An application of life cycle assessment (LCA) within the Catalonian building sector: A case study

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Aplicación del Análisis del Ciclo de Vida (ACV): Caso de estudio en el sector de la construcción en Cataluña

Una aplicació de Cicle de Vida (ACV) al Catalunya sector de la construcció: un estudi de cas

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RESUMEN

El Análisis del Ciclo de Vida (ACV) es una herramienta que es aplicada para evaluar los impactos ambientales a través del ciclo de vida de un producto o un sistema. En este artículo la ACV ha sido aplicada de conformidad con la norma internacional ISO 14040 e ISO 14044. Como caso de estudio, se ha aplicado a una casa ubicada en Barcelona, España, con una vida útil proyectada de 50 años. En este proyecto de investigación se han considerado las fases de construcción, uso (operación y mantenimiento) y desmantelamiento. La energía consumida en la fase de operación se modeló utilizando una combinación de energía eléctrica para aparatos eléctricos como: iluminación, calefacción y refrigeración, y energía a través de gas natural para agua caliente sanitaria y cocina.

Los resultados de esta investigación muestran que el mayor impacto ambiental durante el ciclo de vida de la vivienda se llevó a cabo durante la fase de uso. El impacto total del cambio climático fue de 4.52+01 kg CO2-equiv. m-2 a-1 representando un 92% del total (90% fase de operación y 2% mantenimiento), la fase de construcción representó el 7% y la fase de desmantelamiento contribuyo en menos del 1%. En cuanto a la fase de operación, aire acondicionado tuvo la mayor carga ambiental con 33%, calefacción representó el 9%, seguido por la iluminación con 26% y aparatos eléctricos 19%. Las otras dos actividades del hogar representaron menos del 12% (agua caliente sanitaria 9% y cocina 3%). Durante la fase de construcción, la producción de materiales de construcción representó cerca del 97%, transporte 2% y el porcentaje de gestión de residuos 1%. La demanda total de energía primaria fue 5.26E+01 MJ m-2 a-1 (valor calorífico) de los cuales la demanda de energía primaria no renovable represento el 78% y la demanda de energía renovable del 22%.

En conclusión, un hogar catalán ha sido modelado para evaluar los impactos ambientales utilizando la herramienta de la ACV. Los datos han sido modelados usando la herramienta ambiental del software de GaBi. Por último, la ACV es una herramienta adecuada para evaluar los impactos ambientales en todas las fases del ciclo de vida del edificio.

Palabras clave: ciclo de vida de construcción, sector de la construcción, Cataluña, impactos ambientales.

SUMMARY

Life Cycle Assessment (LCA) tool has been applied to evaluate environmental impacts through the whole building life cycle. LCA has been carried out in accordance to the international standard of ISO 14040 and ISO 14044. As a reference, an application of LCA has been made to a Catalan house located in Barcelona, Spain with a projected 50 years life span. In this work, construction, use (operation and maintenance) and end-of-life phases have been considered. The operational energy consumed during the dwelling period was modeled using a mix of electrical power for electrical appliances, illumination, heating and cooling; and using thermal energy from natural gas for domestic hot water and cooking.

Result shows that the highest environmental impacts during the dwelling's life cycle took place during the use phase. The total impact of global warming potential was 4.52+01 kgCO_2-Equiv. m^{-2} a^{-1} of which use phase accounted for 92% (operation 90% and maintenance 2%), construction represented 7% and end-of-life contributed less than 1%. Regarding the operation phase, cooling had the highest environmental burden with 33%, heating repre

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sented 9%, followed by illumination 26% and electrical appliances 19%. The other two household activities accounted for less than 12% (domestic hot water 9% and cooking 4%) of total phase. During the construction phase, the production of building materials represented about 97%, transport to the job site 2% and waste management 1% of total phase. The total primary energy demand was 5.26E+01 MJ m^{-2} a^{-1} (gross calorific value) of which non-renewable primary energy demand represents 78% and renewable energy demand 22%.
In summary, data for a Catalan home has been provided to evaluate environmental impacts using LCA tool. Data have been modelled into the Gabi software system. Finally, LCA is a suitable tool to evaluate environmental impacts throughout all phases of the building life cycle.

Key words: Building life cycle, Catalonian building sector, Environmental impacts, Household activities, LCA.

