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Life Cycle Assessment in Building: A Case Study on the Energy and Emissions Impact Related to the Choice of Housing Typologies and Construction Process in Spain

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Abstract: While there exists an international trend to develop zero or near zero emissions building solutions by 2020, and European governments continuously update their building regulations to optimize the building envelope and energy systems to achieve this during the building use stage, at least in Spain the building regulations do not take into account the impact of emissions resulting from urbanization and construction activities prior to building use. This research studies in detail the entire emissions balance (and how it may be related to energy efficiency) in a newly built residential cluster project in Mancha Real (Jaén, Spain), and influences due to the choice of different urban typologies. For comparison, terraced housing and low-density, four-floor, multi-family housing alternatives have been studied. The present work assessed the life cycle of the building with the help of commercial software (CYPE), and the energy efficiency and emissions according to the legal regulations in Spain with the official software LIDER and CALENER VYP. After a careful choice of building and systems alternatives and their comparison, the study concludes that the major emissions impact and energy costs of urbanization and building activity occurs during construction, while later savings due to reductions in building use emissions are very modest in comparison. Therefore, deeper analysis is suggested to improve the efficiency of the construction process for a significantly reduced emission footprint on the urban environment.

Keywords: life cycle assessment; green urban economies; terraced housing; low density housing; sustainable building; sustainable city; building embodied energy; building embodied carbon

1. Introduction

1.1. Background

Climate change and energy sustainability are among the five main targets the EC (European Commission) agreed to achieve by 2020. Three specific objectives define this target: to reduce greenhouse gas emissions by at least 20%, to increase energy efficiency by 20%, and to obtain 20% of energy from renewables [1]. Accordingly, the European Parliament (EP) elaborated the guidelines for greenhouse gas emission reduction to be followed by member states.

As buildings are responsible for a large share of the environmental impact, accounting for 40% of total energy consumption, they require specific attention from policy makers [2]. The EP updated its energy directives relating to buildings in 2010, with the ambitious mandate of achieving zero or almost zero energy buildings by 2020 [2]. Member states followed by updating their own national regulations.

Within the European Union (EU), the building industry is an important sector, with a gross operating rate of 10.7%. Spain is the country with the largest percentage of the building industry, with a share in 2010 of 22%, and thus requires very special attention [3]. Even though the real estate bubble burst in Spain has slowed down the frantic construction activity of the 2000s, several expert studies report greater market confidence, which may encourage new residential construction in the near future [4,5]. The published statistics for new building permits indicate a regular rhythm of around 200,000 new units per year in the 1990s, with 1995 being the start of an increase that sharply rose after 1998 and reached its peak of nearly 740,000 units in 2006. The year 2012 marked the lowest point, with less than 60,000 units [6]. After this point, several reports indicate a resurgence of activity. Nonetheless, new construction at a rate of even 60,000 units per year still merits serious consideration for its environmental impact. While housing before the bubble was designed with criteria from the late 1990s, whatever is built from now on must conform to at least the EU 2020 targets for emissions reduction and energy efficiency, which herald a very different world for building design and criteria. The question arises of what to do from the perspective of planning, design, and construction for genuine, sustainable results while maintaining the character of the local urban culture.

Spanish building regulations have been harmonized with the EC guidelines since 2006, and are contained in the CTE (*Código Técnico de la Edificación*, Spanish Building Code) [7]. Within this framework, energy efficiency is regulated by DB-HE (*Documento Básico de Ahorro de Energía*, Basic Document for Energy Savings), first issued in 2006, and updated in 2013 to adapt to the new European Directive 2010/31/EU [8]. Simple environmental assessment procedures were first established in the late 1970s, the main design decision criteria being envelope transmittance and building shape factor (*factor de forma* in Spanish; the result of dividing area A of the envelope by volume V of the building, $S_f = A/V$) [9] (p. 24540). As a side note, *shape factor* is called compactness factor in the USA [10], but in Europe compactness is often defined as the inverse of the shape factor, so larger numbers mean higher compactness [11,12] (pp. 26, 129). Although this simple assessment was in use and allowed until 2013 in Spain as part of a simplified analysis in housing and small buildings, it has been completely phased out in favor of detailed computer simulations to assess the envelope design and the building energy efficiency and carbon emissions. However, building shape factor is still a meaningful parameter when used in conjunction with other parameters such as orientation, shape complexity, and percentage of glazed surfaces, especially for early design decisions [13–15].

Furthermore, renewable energies have become mandatory for a percentage of DHW (Domestic Hot Water) production, and in tertiary buildings providing the percentage of PV (Photo Voltaic) energy production on site is also mandatory [16]. All these measures will surely improve the buildings' performance.

However, there are no special guidelines or provisions regarding energy consumed and emissions produced in the construction process prior to building occupancy. A serious concern arises from this oversight, as the impact of this previous process is something that must be taken into consideration. It is true that research exists on methods for a more complete environmental assessment to fill this gap. LCA (Life Cycle Assessment) is one of them, and has developed greatly in the last 20 years, with many studies trying to develop and test comprehensive methodologies [17–22]. Although there is not yet a definite and universally accepted application methodology, some tools and studies following the guidelines in ISO 14040 [23] are already available, although still in need of improvement.

Khasreen *et al.* [17] present a very complete overview of the LCA process for implementation with its achievements and problems over a 15-year period starting in 1994. They highlight the possibilities and the growing number of studies and methods, but still see a need to find a way to normalize and compare the findings of different LCA studies. Finkbeiner *at al.* [18] present an attempt at a comprehensive LCA sustainability assessment method, including not only environmental issues, but also economic and social issues as well, and consider the environmental aspect of LCA sustainability assessment to be already sufficiently developed compared to the other two aspects.

Zabalza *et al.* [19] present a simplified but comprehensive method for LCA environmental and economic assessment, with a detailed application to one Spanish case study, which can be useful in real-world design decision making. Gong and Song [20] propose another LCA assessment methodology aimed mainly at carbon emissions, studying in a systematic way the different factors related to carbon emissions, applied to a specific case in China. Bragança *et al.* [21] tried to develop yet another method to elaborate a clearer and more standardized LCA method identifying and weighing a set of parameters for environmental performance of buildings. Ortiz *et al.* [22] reviewed the LCA methods development in the period 2000–2007, highlighting the interest of considering the full life cycle.

These studies are encouraging as they show the potential of practical LCA implementation, although they all agree on the need for further research to reach some form of reliable reference method that can be widely applied. There is a gap between the limited focus of normative guidelines and the urgent need to implement wider and more comprehensible assessment tools. Both the efforts of the EU and Spain can be largely limited if there is not a way to fill this gap. Furthermore, in the absence of legal obligation, these more comprehensive assessments are performed only on a voluntary basis in a very small fraction of the whole construction industry. That means less real experience, and fewer examples of practical application of these methodologies.

Research shows that, especially for the construction phase, case studies are essential to improve our knowledge base and understanding of the problem [17,19,24–27]. Khasreen *et al.* [17] compared 30 different case studies. Among them, 16 included the construction process impact. The results showed much heterogeneity, due not only to the different methodologies used in each case but to the wide number of circumstances that make each case unique. Ramesh *et al.* [24] reviewed 73 different cases across 13 countries, and concluded that the embodied energy of buildings accounted for between 10% and 20% of the total impact of buildings. Ma *et al.* [25] analyzed the environmental impact of an intelligent office tower in Tianjin, and estimated that construction process accounted for 32% of the total energy consumption in a lifespan of 50 years, although the percentage decreased with a longer lifespan. Zabalza *et al.* [19], in their case study of a low energy building in Spain, reported an energy consumption impact of 45.7% in the production and construction phase of a building, assuming a 50-year lifespan. In a different study, however, they found the building's embodied energy accounts for over 30% of the total impact [26].

Monahan and Powel [27] found a great potential for carbon impact reduction in residential buildings through the choice of better materials and construction techniques. It is true that case studies are limited and specific, and cannot be extrapolated without compromising their validity. However, they can help validate and improve the tools and methodologies we have so far, and give us an idea of the range of variability of the problem.

An additional question is to what extent it is important to include the wider context of the building in its study and assessment. Buildings are in cities, and rely on the infrastructure of streets and services that have to be built, maintained, and operated. In other words, sustainable buildings are a part of the sustainable city, and addressing only buildings overlooks an important aspect of the problem. City planning and urban design introduce layers of complexity that make it very difficult to apply the same methods used for buildings, due to the number and variety of agents involved, and the much longer time span needed for any action or decision. However, it is possible to enlarge the boundary of the study to include the immediate urban context, or a small neighborhood. Existing building green rating systems are developing and improving quickly and becoming more accepted by the building industry, and most of them offer models that go beyond the building itself to include the assessment of whole neighborhoods and even city planning.

LEED (or Leadership in Energy & Environmental Design) [28] offers a specialized Neighborhood assessment tool. BREEAM (Building Research Establishment Environmental Assessment Methodology) [29] also has a similar tool called BREEAM Communities. CASBEE (Comprehensive Assessment System for Built Environment Efficiency) [30]; in addition to developing an assessment method that includes buildings' immediate context, it offers two specialized modules, Urban

Development and Cities. All these tools, mentioned only as representative examples, attempt to be comprehensive and realistic; however, they differ greatly in their results. For example, Yoon and Park [31] compared the above three certification systems, and although the results were meaningful, and all three systems tend be balanced and comprehensive, they found significant differences among them due to the great variation among different urban cultures. Even though city and urban green certification methods keep improving and expanding, their implementation in real projects is still very limited.

1.2. Objectives and Outline of the Paper

In this context, the present paper has as its main objective a contribution to the pool of building LCA assessment case studies, where the available tools and information are enough to obtain fairly realistic results. To overcome the difficulty of deciding among many and diverse methods that are not yet fully tested, or to avoid undergoing a strict and burdensome certification process, this study also tries to use tools already common and familiar in the professional world: namely, a basic application of the LCA guidelines, with a clear delimitation of the scope of the study, and the use of tools and processes already well tested and established. Notwithstanding the evident limitation derived from the local character and the simplifications necessary in this methodology, this can be balanced by the possibility of immediate application and implementation by any professional in a wide range of cases. Environmental problems do not wait, and the 2020 deadline is just four years away. In order to provide valuable findings, this work attempts to fill the abovementioned gap between regulations and existing assessment tools, not only comparing building alternatives, but also including the construction phase and the immediate urbanization infrastructure, applied to a very specific case study. At this stage, resulting energy consumption and carbon emissions impact are the two parameters assessed, as they align with the EU 2020 agenda. The economic study of cost is intended as an additional merit of this case study, as it is an additional aid for real-world decision making.

Specifically, this paper studies an actually constructed housing cluster, and consists mainly of a comparison of two different alternatives to ascertain their advantages and disadvantages, and to aid in future planning and design decisions. Although this has been conducted with care and rigor, rather than precise calculations of absolute results, a reliable comparison between alternatives has been its main aim.

