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Review

Strategies to Improve the Energy Performance of Buildings: A Review of Their Life Cycle Impact

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Abstract: Globally, the building sector is responsible for more than 40% of energy use and it contributes approximately 30% of the global Greenhouse Gas (GHG) emissions. This high contribution stimulates research and policies to reduce the operational energy use and related GHG emissions of buildings. However, the environmental impacts of buildings can extend wide beyond the operational phase, and the portion of impacts related to the embodied energy of the building becomes relatively more important in low energy buildings. Therefore, the goal of the research is gaining insights into the environmental impacts of various building strategies for energy efficiency requirements compared to the life cycle environmental impacts of the whole building. The goal is to detect and investigate existing trade-offs in current approaches and solutions proposed by the research community. A literature review is driven by six fundamental and specific research questions (RQs), and performed based on two main tasks: (i) selection of literature studies, and (ii) critical analysis of the selected studies in line with the RQs. A final sample of 59 papers and 178 case studies has been collected, and key criteria are systematically analysed in a matrix. The study reveals that the high heterogeneity of the case studies makes it difficult to compare these in a straightforward way, but it allows to provide an overview of current methodological challenges and research gaps. Furthermore, the most complete studies provide valuable insights in the environmental benefits of the identified energy performance strategies over the building life cycle, but also shows the risk of burden shifting if only operational energy use is focused on, or when a limited number of environmental impact categories are assessed.

Keywords: Life Cycle Assessment (LCA); building life cycle; energy efficiency; embodied energy; embodied carbon; insulation materials; renewable energy systems

1. Introduction

Globally, the building sector is responsible for more than 40% of global energy use and contributes approximately 30% of the global Greenhouse Gas (GHG) emissions [1]. Due to its importance for providing basic needs of housing and development, and its magnitude worldwide, reductions in energy consumption and GHG emissions in this sector could make a significant contribution to the global efforts of reducing resource depletion and global warming [2]. This requires vigorous policies, but also effective and conscious actions to decrease the burdens associated to the building sector, in terms of operational and embodied energy use and related emissions. In this regard, first steps were already taken. The International Energy Agency (IEA) aims to achieve an 80% reduction in global emissions by 2050, which has led European countries to focus efforts on optimizing the energy performance [3]. The important contribution of the construction to the global energy consumption and GHG emissions stimulates the demand and development of a considerable amount of research and policies aiming at reducing buildings life cycle impacts. At the European level, the significant role of the construction sector is evident in the number of policies related to construction materials and building products within the European Strategy, including regulations, directives and initiatives [4]. On 19 June 2018, amending the Energy Performance of Buildings Directive was published [5]. The revised provisions will enter into force on 9 July 2018. This revision introduces targeted amendments to the current Directive aimed at accelerating the cost-effective renovation of existing buildings, with the vision of a decarbonised building stock by 2050 and the mobilisation of investments. Regulations, such as the EU Regulation No. 305/2011, aim at: (i) establishing harmonized technical specifications on the assessment of the performance of construction products and on the use of CE marking on these; (ii) simplifying procedures for the drawing up of declarations of performance; and (iii) strengthening the criteria for verification. Directives have the objective to set buildings' requirements, both in terms of energy efficiency and performances [6,7], and of construction materials and products [4,8]. Ad hoc initiatives conclude the set of regulatory strategies targeting the building sector and they include policies regarding resource efficiency, competitiveness, circular economy as overall political, industrial and economic goals, e.g., as proposed in the LEVEL(S) framework [4,9]

Consequently, there has been great focus on reducing the operational energy of buildings, which led to increasingly accurate calculation approaches and highly energy efficient building envelopes and systems [10]. The evaluation of energy consumption and related GHG emissions resulting from the use of buildings is becoming more accurate and being applied in the design of more energy efficient building envelopes, systems and regulations. This means that the contribution of other life cycle stages than the building use stage to the energy consumption as well as GHG emissions is increasing. Their evaluation and reduction will hence be more important in the future [1]. Indeed, the environmental impacts of buildings extend wide beyond the use phase [11], and as we move towards nearly zero energy buildings, the portion of impacts embodied in the building (e.g., associated to materials manufacturing) becomes increasingly significant.

A high share of the energy consumed in European buildings can be related to their heating demand—especially in moderate and cold climates, with a considerable portion associated to thermal losses through the climatic envelope [12]. Thus, increasing and/or improving insulation of the building envelope stands out as a measure to reduce energy consumption. Incorporating technical equipment using renewable energy to cover the remaining amount of energy demand further improves the building operational energy profile. In fact, there is a widely accepted rationale for nearly zero-energy buildings (NZEB) to first reduce the energy demand and then supply from renewable energy sources [13]. According to Mateus et al. [14], a building design must include both passive and active systems (high efficiency and use of renewable energy sources) in order to totally or partially replace the use of non-renewable energy, as passive measures enable to reduce operational energy consumption, but they are not enough to achieve the NZEB level.

Following the previously mentioned recognition that the focus on reducing operational impacts needs to be paralleled with a focus on reducing embodied impacts [10], assessing the loads embodied in those energy efficiency-related systems—such as improved insulation and renewable technical equipment—becomes of utmost importance [3].

Notwithstanding, this clear trend of focusing on carbon and energy-related impact indicators when assessing the building life cycle environmental impact may lead to misguided conclusions, as carbon and energy efficiency measures might lead to an increase in other environmental loads, for example, toxicity and/or ecosystem depletion. Even though stakeholders usually struggle with the interpretation of a long list of impact indicators, grounding decisions based solely on one metric is environmentally risky. Looking at the full building life-cycle and evaluating an exhaustive, but reasonable and targeted set of impact categories provides a complete and efficacious support to enhance scientific knowledge and policy making. In this regard, the European Commission (EC) established Life Cycle Assessment (LCA) as the currently most appropriate available methodology for evaluating the performance of construction products and buildings in its policies and legislation [4], e.g., implementing the Product Environmental Footprint method (PEF) [15]. Additionally, the EC recently commissioned a study to test the applicability of the LCA-based PEF method on the building level [16].