RESUM

L'Anàlisi de de Vida (ACV) és una eina que s'aplica per avaluar els impactes ambientals a través del cicle d'un producte o d'un sistema. En aquest artícle l'ACV s'ha aplicat en conformitat amb la norma internacional ISO 14040 i ISO 14044. Com a cas d'estudi, s'ha aplicat a una casa ubicada a Barcelona, Espanya, amb una vida útil projectada de 50 anys. En aquest projecte d'investigació s'han considerat les fases de construcció, ús (operació i manteniment) i desmantellament. L'energia consumida en la fase d'operació es va modelar utilitzant una combinació d'energia elèctrica, per a aparells elèctrics com ara: enllumenat, calefacció i refrigeració, i l'ús d'energia a través de gas natural: per a calentar aigua sanitària i per cuinar.
Els resultats d'aquesta investigació mostren que el major impacte ambiental durant el cicle de vida de la vivenda corresponen a la fase d'ús. L'impacte total de l'escalfament global va ser 4,52 01 kgCO2-equiv. m-2 a-1 representant un 92% del total (90% fase d'operació i 2% de manteniment), la fase de construcció va representar el 7% i la fase de desmantellament va contribuir en menys de l'1%. Pel que fa a la fase d'operació, l'aire acondicionat va tenir la major càrrega ambiental amb el 33%, la calefacció va representar el 9%, seguit per la il·luminació amb un 26% i els aparells elèctrics 19%. Les altres dues activitats de la llar van representar menys del 12% (aigua calenta sanitària 9% i per cuinar 3%). Durant la fase de construcció, la producció de materials de construcció van representar prop del 97%, el transport un 2% i el percentatge de gestió de residus un 1 %. La demanda total d'energia primària va ser 5.26E 01 MJ m-2 a-1 (valor calorífic) dels quals la demanda d'energia primària no renovable va representar el 78% i la demanda d'energia renovable el 22%.
En resum, una llar catalana ha estat modelada per a avaluar els impactes ambientals utilitzant la metodolgía de l'ACV. Les dades han estat modelades utilitzant el Sofware ambiental GaBi. Finalment, l'ACV és una eina adequada per avaluar els impactes ambientals en totes les fases del cicle de vida de l'edifici.

Paraules clau: cicle de vida de construcció, sector de la construcció de Catalunya, impactes ambientals, activitats de la llar, ACV

1.INTRODUCTION

Social and economically, the Spanish construction industry has been one of the most prominent and competitive sector. In 2006 the construction industry contributed with a growth rate of 5%, it accounted for as much as 18% of Gross Domestic Product (GPD) and with a contribution to Gross Value Added (GVA) of almost 5.3%. Furthermore, construction – together with commerce – remained a sector predominantly made up of companies employing between 10-20 workers and with a high number of self-employed. By region, the growth of the Catalan economy during the last years is due to the growth of internal demand (over 4% in 2005 and 2006) and especially to the construction sector. In 2007, this contribution to the Spanish economy is still a fact today with Catalan production accounting for 18.7 % of total Spanish GDP [1].
Environmentally, taking into account its entire lifespan, the built environment is responsible in each country for 25 to 40% of total energy use, 30 to 40% of solid waste generation and 30 to 40% of global greenhouse gas emissions (GHG) [2]. Nevertheless, some initiatives for tackling adverse environmental impacts have been taken. For example, the European Commission analyzed within its Integrated Product Policy (IPP) in how far housing was relevant with regard to environmental impacts and how these impacts could be reduced systematically. The Environmental Impact of Products (EIPRO) study concluded that housing, food and drink, and private transport sectors were responsible for 70-80% of environmental impacts [3]. This policy looks to identify products within the construction sector with the greatest potential environmental impacts by focusing on the whole product life cycle. Additionally, the Environmental improvement potentials of residential buildings (IMPRO-Building) report presented a systematic overview of how to reduce the environmental life cycle impacts of residential buildings in EU-25 [4].
Due to the fact that the construction industry continues to be one of the biggest contributors to Spain's economic welfare, there is an important concern for environmental scientists, researchers and other stakeholders to apply Life Cycle Assessment as a tool to evaluate environmental impacts and quantify natural resources consumption in order to create goals preventing adverse environmental impacts, consequently enhancing quality of life and allowing people to live in a healthy environment [5].
Therefore, to deal with an increasing concern of today's resource depletion and environmental considerations locally in Catalonia, Life Cycle Assessment (LCA) has been applied to evaluate environmental impacts throughout all phases of the building life cycle. The aim of this study is to evaluate environmental impacts applying the LCA tool to a Catalan house. The investigated life cycle phases are construction, use and end-of-life.

2. LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

Life Cycle Assessment (LCA) tool has been carried out in accordance to the international standard of ISO 14040 [6] and ISO 14044 [7]. The four steps of this methodology are defined as:

1. Goal and scope definition.
2. Inventory analysis.
3. Impact assessment.

4. Interpretation.

2.1 Goal and scope definition

This part consists of defining the functional unit, the system boundaries, limitations and the assumptions. In this work, the goal of the case study is to evaluate environmental impacts throughout all phases of the building life cycle. The functional unit is the m^2 usable living area of the dwelling with a projected 50 years lifespan.

The analysis is divided into the following life cycle steps:

C1. Construction phase: evaluates the material, electricity and energy consumption associated with the extraction of raw materials, the production and manufacturing of the materials, and the energy used by the building machinery. This phase also includes the (T1), which is the transport of the raw materials from the factory to the building site and also the internal waste management with the transport of the wastes generated at the building site to their final destination (T2).

U1. Use phase: includes the operation and maintenance activities.

***O1. Operati*on phase** covers the full service life for HVAC: heating, ventilation and air conditioning, and other activities such as illumination, domestic hot water (DHW), electrical appliances and cooking.

M1. Maintenance and refurbishment phase have been calculated including activities such as repainting, PVC siding, kitchen and bathroom cabinet replacement, reroofing and changing windows. This phase includes the transport (T1 and T2).

E1. End-of-life phase: this evaluates the energy consumed by the machinery used during the demolition; also considers the amount of wastes generated during dismantling of the original construction materials, including their transport (T2) to the final treatment waste.

Figure 1 depicts the system boundaries within this study. This figure presents the scheme of the life cycle of a building system detailing the phases considered.

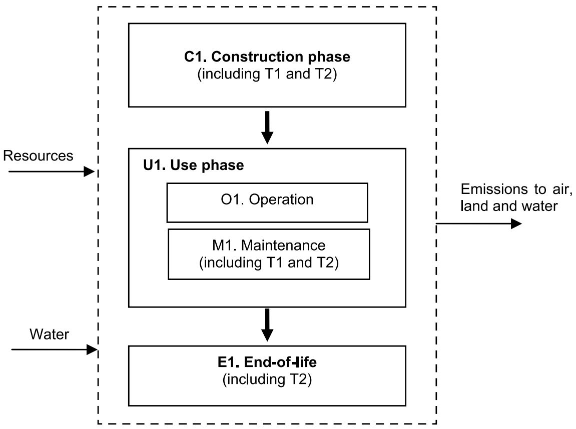

Figure 1. Building system life cycle and phases considered within this study

The following assumptions have been considered:

- The country specific electricity consumption mix is based on 1kWh of the average composition of electricity generated by different power plants for the year 2008.
- The energy consumed for the different household activities will remain constant during the use of the home. The operational energy consumed during the dwelling period was modeled using a mix of electrical power for electrical appliances, illumination, heating and cooling; and using thermal energy from natural gas for DHW and cooking. Four people will be living in the home.
- Transport T1 considers the average distance to be 100 km.
- Transport T2 considers the distance (in km) to the waste management plants closest to the building site.

2.2 Inventory analysis

As a reference a Catalan home located in Barcelona has been chosen. Barcelona is located on the Mediterranean coast at 41º23N, 2º11E, and 12m above sea level. The dwelling has an area of 160m^2 with four bedrooms, an attic, a living, a dining room, a kitchen and two bathrooms. It is two-storeys high and is mainly made of brick. Data were adapted from the model used in previous study [8] where the dwelling has been modeled in accordance to the Spanish Building Technical Code (CTE) [9]. Table 1 summarizes the general construction materials used for the dwelling.

Table 1. Inputs required during the construction phase.