The specific objectives are as follows:

To analyze energy consumption during the preparation and construction process, during the periods of production, infrastructure, and construction, plus the energy consumption resulting from usage.

To compare two commonly used urban typologies, single family terraced housing and low density multi-family housing, for their sustainability especially related to their energy impact and CO_2 emissions.

To expand the sustainability study of both typologies over the first 10 years of use, which is the legal period for design and construction warrantee in Spain, and the period in which most renovations and improvements by owners begin.

To include efficiency comparison as a new decision criterion for urban design decision making, and provide necessary data for this.

To provide conclusions on sustainability criteria regarding typology planning, resource consumption in the urbanization process, land occupancy and providing free and green spaces, and construction and infrastructure cost comparisons.

After the present introduction of the normative framework and current knowledge review and the expression of the study objectives, the second section introduces the methodology of the study, explaining how the LCA assessment tools have been used in conjunction with the official software tools for energy efficiency; the third section describes the case study in detail; and the fourth section presents the results and discussion. Finally, the conclusions show the importance of this case study in particular, not only showing the usefulness of existing tools to go beyond the minimum legal requirements, but also highlighting unique findings that challenge intuitive deductions from existing knowledge, such as the occasional lack of relation between energy efficiency and emissions, or the great portion of energy consumed and emissions produced during construction.

2. Methods

LCA and Software Tools

LCA is based in the guidelines of UNE-EN ISO 14040 and 14044 [23]. The first step is to define a clear delimitation of the study boundaries. As sustainable buildings are part of the sustainable city, it is interesting to position our work within its wider context. For that purpose, Table 1 provides a general overview of the phases and parties involved in the creation of a sustainable city.

Table 1. General overview of aspects, agents, and contents of each phase of the creation of a sustainable city.

Sustainable City Design			
Agents	**Urban Planner** [1]	**Architect** [1]	**User** [4]
Document	Urban plan	Building project	User's manual
Actions	Planning	Building	Operation
Processes	Infrastructure	Construction/systems	Maintenance
Methods	Design and calculation		Regulation/control
Energy Consumption	Construction process energy consumption		Operation energy use
Assessment Parameters [2]	Production/transportation/construction Embodied energy		Energy consumption
	CO_2 emissions		
Assessment tools [3]	Life cycle assessment		
		Energy efficiency, and emissions impact labeling	
Result	Sustainability		Efficiency

[1] Design and planning, in the present research alternative planning and building typologies are studied; [2] Main assessment parameters for decision making, being the core of the present study; [3] Tools used for calculation and assessment, LCA includes just an estimation of future use. The user relies mainly on labeling and maintenance handbook; [4] The users' real behavior can be only estimated following current statistical tools. The present study covers only the first 10 years of lifespan.

The table shows the three main phases of sustainable city design and use with the specific agents involved in each. The most complex component is urban planning and design, as in addition to urban planners and designers it involves policymakers, public administrations, banks and large corporations, sociologists, citizens' associations, lawyers, and others that can participate and influence the final city planning and design.

A building project is more contained in terms of time, scope, and agents, and traditionally involves at least a client, an architect (and related consultants), and a contractor. In spite of the differing time frames, scale, and agents involved, both urban infrastructure and buildings need to be constructed, and have in common the production of a document (planning or project) that collects design and calculations (design methods in the table), and both share a production–transportation–construction process (the energy consumption row in the table) involving embodied energy and carbon emissions (the assessment parameters in the table), which can be assessed with similar LCA tools. They differ, however, in the methods and tools for assessing and rating energy efficiency and emissions impact during the use and operation period. These assessments are becoming standard procedure in buildings, although there are already tools to assess neighborhoods.

The final agent is the user, having mainly the option to use the city and building in an efficient manner, as they were intended to be used. At the city level we should consider different social groups as users whose behavior is very difficult to predict. At the building level the user is better defined, and the user's manual is the document that can ensure correct operation and maintenance, so the energy consumption and the emissions impact are within the project previsions.

In this context, the present work scope includes (i) the immediate context of the urban planning, namely, building typology selection and infrastructure design, construction, and maintenance; (ii) the building design and construction; and (iii) the use phase, assumed to be up to 10 years. In all these, the study concentrates on three factors: (a) energy impact; (b) carbon emissions impact; and (c) economic cost. There are obvious limitations to this approach, such as the uniqueness and specificity inherent to case studies and the reduction of the scope to energy, carbon, and economic cost. However, energy and carbon are two main research concerns, especially in an industry like construction, so a realistic economic study is also important to check the feasibility of the proposals.

Following the ISO 14040 and 14044 guidelines, we can relate the LCA life cycle phases of the building process as follows:

A. Production: A1–A3

Prime Materials Extraction (A1)
Transportation to Manufacture (A2)
Manufacturing (A3)

A. Building Process: A4–A5

Products Transportation (A4)
Installation and Construction Process (A5)

B. Use of the Product: B1–B7

Use (B1)
Maintenance (B2)
Repair (B3)
Replacement (B4)
Rehabilitation/Retrofitting (B5)
Energy Consumption (B6)
Water Consumption (B7)

C. End of Life Cycle: C1–C4

Deconstruction and Demolition (C1)
Transportation (C2)
Reuse and Recycling Management (C3)
Final Disposal (C4)

Figure 1 shows the whole process of the study graphically, with a clear division of the work into two stages: construction and use. The first stage, construction, includes an analysis of the lifecycle production period (A1 to A3) and the construction period (A4 to A5). For this stage, embodied energy, energy consumption, and CO_2 emissions are detailed, along with the economic cost of urbanization and construction. The following period of the life cycle consists of usage (B1), maintenance (B2), and energy consumption (B6) in the present study it is limited to a period of 10 years, for the reasons stated in Section 1.2, and also because it introduces too much variability and uncertainty, the evaluation of which would be beyond the scope of the present study.

The second part focuses on the more conventional process of defining and assessing the building energy and emissions performance in use, related mainly to phase B1 and, more specifically, to B6 of the LCA. From the data derived from the building project and local climate data, simulations are made to check the envelope requirements, calculate the yearly thermal loads, and proceed afterwards to design and calculate HVAC (heating, ventilation, and air conditioning) and DHW (domestic hot water) systems, concluding with an assessment of energy consumption, carbon emissions, and energy rating.

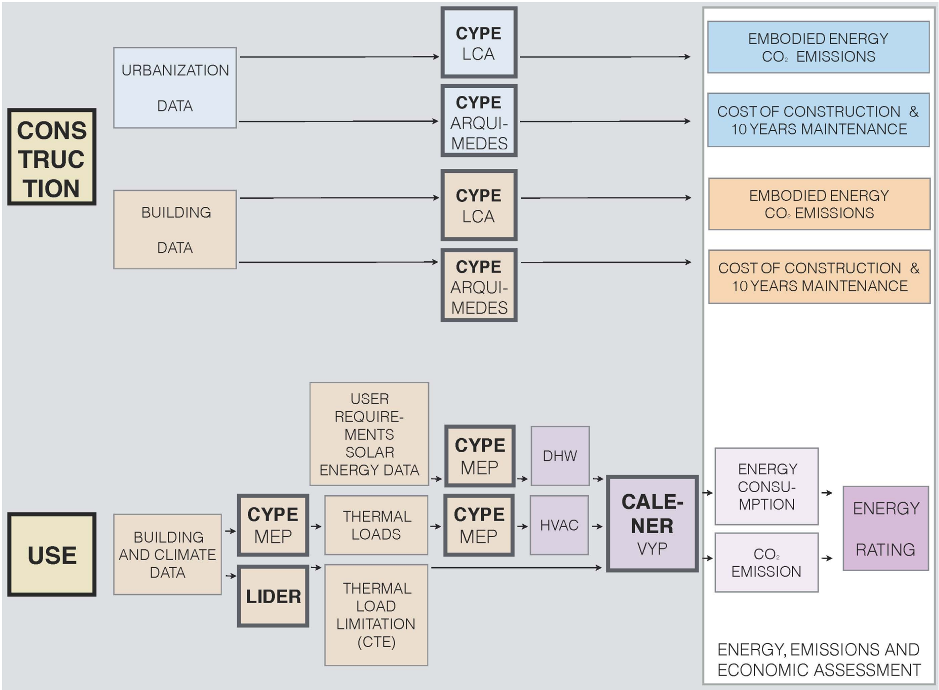


Figure 1. Diagram of the process followed in the present research.

For calculations, we used two sets of software. We first used the commercial package CYPE [32], specifically, three of its specialized modules: CYPE *Análisis de ciclo de vida* (here abbreviated as CYPE LCA) for embodied energy and carbon emissions assessment in phases A1 to A5, CYPE *Arquimedes* to prepare the bill of materials and bill of costs, and CYPE MEP for thermal load calculation, HVAC design, and dimensioning. With the input of geographical data and the precise dimensions and specifications of urbanization, infrastructure, and building units and their equipment, the program calculates economic costs, energy needs, and ecological burdens for the life cycle for up to 10 years of use, from an extensive and constantly updated proprietary database. The detailed relation of all units studied in the two alternatives for LCA is available for download in the Supplementary Materials section (see FileS1: LCABuildingUnits.pdf).

For the purposes of this study, local data from the region (Central Andalusia) for 2012 were used, as with the economic slowdown numbers have barely changed in recent years. All data for the units entered in the program, both for cost estimation and energy/emissions calculations, are classified in the following sections:

0. Previous interventions
D. Demolitions
A. Land preparation
C. Foundations
E. Structure
F. Facade
P. Partitions
I. MEP (Mechanical, electrical, and plumbing) and other technical systems
N. Insulation and waterproofing
Q. Roofs

S. Signaletics and equipment
U. Exterior spaces, urbanization, and landscape
G. Disposal management
X. Quality control
Y. Health and safety during construction period

The second set of software is provided by the Spanish government and composed of two complementary programs, LIDER (*Limitación de Demanda Energética*, Energy Demand Limitation) and CALENER VYP (*Calificación Energética para Vivienda y Pequeños Edificios Terciarios*, Energy Rating for Housing and Small Tertiary Buildings) [33]. Once the building and the envelope are well defined, the energy demand is calculated with LIDER, and after the HVAC and DHW systems are dimensioned and designed, the emissions and final classification are calculated with CALENER VYP. Both programs are based on DOE-2, well localized to each of the different regions and provinces of the country. The whole calculation process in each stage, with the input, tools, and output, is summarized in Figure 2.