Therefore, the ultimate goal of the research presented in this paper was to perform a structured literature review to gain insight into the environmental impacts of various building solutions. These solutions include improving the insulation value of the building envelope and adding on-site equipment for renewable energy generation. These were evaluated in terms of the life cycle environmental impact of the whole building, in order to detect and investigate existing trade-offs in current approaches and solutions proposed by the research community. Moreover, the authors wished to confirm if the specialized literature grounds the NZEB paradigm "efficiency must come first, followed by on-site renewable energy". The review was driven by six fundamental and specific research questions, and performed based on two main tasks: (i) selection of literature studies; and (ii) critical analysis of the studies retrieved in line with the RQs. Further details about the RQs and the methodology used are provided in Section 2. Section 3 provides a general overview of the results and the specific replies retrieved from the meta-analysis for each research question, while Section 4 closes the review with conclusions and future outlooks.

2. Methodology

The research consisted in the preliminary selection and assessment of up-to-date and qualified literature studies to help answer six specific RQs. These are summarized as follows:

- **RQ1**: What is the weight of each life cycle phase in the total environmental impact of a building (product stage of materials, construction process stage, use stage and end-of-life stage)?
    - For a current building;
    - For a low energy building;
    - For a nearly zero energy building (NZEB);
    - For a Passive House building;
    - For an energy positive building.
- **RQ2**: What tipping points for insulation thicknesses are identified in literature? Tipping points are defined as additional insulation thicknesses leading to lower energy efficiency gains than additional impacts.
- **RQ3**: What is the relative contribution of insulation in relation to the total building life cycle impacts and impacts of the construction phase of the building?
- **RQ4:** What is the relative contribution of the technical equipment for renewable energy in relation to the total building life cycle impacts, and in relation to the impact of the construction and use phase (replacement and maintenance)?
- **RQ5:** What is the ratio between impacts produced by insulation in relation to impacts avoided through energy savings? This question also considers the ratio of impacts produced by technical systems for renewable energy in relation to impacts avoided by them.
- **RQ6:** If the life cycle cost (LCC) is also assessed, are the LCC conclusions similar to the LCA conclusions?

An iterative methodological approach was followed, in an attempt to ensure that relevant information published on the matter would be traced. The literature sample was gathered by combining studies knowingly important to answer the research questions according to experts' opinions (following the so-called "snowball approach", as predicted by Litell et al. and Wohlin [17,18]. This review technique consists of an exhaustive summary of high-quality literature on a particular topic. To allow for efficiency and reproducibility, the following research protocol was established based on the research questions.

- The initial list of literature sources could not provide enough qualified information to satisfactorily answer the identified research questions.
- A keyword string for each unanswered question was initially defined, and searched for in Scopus (covering a wide set of international databases, such as ScienceDirect and Springer).
- The final sample of papers was selected through three exclusion rounds, for each keyword string: a title analysis, an abstract analysis and a full paper analysis.
- The literature selected covered different European Member States in order to provide a representative state-of-the-art on the topic and covered different building realities.
- A temporal boundary was established as an exclusion criterion: studies had to be published from 2010 forward, to assure representation of the best available practices.
- The search was restricted to papers published in journals with an Impact factor $\geq$2.

After selecting the final sample of papers, the main findings from the different literature studies were summarised in a matrix. This matrix resembles a data extraction form, containing all information perceived relevant, in an attempt to provide a combined quantitative and qualitative analysis of the scientific state-of-the-art. The form provides a complete overview of the information available in the screened publications, including generic information, building information, LCA modelling, environmental impacts and performances covered, and contribution analysis. These are summarized and linked to the RQs in Table 1, while the matrix and detailed analysis criteria are provided in Supporting Information.

Table 1. Overview of analysis criteria used in the scope of the review to address the research questions (RQ). Supporting criteria and information (SC), necessary to compare the reviewed studies, are also addressed.

Analysis Criteria	SC	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6
Building information	x						
Qualitative or quantitative study	x						
Efficiency strategy proposed (i.e., insulation, automation, etc.)	x	x	x	x	x	x	
Description of the strategy	x	x	x	x	x	x	
Building typology	x	x					
New construction or refurbishment	x	x	x	x	x	x	
Energy performance	x	x			x	x	
Building parts included	x	x					
Gross floor area [m^2]	x						
Net floor area [m^2]	x						
Reference area for EE/EC [m^2]	x						
Final operational energy demand [kWh/m^{2}a]	x		x		x	x	
Final energy demand for electricity, cooling and hot water [kWh/m^{2}a]	x		x		x	x	
LCA modelling							
Reference study period	x						
System boundaries	x	x		x	x		
Database for LCA	x						
Assumptions for LCA	x						
Additional comments for LCA	x						
Insulation materials	x		x	x	x		
LCA software	x						
Indicators assessed	x	x					
Environmental impacts and/or performances covered (according to EN 15978, 15 Modules A to D)							

Table 1. *Cont.*

Climate change	x	x					
Primary Energy	x	x	x		x	x	
Abiotic Depletion Potential	x	x					
Hazardous waste generation	x	x					
Single environmental score	x	x					
Contribution Analysis							
LC stage contribution to the total load (for 15 modules)		x					
Insulation contribution over the total load (for 15 modules)		x					
Insulation vs. Energy savings		x	x			x	
Renewable Energy contribution over the total load (for 15 modules)		x					
Renewable Energy, tipping point		x	x				
Financial costs		x					x

Papers that were not able to quantitatively answer the research questions but provided relevant discussions on the subject were kept in the sample, to enrich the answers provided.

By following this structured and wide review framework, combining experts' knowledge and opinion with a detailed systematic literature review enabled to identify research gaps associated to specific questions and to assure coverage of qualified published information. The matrix, on the other hand, served as a tool that put together all relevant results and combined them mathematically (where applicable).

3. Results

3.1. Overview—Meta-Analysis

Our final literature sample consisted of 59 papers from five different scientific journals and 16 other sources, namely one Environmental Product Declaration, one magazine article, two conference proceedings, one PhD thesis, three research reports and seven case studies, and one methodological report (Figure S1, Supporting Information).

The 59 assessed papers covered 178 case studies from 18 different European countries (Figure S2). Twelve building typologies were described in the case studies, but more than three quarters of the sample investigated residential buildings (Figure 1).