Building Elements	Main building materials used for the dwelling	Thickness (m)	Density (kg/m3)	Area (m2)	Mass (kg)
External walls Windows Pitched roof Internal partitions Ground floor Internal floor Floors Painting and other architectural finishing	Brick Expanded polystyrene (EPS) Plaster Glass (Clear 3MM): 2 units Wooden frame (0.04m) Dividers (0.02m) Clay tile MW stone wool Gypsum plasterboard Gypsum plastering (2 units) Brickwork (inner leaf) Pine (20 % Moisture) (doors) XPS expanded Cast concrete Cast concrete Reinforced concrete Ceramic tiles Wooden flooring Emulsion paints and varnish Mortar Timber	0.140 0.040 0.015 0.003 0.020 0.020 0.025 0.092 0.013 0.013 0.115 0.030 0.060 0.200 0.050 0.250 0.050 0.010 - - -	900 30 825 2500 700 700 2000 30 900 1000 1700 419 38 2000 2000 1110 2500 650 - 2200 650	193 193 114 36 30 7 83 83 144 107 107 140 72 72 145 145 72 72 140 - -	24384 232 2394 271 421 105 4178 230 1693 1403 2110 1760 162 28950 14474 40169 905 470 220 250 850

Table 2. Parameters considered within the operation phase (based on the total consumption).

Household activity	Annual energy consumption	Equipment	Simulation parameters
Domestic hot water	231 m3 natural gas	Mixed gas boiler	30 l / person / day at 60ºC (input 12ºC)
Cooking	96 m3 natural gas	Gas hob oven	22 m3 / person / y
Electrical appliances	1908 kWh electrical	-	12 kWh/m2 / y
Illumination	2569 kWh electrical	-	Installed light power 3.4 W/m2.100 lux
HVAC	4127 kWh electrical Heating (22%) Cooling (78%)	Split system	COP heating 2.35 COP cooling 1.85

In order to calculate the energy consumption for the dwelling, it has been evaluated using the building energy simulation software DesignBuilder which is a user interface for the EnergyPlus thermal simulation engine [10]. Table 2 shows the parameters considered within the operation phase.
Table 3 shows the maintenance and refurbishment activities which have been done according to the following schedule based on a home life of 50 years.

Table 3. *Maintenance schedule based on a 50 years life span.*

Maintenance activities	Years occurring after the construction
Painting (interior and exterior) and door repair	10 - 20 - 30 - 40
PVC Siding	20 – 40
New kitchen and cabinets (bathroom)	15 – 30
New re-roofing and walls repair	15 – 30
Window replacement	15 – 30

Finally, for the waste management, it has been done according to the recommendations of the European Waste Catalogue (EWC) [11] and also takes into account the information on the Catalonian waste catalogue [12]. Therefore, three different waste management scenarios have been chosen:

1. **Recycling**: recyclable wastes are sent to a recycling plant, non-recyclable wastes are sent to an incineration plant and non-recyclable or non-incinerable wastes are sent to landfill. The material recycling results in a credit corresponding to the fact that it enables a subsequent avoidance of the production of virgin material.
2. **Incineration:** incinerable wastes are disposed to an incineration plant and non-incinerable wastes are disposed to landfill. For the residues disposed to incineration, the electrical energy produced has been calculated based on calorific value data. Incineration has credit of power and thermal energy recovery due to the high calorific value of the construction materials wastes.
3. **Landfill**: all the wastes are disposed to landfill.

Table 4 describes the waste management scenarios for some building materials to carry out recycling, incineration and landfill treatments.

Table 4. *Overview of the waste management scenarios and treatment plants*

Construction materials	Waste management scenario	Collection rate	Possible treatment plants	Distance from the home studied to the plant in km (T2)
Aluminum	Recycling	90%	FEMAREC, S.C.C.L.	6.2
Steel	Recycling	90%	FEMAREC, S.C.C.L.	6.2
Wood	Incineration	75%	UNILAND, Cementera, S.A.	38.2
Waste (untreated)	Landfill for inert matter	Variable	CESPA, waste management, S.A.	28.1
PVC	Landfill for non special waste	80%	CESPA, waste management, S.A.	28.1

2.3 Impact assessment
The impact assessment is based upon the CML 2001 method [13]. The impact categories analyzed were:

- Acidification Potential (AP) in [kg SO_2-Equiv.]
- Global Warming Potential (GWP 100 years) in [kg CO_2-Equiv.]
- Eutrophication Potential (EP) in [kg Phosphate-Equiv.]
- Ozone Layer Depletion Potential (ODP) in [kg R11-Equiv.].

To calculate the environmental impacts, the modeling and evaluation was done with the GaBi software system. Finally, background data was taken from the GaBi database 2006 [14].

