sustainability

Article

Primary Energy and Carbon Impacts of Structural Frames with Equivalent Design Criteria: Influence of Different Materials and Levels of Prefabrication

Chiara Piccardo [1,*], Camille Steinik [1], Simone Caffè [2], Alessio Argentoni [3] and Chiara Calderini [2,*]

[1] Department of Civil Engineering, KU Leuven, Campus Ghent, Gebroeders de Smetstraat 1, 9000 Ghent, Belgium
[2] Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Via Montallegro 1, 16145 Genoa, Italy
[3] Tecnostrutture, Via Meucci, 26 I, 30020 Noventa di Piave, Italy
* Correspondence: chiara.piccardo@kuleuven.be (C.P.); chiara.calderini@unige.it (C.C.)

Abstract: This study aims to analyze the life-cycle primary energy and climate impacts of structural frames, paying particular attention to the design and prefabrication of different structural materials. The study considers an existing single-story office building with a composite concrete–steel structure and compares it with two functionally equivalent structures, i.e., a conventional reinforced concrete structure and a conventional steel structure. The existing building is located in San Felice sul Panaro, Italy. This study integrates dynamic structural analysis and life-cycle assessment (LCA). The study finds that the use of different materials can reduce the life-cycle primary energy use and $CO_{2\text{-eq}}$ emissions by up to 12%. Furthermore, the benefits derived from the recovery and recycling of materials can reduce the primary energy use and $CO_{2\text{-eq}}$ emissions by up to 47% and 36%, respectively. The prefabrication of structural elements can also reduce the primary energy use and $CO_{2\text{-eq}}$ emissions in the construction stage. A sensitivity analysis considers changes in the electricity supply system and shows that the primary energy and $CO_{2\text{-eq}}$ emissions due to prefabrication decrease when assuming marginal electricity based on renewable energies. This analysis supports the development of sustainable structural design to meet the standards concerning the whole-life-cycle carbon emissions of buildings.

Keywords: building structures; structural materials; structural design; prefabrication; LCA

Citation: Piccardo, C.; Steinik, C.; Caffè, S.; Argentoni, A.; Calderini, C. Primary Energy and Carbon Impacts of Structural Frames with Equivalent Design Criteria: Influence of Different Materials and Levels of Prefabrication. *Sustainability* **2024**, *16*, 4209. https://doi.org/10.3390/su16104209

Academic Editor: Antonio Caggiano

Received: 1 April 2024
Revised: 10 May 2024
Accepted: 15 May 2024
Published: 17 May 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In recent years, the building sector has progressively broadened its focus on energy use and greenhouse gas emissions from the use stage to the production, construction and end-of-life stages of buildings. As 82% of the greenhouse gas emissions generated by buildings still come from the use phase [1], in Europe, energy efficiency regulations developed in accordance with the Energy Performance Building Directive and its subsequent amendments [2] are projected to reduce such emissions by about 60% by 2030. In addition, a growing body of scientific literature has shown that, as buildings become more energy-efficient, the energy consumption associated with building materials is expected to increase [3,4]. Consequently, the greenhouse gas emissions attributed to building materials could constitute up to 90% of a building's total greenhouse gas emissions [5]. Furthermore, several European countries, including Sweden, Denmark, France, Finland, and the Netherlands, have recently implemented minimum carbon emission requirements, not only for the operational stage but also for the production, construction, and, in certain cases, end-of-life stages of new buildings [6].

Among all the building elements, structural frames typically have the most significant environmental impact throughout the stages of the production, construction, and end-of-life of buildings [7]. Several building materials can be used for structures, with concrete being one of the most widely used [7]. Greater attention concerning the relationship between the structural and environmental performance of buildings can suggest alternative design strategies, as well as a more efficient use (and post-use) of structural materials [8].

In the last two decades, a number of studies have investigated the environmental impact of structural frames through life-cycle assessment [9]. Two main groups of studies can be recognized: studies with a focus on structural materials and studies with a focus on structural design, including prefabrication. Both groups show a few research gaps.

In the first group, studies have investigated the effect of using different structural materials on the environmental impact of buildings in various life-cycle stages. Adalberth [10] and Junnila et al. [11] find that structural materials are the materials with the highest energy use in the production stage, accounting for between 10% and 15% of the life-cycle energy use of the buildings. Adalberth [3] and Jönsson et al. [12] also find that the construction and demolition stages have a marginal impact. Hegeir et al. [13] compare the carbon emissions due to the production of equivalent structural frames made of concrete, steel and timber, respectively, finding significantly different results, with the steel frame having the highest carbon emissions, followed by the concrete and timber frames. Alshamrani et al. [14] compare several structural frames, showing that concrete frames have lower carbon emissions than steel frames in the production stage. Small variations can be found in the impact of the construction stage depending on the structural materials. Cole [15] analyses the construction stage of concrete and steel structures, including the transportation of materials, equipment, workers, and on-site construction activities, and finds that concrete structures have about 20% higher energy use and 15% higher carbon emissions compared to steel structures. Furthermore, Guggemos and Horvath [16] estimate that the construction energy use accounts for about 10% of the life-cycle energy use for the concrete structure, and only 4% for the steel structure. This result is consistent with the study by Junnila and Horvath [11] and can be attributed to the formwork, higher material mass and longer construction process of concrete structures. However, it is observed that the number of studies considering the environmental impacts of structural frames in the construction stage is still limited. This is identified as a gap. Further research should be undertaken to fill this gap and to achieve a more comprehensive overview.

In the second group, a few studies have investigated the effect of using different structural design approaches on the environmental impact of buildings in various life-cycle stages. A recent study by Seyedabadi et al. [17] compares the carbon emissions of two equivalent concrete and steel structures modeled according to different structural design codes. They find that the European code leads to the highest carbon emissions for the steel structures and average carbon emissions for concrete structures, and it results in a minor difference between the steel and concrete structures. Fang et al. [18] confirm that structural design approaches can influence the carbon emissions of structural frames, in some cases leading to their significant reduction. Therefore, to ensure comparability among structural frames made of different materials, the same structural design approach should be used.

Although the selection of structural materials can contribute to the reduction of the environmental impacts of structural frames, alternative design strategies can be additionally considered. A few studies have recently investigated the environmental impacts of prefabrication, with particular attention paid to steel structures, followed by wood and concrete structures [19]. The analysis of concrete structures, respectively, prefabricated and constructed in situ, shows that prefabrication can reduce the carbon emissions in the production and construction stages by between 8% [19] and 18% [20] due to decreased material use and waste generation. The analyzed concrete structures are based on assumptions about the potential prefabrication of post, beam and slab elements. These results are consistent with a study by Tian and Spatari [21], which estimates a reduction in carbon emissions in the production and construction stages of 11% when comparing a conventional concrete structure with a similar prefabricated concrete structure. Jayawardana et al. [19] show a reduction in carbon emissions of 8% when using prefabricated concrete elements instead of conventional ones, though highlighting the need to limit the haul distance of prefabricated elements in order to ensure the reduction of carbon emissions. In the case where the prefabricated structure adopts structural materials with a lower environmental impact, such as wood, prefabrication can reduce the environmental impacts by up to 65% compared to a conventional structure [22]. Among the four aforementioned studies [19–22], all consider the production stage, three studies also include the construction stage, and only one study includes the end-of-life stage with the possible loads and benefits from recycling. Furthermore, in only one study are data from the construction stage, including prefabrication, collected on site and thoroughly described. Therefore, there is a need for a more comprehensive life-cycle analysis of prefabricated structures.

Finally, some studies in the first and second groups also highlight the challenges in comparing results from the literature due to the use of different methodological approaches or the absence of information regarding methodological choices in life-cycle assessments. For example, studies analyzing the impact of structural frames in the end-of-life stage [23,24] suggest that methodological assumptions concerning the disposal and recycling processes of structural materials can significantly influence the calculation of energy use and carbon emissions. Similarly, Moncaster et al. [25] emphasize the importance of stating methodological assumptions, such as temporal boundaries and functional units, when conducting a life-cycle assessment of structural frames. Marrone et al. [26] also observe that several studies not only omit critical information on their methodological assumptions but also compare structural frames with differing features (e.g., different building layouts), which might reduce the comparability. Therefore, information on the methodology is crucial for understanding the environmental impacts related to the use of different structural materials and designs in buildings.

All the aforementioned studies show a causal link between the choice of structural materials or designs and the energy and carbon impacts of structural frames. Additional studies have explored the influence of alternative design strategies to reduce energy use and carbon emissions, such as the recirculation of structural materials and the prefabrication of structural elements. However, such design strategies are often analyzed separately. Furthermore, the prefabrication of structural elements is often based on design assumptions rather than real design projects. Finally, the comparisons between the different types of structural solutions are usually not conducted for the same structural performance.

This study proposes a comprehensive analysis of the primary energy and CO_2 equivalent ($CO_{2\text{-eq}}$) emission impacts of conventional and prefabricated structures, exploring the influence of prefabrication and recirculation of structural elements based on a real structural design and the same structural performance. To this end, this study will use a case-study building located in San Felice sul Panaro, Italy.

Ultimately, this study contributes to understanding the energy and climate implications of different structural materials and structural designs, including prefabrication, in relation to new standards concerning the whole-life-cycle carbon emissions of buildings.

2. Aim and Objectives

The present study aims to analyze the life-cycle primary energy use and $CO_{2\text{-eq}}$ emissions of three functionally equivalent frame structures using different structural materials and different levels of prefabrication while maintaining the same structural performance. The three frame structures consist of a composite concrete–steel structure, which is a real structure, and also a conventional reinforced concrete structure and a conventional steel structure, which have been modeled based on the real structure. The effects of prefabrication on the life-cycle primary energy use and $CO_{2\text{-eq}}$ emissions are observed. As prefabrication largely depends on electrical equipment, the effects of changes to the electricity supply systems are also considered.