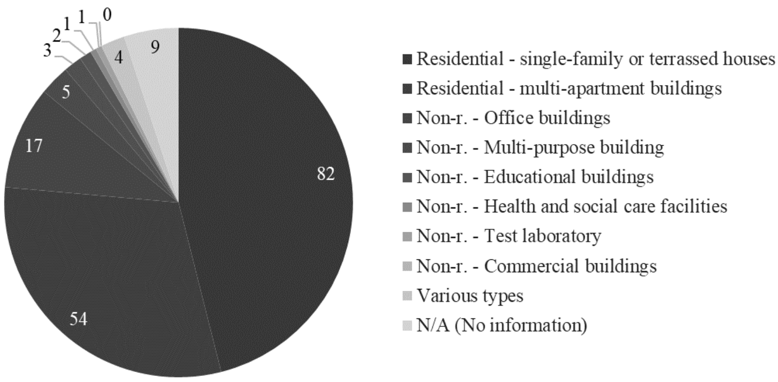

Figure 1. Types of building typology covered by the case studies (Non-r. = non-residential).

Regarding the building energy performance level, 135 of the 178 case studies provided relevant information: most of them were conventional buildings (24%), followed by energy efficient cases (16%) (Figure S3). More than half of the case studies (62%) assessed newly built buildings (Figure S4), while the impacts related to renovations were investigated for 41 studies out of the 178. Technical solutions and strategies to improve the building energy efficiency are quite numerous and nine different types were documented (Figure 2). Thermal insulation of the building envelope (roofs, exterior walls, etc.) and building development improvements clearly prevail, in some cases coupled with technical system replacements or on site-renewable energy production or a combination of both.

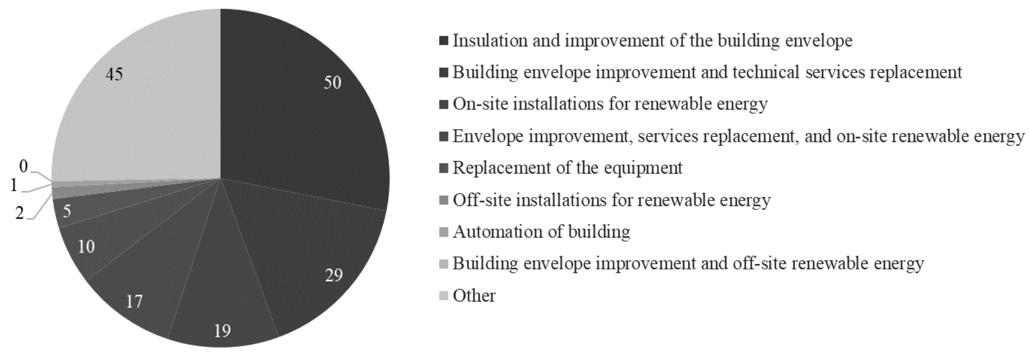

Figure 2. Types of measures to improve the building energy performance covered by the case studies.

Finally, regarding LCA system boundaries, six different product system scopes were identified, ranging from cradle-to-gate to cradle-to-grave, with a clear majority of studies considering the latter (132 out of 178, Figure S5).

An overview of our literature sample (Figure 3) shows that RQ 1, 3 and 4 were the most addressed, represented by the widest portions within the graph, while questions 2, 5 and 6 were less frequently answered or discussed. These latter questions involve a more in-depth analysis of potential benefits and loads associated to insulation (RQ 2 and 5) and economic assessments (RQ6).

The gap in literature indicated that most current studies are limited to documenting insulation materials impacts, without a more thorough assessment of what they mean to the building overall environmental performance. The graph further shows, through the portions' magnitude, if the evaluated literature clearly answered the research question or just helped build knowledge regarding assessed issues. The source type ('paper' or 'other') is also depicted. The empty portions in the outer circle in RQ2, RQ3 and RQ4 refer to 'other' sources.

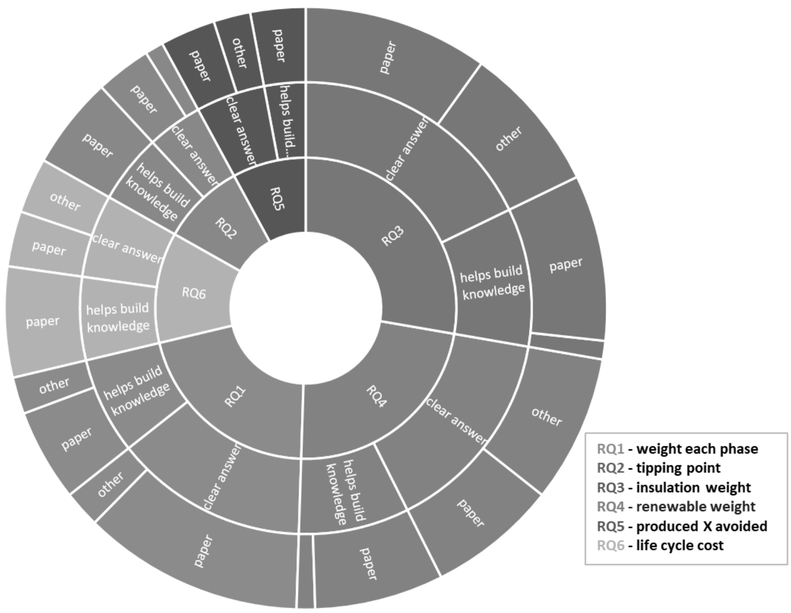

Figure 3. Overview of studies assessed and the amount and type of studies answering the research questions.

3.2. Research Questions

3.2.1. Research Question 1: Weight of Each Life Cycle Stage

In order to answer the first research question, the 132 cradle-to-grave case studies were considered. Of those 132 cases, only 37 cases provided complete figures covering all life cycle stages in order to extract the weight of each phase. These 37 cases cover:

- Seven current buildings or buildings that are built in a conventional way;
- One NZEB building;
- Eight buildings according to Passive House standard;
- Six energy positive buildings;
- Two low energy buildings;
- Two energy efficient buildings;
- And 11 cases in which the paper did not mention or describe which type of energy performance the case represented.