PROCESS SUMMARY TABLE			
	OPTION A ONE FAMILY TERRACED HOUSING		
	OPCION B LOW DENSITY MULTI FAMILY HOUSING		
URBANIZATION	**PROCESS**		
	DESIGN WORK: URBANIZATION PROJECT, BILLS OF MATERIALS/QUANTITIES		
	ENVIRONMENTAL ANALYSIS (LCA A1-A5)		
	INPUT	TOOL	OUTPUT
	BILL OF MATERIALS, PRODUCTS AND COMPONENTS	CYPE (LCA software)	
	BILL OF QUANTITIES		EMBODIED ENERGY
			CO_2 EMISSIONS
	ECONOMIC ANALYSIS (LCA A1-B2 10 YEARS USE)		
	INPUT	TOOL	OUTPUT
	BILL OF QUANTITIES	CYPE (ARQUIMEDES)	URBANIZATION COST
			10 YEAR MAINTENANCE COST
BUILDING	**PROCESS**		
	DESIGN WORK: HOUSING TYPOLOGY ALTERNATIVES ANALYSIS, SELECTION AND DESIGN.		
	BUILDING ENVELOPE PERFORMANCE ANALYSIS, THERMAL LOADS ANALYSIS		
	INPUT	TOOL	OUTPUT
	ENVELOPE DATA	CYPE (CYPECAD MEP)	ENVELOPE THERMAL PERFORMANCE
	ENVELOPE DATA, BUILDING DATA	LIDER	THERMAL LOADS COMPLIANCE WITH CODE (CTE DB-HE)
	ENVELOPE DATA, BUILDING DATA	CYPE (CYPECAD MEP)	DETAILED THERMAL LOADS
	DETAILED THERMAL LOADS, BUILDING DATA	CYPE (CYPECAD MEP)	HVAC SYSTEM DIMENSIONING
	USERS REQUIREMENTS, SOLAR ENERGY DATA	CYPE (CYPECAD MEP)	DHW BOILER DIMENSIONING
	ENVIRONMENTAL ANALYSIS (LCA A1-A5)		
	INPUT	TOOL	OUTPUT
	BILL OF MATERIALS, PRODUCTS AND COMPONENTS	CYPE (LCA software)	
	BILL OF QUANTITIES		EMBODIED ENERGY
			CO_2 EMISSIONS
	ECONOMIC ANALYSIS (*LCA A1-B2 10 YEARS USE)*		
	INPUT	TOOL	OUTPUT
	BILL OF MATERIALS, PRODUCTS AND COMPONENTS	CYPE (ARQUIMEDES)	CONSTRUCTION COST
	BILL OF QUANTITIES		10 YEAR MAINTENANCE COST
USE	**PROCESS** (LCA B1, B6)		
	ENVIRONMENTAL ASSESSMENT. ENERGY EFFICIENCY AND EMISSIONS RATING. LABELING		
	INPUT	TOOL	OUTPUT
	THERMAL LOADS (FROM LIDER SIMULATIONS)	CALENER VYP (ENERGY RATING)	YEARLY ENERGY CONSUMPTION
	HVAC SYSTEMS DATA		YEARLY CO_2 EMISSIONS
	DHW BOILER DATA		ENERGY RATING and LABEL (A to E)
SUMMARY URBANIZATION + BUILDING + USE	**RESULTS**		
	ENVIRONMENTAL ASSESSMENT		
	TOTAL URBANIZATION AND BUILDING		
	EMBODIED ENERGY (LCA A.1-A.5)		
	ENERGY CONSUMPTION (LCA B6 10 YEARS USE)		
	CO_2 EMISSIONS DURING PRODUCTION AND BUILDING PROCESS (phases A.1-A.5)		
	CO_2 EMISSIONS IN USE (LCA B1 10 YEARS USE)		
	TOTAL COSTS (LCA A1-B2 10 YEARS USE)		
	URBANIZATION COST		
	BUILDING COST		

Figure 2. Summary of inputs, processes, tools, and outputs.

3. Description of the Case Study

In order to avoid a general and abstract discussion, this research takes an actual case, examining in detail the entire emissions balance (and how it may be related to energy efficiency) in a newly built residential cluster project in Mancha Real (Jaén, Spain), and the influences of different choices for urban typologies, in order to draw conclusions to better inform designers' decisions in future planning and construction. For comparison, two-floor terraced housing *versus* low-density, four-floor, multi-family housing alternatives have been studied, as they are among the most typical housing solutions in Spain.

3.1. Site and Urban Considerations

The site is a newly developed area south of the town (Figure 3). It is part of a project designed in 1999, part of which was built between 2000 and 2009. In the final year, construction activity stopped, leaving some phases on hold. The terraced housing typology was extremely popular in the 1980s, as it broke the image of impersonal and cheap high rise constructions of the post-war period and the later period of economic development in the 1960s and 1970s, providing a more classy, individual, and "civilized" dream house. Yet most Spanish towns keep considerable areas dedicated to this typology in their urban planning, making this choice still relevant for future planning revisions. However, in this case, a possible reactivation of urban developments in the area was a good motivation to explore alternative multi-family housing possibilities with greater efficiency. For the present study we concentrated on the housing blocks, excluding from the study the common facilities and park areas. The existing planning defines a residential polygon with an area of 31,300 m^2, with a total of 160 one-family terraced housing units distributed among five blocks of 20 units each, alternating with another five blocks of 12 units each (Figure 4). The summary of areas is in Table 2.

Figure 3. Satellite site view (Image © 2015 Digital Globe, Map Data © 2015 Google, Instituto Geográfico Nacional).

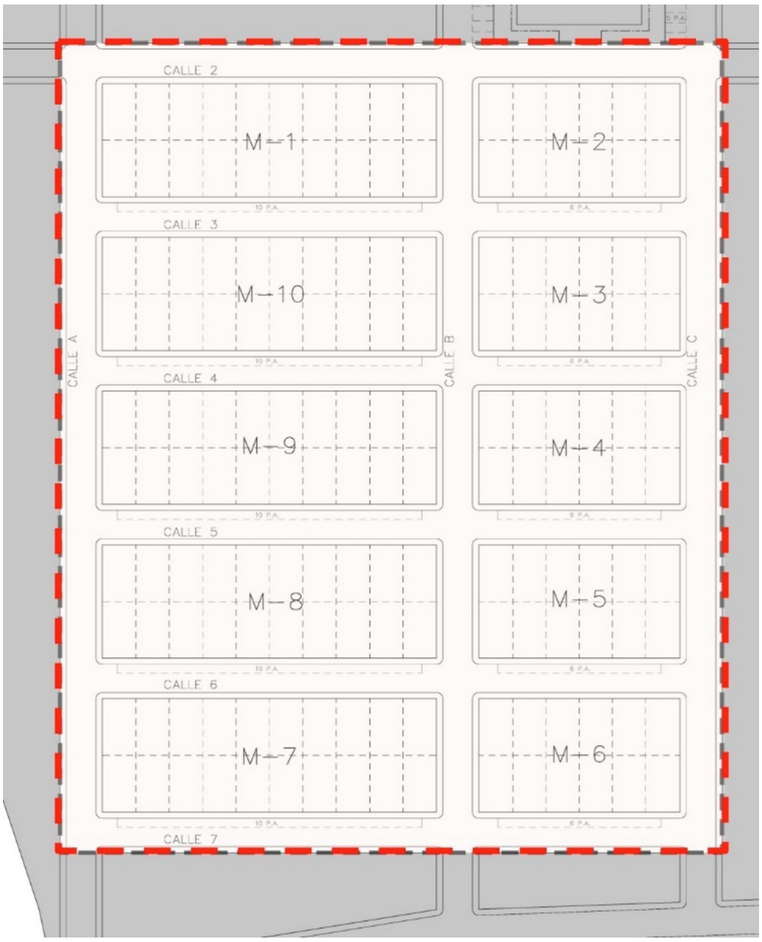


Figure 4. Studied polygon plan, showing the current planning of alternating blocks of 20 and 12 units, numbered M-1 to M-10.

Table 2. Existing planning areas summary.

Zoning	Area (m^2)	Number of Plots	Total (m^2)
20-unit housing plots	2212	5	11,060
12-unit housing plots	1330	5	6650
Street area	13,590	-	13,590
Total			31,300

Although the present study follows the main guidelines for the current planning and construction, for an easier comparative analysis we slightly retouched the blocks, for a total of 10 identical clusters of 16 houses each (Figure 5). This typological proposal was our reference typology. To define the multi-family housing typology, since density impact is not the purpose of this study, and to facilitate comparison, we kept the same number of housing units. Otherwise, Spanish planning traditionally fixes the housing units per hectare (1 Ha = 10,000 m^2). Altering this parameter is possible, but this requires a long legal process, as this is a basic principle and alteration has to be approved by the autonomous government [34]. On the other hand, changing only the building typology while keeping density can be accomplished through a much faster and easier process, and can be approved directly by the municipality, so it is realistic to consider this as a possible alternative in short-term planning decisions.

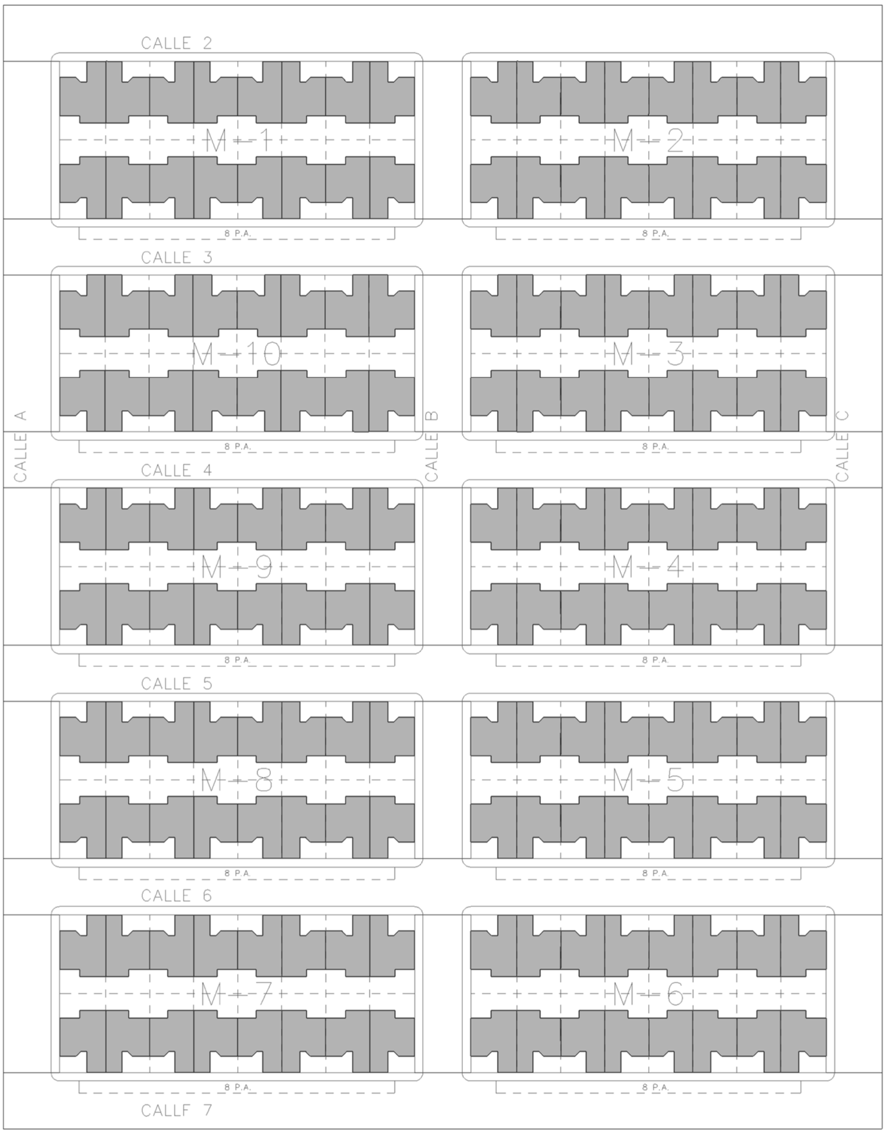


Figure 5. Terraced housing planning with equal clusters of 16 units.