This study thus addresses the gaps that have previously been mentioned. First, it proposes a comprehensive life-cycle assessment encompassing all the life-cycle stages, including the construction stage, which is often neglected in the comparison between different structural materials. Second, this study provides a reliable comparison between different structural frames by reproducing the same building layout, modeling the structural frames to exhibit the same structural performance, and designing them to meet the same fire-resistance performance.

3. Methodology

Our methodological approach consists of the following steps: (i) identifying a real case-study building; (ii) modeling functionally equivalent frame structures using different materials; (iii) analyzing the primary energy use and $CO_{2\text{-eq}}$ emissions of the alternative frame structures; and (iv) analyzing the sensitivity of the calculated primary energy use and $CO_{2\text{-eq}}$ emissions to the electricity supply system. These steps are described below.

3.1. Identification of the Case-Study Building

A case-study building (Figure 1) is used to model the equivalent frame structures analyzed and compared in this study. The case-study building is a single-story office building, located in San Felice sul Panaro (latitude 44.84, longitude 11.14), a municipality in the Emilia Romagna region, Italy. The building was built in 2013 to host the new municipality offices, which moved to the present building after the earthquake in 2012. The floor area is 1250 m^2, with a floor size of 50.5 m × 24.6 m.

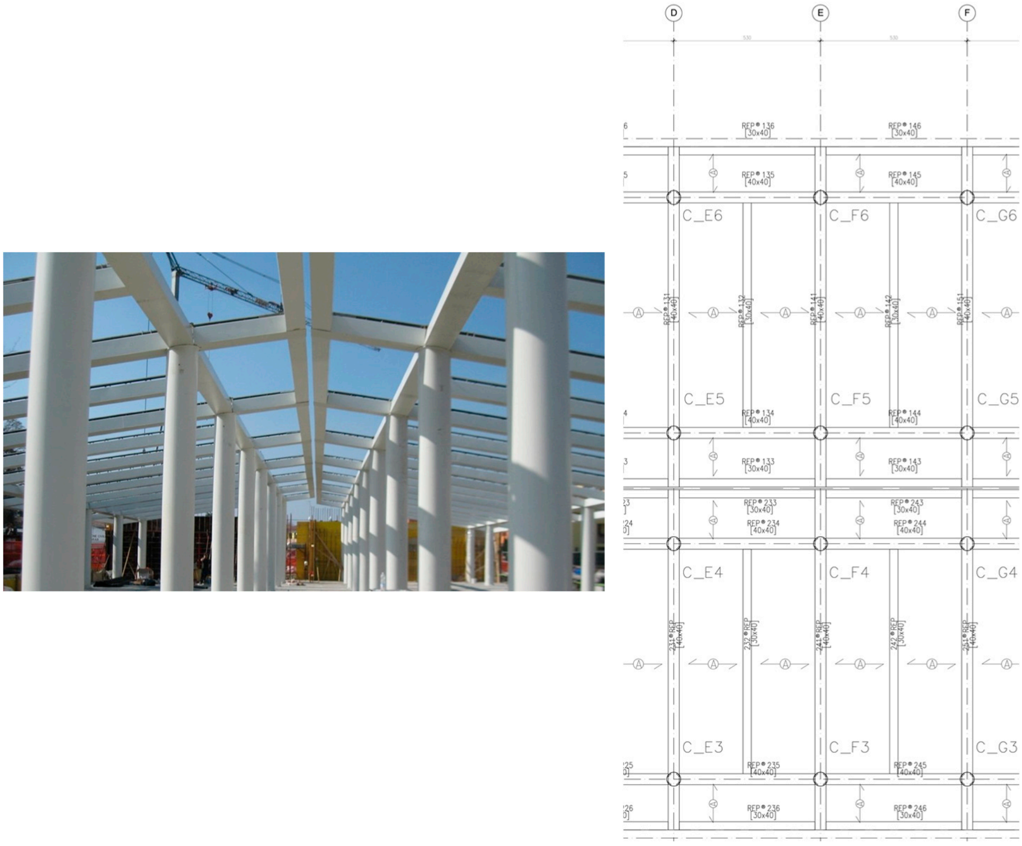

Figure 1. The case-study building: the structure during the construction (**left**) and the design project (plan and reference section, (**right**)).

The load-bearing structure consists of a composite steel–concrete structure. This structure consists of steel tubular columns and U-shaped beams serving as a permanent formwork filled with cast in situ reinforced concrete. The tubular columns have a diameter of 508 mm and thickness of about 6 mm. The U-shaped beams have a cross-section measuring between 300 and 400 mm in width and 300 and 400 mm in height and a span of up to 12 m. The roof floor consists of a reinforced concrete slab over a corrugated steel sheet, with a maximum span of 2.65 m and an overall thickness of 55 mm. The composite steel–concrete structure is designed as a self-supporting structure that does not need any temporary support during the assembly stage. The structure complies with the fire-resistance class of R60 without any additional fire treatment, according to the Eurocode 4 [27]. The composite steel–concrete structure is calculated to have a service life of 50 years and a design reference period for the seismic actions of 100 years.

3.2. Modeling of the Structural Frames

3.2.1. Design Criteria

Two conventional frame structures made of steel and reinforced concrete, respectively, are designed to have equivalent structural performance, fire resistance and architectural adaptability (i.e., internal layout and external envelope of the building) to the original frame structure of the case-study building.

The design of the two conventional frame structures follows the most common current design practice in Italy. All the structures are designed according to the Italian regulations [28]. The following structural criteria are assumed:

- category of occupancy IV [28];
- structure designed to withstand lifesaving limit state (SLV) design earthquake while maintaining substantially elastic behavior, to limit displacements and consequent damage to within acceptable levels even for high-intensity earthquakes;
- design: dynamic modal analysis with response spectrum;
- behavior factor q = 1.5—no ductility.

3.2.2. Conventional Reinforced-Concrete Structure

The single-story building features a framed structure in both the main directions X and Y (Figure 2). In the XZ plane (transversal), the frame is made up of four reinforced concrete columns with respective cross-sections of 70 × 50 cm and 50 × 50 cm, connected by beams of varying height depending on the free span to be covered. In the longitudinal direction, the building consists of nine frames side by side, each with a span of light equal to 5.30 m, except for the projecting parts that constitute its perimeter. The structure thus conceived balances the vertical actions (due to its own weight, permanent loads, and operational loads) through the mutual interaction between the transversal and longitudinal beams and pillars. Conversely, from the point of view of dynamic seismic actions, the building does not present that structural redundancy and exhibits the degree of hyperstatics necessary for it to be ascribed to typically ‘framed’ behavior. Given this, the structure has been analyzed with reference to the usual behavior of ‘inverted pendulum’ structures, for which a factor q = 1.50 is defined.

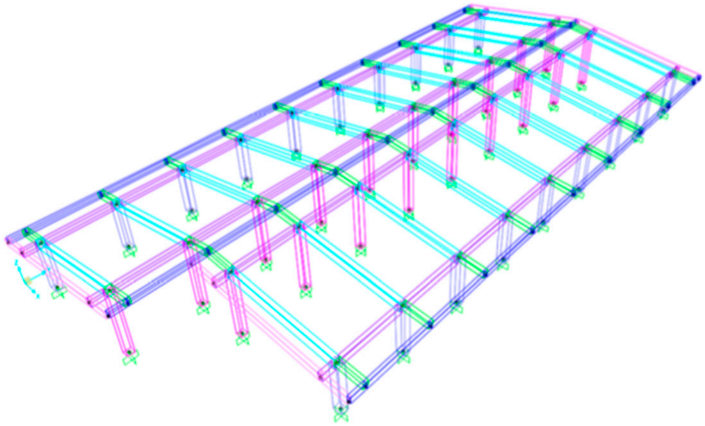

Figure 2. The model of the conventional reinforced-concrete structure.

3.2.3. Conventional Steel Structure

The single-story building features a framed structure in the transversal direction (i.e., in the XZ plane) and a 'pendulum—vertically braced' structure in the longitudinal direction (Figure 3). In the plane of the frame, the structure consists of four HE300A uprights, anchored at the base with a fixed joint around the axis of greater inertia, and hinged in the plane of lesser inertia. The uprights support two IPE400 beams and are connected to them through connections capable of mutually transmitting bending actions. The ridge joint between the IPE400 elements is made with a 'nominally hinged' connection to reduce the local stresses due to the possible transmission of the bending moment. In the longitudinal direction, the structure exhibits pendular behavior, stabilized by a system of vertical bracing arranged over four spans, located at the two ends of the building. The horizontal forces due to wind and earthquake are transmitted to the vertical braces through a system of ridge bracing designed to form a kind of 'rigid' plane capable of redistributing the actions uniformly over the various members.

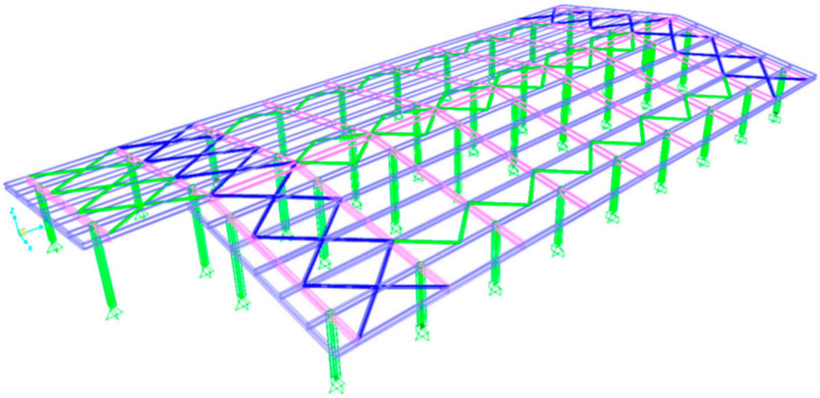

Figure 3. The model of the conventional steel structure.