Based on a careful analysis of these case studies, the authors conclude that it is not possible to deduce a clear (range of the) weight of each life cycle stage in the building life cycle environmental impact as the literature review reveals a large variation in weights. As a general conclusion, it is possible to at least identify a difference in importance of the life cycle stages depending on: (i) conventional buildings versus low energy buildings: decrease in weight of the operational phase; (ii) climatic zone where the building is built (warm versus moderate/cold); (iii) influence of assumption of life span on the weight of the life cycle stages; (iv) impact categories considered. The differences in building typology, building service life, energy performance level, LCA method and the comprehensiveness of the life cycle inventory influence the contribution of the various life cycle stages. Even between buildings with a similar energy performance level, there is a large variety identified. Further details about this analysis and the weight of each life cycle phase per energy performance level and building type are available in Supporting Information.

Some papers provide overall and more complete reflections on the weight ratios of each life cycle stage and are further discussed in the subsequent paragraphs. Cabeza et al. [19] performed a review about LCA and Life Cycle Energy Analysis (LCEA) of buildings. They conclude that for residential buildings, the operational phase contributes more than 80–85% to the total life cycle impacts. Additionally, the authors suggest addressing more research efforts in decreasing the impacts related to this stage.

This claim is debated by Vilches et al. [20], who recognize in another review study that the relationship between the materials' embodied energy and the operational energy (20–80%) is changing in such a way that 40% of the impact is associated with materials and 60% is associated with the operational stage, due to refurbishment and renovations practices. The authors recommend passive design strategies to reduce the building energy demand.

A study by Bastos et al. [21] evaluated the life cycle primary energy and GHG emissions of three different residential building types in Lisbon. The study concludes that the construction, use and retrofit phases account respectively for 14–25%, 69–83% and less than 7% of the overall energy use in a 75-year period. According to the authors, the total energy and GHG emissions related to retrofit measures are higher in larger buildings. However, on a per square meter basis, energy requirements and GHG emissions are slightly lower in larger buildings. This is probably due to the higher ratio of building envelope/floor area in smaller buildings.

Rodrigues and Freire [22] have assessed the environmental impact of alternative scenarios for retrofitting the roofs of houses in Portugal considering a building service life of 50 years. The assessment comprised of 27 alternative retrofit scenarios that combined three types of insulation material (stone wool, extruded polystyrene and polyurethane foam), three insulation levels (40, 80 and 120 mm) and three types of frame material (wood, light steel and lightweight concrete). The results show that the operational energy phase has the biggest contribution over the complete life cycle followed by the construction phase. However, it also shows a negative correlation between the weight of the operational energy phase and the weight of construction phase when the insulation thickness increases.

Allacker [23] analysed the life cycle environmental impact (18 impact categories) of 16 representative residential buildings in the Belgian context (moderate climate) assuming a building service life of 60 years. The study reveals that the weight of the life cycle stages is influenced by the energy performance, the building typology and building layout (building compactness). The study reveals that for existing (conventional energy performance) detached dwellings, the use phase is responsible for 71–86% of the life cycle impact, while for low energy detached houses the weight of the use phase is reduced to 39–60%. For semi-detached, the weights of the use phase obtained are 73–89% for existing buildings and 35–61% for low-energy buildings. For terraced houses, the use phase is responsible for 69–87% of the life cycle impact in conventional buildings, while in low energy buildings, the use phase is responsible for 47–58% of the impact. For apartments, the use phase is responsible for 54–83% of the life cycle impacts in the case of existing buildings and for 51–64% in the case of low-energy buildings. In summary, it is noticed that in existing buildings, which are hardly insulated, the use phase is responsible for the highest share in environmental impacts (up to 89% of the life cycle impacts). For low energy buildings, the picture changes as the use phase causes less environmental burdens and hence its weight is reduced to an important extent. In consequence, in low energy buildings, the other life cycle stages become more important with a weight up to 65%.

3.2.2. Research Question 2: Tipping Point for Insulation

Five publications have been found which explicitly discuss the identification of tipping points in the context of insulation thickness [19,23–26]. From the five publications, two are based on the same research [23,24]. The papers cover various climatic contexts, including a moderate climate (Belgium), a warm climate (Spain and Portugal) and a cold climate (Sweden). The papers focus either on a building element, e.g., roof [20] and floor on grade [23,24] or an entire building [23,25,26]. The service life considered is 50 years (with sensitivity analysis of 30 and 60 years) for Pombo et al. [25] and Liu et al. [26], and 60 years for Allacker [23,24].

The various papers used the same approach to determine the optimal insulation level. The optimal insulation level is determined by quantifying the marginal life cycle environmental benefit of additional insulation levels. The studies all stress the importance of considering the entire life cycle of the building when aiming at a reduction of the environmental impacts.

Although the various papers identified tipping points, these tipping points are not identical. These are influenced amongst others by the climatic context, the application (e.g., roof insulation versus floor insulation), the insulation material, the heating system and the environmental impact category. As all studies focused on residential buildings, the influence of the function of the building on the tipping points has not been addressed through our review study. Moreover, some of the studies included an analysis of the tipping points both from an environmental and cost perspective, i.e., Allacker [23,24] and Liu et al. [25]. Pombo et al. [26] solely made an analysis of tipping points from a cost perspective. The studies focussing on tipping points from a financial perspective are further discussed in Section 3.2.6.

Allacker [23,24] and Rodrigues and Freire [22] investigated tipping points at element level.

A first illustration of the identification of tipping points for the insulation thickness is the PhD research of Allacker [23], where the optimal insulation level is studied for various building elements of residential buildings, such as roofs, external walls and floors in a moderate climate. The optimisation study of the floor on grade is furthermore reported in detail in [24]. For the floor on grade, 81 alternative scenarios for floors in new buildings in Belgium have been analysed, varying in floor bed filling, screed type, insulation type and thickness, and floor covering. For the insulation of the floor, the following alternatives were studied: PUR foam, insulation board under the concrete slab (PUR, EPS, XPS and resol), insulation board on top of the concrete slab (PUR, stone wool, resol, EPS and XPS). The two studies investigate and report different tipping points for various insulation materials evaluated, comparing them with the environmental impact for the production and transport to the construction site versus the life cycle environmental impact of the building element.