3.2. *Typology Choices and Definition*

To explore typological alternatives, we kept as a reference the existing design and room dimensioning and composition. We updated all the HVAC systems as well as envelope quality and performance to present-day standards [8]. The dwelling units are composed of three bedrooms and a bathroom on the upper floor, and a living/dining room with a kitchen and a small toilet on the lower floor, for a total of 108 m^2 of floor area. Additionally, they all have a parking space of about 19 m^2 on the ground floor. This size and composition is typical for this kind of housing, in the more economical and affordable versions. We did not change this, as it is familiar and easy to manage in our calculations. Therefore, we did not enter into discussions about innovating typologies (new and more efficient designs for new ways of life) or reducing the floor area, although this could be a subject for further study. As we mentioned above, this was our reference house unit, grouped in paired rows of eight units, for a planned cluster of 16 units per town block. We called this typology Alternative A (Figures 5 and 6). For wider reference, similar houses in semi-detached and detached versions were analyzed in terms of area, volume, and compactness for preliminary comparison.

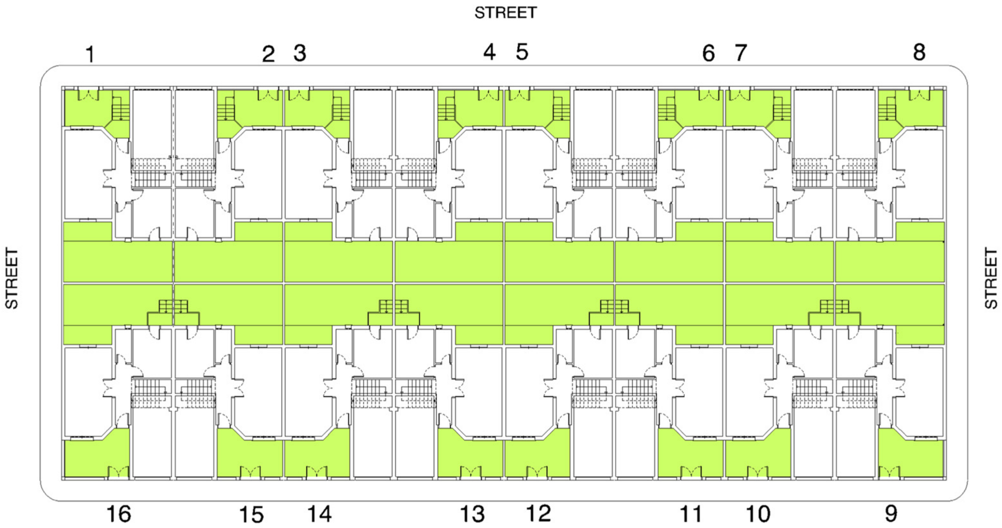
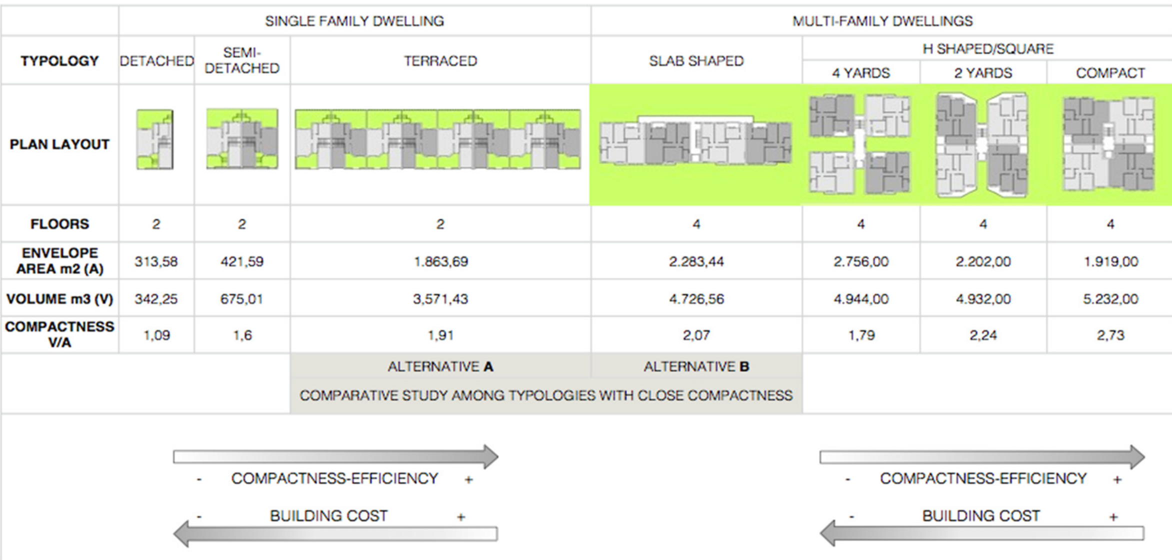


Figure 6. Detail of Alternative A based on a row of eight houses (half a cluster).

The alternative typology chosen for comparison is a low density, four-floor, multi-family building. For comparable elements, the housing units are similar in size and composition to their counterparts. The car parking spaces are provided in a common semi-basement parking area, with the ground floor raised half a floor over ground level. Parking spaces are between 20 and 25 m^2 per car. Several alternatives to four-floor blocks with four units per floor building typologies were studied: an H-shaped block with four open yards, an H-shaped block with two open yards, compact square blocks, and slab-shaped or open linear blocks. All alternatives and their parameters are summarized in Figure 7 below. Among these, we chose the last one, as it provides cross-ventilation and a similar orientation of all units for optimum sunlight planning, and the combination of compactness and general proportion and orientation is the closest to the terraced housing solution we are comparing with. We called this Typology B (Figures 8 and 9). Table 3 shows the resulting areas for housing and streets in both alternatives (Figure 7). The complete set of urbanization and architectural drawings is available for download in the Supplementary Materials section (see FileS2: AltA_Drawings.zip, FileS3: AltB_Drawings.zip).



	SINGLE FAMILY DWELLING			MULTI-FAMILY DWELLINGS			
TYPOLOGY	DETACHED	SEMI-DETACHED	TERRACED	SLAB SHAPED	H SHAPED/SQUARE 4 YARDS	H SHAPED/SQUARE 2 YARDS	COMPACT
PLAN LAYOUT							
FLOORS	2	2	2	4	4	4	4
ENVELOPE AREA m2 (A)	313,58	421,59	1.863,69	2.283,44	2.756,00	2.202,00	1.919,00
VOLUME m3 (V)	342,25	675,01	3,571,43	4.726,56	4.944,00	4.932,00	5.232,00
COMPACTNESS V/A	1,09	1,6	1,91	2,07	1,79	2,24	2,73
			ALTERNATIVE **A**	ALTERNATIVE **B**			
			COMPARATIVE STUDY AMONG TYPOLOGIES WITH CLOSE COMPACTNESS				

Figure 7. Summary of typologies, with basic parameters of envelope, area, volume, and compactness.

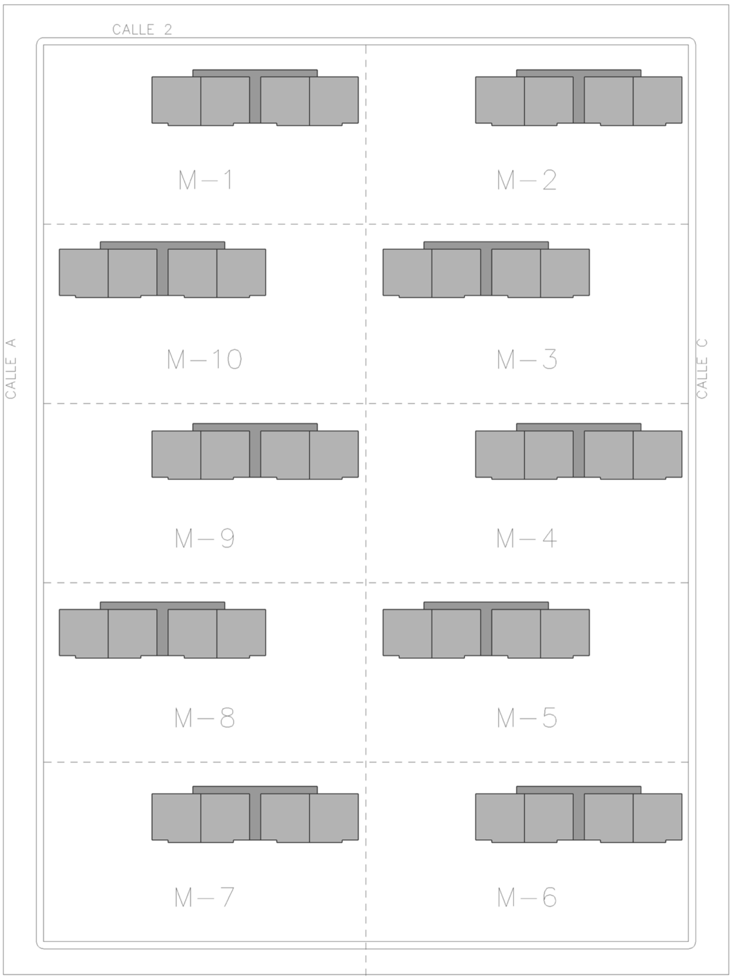


Figure 8. Alternative B, resulting street and 10 plots layout (numbered M-1 to M-10), each of them holding one multi-family building with 16 dwelling units.

