG: una visione chiara sul futuro dell’edilizia sostenibile” (September 11, 2024)

[24] Taylor Roughan, “How to Develop an Impactful ESG Strategy in 5 Steps” (July 2024)

[25] Catalyst, “Net Zero Carbon Training” (November 22, 2024)

[26] Gustav Haaland, “Transition risks: what property owners need to know” (October 16, 2024)

[27] Sally Anne Stone, Shelley Kinsella, “Stranded Real Estate – A Real Possibility” (June 12, 2023)

[28] CRREM Project, “Objectives and Benefits”, doi: https://www.crrem.eu/objectives-and-benefits/

[29] Clementine Tanguy, “Discounting: the impact of ESG performance on asset value” (January 13, 2022)

[30] Stephen Cousins, “Valuation: green premium vs brown discount” (November 17, 2022)

[31] CRREM Project, “User manual for the CRREM Risk Assessment Tool v2” (June 2024)

[32] Lorenzo Esposito, “Che cos’è la EU Taxonomy che cataloga le attività economiche in base alla sostenibilità” (March 8, 2022)

[33] PEEB, “The EU Taxonomy – What does it mean for buildings?” (May 2021)

[34] Ecobio manager, “Six sets of EU Taxonomy Technical Screening Criteria – Everything You Need to Know” (September 2024)

[35] Celsia, “Taxonomy Terms Explained: a glossary for the EU taxonomy” (April 28, 2022), doi: https://www.celsia.io/blogs/taxonomy-terms-explained-a-glossary-for-the-eu-taxonomy

[36] European Union, “Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency” (June 19, 2018), doi: https://eur-lex.europa.eu/eli/reg/2020/852/oj/eng

[37] European Union, “Regulation (EU) 2019/2088 of the European Parliament and of the Council of 27 November 2019 on sustainability-related disclosures in the financial services sector” (December 9, 2019), doi: https://eur-lex.europa.eu/eli/reg/2019/2088/oj/eng

[38] European Union, “Regulation (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 on Corporate Sustainability Reporting (CSRD)” (December 16, 2022), doi:

https://eur-lex.europa.eu/eli/dir/2022/2464/oj/eng

[39] Findings, “Navigating CSRD – A Practical Guide for Sustainability Managers” E-Book, (April 2024)

[40] Adriana Casado Barral, “Understanding the Relationship Between CSRD, EU Taxonomy, and SFDR: A Comprehensive Guide” (September 18, 2023)

[41] Ciaran O’Leary, “EU Taxonomy Alignment Can Increase Access to Capital and Future-proof Your Assets” (August 28, 2024)

[42] European Commission, “EU Taxonomy for Sustainable Activities”, doi:
EU taxonomy for sustainable activities - European Commission

[43] World Green Building Council, “Integrating Life Cycle Global Potential into the EU Taxonomy” (January 2025), doi:
WorldGBC-EU-Taxonomy-policy-briefing.pdf

[44] Energiesprong, “Catalogo Soluzioni” (December 2023)

[45] CRREM Project, “Risk Assessment Tool”, available at:
Risk Assessment Tool – CRREM Project