A second example is the study by Rodrigues and Freire [22] in which tipping points for the majority of the insulation materials and impact categories are reported for a warm climate. According to the authors' results for insulation thicknesses of 80 mm or more, the reduction in operational energy, due to a further increase of 40 mm, is not significant (5% or less), while the embodied impacts increase from 6 to 20%.

Tipping points at the building level were investigated by Allacker [23] for a moderate climate and by Pombo et al. [26] for a warm climate. Pombo et al. [26] proposed a methodology to assess different retrofitting solutions and they studied the optimal insulation level for retrofitting apartment blocks from the 1960s in Madrid (Spain), both from an environmental as well as cost perspective. The comparative study analyses eight scenarios ranging from Business as Usual (BAU), through Spanish Building Regulation requirements (for new buildings) up to the Passive House standard. The study reveals that the Passive House Standard is too strict and solutions that follow Spanish regulations for new buildings and maximum insulation thickness for one element (roof or facade with 24 cm mineral wool and 16 cm expanded polystyrene) offer the best optimization practice for the building typology evaluated.

A second example at the building level is the study of Allacker [23] in which an optimisation of 16 representative dwelling types in the Belgian context has been presented. In this study, a very broad set of technical solutions for the various building elements have been assessed at building level, which resulted in more than 20,000 variants per dwelling type. Based on this study, an optimal insulation and optimal energy performance level have been determined for the 16 representative buildings. The optima have been identified both from an environmental and financial perspective. The results revealed that the optimal levels depend on the building type (i.e., terraced, detached, semi-detached and apartment) and size/layout of the dwelling. The optima identified for some building typologies revealed to be compliant with the passive house standard, while for other building types the passive house standard was beyond the tipping point. Moreover, the optimal levels differed from an environmental and cost perspective (see Section 3.2.6).

3.2.3. Research Question 3: Weight of Insulation Materials in Total Building Life Cycle Impact

Six papers covered the weight of insulation materials within a whole building life cycle impact [12,27–31]. These show a wide range of contribution percentages, intimately related to the building type and construction technology, the insulation material used and the types of environmental indicators covered.

Blengini and Di Carlo [27] evaluated a low energy house built in Italy. The results show that the insulation materials (cork slab, polystyrene and wood wool) embodied energy represents approximately 9% of the gross energy use of the house throughout its life cycle. Mosteiro Romero et al. [29] analysed the impact of the same building typology, located however in Switzerland, and in compliance with Minergie-P standard, i.e., compliant with the Passive House Standard. The share of the insulation materials (expanded polystyrene, polyurethane and mineral wool) represents 10% of the life cycle primary energy demand of the house.

Figure 4 shows that the share of insulation in the total energy demand of a building lies around 10% in low-energy single-family houses [27,29] and in multi-family buildings, when the end-of-life phase is disregarded. The share of insulation represents around 2% of the building life cycle impact in multi-family buildings [31].

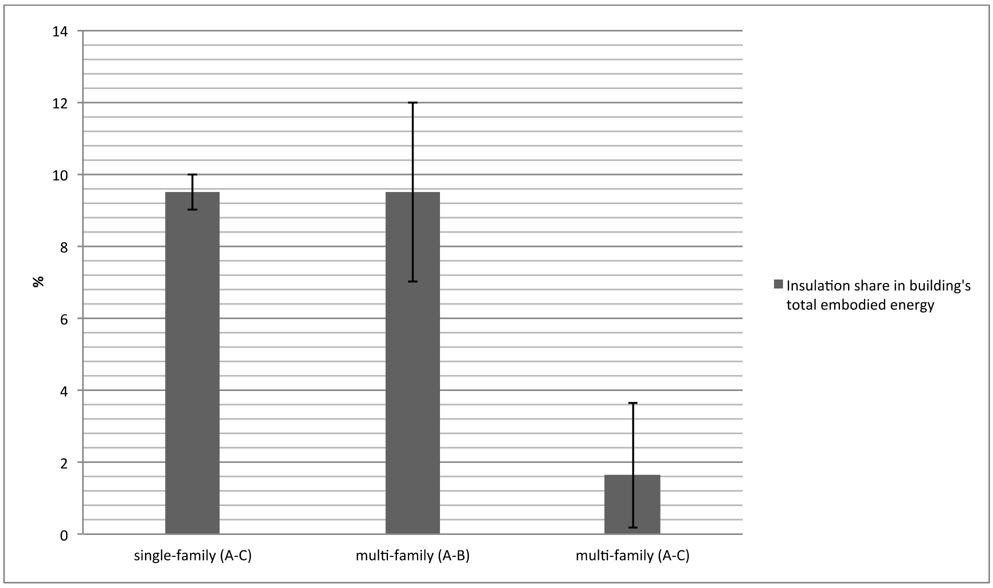

Figure 4. Share of the insulation in the building life cycle energy use considering single-family and multi-family residential buildings. The error bars are related to variation in contribution percentages. Acronyms A, B and C refer to the building's life cycle stages according to EN 15978, namely products manufacturing stage, use stage and end-of-life stage, respectively. The first column shows results range extrapolated from [27,29]. The second column shows the contribution range found by [12] considering a standard and a well-insulated building, excluding the building end-of-life phase (C). The third column indicates contribution extrapolated from [31] considering an existing building with no refurbishment, with medium refurbishment and with advanced refurbishment.

Takano et al. [30] evaluated a typical single-family house located in Finland considering renewable and non-renewable embodied energy separately, assuming a 50-year building service life. Depending on the material and its thickness, insulation contributed 11–17% of the total non-renewable primary energy associated to the whole building.

Following a different approach, Atenaert et al. 26 evaluated the impact of individual housing units (19 flats in a single house) built according to low energy standards in Belgium. Authors provided results in a single score format (i.e., aggregating results from all impact categories assessed based on weighting scores), in what they call eco-scores. The building service life considered was not made clear in the paper. Original insulation materials represented 4.79% of total eco-score for one flat's life cycle, while best alternative materials represented 0.52% of total eco-score for the flat's life cycle.