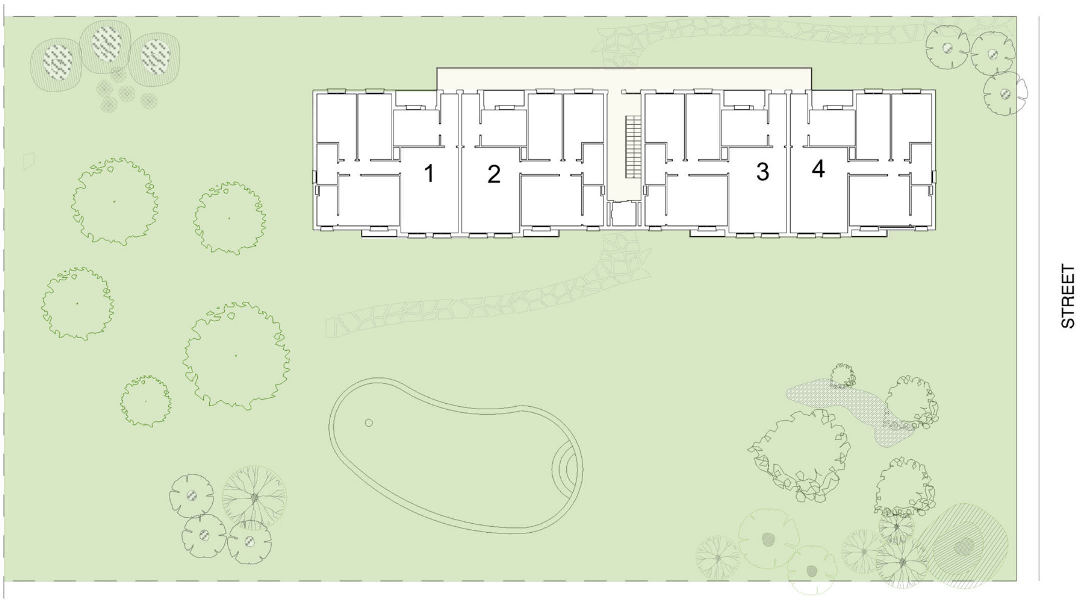


Figure 9. Floor plan detail of Alternative B building in its plot, with four units per floor, and a total of 16 dwelling units per building.

Table 3. Alternatives A and B resulting areas.

Zoning	A-Area (m^2)	Number	Total (m^2)	B-Area (m^2)	Number	Total (m^2)
Plot Area	1772.4	10	17,724	25,932.5	10	25,935
Street area	13,576	1	13,576	5365	1	5365
Total site			31,300			31,300
(m^2 street)/(m^2 plot)			0.77			0.21
Built floor area	2000.27	10	20,002.7	2252.72	10	22,527.2

3.3. Envelope and HVAC systems Definition

The envelope specifications are defined according to the CTE documents for energy efficiency [8]. CYPE MEP calculates the envelope performance. With the input of the building envelope data, the description of each of the building spaces to be heated/cooled, and the climatic data in the software database, CYPE MEP calculates the complete list of thermal load and LIDER checks the compliance with CTE requirements. With the thermal loads input, CYPE MEP helps with designing and dimensioning the HVAC systems. Two HVAC (heating, ventilation, and air conditioning) alternatives have been checked to compare their differing impact on costs and emissions:

I Air–air heat pump for heating and cooling
II Biomass heating with radiators and air-water heat pump system for cooling.

The DHW heating is calculated based on an estimation of the users' consumption and solar radiation data. The main energy source is a set of solar panels installed on the roof. Alternative I includes electrical backup by Joule heating. Alternative II is studied in two variations, IIa also with a Joule heating backup, and IIb with a biomass boiler backup. Table 4 summarizes the HVAC and DHW backup energy systems alternatives. The technical documents related to this section are available for download in the Supplementary Materials section as follows:

- FileS4: Envelope_Definition; Detailed description of the envelope.
- FileS5: Envelope_CTE; Justification for compliance with the CTE thermal requirements
- FileS6: Thermal_Loads: Summary of the thermal loads used in the calculations.
- FileS7: Solar_DHW; Solar energy DHW production calculations.

Table 4. Summary of HVAC and DHW backup energy systems alternatives.

	TYPOLOGY A	TYPOLOGY B
HVAC OPTION I	**Heating and cooling: Air-air heat pump**	
	System air-air Split 1 × 1 SCM 60ZJ MITSUBISHI nominal power 7.5 Kw. EER 3.41	System air-air Split 1 × 1 FDC 71VNX MITSUBISHI nominal power 7.1 Kw, EER 3.41
	2 Fan-coil (one per floor) SRR 35Z MITSUBISHI nominal power 3.5 Kw each	1 fan-coil FDN 71V MITSUBISHI nominal power 7.1 Kw
	Air ducts with impulsion and return in rooms	air ducts with impulsion and return per room
HVAC OPTION II	**Heating:** Biomass heating with radiators. **Cooling:** air-water heat pump system	
	Heating	
	biomass boiler CLIBER-GILLES, model HPK-RA 20, with annex pellet storage and continuous feed by non-end screws	biomass boiler CLIBER-GILLES, model HPK-RA 140, with annex pellet storage and continuous feed by non-end screws
	hot water aluminum radiators with impulsion and return pipes	hot water aluminum radiators with impulsion and return pipes
	Cooling	
	air-water system equipment on roof CIAT-RTBH, power 5.80 Kw 1 ceiling fan-coil CIAT, series KCN power 5.20 Kw	air-water system equipment on roof for air conditioned CIAT-RWB, power 59.5 Kw 1 ceiling fan-coil per apartment CIAT, series KCN, power 5.20 Kw
	air distribution by ducts with impulsion and return in each room	air distribution by ducts with impulsion and return in each room
DHW option I and IIa	Solar Panels + Electric Joule Heat backup	
DHW option IIb	Solar Panels + Biomass Boiler Backup	

4. Results and Discussion

4.1. Energy and Emissions Study in the Different Stages of the LCA

4.1.1. Urbanization and Construction (LCA Stages A1 to A5)

The results of the calculations for embodied energy and carbon emissions from infrastructure construction (stages A1 to A5 of LCA) are summarized in Table 5 for the two alternatives. Details are included in Appendix A, Tables A1–A4.

Table 5. Summary of urbanization embodied energy and CO_2 emissions.

Urbanization Energy and Emissions Impact		
Typology	A	B
Embodied Energy (kWh)	8,933,114	3,324,881
CO_2 Emissions (kg)	3,318,170	1,221,450

In the same manner we calculated the results for energy consumption (embodied energy) and carbon emissions from the building construction (stages A1 to A5 of LCA), as detailed in Table 6 below. Details are included in Appendix A, Tables A5–A8.

Table 6. Summary of urbanization embodied energy and CO_2 emissions.

Construction Energy And Emissions Impact		
Typology	A	B
Embodied Energy (kWh)	45,878,596	35,042,540
CO_2 Emissions (kg)	14,539,800	11,195,000

4.1.2. Operation in the First 10 Years (LCA Stages B1, B6)

Alternative I: Air–air heat pump for heating and cooling. Hot solar water with Joule effect backup. A description of the HVAC and DHW systems is provided in Section 3.3. For Alternative II, the CALENER VYP assessment program estimated the energy demand and emissions, and provided the energy qualification labels. *Alternative IIa: Biomass heating with radiators and air–water heat pump system for cooling. Hot solar water with Joule heat effect backup*. With the data in Section 3.3, the yearly demand estimation and rating labels were calculated with the CALENER VYP assessment program as in the previous case. *Alternative IIb: Biomass heating with radiators and air-water heat pump system for cooling. Hot solar water with biomass boiler backup*. This variation was made to improve the emissions reduction for a better qualification.

Table 7 summarizes the CALENER VYP results, for the entire set of 160 dwelling units in the first 10 years of use. The CALENER VYP detailed output labels are included in Appendix B, Figures B1–B6.

Table 7. Summary of CALENER VYP results of energy and emissions impact during building use (10 years).

Energy and Emissions Impact in the Building Use Period (10 Years)				
		ALT I.	**ALT II.a**	**ALT II.b**
Typology **A**	Energy consumption (kWh)	13,575,520	21,363,400	19,508,490
	CO_2 emissions (kg)	3,383,040	1,407,060	641,020
	EMISSIONS RATING	**C**	**B**	**A**
Typology **B**	Energy consumption (kWh/year)	11,523,890	15,008,100	13,778,330
	CO_2 emissions (kg/year)	2,880,520	1,082,330	590,360
	EMISSIONS RATING	**D**	**B**	**A**

In order to facilitate the discussion, all data in the previous tables and images have been summarized in Table 8, for all the lifecycle stages studied, with typologies A and B side by side.

The first part of the table is straightforward, and the results are not surprising. Even though the multi-family typology calls for about 10% more built area, due to its compactness and reduced needs for urban infrastructure (streets and services, 13,576 m^2 for typology A, and 5365 m^2 for typology B), the energy and emissions impact is considerably smaller than for the single family typology. In the urbanization stage the differences are considerable. Typology A consumes nearly 170% (2.69 times) more energy, with emissions also 172% (2.72 times) CO_2 higher than Typology B. In the building stage the differences are also remarkable, although less dramatic. Typology A consumes almost 31% more energy, and emits almost 30% more CO_2 than Typology B.

The 10-year energy use required a deeper analysis, as there are many alternatives for heating and cooling systems. The building envelope was defined based on the legal standards for lower thermal loads, as for comparison the important factor is that both typologies have similar solutions. Thermal loads (heating and cooling) are not detailed here in the interest of brevity, and Table 8 provides only the results of the total primary energy used and total carbon emissions for each HVAC alternative (I and II) described in Section 3.3 above. Hot water requirements depend on the users, and therefore are the same in both typologies. Solar heat collection with either an electrical backup (Joule heat effect) as in Alternative I and IIa or a biomass boiler as in Alternative IIb was studied. Even though the hot water energy demands are very modest compared to heating and cooling, the backup proved to have a significant impact on the total primary energy and especially on carbon emissions.

The later section of Table 8 provides results for 10 years of energy consumption and carbon emissions, and adds them to the infrastructure and construction impact for three different totals for Typologies A and B, one for each alternative studied. The first alternative (Alt. I) proved counter-intuitive, as being the most energy efficient it resulted in a very mediocre emissions mark (C for the single family unit, with over 169 kg of CO_2 per m^2 of building, and D for the multi-family unit, with 130 kg of CO_2 per m^2 of building over 10 years). With more efficient energy use, due to the electricity production in Spain (which in spite of its modernization efforts still heavily relies on thermal centrals), this has as a result a more mediocre primary energy efficiency than expected (but better than the other alternatives), and the worst carbon emissions results of all. When comparing typologies, not surprisingly B is always more efficient than A, in both consumption and emissions.

Alternative IIa with a biomass boiler resulted in a better emissions mark (B for both, with a greatly reduced 70 kg of CO_2 per m^2 of building in a single family typology, and 49 kg of CO_2 per m^2 in a multi-family building over 10 years). However, since this improvement attained only a B, we studied how to further reduce emissions with Alternative IIb. At this stage, even the very modest energy consumption of the domestic hot water contributed to this result. By changing the electrical backup in the hot water tank for a biomass boiler backup, emissions mark A was reached, with a carbon emission near ideal (32 kg of CO_2 per m^2 of a single family typology, and 27 kg of CO_2 per m^2 of a multi-family building over 10 years). However, when compared to the Alternative IIa results, we found that the CO_2 savings did not compensate for the higher energy consumption, and decided on Alternative IIa for our comparative study with the economic cost analysis.