Differently from the other structures, this structure would require fire protection to meet the fire standard. Therefore, the covering of all the visible steel elements in the building with a 3 cm layer of gypsum plasterboard has been assumed. The visible parts have been deduced from the current layout of the case-study building.

3.3. Life-Cycle Assessment

A life-cycle assessment (LCA) is performed to calculate the primary energy use and $CO_{2\text{-eq}}$ emissions of the three frame structures according to the standards EN 15978 [29] and EN 15804 [30].

Each frame structure is assumed to be assembled at the current time and to have a service life of 50 years. The LCA considers the entire frame structure as a functional unit, encompassing auxiliary materials needed for construction operations as well as other materials required to fulfil equivalent functions (e.g., protective materials ensuring the structural elements meet the minimum fire-resistance standards).

The following life-cycle stages of the frame structures are considered: production (modules A1–A3); construction (modules A4–A5); use, limited to maintenance (module B2); and end-of-life (modules C1–C3), including the potential benefits and loads from recovery and recycling (module D). The operational energy use for heating, cooling and ventilation of the case-study building is excluded, as it is not relevant to the present study. The primary energy and carbon benefits resulting from the recovery and recycling of materials after the end-of-life stage are considered by extending the system boundary, as recommended by the standard EN 15978 [29].

The impact assessment calculates the life-cycle primary energy use and $CO_{2\text{-eq}}$ emissions of the three structural frames, which are described through the indicators Cumulative Energy Demand (CED), expressed in MWh, and Global Warming Potential (GWP), expressed in tons $CO_{2\text{-eq}}$, respectively. The CED is the overall energy extracted from nature to produce products, excluding the energy recoverable from wastes [31]. Therefore, it covers both direct and indirect primary energy use, including electricity and fuels for the production of energy and materials used throughout the life cycle of the frame structures. The CED is calculated through the software SimaPro v. 9.1 [32] based on the Ecoinvent database v. 3.6 [33]. The system model used is an Allocation, cut-off by classification, system. The GWP is the potential contribution of a substance to the greenhouse effect. The GWP is calculated based on the emission factors for energy production [34], including fossil and biogenic carbon sources.

The life-cycle inventory, including the material inventory of the three structural frames, is thoroughly described in the following sub-sections.

3.3.1. Material Inventory

The material quantities of the composite steel–concrete structure are calculated based on the construction drawings of the original frame structure, while the material quantities of the conventional concrete and steel structures are based on the construction drawings of the modeled frame structures.

The finishing materials are considered. Specifically, in the conventional concrete structure, a 3 cm layer of gypsum plasterboard has been considered for fire protection. Plaster and paint, when appropriate and useful for fire protection, have been considered as a finishing layer for the structural frames.

Auxiliary materials for construction operations (i.e., formworks for concreting, temporary supporting structures) are considered and their primary energy use and carbon impacts are allocated based on the number of uses derived from commercial data: 1 single use for polyethylene formwork; 20 uses for timber formwork; 150 uses for steel supporting structure (Table 1). Polyethylene formworks are used in both the composite steel–concrete structure and conventional steel structure to seal potential gaps in the prefabricated structure, such as the edges of corrugated steel sheets, before pouring concrete for final casting on site. Furthermore, in the conventional concrete structure, polyethylene elements are integrated in the prefabricated 'predalles' slabs used in the roof with the function of reducing the weight of the roof floor.

Table 1. Auxiliary materials and number of uses per frame structure.

Frame Structure	Auxiliary Material	Number of Uses
Conventional concrete structure	Timber formwork	20
	Steel supporting structure	150
Conventional steel structure	Polyethylene foam	1
Composite steel–concrete structure	Polyethylene foam	1
Conventional concrete structure	Timber formwork	20

The material quantities take into account the wastage on the construction site, increasing the weight of materials through the application of the following percentage values from Blengini [24]: 7% for cast-in-place concrete, steel and reinforcing steel; 10% for gypsum board, mortar and plaster; and 7% for wood and paint. Materials used in the prefabricated elements are assumed to result in zero waste. The percentage values for the structural materials were previously compared with the literature data [35–37]. Consistent data were found for steel and reinforcing steel, whereas significant variations, up to 90% of the assumed value, were found for cast in situ concrete.

3.3.2. Production Stage

The production stage covers all the operations needed for the extraction of raw materials (module A1), the transportation to and between the manufacturing sites (module A2) and the manufacturing of building products (module A3).

Process data for each product are based from the Ecoinvent database [33], where elementary flows along the materials' supply chain are aggregated based on secondary data. Process data refers to the European (RER) production system, if possible, or to European countries. The allocated elementary flows from the manufacturing of infrastructure are included, even though they are supposed to be marginal.

3.3.3. Construction Stage

The construction stage covers the transport of building materials between the manufacturing and construction sites, including intermediate processing and distribution (module A4), as well as all construction operations for the frame structures (module A5).

The transport primary energy use and $CO_{2\text{-eq}}$ emissions are calculated based on the following assumptions concerning the haul distances and means of transport. For materials used in the composite steel–concrete structure, the haul distance values are calculated based on the shipping documents provided by the construction company, complying with the Italian regulation on shipping documents [38] and the standard EN 10204 [39]. Since the manufacturing sites are mainly located in the European area, typical data for transportation in Europe are adopted, assuming road transportation occurring by a diesel-fueled truck of 26 tons with a capacity of 50% with consuming 1.3 MJ/t-km and emitting 82 $gCO_{2\text{-eq}}$/t-km based on the Network for Transport Measures' database [40]. The values of the energy consumption and $CO_{2\text{-eq}}$ emissions are given well-to-wheel (wtw) and include the entire energy process, from the production of the primary fuel up to the combustion of the fuel in the vehicle [40]. The transport of the concrete mix is assumed to occur by a mixer truck of 15 m^3 consuming 45 L/100 km, based on information from the construction company. The return trip of the empty truck is neglected. The transport primary energy use and $CO_{2\text{-eq}}$ emissions of the conventional steel and concrete structures are calculated by multiplying the weight of each material by the specific transport primary energy use (kWh/kg) and $CO_{2\text{-eq}}$ emissions ($kgCO_{2\text{-eq}}$/kg) derived from the same materials as the composite steel–concrete structure. For other building materials used in the conventional steel and concrete structures (i.e., gypsum board, mortar, timber formwork and steel support posts), the average distances between the manufacturing and construction sites are calculated based on the current production system.

The construction of frame structure encompasses both off-site and on-site construction activities. The off-site construction activities specifically concern the composite steel–concrete and the conventional steel structures and consist of the prefabrication of steel connections, as well as the pre-assembly of the steel elements in columns and beams. These activities take place in the factory of the construction company and mainly require electricity. The off-site final energy use is estimated to be 0.05 kWh/kg, according to a communication from the construction company. The on-site construction activities include all the works needed to assemble the frame structure on the building site, excluding earthworks and the construction of the basement. The operation of equipment for workers (e.g., lighting and heating systems) is also excluded. These activities concern all three structures and entail the use of construction equipment, usually consuming electricity or diesel. Activities performed through handheld tools are excluded. The on-site final energy use is calculated based on the type and usage time of on-site equipment. The usage time of equipment is taken from the construction daily reports of the composite steel–concrete structure or, alternatively, from Grosso [41], estimating the average time duration of construction activities by Italian contractors. The technical characteristics of the equipment are based on the communication from the construction company. The construction $CO_{2\text{-eq}}$ emissions distinguish between electrical and diesel-fueled equipment.

3.3.4. Maintenance Stage

The use stage only covers the maintenance of worn-out materials, as required to maintain the functional and technical performance of the frame structures throughout their life cycle. Specifically, this stage includes the production, transport and construction of the new materials needed for the maintenance. The inventory of materials follows the method already described in Section 3.3.1, while the inventory of processes in the production and construction stages follows the methods described in Sections 3.3.2 and 3.3.3. The maintenance activities only concern non-structural materials used for fire protection and finishing, as the structural materials are assumed to have the same service life as the case-study building.

The numbers of maintenance cycles of the building materials are calculated according to the formula from EN 15978 [29], dividing the service life of the case-study building by the standard service lives of the materials, rounded up to the higher integer value. The standard service lives of materials are based on maintenance data for the Italian building stock, reported by Molinari [42,43] (Table 2). The maintenance primary energy use and $CO_{2\text{-eq}}$ emissions are calculated by multiplying the primary energy use and $CO_{2\text{-eq}}$ emissions to produce, transport and construct each building material by the estimated number of maintenance cycles.

Table 2. Standard service lives of non-structural materials for the Italian building stock by level of exposure (N = normal; E = exposed).

Material	Service Life [years]	Exposure Level [N/E]	Reference
Gypsum board	75	N	[43]
	40	E	[43]
Mortar	70	N	Average value from [42]
	35	E	Average value from [42]
Varnish	7	N	[43]
	2	E	[43]

3.3.5. End-of-Life Stage and Potential Benefits from Recovery and Recycling

The end-of-life stage encompasses the demolition of the frame structure (module C1), as well as the transport (module C2) and processing (module C3) of construction and demolition waste (CDW). Landfilling is neglected.

Demolition and Sorting of CDW

The primary energy use and $CO_{2\text{-eq}}$ emissions from the demolition and sorting of CDW are calculated based on Ecoinvent data [33]. Based on standard practices, it is assumed that both the composite concrete–steel and conventional concrete frame structures are demolished and the mixed waste is sorted off-site, while the conventional steel structure is disassembled, with the exception of the column base plates and the roof slabs, which are demolished and sorted off-site as mixed waste. The CO_2 absorption due to the carbonation of concrete during the demolition and sorting stage is estimated based on the calculation approach reported by Dodoo et al. [44]. To consider the exposure level of the concrete surfaces, the corrective factors from Pade and Guimaraes [45] are applied. An extended time of 100 years is considered to estimate the CO_2 absorption from concrete, based on EN 15978 [29].