A general conclusion that arose from the analysed sample of papers is that insulation materials, even though presenting a non-negligible embodied impact in low energy and passive buildings, highly contribute to lowering the buildings primary energy use and global warming potential throughout their life cycle, when compared to standard buildings with little or no insulation (as shown by [12,27,31]). These findings are in line with the review performed by Vilches et al. [20], which states that insulation materials can reduce the overall building impact throughout its life cycle.

The review includes references to seven papers. One could then assume that overall insulation materials' embodied weight is basically offset within the operational phase of the built environment until a tipping point is reached (see RQ2).

3.2.4. Research Question 4: Weight of Renewable Energy Services in Total Building Life Cycle Impact

Seven publications have been found which explicitly discuss the weight from technical systems for renewable energy in relation to total building life cycle impacts [3,32–37]. However, a certain research gap in published papers regarding those services' share to total building loads arose in this review.

Only two of all analysed papers provided information on the actual contribution of on-site renewable systems to the building's environmental impact [33,37]. Additionally, four other papers [3,32–36] provided qualitative information considered relevant to the research question.

Passer et al. [37] concluded that specific construction products embedded within the technical building equipment are environmentally significant for the building life cycle and should therefore not be excluded from any study when specifying the cut-off criteria. In multi-family residential buildings, the contribution of technical building equipment to some environmental impact categories can be quite important. For the impact category eutrophication potential (EP), it varied between 12% and 43%, where for the acidification potential (AP) the range was from 10% to 24%. For the total primary energy demand, the renewable technical equipment share varied from 2.4% to 5.3%. The latter authors' findings are in line with the conclusions from Himpe et al. [32], who assessed the financial and external environmental costs related to typical heating and ventilation systems in newly built dwellings in Belgium. Himpe et al. [32] studied both renewable and non-renewable options for the mentioned services applied to two differently insulated variants of the same single-family dwelling, assuming a 60-year building service life. They showed that initial environmental costs of renewable heating systems were high—which points to the importance of their inclusion in environmental assessments.

The on energy and carbon-related indicators consistently point to the net-benefits of using renewable technical systems, which is not always replicated when different environmental indicators are taken into account. This was confirmed by Gustafsson et al. [35], who analysed the environmental aspects of renovation packages on typical European office buildings. They showed that the use of photovoltaic (PV) panels implied an increase in the office buildings life cycle loads in Nordic, Continental and Mediterranean climates, especially when considering the Particulate Matter formation indicator.

Regarding the importance of non-carbon-related indicators, Passer et al. [36] evaluated 45 design variations in a real single-family house project in Austria. The scenarios consisted of four main construction types (brick, concrete, wood-chip concrete and prefabricated timber wood construction) in combination with different energetic standards (low to plus energy) as well as different technical building systems (pellets, heat pump, solar heating and PV). They showed that heat pumps have a considerably high ODP due to the cooling refrigerants used. Accordingly, [29], who assessed heat and ventilation systems together, showed the significant contribution of those systems to the ODP impact category in the material placement phase. The heating system adopted was a brine-to-water heat pump, which most likely governed such a high contribution to ODP, corroborating with the findings from Passer et al. [36].

Desideri et al. [33] focused on a different building typology and performed an LCA of an Italian multi-purpose zero energy building with PV panels and a solar thermal system. Results were presented in a single score format. The impact coming from the production stage of the renewable technical systems' represents 4.2% of the building's total life cycle loads—which is similar to what Audenaert et al. [26] found for insulation materials in an apartment built according to Flemish low energy standards. Passer et al. [37] made a similar observation. They evaluated different refurbishment strategies applied to a multi-family residential building built in 1961. They concluded that the absolute impact of using PV panels is substantially greater than that of a solar thermal system. However, they highlighted that the benefit gained in terms of the operational non-renewable primary energy demand (PENR) is much higher than the amount of embodied energy invested in the use of PV compared to a solar thermal system. The authors recommended a combination of the two types of on-site renewable equipment to achieve an optimum outcome in terms of PENR and other environmental impact indicators.

To summarize, in low energy buildings, renewable technical systems seem to perform in the same way as insulation materials: high embodied impacts, albeit somewhat offset in the building use phase.

In an attempt to identify the best option between a very high insulation level versus renewable energy generation, Goggins et al. [34] assessed two different refurbishment strategies applied to an Irish single-family house to achieve a NZEB. They concluded that the very high insulation level outperforms the on-site renewables strategy in terms of embodied energy and GHG emissions (due to the high embodied impact of PV). The opposite happens in terms of operational carbon (due to the high GWP factor of the Irish electrical grid). Authors state that with the trend of decarbonizing the electricity grid, the role of PVs in reducing operational carbon will become less significant in the future. One could derive from their research that a design strategy primarily focusing on a high-performance envelope outplays a strategy focusing on renewable energy systems, both environmentally and economically.

When measuring and/or comparing insulation and technical systems' contribution to the buildings overall environmental impact, widening the scope of impact categories assessed provides a more complete environmental profile. The papers that covered non-carbon related impact categories showed that for those indicators impacts are mainly coming from renewable energy systems. As pointed out by Goggins et al. [34], there is a decarbonisation trend observed in electricity grids. In this framework it is suggested to also focus future research on toxicity and ecosystem depletion-related indicators to avoid potential burden shifting.

3.2.5. Research Question 5: Impacts Caused vs. Impacts Avoided

Three papers have been found that describe case studies in which the impacts and benefits through energy savings from retrofitting measures have been presented [3,38,39]. In two review papers [19,20] additional insights related to this research question are provided too.

Based on the five papers, it can be concluded that there is no straightforward ratio between the impacts caused by the production of insulation or of technical systems for renewable energy and their related avoided impacts. This is due to the influence of different parameters, such as climatic context, type and size of the measures, and the reference situation to which the comparison was made.

Ardene et al. [38] provide results of six European case studies. The ratio of the impacts related to the production stage versus avoided impacts for PV varies between 6.8% and 24.2%, and for solar thermal plants between 1.2% and 15.8%. The ratio of the case with the wind turbines is calculated at 4.5%. For insulation, production stage versus avoided impacts ratio is between 1.7% and 6%.