3 INTERPRETATION AND RESULTS

This is the last step in the LCA methodology. Results are expressed in the functional unit of the life cycle model which is the ‘use’ of 1m^2 living area. The life span corresponds to 50 years of living in the house with all maintenance activities considered and the consumption of energy for the different household activities.
The highest environmental impacts during the dwelling’s life cycle took place during the use phase. For example, the total impact of global warming potential (GWP) was 4.52E+01 kgCO_2-Equiv. m^{-2} a^{-1} of which use phase accounted for 92% (operation 90% and maintenance 2%), construction phase represented 7% and end-of-life phase contributed less than 1%. Table 5 shows the total environmental impact results for the dwelling life cycle studied.

3.2 Results of the construction phase
Environmental loads of the construction phase have been evaluated starting from the building materials, transport to the building site, the energy consumed by the machinery, and the disposal of material and packaging wastes.
Result shows that the production of building materials represented 97% of the total environmental impacts, transport to the job site 2% and waste management 1%. During the construction phase the total primary energy demand was 5.26E+01 MJ m^{-2} a^{-1} (gross calorific value) of which non renewable primary energy demand represents 78% and renewable energy demand 22%.
The contributions to the total primary energy demand (non-renewable and renewable) of the production materials are shown in figure 2. External walls had the highest value in non-renewable energy demand, accounting for about 1.35E+01 MJ m^{-2} a^{-1}. Internal floor with 1.12E+01 MJ m^{-2} a^{-1}, internal portions with 8.13E+00 MJ m^{-2} a^{-1} and

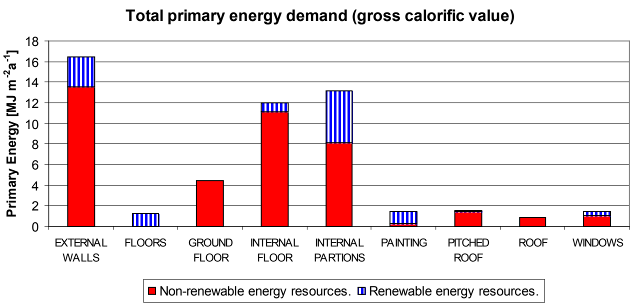

Figure 2. *Total primary energy demand of building elements*

ground floor 4.43E+00 MJ m^{-2} a^{-1} are also important in terms of the total energy demand. Results in floors and internal portions system, renewable primary energy are high with about 1.23E+00 MJ m^{-2} a^{-1} and 4.99E+00 MJ m^{-2} a^{-1} respectively, of which in both systems 27% is due to the use of timber. Therefore, sustainable managed wood can be not only positive for its carbon sequestration but also for avoiding the fossil energy consumption for concrete manufacturing. Figure 2 shows the contribution of the construction system for the total energy source indicator.
Regarding the significant environmental issue of global warming potential (GWP), there was a total emission of 3.47E+00 $kgCO_2$-Equiv. m^{-2} a^{-1}, of which internal floor ac

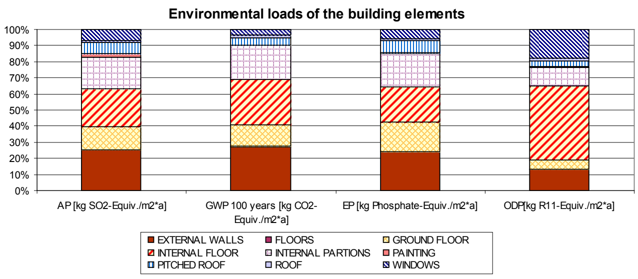

Figure 3. *Environmental loads of building elements*

counted for 27%, external floor 26% and internal portions 20% due to the use of solid brick with 37%. The other two important materials were steel with about 18% and concrete mix with 11%. Figure 3 shows the final distribution of the environmental impacts by system of the construction phase.

3.3 Results of the use phase

This section covers the results for the operation and maintenance activities. Therefore, in order to calculate environmental impacts during the operation phase, building simulation and energy consumption analysis of the dwelling were assessed. The simulation results of the operation for the household activities such as HVAC have the highest environmental burden; cooling presented 33% and heating 9% of the impact during the dwelling's life cycle, followed by illumination 26% and electrical appliances 19%. The other two household activities accounted for less than 12% (DHW 9% and cooking 4%).