Transportation of CDW

CDWs are transported from the building site to the processing plant or final disposal site. The haul distances are calculated based on data from the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna [46], which studied the waste chain in the Emilia Romagna region, where the case-study building is located. Processing plants not listed in [46] (i.e., processing plant for concrete rubbles and gypsum board) are identified based on the current waste management system (Table 3).

Table 3. Haul distances by CDW category.

CDW	Waste Destination	Haul Distance [km]
Concrete rubble	Backfilling	65
Gypsum board	Recycling of gypsum board	330
Steel scarp	Recycling of metal scraps	225
Combustible waste	Incineration	30
Other	Landfilling	30

Benefits from Recovery and Recycling of CDW

The system boundary is extended to include the primary energy and $CO_{2\text{-eq}}$ benefits from energy recovery, backfilling and recycling of CDW, which are assumed to be equal to the production primary energy use and $CO_{2\text{-eq}}$ emissions of the substituted primary materials and fossil fuels minus the primary energy use and $CO_{2\text{-eq}}$ emissions due to the waste processing, respectively. Process data for the waste processing of the substituted primary materials are based on Ecoinvent data [33].

The CDW destinations are based on common waste management practices in Italy, assuming the maximization of recycling for concrete rubble, steel scraps and gypsum boards. The reuse option is excluded because of uncertainties in the quality and performance of building materials after the demolition works. The recovery rates of CDWs are based on the current technology: 60% for concrete, 90% for gypsum board, 90% for steel.

3.4. Sensitivity Analysis

A sensitivity analysis is performed to evaluate the effects of changes in the production, construction and disposal of materials throughout the life cycle of the frame structures. Specifically, the effect of marginal changes in the electricity supply system are considered. In Italy, natural gas currently dominates the fossil-based electricity production, while coal shows a negative trend, as it has gradually been replaced by natural gas in the last decade [34]. The electricity production from wind and solar energy sources shows an increase by factors of two and twelve, respectively, since 2010 [34].

Marginal electricity is uncertain; therefore, three scenarios has been considered based on standalone production with fossil coal, fossil gas or a mix of wind (45%) and solar (55%), respectively, as a marginal source of electricity instead of the average electricity supply mix. The primary energy use and $CO_{2\text{-eq}}$ emissions are thus calculated assuming marginal electricity produced in coal- or gas-fired power plants with conversion efficiency corresponding to European average technology.

The electricity use is calculated based on adjusted Ecoinvent data in order to account for marginal electricity. The primary energy use is estimated based on a calculation approach documented in Gustavsson et al. [47] for the first time. The conversion efficiency of fossil coal- and gas-fired condensing plant is assumed to be 35% and 43%, respectively, based on the average efficiency data for European plants [48]. The $CO_{2\text{-eq}}$ emissions of electricity production from fossil coal, fossil gas and combined wind–solar are based on Ecoinvent carbon intensities equal to 0.38, 0.25 and 0.04 kg $CO_{2\text{-eq}}$/kWh, respectively. Transportation and construction activities based on fossil fuels are unchanged in this sensitivity analysis.

4. Results

4.1. Material Quantities

The mass of materials used in the three structural frames, including auxiliary materials, is shown in Table 4. The total mass of the conventional concrete structure is the highest (788 tons), followed by the composite steel–concrete structure (585 tons) and the conventional steel structure (362 tons).

Table 4. Mass (tons) of materials by building element of the conventional concrete, conventional steel and composite steel–concrete frame structures.

	Conventional Concrete Structure	**Conventional Steel Structure**	**Composite Steel–Concrete Structure**
Structural materials			
Concrete	*667*	*190*	*490*
Beams	240	0	236
Posts/columns	120	1	70
Roof floor	307	189	184
Steel (reinforcing)	*56*	*9*	*43*
Beams	18	0	26
Posts/columns	13	3	12
Roof floor	25	7	5
Steel	*0*	*100*	*50*
Beams	0	62	21
Posts/columns	0	20	14
Roof floor	0	18	15
Finishing materials			
Plaster	*24*	*2*	*0*
Beams	7	1	0
Posts/columns	5	0	0
Roof floor	12	1	0
Plasterboard	*0*	*58*	*0*
Beams	0	27	0
Posts/columns	0	6	0
Roof floor	0	25	0
Paint	*0*	*2*	*0*
Beams	0	1	0
Posts/columns	0	0	0
Roof floor	0	1	0
Auxiliary materials			
Wood	*20*	*0*	*0*
Beams	14	0	0
Posts/columns	6	0	0
Roof floor	0	0	0
Steel	*20*	*0*	*0*
Beams	11	0	0
Posts/columns	9	0	0
Roof floor	0	0	0
Polystyrene	*0*	*0*	*0*
Beams	0	0	0
Posts/columns	0	0	0
Roof floor	0	0	0
Total	788	362	585

Concrete represents the highest share of structural materials in mass, accounting for 92, 84 and 64% in the conventional concrete, composite steel–concrete and conventional steel structures, respectively, while steel accounts for the remainder. The conventional concrete and composite steel–concrete frame structures show similar mass values of concrete in the beams but significantly different mass values of concrete in the posts/columns and roof floors, where the composite structure uses 40% less concrete. In addition, the composite steel–concrete frame structure uses 47% more reinforcing steel in the beams but 10 and 80% less reinforcing steel in the columns and roof floor, respectively, compared to the conventional concrete structure.

The mass of the finishing materials shows significant differences between the analyzed frame structures due to different needs in terms of weathering and fire protection. Plaster and plasterboard show significant mass values, achieving 3 and 16% of the total mass, in the conventional concrete and conventional steel frame structures, respectively. The composite steel–concrete frame structure does not need any additional finishing materials, except paint. Auxiliary materials only have significant mass values in the conventional concrete frame structure, where they account for 5% of the total mass. The conventional steel and composite steel–concrete frame structures exclusively use stay-in-place formworks or disposable formworks made of polystyrene in the roof floors, with negligible mass.

4.2. Primary Energy Use

Table 5 shows the primary energy use of the three structural frames per material and life-cycle stage. The results are also summarized in Figure 4.

Table 5. Primary energy use (MWh) of the three structural frames in different life-cycle stages (modules): production (A1–3), construction (A4–5), maintenance (B2), end-of-life (C1–4) and benefits from recovery and recycling (D).

	Life-Cycle Modules								
	A1–3	**A4**	**A5**	**B2**	**C1**	**C2**	**C3**	**C4**	**D**
Conventional concrete structure	*659*	*38*	*40*	*28*	*25*	*18*	*15*	*15*	*−281*
Concrete	69	27	37	0	11	13	14	13	−5
Steel	409	7	2	0	14	5	0	0	−276
Insulation	149	0	0	0	0	0	0	0	0
Finishing materials	25	3	0	28	0	0	1	1	0
Auxiliary materials	8	0	0	0	0	0	0	0	0
Conventional steel structure	*883*	*50*	*25*	*69*	*29*	*19*	*5*	*5*	*−519*
Concrete	18	5	12	0	3	4	4	4	−1
Steel	804	38	12	0	25	8	1	0	−508
Finishing materials	61	7	1	69	1	7	1	1	−10
Auxiliary materials	0	0	0	0	0	0	0	0	0
Composite concrete–steel structure	*762*	*40*	*34*	*34*	*30*	*17*	*11*	*11*	*−443*
Concrete	46	13	24	0	8	9	10	10	−4
Steel	712	27	11	0	22	7	1	0	−439
Finishing materials	1	0	0	34	0	0	0	0	0
Auxiliary materials	2	0	0	0	0	0	0	0	0

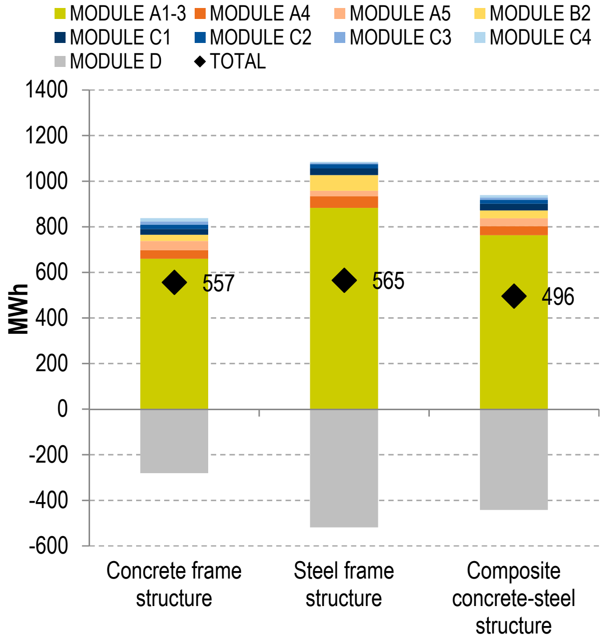

Figure 4. Primary energy use (MWh) of the three structural frames in different life-cycle stages (modules): production (A1–3), construction (A4–5), maintenance (B2), end-of-life (C1–4) and benefits from recovery and recycling (D).