The authors concluded that the most significant benefits (energy saving and avoided GWP) are mainly related to the improvement of the thermal insulation level of the building envelope (high-efficiency windows, and thermal insulating boards). Substitution of insulation, lighting and glazing components moreover proved to be efficient solutions too. In all the case studies, renovation of HVAC plants and lighting systems provide significant energy benefits.

Asdrubali et al. [39] presented three Italian cases: a single-family detached house, a multi-family residential building and an office building. For each case, different energy optimisation scenarios (e.g., improvement of the building envelope or changing building services) were assessed and compared to the baseline scenario. Based on the results the authors concluded that in the case of the single-family home, improving envelope solutions (such as insulating materials and type and width of masonry) results in a reduction of gas consumption for heating of 17%. The environmental impact decreased with 2.8% and 13.2% for the construction phase and use stage respectively. Another conclusion is that adding thermal solar panels in the case of the multi-family residential building has a bigger effect when looking at the relative impacts/benefits during construction stage and operating phase than adding PV panels and integrating renewable energy sources (RES).

An Austrian case study of a residential home refurbishment was described by Passer et al. [37]. Various refurbishment scenarios were assessed consisting of three facade refurbishment strategies and five strategies for on-site energy generation for space heating and sanitary hot water production. The options have been evaluated for today's mix of fossil and renewable energy sources and for one future renewable energy mix. Passer et al. [37] concludes that adding on-site energy generation significantly reduces the amount of operational energy, but doubles the embodied energy. The results also show that the minimum refurbishment reduces the operational energy by more than two thirds compared to the no refurbishment scenario. The in-depth refurbishment has the highest embodied energy (123–129 MJ/m^{2}yr), but the operational energy is only 1 MJ/m^{2}yr with solar thermal and PV. When increasing the PV area, the total PENR becomes negative due to the benefits provided by the delivered energy produced on site. The benefit gained in terms of the operational non-renewable primary energy is much greater than the amount of embodied energy invested in the use of PV area than in the solar thermal area.

In addition to the above-mentioned papers, complementary information can be found in review papers by Vilches et al. [20] and Cabeza et al. [19]. Vilches et al. [20] described the results of a retrofit case study dating from 2013 of an existing Mediterranean single-family house assessed by Beccali et al. [40]. In that case, the most significant contribution to the primary energy demand of the retrofit actions was the envelope thermal insulation, which decreased the primary energy demand by approximately 80%, while the PV plant decreased this energy demand by approximately 18%. It is also reported that the retrofit actions decreased the environmental impacts by approximately 30–35% at the end of the life cycle. In the same review paper, the study by Assigo De Larriva et al. [41] regarding a multi-family house refurbishment in Spain was also described. One of the main conclusions of this study was that for buildings located in temperate climates, more savings are achieved by designing ventilation systems than by implementing insulation measures [20]. A similar conclusion was drawn in the review paper by Cabeza et al. [19] in which an Australian single-family residency case study by Fay et al. [42] was discussed. It was found that the addition of higher levels of insulation in Australia paid back its initial embodied energy in life-cycle energy terms in around 12 years. However, the saving represented less than 6% of the total embodied energy and operational energy of the building over a 100-year life cycle. This indicates that there may be other strategies worth pursuing before adding more insulation.

3.2.6. Research Question 6: Comparing LCC and LCA Findings

The majority of the papers reviewed through the systematic literature study focused on the evaluation of the environmental impacts. A limited number also deals with the estimation/assessment of investment cost and/or LCC [23–26,34–36,43–45]. These findings were confirmed by two review papers on the topic [19,20]. Both review papers conclude that there is a general lack of LCC studies.

The studies that included a cost assessment do cover various climatic contexts, i.e., warm climate [26,45], moderate climate [23,24,35,36,43,44] and cold climate [25] or even several climatic contexts were studied in the same study [35]. The method most often used in the papers is the determination of the annual net cost savings due to reduced spatial heating when buildings are better insulated compared to business-as-usual or when existing buildings are being retrofitted. All studies focus on residential buildings, except for the study of Gustafsson et al. [35] who investigated energy renovation packages for European office buildings.

The main conclusion from the systematic literature review is that a limited number of studies are found on life cycle cost and even less comparing these with environmental LCA studies. The studies reviewed assessing both life cycle environmental impacts (based on LCA) and life cycle costs (based on LCC) highlight that decisions based on these criteria often differ. From a financial perspective, lower insulation levels of building elements and energy performance levels of buildings have been identified as tipping points compared to those identified from an environmental perspective.

4. Discussion and Conclusions

This paper is based on a thorough review of published literature on LCA and LCC of buildings. In general, building case studies are known to be difficult to compare due to the large variety of case specific properties and parameters such as building typologies, energy performance levels, climatic context, methodological choices in LCA (e.g., acc. to EN15804/EN15978, ISO14040/ISO14044, PEF), and the comprehensiveness of the life cycle inventory. As expected, differences in methodological approaches hindered collective conclusions to clearly answer the research questions. Nonetheless, this research points out scientific gaps, diverse methodological choices, and current environmental status of European buildings.

Regarding the specific studies addressing the different research questions, we could notice that RQ1, RQ3 and RQ4 could be addressed more easily, while the topics in questions RQ2, RQ5 and RQ6 were less frequently dealt with in literature.

Studies addressing the weight of individual life cycle stages (RQ1) show a large variation in the weight of each life cycle stage. Therefore, no clear common contribution of individual stages could be deduced. Nevertheless, the literature review showed that the operational energy use still dominates the life cycle environmental impact of conventional (existing) buildings, representing up to 89% of the overall impact. However, a changing trend is noticed for more recent low energy buildings. For low energy buildings, the other life cycle stages become more important, representing up to 65% of the building life cycle contribution.

Tipping points for different measures (RQ2) vary widely. These showed to be influenced amongst others by the climatic context, the building typology and building layout (compactness), the application (e.g., roof insulation versus floor insulation), the type of insulation material, the heating system and the environmental impact categories considered. It is important to remark that all studies in our literature review focus on residential buildings, hence the influence of the building function on tipping points has not been addressed. As the literature review revealed that tipping points at building level depend on the building typology and layout, it is recommended to thoroughly study the building design in the design stage to efficiently fulfil the NZEB requirements and to avoid trespassing tipping points. With other words, achieving NZEB requirements in a not-well considered building design could lead to a waste of natural resources and money.