Table 6. *Total environmental impact for the household activities analyzed.*

Environmental impact / Household activity	AP kgSO2-Equiv. m-2 a-1	GWP kgCO2-Equiv. m-2 a-1	EP kgPhospate – Equiv. m-2 a-1	ODP kgR11-Equiv. m-2 a-1
Total Impact	2.61E-01	4.06E+01	1.17E-02	6.02E-06
Heating	10%	9%	10%	10%
Cooling	37%	33%	35%	38%
Electrical appliances	22%	19%	21%	22%
Illumination	29%	26%	28%	30%
Cooking	1%	4%	2%	0%
Domestic hot water	2%	9%	5%	0%

The life cycle impacts of all household activities for the environmental impact category of global warming potential shows that cooling accounted for a total of 1.34E+01 $kgCO_2$-Equiv. m^{-2} a^{-1}, followed illumination 1.06E+01, electrical appliances 7.91E+00, heating 3.68E+00, DHW 3.52E+00 and cooking 1.46E+00. Table 6 shows the total environmental impacts results for the different household activities considering an occupation of 50 years life span.
Environmental impacts due to maintenance activities contributed less than 2% of the use phase.

3.4 End-of-life phase

The total environmental impacts of this phase represented less than 1% of the total life cycle. GWP accounted for 2.96E-01 kgCO2-Equiv. m-2 a-1, which includes the green house gases (GHG) emitted to the atmosphere due to the energy consumed by the machinery used during the demolition; the amount of wastes generated during dismantling of the original construction materials, including their transport of the final destination. Environmental loads and credits were also included assuming corresponding waste treatment plants and including positive credits from recycling and energy recovery.

Table 5. *Total environmental impact results for the dwelling life cycle studied*

Phase / Environmental Impact	Construction		Use				End-of-life	
			Operation		Maintenance			
	Emissions	% (total phase)	Emissions	% (total phase)	Emissions	% (total phase)	Emissions	% (total phase)
AP [kg SO2-Equiv. m-2 a-1]	7.33E-03	2.7	2.61E-01	95.5	4.22E-03	1.5	7.31E-04	0.3
GWP 100 years [kg CO2-Equiv. m-2 a-1]	3.47E+00	7.7	4.06E+01	89.9	7.89E-01	1.7	2.96E-01	0.7
EP [kg Phosphate-Equiv. m-2 a-1]	8.27E-04	6.4	1.17E-02	91.1	2.25E-04	1.8	9.34E-05	0.7
ODP [kg R11-Equiv. m-2 a-1]	1.52E-07	2.5	6.02E-06	96.7	4.69E-08	0.8	5.61E-09	0.1

4. CONCLUSION AND OUTLOOK

In this study the environmental impacts for a Catalan home is evaluated. The construction, use and end-of-life phases have been studied in detail.

The construction phase included the production of building materials, the energy used by the building machinery in the job site, the transport of building materials and the final disposal of building material and packaging wastes; the use phase took into account the operation and maintenance activities and the end-of-life phase considered the amount of wastes generated during dismantling of the original construction materials, including their transport to the final destination.

Result shows that the highest environmental impacts during the dwelling's life cycle took place during the use phase (operation and maintenance). For example, the total impact of global warming potential (GWP) was 4.52+01 $kgCO_2$-Equiv. m^{-2} a^{-1} of which use phase accounted for 92% (operation 90% and maintenance 2%), construction phase represented 7% and end-of-life phase contributed less than 1%.

During the construction phase result shows that the production of building materials represented 97% of the total environmental impacts, transport to the job site 2% and waste management 1%. The total primary energy demand was 5.26E+01 MJ m^{-2} a^{-1} (gross calorific value) of which non renewable primary energy demand represents 78% and renewable energy demand 22%.

Regarding the operation phase, cooling has the highest environmental burden with 33% and heating 9% of the impact during the dwelling's life cycle, followed by illumination 26% and electrical appliances 19%. The other two household activities accounted for less than 12% (DHW 9% and cooking 4%).

In summary, data for a Catalan home has been provided to evaluate environmental impacts using Life Cycle Assessment tool. Data have been modelled into the Gabi software system. Future work within this study will include the comparison with a German reference home or another more (or less) energy efficient Mediterranean house to see the influence and what the change in the energy or hot water supply to renewable sources would imply. Finally, LCA is a suitable tool to evaluate environmental impacts throughout all phases of the building life cycle.

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