The conventional steel structure, despite being the lightest structure, shows the highest life-cycle primary energy use, with 1084 MWh, followed by the composite concrete–steel structure, with 938 MWh, and the conventional concrete structure, with 838 MWh. If the energy benefits from recovery and recycling (module D) are included, the net primary energy use is the highest for the conventional steel structure and the lowest for the composite concrete–steel structure. Overall, the production stage (modules A1–A3) accounts for between 80% and 82% of the primary energy use for all three structures, followed by the construction stage (module A4–A5) and the end-of-life stage (modules C1–C4). The material associated with the highest primary energy use throughout the entire life cycle is steel in the conventional steel and composite concrete–steel structures, accounting for 67% and 69% of the total primary energy, respectively, and concrete in the conventional concrete structure, accounting for 32% of the total primary energy use.

The production primary energy is equal to 659 MWh, 762 MWh and 883 MWh for the conventional concrete, composite steel–concrete and conventional steel structures, respectively. In all the structural frames, steel (incl. reinforcing steel) accounts for the highest share of the production primary energy use, equal to 408 MWh (62%), 803 MWh (91%) and 712 MWh (93%) for the conventional concrete, composite steel–concrete structures and conventional steel, respectively. In the conventional steel structure, the finishing materials represent the second highest share of primary energy with 61 MWh (7%). In the conventional concrete structure, the remaining production primary energy use is from the extruded polystyrene integrated in the 'predalles' slabs of the roof floor with 149 MWh (23%), the concrete with 69 MWh (10%), and the finishing materials with 25 MWh (4%). In the composite concrete–steel structure, the concrete accounts for 46 MWh (6%) and the rest is for finishing and auxiliary materials.

In the transport stage (module A4), the conventional steel structure shows the highest primary energy use (50 MWh), followed by the composite concrete–steel (40 MWh) and conventional concrete (38 MWh) structures. Table 6 shows the primary energy use per mass unit that has been calculated for the different materials based on the transport bills for the composite concrete–steel structure and commercial data. Steel elements typically show higher primary energy use due to the higher haul distance compared to concrete elements.

Table 6. Specific primary energy use (kWh/kg) for transportation of materials.

Material	kWh/kg
Cement	0.025
Concrete	0.015
Gravel	0.009
Steel (corrugated sheet)	0.080
Steel (plates)	0.219
Steel (post and beams)	0.140
Steel (reinforcing bars)	0.060

In the construction stage (module A5), the conventional concrete structure shows the highest primary energy use, with 40 MWh against 34 MWh and 25 MWh for the composite concrete–steel and conventional steel structures, respectively. For the conventional concrete and composite concrete–steel structures, the construction of concrete elements is the most energy-intensive, accounting for 37 MWh and 24 MWh, equal to 94% and 68% of the construction primary energy use, respectively. For conventional steel, the primary energy use is more evenly distributed between the concrete and steel elements, both accounting for about 12 MWh and 49% of the construction primary energy. For all the structural frames, the energy consumed during the construction stage for auxiliary materials is negligible. The energy for finishing materials is very low (2%) for the conventional steel structure or negligible for conventional concrete and composite concrete–steel structure, as they are mainly installed through handheld tools. Overall, the prefabrication of elements off-site accounts for 0%, 3% and 7% of the construction primary energy use in the conventional concrete, composite concrete–steel and conventional steel structures, respectively.

The maintenance stage (module B2) only involves finishing materials. The maintenance primary energy use is the highest in the conventional steel structure (69 MWh) due to the high quantity of materials' used, including gypsum plasterboard, gypsum plaster and acrylic varnish. This is followed by the composite concrete–steel (34 MWh) and conventional concrete (28 MWh) structures. The maintenance stage accounts for 12%, 7% and 5% of the total primary energy use of the conventional steel, composite concrete–steel and conventional steel structure, respectively.

In the end-of-life stage, the demolition (module C1) shows the highest primary energy use. The demolition of steel elements is the most energy-intensive activity, with 25 MWh (86%) 22 MWh (73%) and 14 MWh (56% of demolition primary energy use) for the conventional steel, composite concrete–steel, and conventional concrete structures, respectively. The demolition of concrete is the second most relevant activity with 11 MWh (43%), 8 MWh (27%) and 3 MWh (10%) for the conventional concrete, composite concrete–steel and conventional steel structures, respectively. The demolition of the other materials has negligible primary energy use. The transport of CDW (module C2) is the second most energy-intensive stage. For the conventional concrete and composite concrete–steel structures, transporting concrete accounts for the highest share of end-of-life primary energy use with 13 MWh (72%) and 9 MWh (57%), respectively. For the same structures, the transport of finishing materials is negligible. For the conventional steel, the transport of steel is the most impactful with about 8 MWh (44%), followed by finishing materials with 7 MWh (37%) and concrete with 4 MWh (19%). The transport of auxiliary materials for all the structures is negligible

The benefits from recovery and recycling (module D) are the highest for steel recycling, which makes up about 98% of the benefits for the conventional steel and composite concrete–steel structures. The recycling of concrete (i.e., recycled aggregates) and finishing materials also provides 2% of the benefits for the conventional concrete and conventional steel structures, respectively. The primary energy use for the transport and sorting of CDW (modules C2–C3) is lower than the benefits achievable by the recovery and recycling of CDW (module D).

Finally, the primary energy use in the disposal stage (module C4) is the highest for the conventional concrete structure (15 MWh), followed by the composite concrete–steel structure (11 MWh) and the conventional steel structure (5 MWh). For all the structures, the disposal of concrete accounts for the highest share, ranging between 81% and 96%. Disposal of finishing materials is the second most impactful process for steel structures with 14%. Other materials are less impactful and can be considered negligible.

4.3. $CO_{2\text{-}eq}$ Emissions

Table 7 shows the $CO_{2\text{-eq}}$ emissions of the three structural frames per material and life-cycle stage. The results are also summarized in Figure 5.

The conventional steel structure has the highest $CO_{2\text{-eq}}$ emissions (440 $tCO_{2\text{-eq}}$), followed by the composite concrete–steel (384 $tCO_{2\text{-eq}}$) and conventional concrete (334 $tCO_{2\text{-eq}}$) structures. If the $CO_{2\text{-eq}}$ benefits (module D) are included, the net primary energy use is the highest for the conventional steel and the lowest for the composite concrete–steel structure.

The production $CO_{2\text{-eq}}$ emissions of the conventional concrete, conventional steel and prefabricated steel–concrete structural systems are 290, 392 and 341 $tCO_{2\text{-eq}}$, respectively. The highest share of $CO_{2\text{-eq}}$ emissions is accounted for by steel in all the structural frames, ranging between 64% in the conventional concrete structure and about 93% in both the conventional steel and composite concrete–steel structures. In particular, about half of the production $CO_{2\text{-eq}}$ emissions is represented by the beams. In the conventional concrete and composite steel–concrete structures, reinforcing steel significantly contributes to the production $CO_{2\text{-eq}}$ emissions. The $CO_{2\text{-eq}}$ emissions required to produce finishing materials are the highest in the conventional steel structure due to the use of gypsum board for fire protection. The allocated $CO_{2\text{-eq}}$ emissions to produce auxiliary materials are negligible in all the structural frames. The use of integrated steel formworks in the conventional steel and prefabricated steel–concrete structural systems represents an advantage in terms of the production $CO_{2\text{-eq}}$ emissions. The $CO_{2\text{-eq}}$ emissions from the calcination reaction, which are included in the Ecoinvent unit process of cement manufacturing, account for 41, 12 and 30 tons of $CO_{2\text{-eq}}$ in the conventional concrete, conventional steel and composite concrete–steel structures, thus accounting for 10%, 3% and 7% of the respective production CO_2-eq emissions.

Table 7. $CO_{2\text{-eq}}$ emissions ($tCO_{2\text{-eq}}$) of the three structural frames in different life-cycle stages (modules): production (A1–3), construction (A4–5), maintenance (B2), end-of-life (C1–4) and benefits from recovery and recycling (D).

	Life-Cycle Modules								
	A1–3	**A4**	**A5**	**B2**	**C1**	**C2**	**C3**	**C4**	**D**
Conventional concrete structure	*290*	*11*	*12*	*5*	*6*	*5*	*2*	*2*	*−88*
Concrete	24	8	11	0	3	4	2	2	−1
Steel	186	2	1	0	3	1	0	0	−87
Insulation	69	0	0	0	0	0	0	1	0
Finishing materials	10	1	0	5	0	0	0	0	0
Auxiliary materials	1	0	0	0	0	0	0	0	0
Conventional steel structure	*392*	*15*	*8*	*12*	*7*	*6*	*1*	*1*	*−162*
Concrete	7	2	4	0	1	1	1	0	0
Steel	363	11	4	0	6	2	0	0	−161
Finishing materials	22	2	0	12	0	2	0	0	−2
Auxiliary materials	0	0	0	0	0	0	0	0	0
Composite concrete-steel structure	*341*	*12*	*10*	*6*	*7*	*5*	*2*	*1*	*−139*
Concrete	18	4	7	0	2	3	2	1	−1
Steel	321	8	3	0	5	2	0	0	−139
Finishing materials	1	0	0	6	0	0	0	0	0
Auxiliary materials	1	0	0	0	0	0	0	0	0

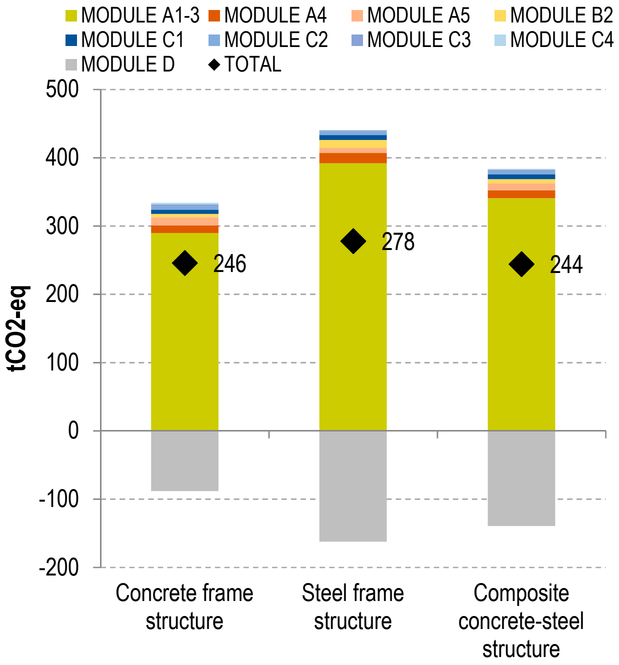

Figure 5. $CO_{2\text{-eq}}$ emissions ($tCO_{2\text{-eq}}$) of the three structural frames in different life-cycle stages (modules): production (A1–3), construction (A4–5), maintenance (B2), end-of-life (C1–4) and benefits from recovery and recycling (D).