The contribution of insulation materials to the life cycle impact of the building shows a wide variation (RQ3). The contribution is closely related to the building type, the insulation material used, and the types of environmental indicators covered. The studies prove that the embodied impact of insulation materials is not negligible, but they still have a low share in comparison with other building materials with the benefit of providing environmental gains due to their contribution to increased energy efficiency of a building. A critical remark which needs to be made here is the importance of the insulation materials application method. The current trend of installing adhesive insulation materials potentially influences the end-of-life stage of the materials the insulation is attached to (i.e., reducing their recycling potential). The environmental impact of insulation materials might hence be larger than simply the impact of the material itself.

Similarly, also for the weight of renewable energy services, a wide variety was shown in the papers (RQ4). Considerations about the use of renewable technical systems and insulation materials are similar in low energy buildings: high embodied impacts, albeit somewhat offset in the building use phase. From one of the papers, one could derive that a design strategy primarily focused on a high-performance envelope outperforms a strategy focused on renewable energy systems, both environmentally and economically. Moreover, when measuring and/or comparing insulation and technical systems contribution to the overall impact of the built environment, widening the scope of impact categories assessed provides a "level playing field", meaning adding non-carbon related environmental impact categories like toxicity and land use. The literature review revealed that especially for the technical systems it is important to comprehensively assess all impact categories to avoid burden shifting, complying with recent recommendations by draft EN 15804 + A2 and PEF.

For the impacts caused by insulation materials or renewable energy services, as well as the related avoided impacts (RQ5), no explicit ratios could be extrapolated from the literature investigated. This is again due to the influence of multiple parameters, such as climatic context, type and extent of the measures, and the reference situation these measures are compared to.

Only a limited number of studies provided insight regarding decisions made based on LCC and even less compared these with environmental LCA studies (RQ6). The studies assessing both the life cycle environmental impact (based on LCA) and life cycle cost (based on LCC) highlight that decisions based on these criteria often differ. For example, the financial tipping points of building elements' insulation extent and building's energy performance level were lower (i.e., less insulation is already good enough) than tipping points from an environmental perspective (i.e., still more insulation was better). The main reason for the differences between environmental and economic impact is the (high) labour cost in the latter which is not reflected in environmental impacts. From this learning, it could be concluded that a tax shift from labour to environmental impacts would allow to align financial and environmental decisions more. Such alignment is seen as important in the overall aim to move towards a more sustainable built environment as current decision taking is often driven by financial considerations.

Finally, two important research gaps arose from this review, namely comparability and reliability, which have influenced the outcome of this research in such a way that it was not possible to derive a clear range of ratios, tipping points or contribution percentages based on the various papers reviewed. As stated earlier, comparability is also affected by differences in LCA modelling owing to the assumptions and methodological choices made as well as the level of detail and completeness of the life cycle inventory [46]. The latter is often constrained by the absence of qualified information on certain building products. Furthermore, a lack of a harmonized and generally applied assessment methodology to measure embodied environmental impacts (beyond embodied energy and carbon) could be identified. This conclusion is also confirmed by the review studies done by other researchers [19,20]. Transparency and clear documentation are indispensable to allow for reproducibility and should always be solicited when writing and/or reviewing scientific papers and reports. Building-related initiatives such as the EeB Guide [47] PEF4 buildings [16], LEVEL(s) [9], or IEA EBC Annex 72 [48] also support this recommendation.

The literature reviews moreover revealed that it is important to investigate building materials and technical systems from a full life cycle perspective. Some solutions indeed may result in an environmental gain during use stage but could at the same time have a substantial environmental impact during the product stage. For instance, the embodied impact of renewable energy systems is currently neglected in the majority of decision making processes, largely due to a lack of information and numerous variations in systems available. Including this aspect in decision making is crucial as such technical systems can have major embodied impacts which may influence decisions made under a life cycle perspective.

Our research confirmed the significance of a full life cycle calculation approach when assessing energy efficient buildings in order to avoid unintentional burden-shifting between life cycle stages, i.e., between embodied and operational impacts.

The net zero rationale of focusing first on reducing the energy demand is not necessarily confirmed in published literature. Although its alternative might be counterintuitive, the investigated publications assess both issues separately or compare "energy saving" and "energy production" approaches.

In conclusion, the results of this study highlight the importance of broadening the set of impact categories assessed. The current focus of environmental assessment being restricted to carbon emissions and energy consumption might misguide decisions, especially as we move towards a global decarbonisation of electricity grids and circular economy in industrial practice. Recent proposals of using LCA methods and weighting sets based on the carrying capacity of the earth's ecosystem [49,50], could prove very valuable in interpreting and classifying results of building LCAs. This is especially important to guide buildings' operation and the construction sector to unerringly reduce consumption of resources and energy in order to help fulfil targets set out in e.g., the UNs sustainable development goals (SDG).

For further information on all studies we reviewed a full list is provided in Supporting Information.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-5309/8/8/105/s1, and include additional details in sections S1 Methodology, S2 Results, and S3 Additional studies reviewed. Supporting information include the following figures and tables. Figure S1: Number and types of papers reviewed; Figure S2: Number of countries covered by the case studies; Figure S3: Types of energy performance levels covered by the case studies; Figure S4: Division of new built – renovation case studies; Figure S5: Types of system boundaries covered by the case studies. Table S1: Life cycle impact assessment of three stone wool insulation thicknesses: 40, 80 and 120 mm (functional unit of 1 m^2 of living area over a period of 50 years). (Rodrigues and Freire, 2014, p. 213); Table S2: Illustrative examples of the weight of each stage of conventional cases; Table S3: Illustrative example of the weight of each stage of a NZEB case; Table S4: Illustrative examples of the weight of each stage of passive house cases; Table S5: Illustrative examples of the weight of each stage of energy positive cases; Table S6: Illustrative examples of the weight of each stage of low energy cases.

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