Table 8. Comparison of embodied energy and carbon emissions LCA for Typologies A and B.

Typology	Single-Family Housing		Multi-Family Housing	
Alternatives	Typology **A**		Typology **B**	
Total Built Area (m^2)	20,003		22,227	
	per m^2	total	per m^2	total
Urbanization and Infrastructure				
Embodied Energy (kWh)	447	8,933,114	150	3,324,881
CO_2 emissions (kg)	166	3,318,170	55	1,221,450
Building Construction				
Embodied Energy (kWh)	2,294	45,878,596	1,577	35,042,540
CO_2 emissions (kg)	727	14,539,800	504	11,195,000
10 Years USE				
ALT I. Cooling and Heating W/Heat Pump air-air, DHW (SOLAR + JOULE)				
EMISSIONS LABEL	C		D	
Primary Energy Use (kWh)	679	13,575,520	518	11,523,890
CO2 emissions (kg)	169	3,383,040	130	2,880,520
Urbanization + Build + 10 Years USE				
Total Energy kWh	3,419	68,387,230	2,245	49,891,311
Total CO_2 kg	1,062	21,241,010	689	15,296,970
10 Years USE				
ALT IIa Biomass Heating, Heat Pump Cooling, DHW (SOLAR + JOULE)				
Emissions Label	B		B	
Primary Energy Use (kWh)	1,068	21,363,400	675	15,008,100
CO_2 emissions (kg)	70	1,407,060	49	1,082,330
Urbanization + Build + 10 Years USE				
Total Energy kWh	3,808	76,175,110	2,401	53,375,521
Total CO_2 kg	963	20,005,730	607	13,498,780
10 Years USE				
ALT IIb Biomass Heating, Heat Pump Cooling, DHW (SOLAR + BIOMASS)				
Emissions Label	A		A	
Primary Energy Use (kWh)	975	19,508,490	620	13,778,330
CO_2 emissions (kg)	32	615,820	27	590,360
Urbanization + Build + 10 Years USE				
Total Energy kWh	3,970	74,320,200	2,654	52,145,751
Total CO_2 emissions kg	963	18,473,790	585	13,006,810

The above discussion is graphically depicted below (Figures 10 and 11), where one can readily observe that in the alternatives studied, energy and carbon efficiency are not related (they are actually inversely related in some cases), although results may vary for more alternatives or other countries with different electrical production systems. Apart from the improvements in energy use over the 10 years period, it became evident that the largest energy and emissions impact occurs during the infrastructure and construction process. In our example, only changing the typology brought energy and emissions benefits of 334 kg of CO_2 per m^2 of the multi-family building, much larger than what can be gained over 10 years (or more) of very efficient operation (as in the 22 kg of CO_2 per m^2 saved in typology B when changing from Alt. IIa to Alt. IIb). Furthermore, larger gains in operational efficiency will bring very modest benefits, while construction and urbanization still have much room for improvement.

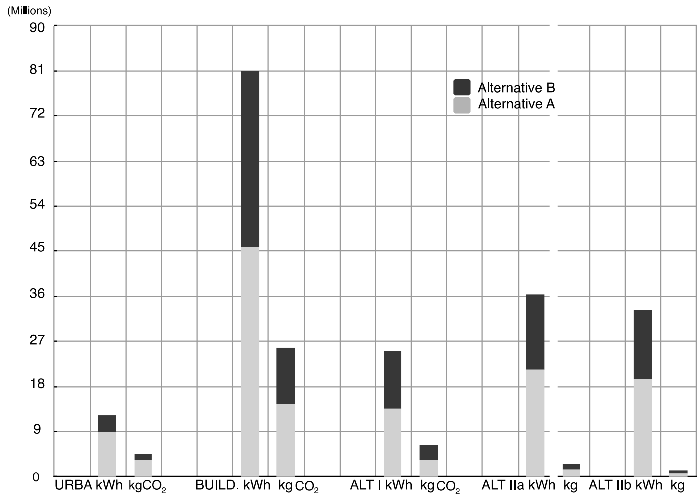


Figure 10. Comparison of energy consumption (**left column**) and CO_2 emissions (**right column**) in the phases of infrastructure construction, building, and 10 years of operation under three alternatives. Values for Typology A are in light grey, and those for Typology B are in dark gray. Numbers are total absolute values in kWh and kg of CO_2 for 10 years of operation of the 160 housing units.

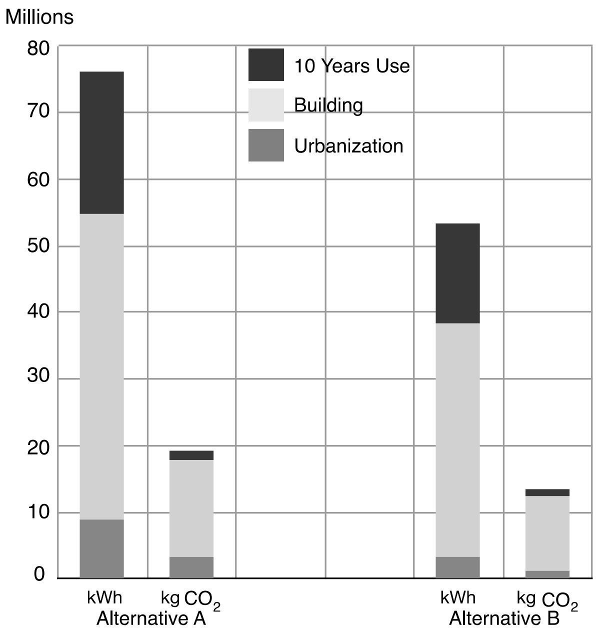


Figure 11. Comparison of energy consumption and CO_2 emissions, for urbanization (medium gray), construction (light gray), and 10 years of operation (dark gray), with Typology A on the left and Typology B on the right. The graph is simplified and only shows results for Alternative IIa. Numbers are total absolute values in kWh and kg of CO_2. The greater impact of the building construction period is clear, for carbon emissions.

Figure 12 shows the percentage of carbon impact in urbanization, building, and 10 years' operation. The embodied carbon footprint in the urbanization and construction process is 92% to 93% of the total in the first 10 years of use.

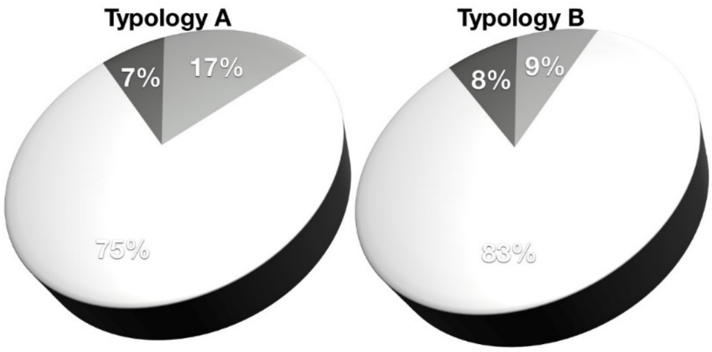


Figure 12. Percentage of carbon impact in urbanization (medium gray), construction (light gray), and 10 years of operation (dark gray), Typologies A and B. Graph simplified for Alternative IIb.

4.2. Economic Study

The total monetary cost in euros has been calculated for the chosen Alternative IIa in both typologies, with a summary in Table 9. Detailed calculations of the costs are available for download in the Supplementary Materials Section:

FileS1: LCA Building units
FileS8: Urbanization costs estimation
FileS9: Urbanization 10-year maintenance cost
FileS10: Typology A construction cost estimate (16 units)
FileS11: Typology B construction cost estimate (one building)
FileS12: Building maintenance cost

Table 9. Comparative total costs of both typologies, in euros.

Typology	**Single-Family Housing**		**Multi-Family Housing**	
Alternatives	**Typology A**		**Typology B**	
Total Built Area (m^2)	20.003		22.227	
	per m^2	total	per m^2	total
URBANIZATION A1 to A5 (€)	59.56	1,191,378.68	20.49	455,431.23
URBANIZATION B1 to B2 (€)	10.52	210,431.56	3.68	81,795.36
BUILDING A1 to A5 (€)	830.55	16,613,491.65	610.87	13,577,807.49
BUILDING B1, B6 (€)	215.74	4,315,447.22	142.14	3,159,345.78
TOTAL COSTS (€)	**1,116.37**	**22,330,749.11**	**777.18**	**17,274,379.86**

For simplicity and to facilitate further comparisons, economic estimates are calculated over the real material cost of materials, equipment, and construction. Further cost variables, such as VAT and contractor costs and benefits, have been excluded. For VAT, the tax rate has not only changed several times over the years, but will likely continue to do so in the future according to political and economic circumstances. Even in the same time period, VAT is not applied homogeneously. For example, in 2015, the purchase of a newly built house was assessed a 10% VAT, but if the house was subject to any public subvention, the charge was only 4% [35]. This led to a complication beyond the scope of the present study, which is centered construction cost. For contractor costs and benefits, e.g., contracts with public administrations, the tender must add 6% as a benefit and 13% as overhead and exploitation costs over the net cost [16]. For private construction in the free market these percentages change significantly.

As expected, the costs for Typology B are more contained, with the largest difference in infrastructure (with a ratio close to 3:1) and a considerable difference in building construction and maintenance, with Typology A being on average over 41% more expensive than Typology B when comparing unitary costs, and near 30% when comparing total costs.

The energy costs of heating and cooling and hot water are included in the totals in the last line of Table 9, comprising stages B1 and B6 of the life cycle period. It is noteworthy that the biomass equipment is considerably more expensive than the simpler heat pump system. For Typology A, the total cost increase was estimated at €190,000 (almost 3.5 times more expensive), and for Typology B, €94,000 (2.25 times higher). However, even when the energy efficiency of the biomass boilers is smaller, the price difference between electricity and biomass fuel at the time of the study accounted for considerable savings (almost €25,000 per year in Typology A, and €13,500 per year in Typology B). If the relative price difference persists over time, the higher cost of the heating system can pay for itself before the end of the 10-year period studied (we roughly calculated this at constant money value, for around 7.5 and 7 years, respectively). Lower operation costs can be an additional incentive, along with lower carbon emissions. We only need both developers and users to consider the long term, not the immediate upfront costs, which is not easy in a strained market.

4.3. Other Considerations

In addition to the clear ecological benefits of the small collective housing over the individual single-family terraced housing, there are more variables to be considered for final planning decisions. It is sufficient to compare the resulting plans of one block of terraced housing and one block of multi-family houses to ascertain differences in the resulting house and urban space definitions (Figures 5–8). The drawings are to be considered diagrammatic, as we did not intend to make an ideal design, simply a suitable typological object defined well enough for this study. Suitable design can produce acceptable results in any of the typologies, but we did not consider that factor.