The transport $CO_{2\text{-eq}}$ emissions range between 11 and 15 tons $CO_{2\text{-eq}}$, depending on the haul distance and the mass of materials. Concrete accounts for about 70% of the transport $CO_{2\text{-eq}}$ emissions in the conventional concrete structure, and for 11% and 32% in the conventional steel and composite concrete–steel structures, respectively. The respective share for steel is equal to 19%, 75% and 68%. The transport of reinforcing steel is negligible in the conventional steel structure. The $CO_{2\text{-eq}}$ emissions allocated to transport auxiliary and finishing materials are also negligible.

The construction $CO_{2\text{-eq}}$ emissions are equal to 18, 10 and 8 tons $CO_{2\text{-eq}}$ in the conventional concrete, composite concrete–steel and conventional steel structures, respectively. In the conventional concrete structure, the $CO_{2\text{-eq}}$ emissions from mixing and pouring concrete account for 60% of the construction $CO_{2\text{-eq}}$ emissions, while the remainder mainly results from the preparation of reinforcing steel bars. The $CO_{2\text{-eq}}$ emissions resulting from the assembly and disassembly of the auxiliary materials (i.e., formworks) are negligible. In the composite concrete–steel structure, the $CO_{2\text{-eq}}$ emissions from mixing and pouring concrete are slightly lower, about 50% of the construction $CO_{2\text{-eq}}$ emissions, while the $CO_{2\text{-eq}}$ emissions from the assembly of steel and reinforcing steel account for about 20% and 30%, respectively. The $CO_{2\text{-eq}}$ emissions from the assembly and disassembly of the auxiliary materials are zero because the system uses the stay-in-place/integrated formworks or polyethylene formwork to install and remove by hand. In the conventional steel structure, steel represents about half of the construction $CO_{2\text{-eq}}$ emissions, with the assembly of steel elements accounting for about 70% of this share, while the remainder mainly results from the construction of the joint between the basement and the columns. The construction of the finishing materials (i.e., gypsum boards) is negligible, accounting for about 3% of the construction $CO_{2\text{-eq}}$ emissions. In the three frame structures, the construction of the beams, including the assembly and disassembly of the formworks, represents the highest share of construction $CO_{2\text{-eq}}$ emissions, ranging between 42% and 45%, followed by the construction of the roof, between 28 and 35%, and posts/columns, between 24 and 27%. The construction activities linked to finishing materials such as plaster and paint are assumed to occur through handheld tools and hence to have zero $CO_{2\text{-eq}}$ emissions. The prefabrication of elements off-site is included in the construction stage and it accounts for 1%, 4% and 9% of the construction $CO_{2\text{-eq}}$ emissions in the conventional concrete, composite concrete–steel and conventional steel structures, respectively.

The maintenance $CO_{2\text{-eq}}$ emissions are equal to 12, 6 and 5 tons $CO_{2\text{-eq}}$ for the conventional steel, conventional concrete and composite concrete–steel structures, respectively. Maintenance activities include the replacement of plaster or gypsum plasterboards, as well as the renovation of paints. The $CO_{2\text{-eq}}$ emissions from paint are the most relevant in the conventional concrete and composite concrete–steel structures, while the $CO_{2\text{-eq}}$ emissions from plasterboard are significant in the conventional steel structure. However, the maintenance $CO_{2\text{-eq}}$ emissions of the three frame structures are negligible compared to the production $CO_{2\text{-eq}}$ emissions. This study only considers the maintenance of the finishing materials, assuming the structural materials to have the same life span as the building.

The end-of-life $CO_{2\text{-eq}}$ emissions of the conventional concrete, composite concrete–steel, and conventional steel structures are 16, 15 and 14 tons $CO_{2\text{-eq}}$, respectively. The $CO_{2\text{-eq}}$ emissions generated by the demolition account for the highest share, ranging between 38% for the conventional concrete structure and 50% for the conventional steel structure. The transport $CO_{2\text{-eq}}$ emissions of the three frame structures are similar, ranging between 32% and 38%. The $CO_{2\text{-eq}}$ emissions generated by the sorting and disposal of CDW account for the remainder. In the conventional steel and composite concrete–steel structures, the sorting of CDW generates more $CO_{2\text{-eq}}$ emissions compared to the disposal because the share of CDW sorted before recycling is higher than that disposed of (i.e., landfilled).

The $CO_{2\text{-eq}}$ benefits from energy recovery and recycling of CDW are equal to 162, 139, and 88 tons $CO_{2\text{-eq.}}$ for the conventional steel, conventional concrete, and composite concrete–steel structures, respectively. In all the frame structures, the recycling of steel scraps contributes the highest share of $CO_{2\text{-eq}}$ benefits, equal to about 98% of the total

$CO_{2\text{-eq}}$ benefits, while the contribution of other CDW is negligible. The recycling of concrete rubbles accounts for about 1% of the $CO_{2\text{-eq}}$ benefits in the conventional concrete structure. Similar $CO_{2\text{-eq}}$ benefits are calculated for the energy recovery of the allocated timber formworks and the recycling of gypsum board waste in the conventional steel structure.

Finally, the $CO_{2\text{-eq}}$ benefits due to the CO_2 absorption during the carbonation of crushed concrete waste are estimated for the three structural frames. Such benefits have not been considered in Table 7 and Figure 5. In the conventional steel structure, the CO_2 absorption from concrete carbonation is equal to 9 tons of CO_2 and it is mainly due to the crushed concrete of the roof floor. In the conventional concrete structure, the CO_2 absorption from concrete carbonation generates the highest CO_2 benefits, with 20 tons of CO_2 absorbed during the storage of crushed concrete and subsequent backfilling of recycled concrete aggregates, and 14 tons CO_2 absorbed during the landfilling of crushed concrete unsuitable for backfilling. In the composite concrete–steel structure, the respective values of CO_2 absorption are 14 and 10 tons of CO_2. Therefore, if considering the CO_2 absorption due to the additional carbonation of crushed concrete waste, the total $CO_{2\text{-eq}}$ benefits can increase by 39%, 17% and 6% in the conventional concrete, composite concrete–steel and conventional steel, respectively. The rate of increase in the conventional concrete structure is higher compared to the other structures, as its $CO_{2\text{-eq}}$ benefits from the energy recovery and recycling of CDW are lower.

4.4. Sensitivity Analysis

The sensitivity analysis calculates the sensitivity of the primary energy and $CO_{2\text{-eq}}$ emission results to changes in the electricity supply system. Electricity is used in the production, construction, maintenance and end-of-life stages of the three frame structures.

The total net primary energy use of the three frame structures recalculated based on the marginal electricity from fossil coal, fossil gas and wind–solar is shown in Figure 6. The total net primary energy use is equal to 627 MWh, 669 MWh and 572 MWh for the conventional concrete, conventional steel and composite concrete–steel structures, respectively, when assuming marginal electricity based on fossil coal. These results show higher primary energy use for all three frame structures, albeit consistent values, compared to the baseline calculation with average electricity mix. The primary energy use decreases to 94% for all the frame structures when assuming marginal electricity based on fossil gas instead of coal. The respective percentage when assuming marginal electricity based on combined wind–solar is 84%, 81% and 79% for the conventional concrete, composite concrete–steel and conventional steel structures, respectively.

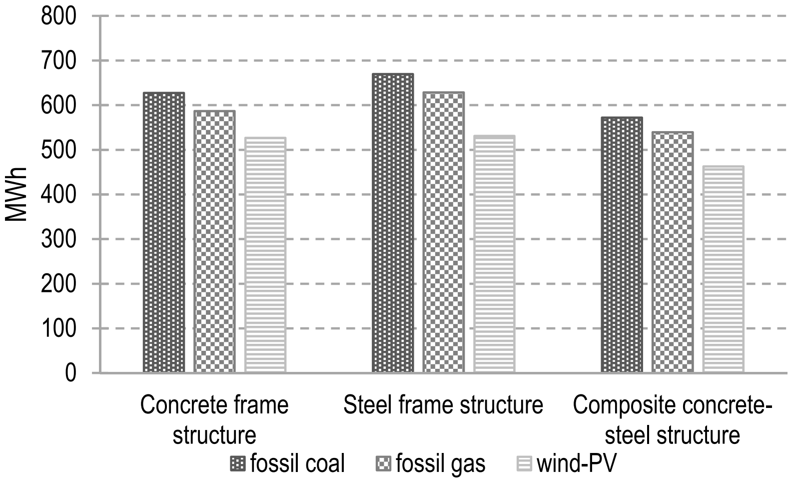

Figure 6. Total primary energy use (MWh) of the conventional concrete, conventional steel and composite concrete–steel structures with marginal electricity based on fossil coal, fossil gas and wind–solar.

The total net $CO_{2\text{-eq}}$ emissions recalculated based on the marginal electricity from fossil coal, fossil gas and wind–solar are shown in Figure 7. The total net $CO_{2\text{-eq}}$ emissions are equal to 305 ton of $CO_{2\text{-eq}}$, 282 ton of $CO_{2\text{-eq}}$, and 259 ton of $CO_{2\text{-eq}}$ for the conventional steel, conventional concrete and composite concrete–steel structures, respectively, when assuming marginal electricity based on fossil coal. The $CO_{2\text{-eq}}$ emissions decrease to about 80% for all the structures when considering fossil coal, and to 71%, 68% and 66% for the conventional concrete, composite concrete–steel and conventional steel structures, respectively, when considering wind–solar marginal electricity. Therefore, the decrease in $CO_{2\text{-eq}}$ emissions when changing the marginal electricity based on fossil coal into fossil gas or wind–solar is more significant compared to the primary energy use.

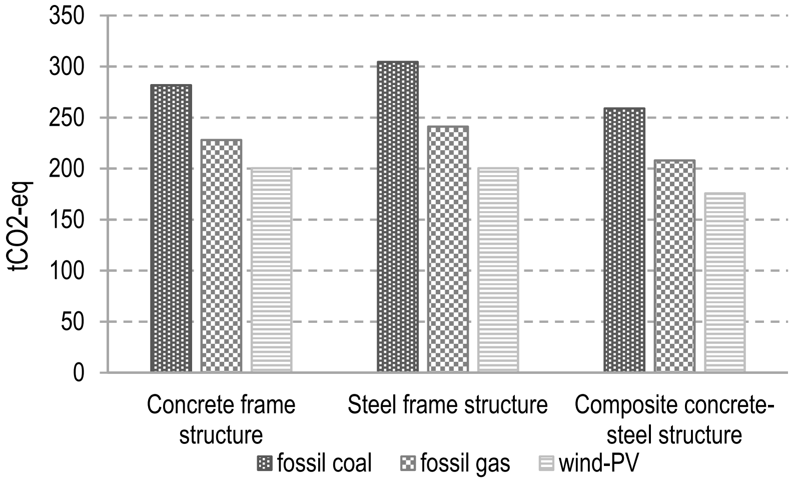

Figure 7. Total $CO_{2\text{-eq}}$ emissions (ton $CO_{2\text{-eq}}$) of the conventional concrete, conventional steel and composite concrete–steel structures with marginal electricity based on fossil coal, fossil gas and wind-solar.

Without considering the primary energy and $CO_{2\text{-eq}}$ benefits from recovery and recycling (module D), the total primary energy use and $CO_{2\text{-eq}}$ emissions of the composite concrete–steel structures are still higher than for the conventional concrete structure.

The variations in the decrease in the primary energy use depend on the share of electricity used by the frame structures throughout the entire life cycle. Furthermore, when assuming the marginal electricity to be less energy- and carbon-intensive, the benefits from the recovery and recycling of CDW in the end-of-life stage reduce due to the lower primary energy and $CO_{2\text{-eq}}$ emissions avoided from the substitution of virgin materials or electricity sources.

5. Discussion

Three frame structures, namely conventional concrete, conventional steel and composite concrete–steel structures, have been modeled according to structural design standards to have the same structural performance. A real building with a composite concrete–steel structure has been taken as a case study. The entire life cycle of the three frame structures has been analyzed with the exception of the operation modules of the building (i.e., use, repair, replacement, refurbishment, operational energy and water use).

The three frame structures show different levels of prefabrication. In the conventional concrete structure, all the structural elements are typically constructed on-site, with the exception of the 'predalles' slabs used in the roof. In the conventional steel structure, the steel profiles and plates are premanufactured off-site and assembled on-site. In the composite concrete–steel structure, the steel profiles, plates and reinforcing steel bars are premanufactured and preassembled in posts and beams off-site and then poured with concrete on-site.

The choice of structural materials is shown to be relevant for all the structural frames and in most of the life-cycle stages. The conventional steel structure shows the highest primary energy use and $CO_{2\text{-eq}}$ emissions, confirming the findings of previous literature studies and consistent with the results from [17] about European building codes. The production stage is the most relevant life-cycle stage, accounting for about 80% of the total primary energy use and about 88% of the total $CO_{2\text{-eq}}$ emissions in all the structural frames. In this stage, structural materials account for the highest shares of primary energy use and $CO_{2\text{-eq}}$ emissions, both between 73% and 99%, while finishing and auxiliary materials account for the remainder. Finishing materials usually have a minor impact, except for the conventional steel structure where the gypsum plasterboard used for fire protection alone accounts for about 7% of the primary energy use and $CO_{2\text{-eq}}$ emissions. In the construction stage, the impacts of transportation (module A4) are almost equivalent to the impacts of construction operations (module A5) in the conventional concrete structure, but they are higher in the composite concrete–steel and conventional steel structures. This is attributed to the longer haul distances and higher number of intermediate distributions that typically affect the steel supply chain compared to concrete. However, the transportation impacts might differ significantly depending on the geographical context and the accessibility of materials. In the end-of-life stage, the structural frames with the highest share of concrete show a higher impact. This mainly can be attributed to the weight of concrete. Furthermore, the conventional and composite concrete–steel structures generate the highest benefits due to the recycling of steel, potentially reducing the total primary energy use and $CO_{2\text{-eq}}$ emissions by 47% and 36%, respectively. The recycling of concrete into aggregates provides lower benefits due to its lower recovery rate and recycling efficiency. Auxiliary materials, such as formworks, have a minor impact as they can be reused multiple time.

Prefabrication especially affects the production and construction stages. Particularly, the primary energy use and $CO_{2\text{-eq}}$ emissions due to prefabrication are shifted from on- to off-site. In this regard, a methodological issue has been observed. Some studies in the literature attribute the impacts of prefabrication to the production stage, while others attribute them to the construction stage. In this study, the impacts of the prefabrication of structural elements are included in the construction stage according to the standard EN 15978 [29]. This standard attributes all the construction processes, such as 'in-situ construction, off-site construction assembly of pre-fabricated products or any combination of these', to the construction stage (module A5). However, confusion might arise because, according to the same standard, the boundaries of the production stage (modules A1–A3) cover the 'cradle to gate' processes for the materials and services. Therefore, it is unclear whether prefabrication, which consists of off-site operations, should be included in the production or construction stage. This methodological uncertainty can reduce the comparability among studies.

In this study, most of the prefabrication activities are related to steel materials. For example, the following activities have been considered off-site: cutting of steel elements, and folding and welding of reinforcing bars. The primary energy use and $CO_{2\text{-eq}}$ emissions due to the energy use for the prefabrication of structural elements account for nearly zero in the conventional concrete structure, 37% and 42% in the conventional steel structure, and 21% and 25% in the composite concrete–steel structure, respectively. As prefabrication activities depend on electricity, the sensitivity analyses show that, if assuming renewable energies to provide electricity off-site, the primary energy use and $CO_{2\text{-eq}}$ emissions due to prefabrication can significantly decrease. However, the need for prefabrication could increase the haul distance related to structural elements and, consequently, the primary energy use and $CO_{2\text{-eq}}$ emissions in the transportation stage (module A4). However, the haul distance is influenced by the supply chain of prefabricated structural elements. Finally, in the end-of-life stage, the quantity of waste generated from the prefabrication of structural elements has been considered equal to zero, assuming the optimized use of materials.

6. Conclusions

The present study analyzes the life-cycle primary energy use and $CO_{2\text{-eq}}$ emissions of three frame structures using different structural materials and different levels of prefabrication while maintaining the same structural performance.

A few points can be highlighted regarding the use of different structural materials:

- The choice of structural materials has a strong influence on the primary energy use and $CO_{2\text{-eq}}$ emissions in all the life-cycle stages and, especially, in the production stage.
- The impact of finishing materials for fire protection is relevant, especially in the production and maintenance stages; auxiliary materials (e.g., formworks) are negligible.
- Analyzing structural frames with different materials but the same structural performance and compliance with fire standards is key to achieving comparable results.

A few points can also be highlighted regarding prefabrication:

- The prefabrication of structural elements can shift the primary energy use and $CO_{2\text{-eq}}$ emissions from on- to off-site.
- As prefabrication mostly depends on electricity, the adoption of off-site renewable energy technologies for the production of electricity can reduce the primary energy use and $CO_{2\text{-eq}}$ emissions due to prefabrication.
- The prefabrication of structural elements can reduce the material wastage and increase the recycling rate of residues off-site, increasing the primary energy and $CO_{2\text{-eq}}$ benefits.
- Structural frames with lower levels of prefabrication, such as the analyzed conventional concrete structure, show higher primary energy use and $CO_{2\text{-eq}}$ emissions related to on-site operations in the construction stage.

As a methodological note, this study shows that there are uncertainties as to whether the impact of prefabrication should be included in the production or construction stage based on the current literature. Following the standard EN 15978 [29], this study attributes the impacts related to the prefabrication of structural elements to the construction stage.

Finally, this study has few limitations. First, the foundations of the three frame structures have not been considered. Foundations could have an impact on the primary energy use and $CO_{2\text{-eq}}$ emissions of the single structural frames but a limited impact on the comparative results. Second, this study does not consider uncertainties as to the material wastage in the production, construction and end-of-life stages. Further research could investigate this aspect. Third, this study does not consider the structural behavior in probable high-severity events. Further research could help understand the implications of using different building materials in relation to extreme events throughout the structure's life cycle.

Analyzing the primary energy and carbon impacts of structural frames is important for informing designers, leading to improved sustainability in structural design. It also supports decision-makers in meeting new regulations that introduce the assessment of the whole-life-cycle carbon emissions of buildings, including the carbon emissions from materials.