In comparing both plans, we can see the advantages of Typology A. Living directly on the grounds, having total ownership of the building and land, direct access from the street, and an individual parking space, without depending on elevators or common stairs, are popular features. The negative aspects are the narrowness of the open spaces, the complete absence of communal green areas, relatively reduced privacy due to neighbors' windows being very close, and the limitations in design, as the space is so tight that few variations are possible in massing or building disposition. For accessibility, the second floor is always limited, as the only possible access is via the stairs.

Collective housing offers more distance from streets and safer, wider pedestrian and communal green areas. The abundance of space provides sufficient freedom to change the block design and position to adapt to topography or other circumstances. An elevator would make all floors accessible, and more distance between windows would provide more privacy between buildings. Some negative aspects are the shared ownership with permanent negotiation of costs and management, the added cost of maintaining large green spaces, the privacy problems of having many surrounding neighbors, and the sense of isolation, as one must choose between being outside the building in an open space, or confined inside the apartment.

5. Conclusions

Table 10 summarizes the basic results of the study. The analysis clearly shows the advantage of multi-family housing typologies over single-family terraced housing typologies, in terms of both economic and ecological costs. The multi-family typology also allows for more opportunities for communal activity and shared spaces, which also count as desirable social sustainability features. Therefore, we consider it advisable to consider adopting this typology in existing planned areas where short or midterm decisions must be made without changing the densities established by law. If demand for terraced housing still exists, we would suggest keeping the proportion of these relatively small in order to provide variety, while clearly informing the users of the impact and costs of this typology.

Table 10. Summary of the comparative ecological and economic costs of both typologies.

Typology	Single-Family Housing		Multi-Family Housing		Comparison	
Alternatives	**Typology A**		**Typology B**		**(ALT A)/(ALT B)**	
	per m^2	total	per m^2	total	per m^2	total
Total Built Area (m^2)	20,003		22,227		0.90	
Green Space (m^2)	0.3	6001	0.96	21,338	0.31	0.28
Total energy (10 years, kWh)	3,808	76,175,110	2,401	55,375,521	1.59	1.43
CO_2 emissions (10 years, kg)	963	19,265,030	607	13,498,780	1.59	1.43
Cost (10 years, €)	1135.75	22,718,407.25	753.02	16,737,375.54	1.51	1.36

A second important finding is the necessity of studying energy saving systems in detail for each alternative, and the need to also know the real impact of the primary energy produced. In this case, the results have been counter-intuitive. We were surprised to see that in some cases less energy consumption produced more CO_2 emissions, when we would think the numbers are directly correlated. Different countries or even regions, and different times may completely change the results, especially for the type of electricity used. In Spain, electricity production is still largely through dirty and low efficiency means, producing disappointing results, even with the implementation of the most modern and efficient HVAC control systems.

A third unintended but surprising finding was the extremely high impact of construction in the context of the whole life cycle analysis. The correct typology choice greatly reduced the ecological impact of the urbanization and construction phases. The embodied energy and emissions of this phase are enormous. In the first 10 years of LCA in this case they account for more than 90%; simply by deciding on the optimal typology, this can be reduced by 1.55. Therefore, building and urban typologies deserve much more attention, as their impact-reducing potential can be very significant. While we need to keep working on progressive improvements in the efficiency of buildings in their use stages, as we approach zero or near zero emissions buildings, we see that the potential gains made beyond what has already been achieved are relatively modest compared to the remaining impact of the construction process.

Finally, the present case study helped to add relevant data to existing research on the subject, so this can be useful in understanding the impact of early design and small-scale planning decisions, and the impact of the construction process. The methodology used relies on available tools and can be easily applied to different cases, producing comparable results and overcoming one of the difficulties of present research. This demonstrated meaningful energy and carbon assessments, and can fill the gap between the legal requirements and the wider environmental improvements needed in construction. Furthermore, the inclusion of a detailed economic study provides additional help in decision making. Further study is needed to compare these results with outputs obtained from different methodologies. Also, further research can work on identifying specific materials and processes that could reduce construction's environmental impact.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/8/3/287/s1, FileS1: LCABuildingUnits; Detailed relation of construction units for LCA; FileS2: AltA_Drawings.zip; Complete collection of Architectural Drawings, Alt. A; FileS3: AltB_Drawings.zip; Complete collection of Architectural Drawings, Alt. B; FileS4: Envelope_Definition; Detailed description of the envelope; FileS5: Envelope_CTE; Justification for compliance with the CTE thermal requirements; FileS6: Thermal_Loads: Summary of the thermal loads used in the calculations; FileS7: Solar_DHW; Solar energy DHW production calculations; FileS8: Urbanization costs estimation; FileS9: Urbanization 10 Year Maintenance Cost; FileS10: Typology A Construction Cost Estimate (16 units); FileS11: Typology B Construction Cost Estimate (One building); FileS12: Building maintenance cost.

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Author Contributions: Antonio Ángel Rodríguez Serrano developed the original research, performed all calculations and discussed the results. Santiago Porras Álvarez reviewed and checked the calculations, completed the references, summarized the research and wrote the article.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A: LCA Detail of Embodied Energy and Carbon Emissions for Urbanization and Building, Stages A1–A5

In the tables below, the letters in the first column "Chapters" have the following meaning:

0. Previous interventions
D. Demolitions
A. Land preparation
C. Foundations
E. Structure
F. Facade
P. Partitions
I. MEP (Mechanical, electrical, and plumbing) and other technical systems
N. Insulation and waterproofing
Q. Roofs
S. Signaletics and equipment
U. Exterior spaces, urbanization, and landscape
G. Disposal management
X. Quality control
Y. Health and safety during the construction period

The results of the calculations for energy consumption (embodied energy) and carbon emissions of infrastructure construction (stages A1 to A5 of LCA) are detailed in Tables A1–A4 for each of the two alternatives A and B. From now on, for clarity, the data in tables related to Typology A are written in blue, while data related to Typology B are written in green. The results are summarized as follows: Typology A urbanization total embodied energy in stages A1 to A5 is 31,903,977.64 MJ × 0.28 ≈ 8,933,114 kWh (rounding 1 MJ ≈ 0.28 kWh); urbanization total CO2 emissions in stages A1 to A5 is 3,318.17 tons. Typology B urbanization total embodied energy, stages A1 to A5 is 11,874,576.65 MJ × 0.28 ≈ 3,324,881 kWh; urbanization total CO2 emissions in stages A1 to A5 is 1,221.45 tons.

Table A1. Embodied energy during urbanization construction (MJ) in Typology A.

Typology A. Embodied Energy (MJ)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (MJ)**
A	2,114,928.57	58,385.91	953,275.36	3,126,589.84
U	15,132,949.59	316,360.03	10,745,621.89	26,194,931.51
I	2,539,693.70	34,535.00	8,227.59	2,582,456.29
Total	19,787,571.86	409,280.94	11,707,124.84	**31,903,977.64**

Table A2. CO_2 emissions during urbanization construction (tons) in Typology A.

Typology A. CO_2 Emissions (ton)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (ton)**
A	265.17	4.32	70.57	340.06
U	1860.47	23.42	795.25	2679.14
I	295.79	2.55	0.63	298.97
Total	2421.43	30.29	866.45	**3318.17**

Table A3. Embodied energy during urbanization construction (MJ) in Typology B.

Typology B. Embodied Energy (MJ)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (MJ)**
A	516,384.14	17,713.88	454,226.17	988,324.19
U	5,861,637.16	123,082.09	4,133,813.17	10,118,532.42
I	754,897.30	9,795.39	3,027.35	767,720.04
Total	7,132,918.60	150,591.36	4,591,066.69	**11,874,576.65**

Table A4. CO_2 emissions during urbanization construction (ton) in Typology B.

Typology B. CO_2 Emissions (ton)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (ton)**
A	62.29	1.31	33.63	97.23
U	721.13	9.11	305.93	1036.17
I	87.10	0.72	0.23	88.05
Total	870.52	11.14	339.79	**1221.45**

The results for energy consumption (embodied energy) and carbon emissions of the buildings construction (stages A1 to A5 of LCA) are detailed in Tables A5–A8. The results are summarized as follows: Typology A building total embodied energy in stages A1 to A5 is 16,385,213.03 MJ × 0.28 × 10 ≈ 45,878,596 kWh (rounding 1 MJ ≈ 0.28 kWh, and multiplying by 10 clusters of 16 units); building total CO2 emissions in stages A1 to A5 is 1,453.98 tons × 10 = 14,539.8 tons (result for 160 units). Typology B building total embodied energy in stages A1 to A5 is 12,515,193.09 MJ × 0.28 × 10 ≈ 35,042,540 kWh (rounding 1 MJ ≈ 0.28 kWh, and multiplying by 10 buildings of 16 units); building total CO2 emissions in stages A1 to A5 is 1,119.50 tons × 10 = 11,195 ton (result for 160 units).

Table A5. Embodied energy during building construction (MJ) in Typology A (16 units).

Typology A. Embodied Energy (MJ)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (MJ)**
A	523,804.96	15,759.79	279,662.08	819,226.83
C	4,310,894.69	55,062.89	23,156.77	4,389,114.35
E	4,651,270.24	78,685.96	6,166.55	4,736,122.75
F	2,020,224.77	26,226.58	3,524.74	2,049,976.09
P	969,193.76	11,466.07	2,286.30	982,946.13
I	1,083,460.25	6,822.57	675.95	1,090,958.77
N	402,698.61	8,161.10	73.18	410,932.89
Q	471,678.19	13,832.61	345.24	485,856.04
R	1,252,405.57	54,246.00	2,119.27	1,308,770.84
S	102,242.74	945.66	9.25	103,197.65
Y	7,947.04	114.63	49.02	8,110.69
Total	15,795,820.82	271,323.86	318,068.35	**16,385,213.03**

Table A6. CO_2 emissions during building construction (ton) in Typology A (16 units).

Typology A. CO_2 Emissions (ton)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (ton)**
A	59.20	1.17	20.70	81.07
C	370.29	4.07	1.72	376.08
E	404.94	5.82	0.52	411.28
F	178.03	1.94	0.30	180.27
P	74.88	0.85	0.20	75.93
I	114.52	0.51	0.08	115.11
N	56.92	0.60	0.01	57.53
Q	37.26	1.02	0.03	38.31
R	104.07	4.01	0.22	108.30
S	9.20	0.07	0.00	9.27
Y	0.81	0.01	0.01	0.83
Total	1410.12	20.07	23.79	**1453.98**

Table A7. Embodied energy during building construction (MJ) Typology B (1 building).