Author Contributions: Conceptualization, C.P. and C.C.; Methodology, C.P., S.C. and C.C.; Formal analysis, C.P., C.S. and S.C.; Resources, A.A.; Writing—original draft, C.P., S.C. and C.C.; Writing—review & editing, C.P. and C.C.; Supervision, C.C.; Funding acquisition, C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [Tecnostrutture s.r.l.].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The support from Tecnostrutture s.r.l. is acknowledged by the authors. The recommendations expressed in this paper do not necessarily reflect the views of the supporting company.

Conflicts of Interest: The authors declare that this study received funding from Tecnostrutture s.r.l. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

References

1. United Nations Environment Programme. *Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2022.
2. European Parliament and Council. Directive 2018/844 of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. PE/4/2018/REV/1. *Off. J. Eur. Union* **2018**, *L 156*, 75–91.
3. Adalberth, K.; Almgren, A.; Holleris Petersen, E. Life cycle assessment of four multi-family buildings. *Int. J. Low Energy Sustain. Build.* **2001**, *2*, 1–21.
4. Sartori, I.; Hestnes, A.G. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy Build.* **2007**, *39*, 249–257. [CrossRef]
5. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation. *Appl. Energy* **2020**, *258*, 114107. [CrossRef]
6. Rasmussen, F.N.; Birgisdóttir, H.; Malmqvist, T.; Kuittinen, M.; Häkkinen, T. Embodied carbon in building regulation—Development and implementation in Finland, Sweden and Denmark. In *The Routledge Handbook of Embodied Carbon in the Built Environment*; Routledge: London, UK, 2023; ISBN 978-1-00-327792-7.
7. Cabeza, L.F.; Boquera, L.; Chàfer, M.; Vérez, D. Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis. *Energy Build.* **2021**, *231*, 110612. [CrossRef]
8. Tsimplokoukou, K.; Lamperti, M.; Negro, P. *Building Design for Safety and Sustainability*; Publications Office of the European Union: Luxembourg, 2014.
9. Pongiglione, M.; Calderini, C. Sustainable Structural Design: Comprehensive Literature Review. *J. Struct. Eng.* **2016**, *142*, 04016139. [CrossRef]
10. Adalberth, K. Energy use in four multi-family houses during their life cycle. *Int. J. Low Energy Sustain. Build.* **1999**, *1*, 1–20.
11. Junnila, S.; Horvath, A.; Guggemos, A.A. Life-Cycle Assessment of Office Buildings in Europe and the United States. *J. Infrastruct. Syst.* **2006**, *12*, 10–17. [CrossRef]
12. Jonsson, A.; Bjorklund, T.; Tillman, A.-M. LCA of concrete and steel building frames. *Int. J. LCA* **1998**, *3*, 216–224. [CrossRef]
13. Hegeir, O.A.; Kvande, T.; Stamatopoulos, H.; Bohne, R.A. Comparative Life Cycle Analysis of Timber, Steel and Reinforced Concrete Portal Frames: A Theoretical Study on a Norwegian Industrial Building. *Buildings* **2022**, *12*, 573. [CrossRef]
14. Alshamrani, O.S. Life cycle assessment of low-rise office building with different structure–envelope configurations. *Can. J. Civ. Eng.* **2016**, *43*, 193–200. [CrossRef]
15. Cole, R.J. Building environmental assessment methods: Assessing construction practices. *Constr. Manag. Econ.* **2000**, *18*, 949–957. [CrossRef]
16. Guggemos, A.A.; Horvath, A. Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings. *J. Infrastruct. Syst.* **2005**, *11*, 93–101. [CrossRef]
17. Seyedabadi, M.R.; Karrabi, M.; Shariati, M.; Karimi, S.; Maghrebi, M.; Eicker, U. Global building life cycle assessment: Comparative study of steel and concrete frames across European Union, USA, Canada, and Australia building codes. *Energy Build.* **2024**, *304*, 113875. [CrossRef]
18. Fang, D.; Brown, N.; De Wolf, C.; Mueller, C. Reducing embodied carbon in structural systems: A review of early-stage design strategies. *J. Build. Eng.* **2023**, *76*, 107054. [CrossRef]
19. Jayawardana, J.; Sandanayake, M.; Jayasinghe, J.A.S.C.; Kulatunga, A.K.; Zhang, G. A comparative life cycle assessment of prefabricated and traditional construction—A case of a developing country. *J. Build. Eng.* **2023**, *72*, 106550. [CrossRef]
20. Du, Q.; Bao, T.; Li, Y.; Huang, Y.; Shao, L. Impact of prefabrication technology on the cradle-to-site CO_2 emissions of residential buildings. *Clean Technol. Environ. Policy* **2019**, *21*, 1499–1514. [CrossRef]
21. Tian, Y.; Spatari, S. Environmental life cycle evaluation of prefabricated residential construction in China. *J. Build. Eng.* **2022**, *57*, 104776. [CrossRef]
22. Tavares, V.; Soares, N.; Raposo, N.; Marques, P.; Freire, F. Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. *J. Build. Eng.* **2021**, *41*, 102705. [CrossRef]
23. Xing, S.; Xu, Z.; Jun, G. Inventory analysis of LCA on steel- and concrete-construction office buildings. *Energy Build.* **2008**, *40*, 1188–1193. [CrossRef]
24. Blengini, G.A. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Build. Environ.* **2009**, *44*, 319–330. [CrossRef]
25. Moncaster, A.M.; Pomponi, F.; Symons, K.E.; Guthrie, P.M. Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system. *Energy Build.* **2018**, *173*, 389–398. [CrossRef]
26. Marrone, G.; Imperadori, M.; Sesana, M.M. Life-cycle assessment of light steel frame buildings: A systematic literature review. In *Life-Cycle of Structures and Infrastructure Systems*; CRC Press: Boca Raton, FL, USA, 2023.

27. *EN 1994-1-2*; Eurocode 4 Design of Composite Steel and Concrete Structures: Part 1.2: General Rules, Structural Fire Design. European Committee for Standardisation: Brussels, Belgium, 2004.
28. *EN 1991-1-1*; Eurocode 1: Actions on Structures—Part 1-1: General Actions—Densities, Self-Weight, Imposed Loads for Buildings. European Committee for Standardisation: Brussels, Belgium, 2002.
29. *EN 15978*; Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. European Committee for Standardization: Brussels, Belgium, 2012.
30. *EN 15804*; Sustainability of Construction Works—Environmental Product Declarations—Core rules for the Product Category of Construction Products. European Committee for Standardization: Brussels, Belgium, 2012.
31. Frischknecht, R.; Jungbluth, N.; Althaus, H.-J.; Bauer, C.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Köllner, T.; et al. *Implementation of Life Cycle Impact Assessment Methods*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
32. PRé Sustainability SimaPro Database Manual. Methods Library. Available online: https://support.simapro.com/s/article/SimaPro-Methods-manual (accessed on 29 March 2024).
33. Ecoinvent Ecoinvent v. 3.6. Available online: https://ecoinvent.org/ (accessed on 29 March 2024).
34. ISPRA. *Fattori di Emissione Atmosferica di Gas a Effetto Serra nel Settore Elettrico Nazionale e nei Principali Paesi Europei [Greenhouse Gas Emission Factors in the National Electricity Sector and Major European Countries]*; ISPRA: Rome, Italy, 2019.
35. Chen, T.Y.; Burnett, J.; Chau, C.K. Analysis of embodied energy use in the residential building of Hong Kong. *Energy* **2001**, *26*, 323–340. [CrossRef]
36. Tam, V.W.Y.; Tam, C.M.; Zeng, S.X.; Ng, W.C.Y. Towards adoption of prefabrication in construction. *Build. Environ.* **2007**, *42*, 3642–3654. [CrossRef]
37. Hong, J.; Shen, G.Q.; Mao, C.; Li, Z.; Li, K. Life-cycle energy analysis of prefabricated building components: An input–output-based hybrid model. *J. Clean. Prod.* **2016**, *112*, 2198–2207. [CrossRef]
38. Presidential Decree n. 472 of 14 August 1996 (Italy); 1996. Available online: https://www.normattiva.it/uri-res/N2Ls?urn:nir:presidente.repubblica:decreto:1996-08-14;472~art1 (accessed on 7 May 2024).
39. *EN 10204*; Metallic Products. Types of Inspection Documents. European Committee for Standardization: Brussels, Belgium, 2004.
40. Network for Transport Measures Road Cargo Transport Baselines Europe. Available online: https://www.transportmeasures.org (accessed on 29 March 2024).
41. Grosso, L. *Tempario Per Opere Edili Civili [Time List for Civil Construction Works]*; IlSole24: Milan, Italy, 2007.
42. Molinari, C. *Manutenzione in Edilizia. Nozioni, Problemi, Prospettive [Maintenance in Construction. Concepts, Problems, Perspectives]*; Franco Angeli: Milan, Italy, 1989.
43. Molinari, C. *Procedimenti e Metodi della Manutenzione Edilizia [Building Maintenance Procedures and Methods]*; Sistemi Editoriali: Naple, Italy, 2002.
44. Dodoo, A.; Gustavsson, L.; Sathre, R. Carbon implications of end-of-life management of building materials. *Resour. Conserv. Recycl.* **2009**, *53*, 276–286. [CrossRef]
45. Pade, C.; Guimaraes, M. The CO_2 uptake of concrete in a 100 year perspective. *Cem. Concr. Res.* **2007**, *37*, 1348–1356. [CrossRef]
46. ARPAE. *Piano Regionale di Gestione dei Rifiuti [Regional Waste Management Plan]*; ARPAE: Bologna, Italy, 2020.
47. Gustavsson, L.; Joelsson, A.; Sathre, R. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *Energy Build.* **2010**, *42*, 230–242. [CrossRef]
48. Graus, W.; Worrell, E. Trend in efficiency and capacity of fossil power generation in the EU. *Energy Policy* **2009**, *37*, 2147–2160. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.