Typology B. Embodied Energy (MJ)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (MJ)**
A	145,267.82	11,617.71	321,562.29	478,447.82
C	2,619,012.25	33,186.68	11,983.63	2,664,182.56
E	3,407,155.89	53,225.15	3133.69	3,463,514.73
F	1,537,022.36	16,881.63	2301.71	1,556,205.70
P	1,136,864.05	13,393.96	2511.35	1,152,769.36
I	1,006,289.90	6,052.40	753.95	1,013,096.25
N	380,807.84	8,869.36	115.92	389,793.12
Q	289,973.32	8,451.64	214.67	298,639.63
R	1,302,920.84	46,371.47	2328.75	1,351.621.06
S	138,397.28	1,160.96	11.64	139,569.88
Y	7175.57	111.80	65.61	7352.98
Total	11,970,887.12	199,322.76	344,983.21	**12,515,193.09**

Table A8. CO_2 emissions during building construction (ton) in Typology B (one building).

Typology B. CO_2 Emissions (ton)				
Chapters	**A1-A2-A3 Product**	**A4 Transport**	**A5 Construction**	**Total (ton)**
A	13.93	0.86	23.80	38.59
C	224.82	2.46	0.89	228.17
E	295.82	3.94	0.25	300.01
F	147.19	1.25	0.20	148.64
P	88.58	0.99	0.22	89.79
I	109.58	0.45	0.09	110.12
N	51.22	0.66	0.01	51.89
Q	22.94	0.63	0.02	23.59
R	110.89	3.43	0.24	114.56
S	13.33	0.09	0.00	13.42
Y	0.70	0.01	0.01	0.72
Total	1079.00	14.77	25.73	**1119.50**

Appendix B: CALENER VYP Label Output

NOTE: CALENER VYP label output is a bitmap. Here we reproduce a literal English translation of the original Spanish labels. For Typology A, a software bug probably resulted in the heating emissions being zero, which is not consistent with the energy demand. That bug also produced an inconsistent number in the original research and in the previous conference paper, whose reason we have been able to detect only now. Although the error did not affect the results of the research, we corrected it by hand, and Figures B3 and B5 show the corrected numbers in red. The values per square meter in CALENER VYP tables are calculated based on the area of only the rooms with heating/air conditioning. However, in the main text, we made the calculations by dividing the total values of kWh or kg by the total built area.

Building Energy Rating Parameter $kgCO_2/m^2$	Assessed Building			Reference Building		
<8.2 A						
8.2~14.4 B						
14.4~23.2 C		19.1 C				
23.2~36.6 D						
>36.6 E					37.2 E	
F						
G						
	Rating Class	kWh/m^2	kWh/year	Rating Class	kWh/m^2	kWh/year
Heating Energy Demand	E	80.5	8911.5	E	98.4	10893.1
Cooling Energy Demand	A	6.9	763.8	A	7.8	863.5
	Rating Class	$kgCO_2/m^2$	$kgCO_2$/year	Rating Class	$kgCO_2/m^2$	$kgCO_2$/year
Heating CO_2 Emissions	C	14.6	1616.3	E	31.5	3487.1
Cooling CO_2 Emissions	A	1.4	155.0	C	3.0	332.1
DHW CO_2 Emissions	D	3.1	343.2	D	2.7	298.9
Total CO_2 Emissions			2114.4			4118.1

Energy efficiency label data

	Assessed Building		Reference Building	
	per square meter	per year	per square meter	per year
Final Energy Consumption (kWh)	29.4	3259.6	148.9	16488.2
Primary Energy Consumption (kWh)	76.6	8484.7	166.2	18394.2
CO_2 Emissions (kg CO_2)	19:01	2114.4	37.2	4118.1

Figure B1. Energy and CO_2 emissions estimation and labeling output for Typology A, Alt. I, one house.

Building Energy Rating Parameter $kgCO_2/m^2$	Assessed Building			Reference Building		
<5.6 A						
5.9~9.8 B						
9.8~15.9 C						
15.9~25.0 D		17.4 D			24.5 D	
>25.0 E						
F						
G						
	Rating Class	kWh/m^2	kWh/year	Rating Class	kWh/m^2	kWh/year
Heating Energy Demand	D	46.7	77310.5	E	58.0	96017.3
Cooling Energy Demand	C	9.8	16223.6	C	10.2	16885.8
	Rating Class	$kgCO_2/m^2$	$kgCO_2$/year	Rating Class	$kgCO_2/m^2$	$kgCO_2$/year
Heating CO_2 Emissions	D	12.6	20858.9	E	18.6	30791.8
Cooling CO_2 Emissions	C	2.7	4469.8	D	3.9	6456.3
DHW CO_2 Emissions	D	2.1	3476.5	D	2.0	3310.9
Total CO_2 Emissions			28805.2			40559.0

Energy efficiency label data

	Assessed Building		Reference Building	
	per square meter	per year	per square meter	per year
Final Energy Consumption (kWh)	29.1	48134.7	92.9	153786.2
Primary Energy Consumption (kWh)	69.6	115238.9	108.3	179241.0
CO_2 Emissions (kg CO_2)	17.4	28805.2	24.5	40559.0

Figure B2. Energy and CO_2 emissions estimation and labeling output for Typology B, Alt. I, one building.

Building Energy Rating Parameter kgCO$_2$/m^2	Assessed Building			Reference Building		
<5.6 A						
5.9~9.8 B		7.9 B				
9.8~15.9 C						
15.9~25.0 D						
>25.0 E					30.7 E	
F						
G						
	Rating Class	**kWh/m^2**	**kWh/year**	**Rating Class**	**kWh/m^2**	**kWh/year**
Heating Energy Demand	E	70.3	125226.7	E	80.9	144108.7
Cooling Energy Demand	B	6.6	11756.7	B	7.4	13181.8
	Rating Class	**kgCO$_2$/m^2**	**kgCO$_2$/year**	**Rating Class**	**kgCO$_2$/m^2**	**kgCO$_2$/year**
Heating CO_2 Emissions	A	1.9	3382.1	E	25.9	46136.2
Cooling CO_2 Emissions	B	1.7	3028.2	C	2.8	4987.7
DHW CO_2 Emissions	E	4.3	7659.7	D	2.0	3562.6
Total CO_2 Emissions		7.9	14070.0			54686.5

Energy efficiency label data

	Assessed Building		Reference Building	
	per square meter	**per year**	**per square meter**	**per year**
Final Energy Consumption (kWh)	105.0	187071.4	121.9	217074.7
Primary Energy Consumption (kWh)	119.9	213634.0	137.1	244241.9
CO_2 Emissions (kg CO_2)	7.9	14070.0	30.7	54686.5

Figure B3. Energy and CO_2 emissions estimation and labeling output for Typology A, Alt. IIa, one cluster of 16 houses.

Building Energy Rating Parameter kgCO$_2$/m^2	Assessed Building			Reference Building		
<5.6 A						
5.9~9.8 B		6.6 B				
9.8~15.9 C						
15.9~25.0 D					24.6 D	
>25.0 E						
F						
G						
	Rating Class	**kWh/m^2**	**kWh/year**	**Rating Class**	**kWh/m^2**	**kWh/year**
Heating Energy Demand	D	48.0	78714.6	E	58.6	96097.4
Cooling Energy Demand	C	9.5	15578.9	C	10.3	16890.8
	Rating Class	**kgCO$_2$/m^2**	**kgCO$_2$/year**	**Rating Class**	**kgCO$_2$/m^2**	**kgCO$_2$/year**
Heating CO_2 Emissions	A	1.2	1967.9	E	18.7	30665.9
Cooling CO_2 Emissions	C	2.4	3935.7	D	3.9	6395.6
DHW CO_2 Emissions	E	3.0	4919.7	D	2.0	3279.8
Total CO_2 Emissions			10823.3			40341.2

Energy efficiency label data

	Assessed Building		Reference Building	
	per square meter	**per year**	**per square meter**	**per year**
Final Energy Consumption (kWh)	77.7	127344.6	93.7	153690.3
Primary Energy Consumption (kWh)	91.5	150081.0	109.2	179098.1
CO_2 Emissions (kg CO_2)	6.6	10823.3	24.6	40341.2

Figure B4. Energy and CO_2 emissions estimation and labeling output for Typology B, Alt. IIa, one cluster of 16 houses.

Building Energy Rating Parameter kgCO₂/m²	Assessed Building			Reference Building		
<5.6 A		3.6 A				
5.9~9.8 B						
9.8~15.9 C						
15.9~25.0 D						
>25.0 E					30.7 E	
F						
G						
	Rating Class	kWh/m²	kWh/year	Rating Class	kWh/m²	kWh/year
Heating Energy Demand	E	70.3	125226.7	E	80.9	144108.7
Cooling Energy Demand	B	6.6	11756.7	B	7.4	13181.8
	Rating Class	kgCO₂/m²	kgCO₂/year	Rating Class	kgCO₂/m²	kgCO₂/year
Heating CO_2 Emissions	A	1.9	3381.8	E	25.9	46136.2
Cooling CO_2 Emissions	B	1.7	3028.2	C	2.8	4987.7
DHW CO_2 Emissions	A	0.0	0.0	D	2.0	3562.6
Total CO_2 Emissions		3.6	6410.0			54686.5

Energy efficiency label data

	Assessed Building		Reference Building	
	per square meter	per year	per square meter	per year
Final Energy Consumption (kWh)	105.3	187625.6	121.9	217074.7
Primary Energy Consumption (kWh)	109.5	195084.9	137.1	244241.9
CO_2 Emissions (kg CO_2)	3.6	6410.0	30.7	54686.5

Figure B5. Energy and CO_2 emissions estimation and labeling output for Typology A, Alt. IIb, one cluster of 16 houses. Numbers in red are edited and calculated by hand.

Building Energy Rating Parameter kgCO₂/m²	Assessed Building			Reference Building		
<5.6 A		3.6 A				
5.9~9.8 B						
9.8~15.9 C						
15.9~25.0 D					24.6 D	
>25.0 E						
F						
G						
	Rating Class	kWh/m²	kWh/year	Rating Class	kWh/m²	kWh/year
Heating Energy Demand	D	48.0	78714.6	E	58.6	96097.4
Cooling Energy Demand	C	9.5	15578.9	C	10.3	16890.8
	Rating Class	kgCO₂/m²	kgCO₂/year	Rating Class	kgCO₂/m²	kgCO₂/year
Heating CO_2 Emissions	A	1.2	1976.9	E	18.7	30665.9
Cooling CO_2 Emissions	C	2.4	3935.7	D	3.9	6395.6
DHW CO_2 Emissions	A	0.0	0.0	D	2.0	3279.8
Total CO_2 Emissions			5903.6			40341.2

Energy efficiency label data

	Assessed Building		Reference Building	
	per square meter	per year	per square meter	per year
Final Energy Consumption (kWh)	77.7	127344.6	93.7	153690.3
Primary Energy Consumption (kWh)	84.0	137783.3	109.2	179098.1
CO_2 Emissions (kg CO_2)	3.6	5903.6	24.6	40341.2

Figure B6. Energy and CO_2 emissions estimation and labeling output for Typology B, Alt. IIb, one building.

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