CODEN STJSAO
ZX470/1601

ISSN 0562-1887
UDK 621.315.016.2

Methodological aspects and design implications to achieve life cycle low emission buildings. A case study: LCA of a new university building *

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Keywords

Life cycle assessment
Sustainable buildings
Low emission buildings
Building materials
Sensitivity analysis
Scenarios

Ključne riječi

Analiza životnog ciklusa
Održive zgrade
Zgrade s niskim emisijama
Građevinski materijali
Analiza osjetljivosti
Scenariji

Primljeno (Received): 2012-03-06
Prihvaćeno (Accepted): 2012-05-15

Original scientific paper

Abstract: All new residential, office and service buildings built in the EU from 2020 will be nearly zero-energy buildings, defined as buildings that on an annual basis generate approximately the same amount of energy as they require. This will promote on-site generation from renewable sources and the incorporation of energy efficient equipment in buildings, but it is not enough. The life cycle assessment of buildings considers the impact in all stages of their life cycle.

The aim of the paper is to present the life cycle assessment as an adequate methodology for designing new "Life Cycle Low Emission Buildings". The methodology is applied to a new University building in Spain which aims to be a singular and exemplary model of sustainability. Several sensitivity analyses based on different scenarios are proposed in order to identify the most significant variables and parameters. In conclusion, some recommendations for reducing the emissions during the whole life cycle of the building are assessed. The results demonstrate the high impact of the urban mobility of the occupants and other indirect impacts, if they are included within the system boundaries of the assessment.

The paper has been developed within the framework of the "EnerBuiLCA" project co-financed by the ERDF – SUDOE Interreg IV B and the "ECOURBAN" project, financed by the Spanish Ministry of Science and Innovation.

*Metodološki aspekti i učinci projektiranja zgrada s niskim emisijama životnog ciklusa. Studija slučaja: LCA nove sveučilišne zgrade

Izvorni znanstveni članak

Sažetak: Sve nove rezidencijalne, poslovne i uslužne zgrade izgrađene u EU će od 2020 biti gotovo energetski neutralne, odnosno na godišnjoj će razini proizvoditi približno jednako energije koliko i troše. To će promovirati proizvodnju energije na mjestu potrošnje iz obnovljivih izvora te korištenje energetski efikasne opreme u zgradarstvu, no to nije dovoljno. Analiza životnog ciklusa zgrada uzima u obzir njihov utjecaj tokom cijelog životnog vijeka.

Cilj ovog članka je prezentirati analizu životnog ciklusa kao adekvatnu metodu proračuna novih „Zgrada s niskim emisijama tijekom cijelog životnog ciklusa“. Metoda je primijenjena na novu zgradu sveučilišta u Španjolskoj koja ima za cilj biti jedinstveni primjer održivosti. Predloženo je nekoliko analiza osjetljivosti temeljenih na različitim scenarijima u svrhu određivanja najznačajnijih varijabli i parametara. U zaključku su ocijenjene neke preporuke za smanjenje emisija tokom cijelog životnog ciklusa. Rezultati demonstriraju visok utjecaj urbane mobilnosti korisnika i ostalih neizravnih utjecaja, ako su uključeni u granice sustava procijene.

Članak je razvijen unutar projekta "EnerBuiLCA" koji je sufinanciran od strane ERDF – SUDOE Interreg IV B i projekta "ECOURBAN", kojeg financira španjolsko Ministarstvo znanosti i inovacija.

1. Introduction: how can we assess the impact of a building?

Today, the construction sector is fully aware of its huge responsibility, being the highest energy consumer in the EU (about 40%) and the main contributor of GHG emissions (about 36% of the EU's total CO_2 emissions and about half of the CO_2 emissions which are not covered by the Emission Trading System) [1].

The current European regulations and the principal building standards only focus on reducing the direct impact of buildings associated with the final energy consumption necessary to meet air conditioning, lighting and hot water needs throughout their useful life, implementing several energy efficiency measures [2]. Nevertheless there are some indirect impacts associated with the other stages of a building's useful life, including the manufacture and transport of its components, and the construction and final disposal of the building, whose relative significance is ever greater, as the regulations allow advances towards the reduction of direct impacts.

Symbols/Oznake

LCA	- Life Cycle Assessment/Analiza životnog ciklusa	*IPPC*	- Intergovernmental Panel on Climate Change/ Međuvladin panel o klimatskim promjenama
LCI	- Life Cycle Inventories/ Popis utrošene energije i materijala u životnom ciklusu	*CED*	- Cumulative Energy Demand/ Kumulativna potreba za energijom
LC-ZEB	- Life Cycle Zero Emission Building/ Zgrade bez emisija za vrijeme cijelog životnog ciklusa	*GWP*	- Global Warming Potential/ Potencijal globalnog zatopljenja
ERFD	- European Regional Development Fund/ Europski fond za regionalni razvoj	*RES*	- Renewable Energy Sources/ Obnovljivi izvori energije
Units/Jedinice			
kWp	- Kilowatts-peak/ Kilovat vršne snage	tCO_2-Eq	- Tons of CO_2 equivalent/ Tona ekvivalentog CO_2
TJ-Eq	- Equivalent terajoules/ Ekvivalentni teradžul	tkm	- Tons per kilometer/ Tona po kilometru

The first documented attempts to construct "Zero-Energy Buildings" were "Solar Houses" [3]. This standard involves high insulation thicknesses and high solar gain, actually achieving "Zero-Heating Buildings". However, this standard may be inappropriate depending on the internal loads of the building and the climate of the location. In addition, the increasing indirect consumption of the buildings is not considered.

"Solar Houses" have been influential in the current standards of low-energy buildings, such as the "Passive House" standard proposed by Professors Bo Adamson and Wolfgang Feist and validated by the Passivhaus-Institut in Darmstadt (Germany). This standard applies the principles of high insulation and air tightness and the implementation of heat recovery ventilation systems [4]. Currently, this standard is being adopted successfully in Central European countries like Germany and Austria, and is spreading to the rest of the world. There are at present more than 15,000 "Passive House" buildings.

A standard promoted by both the DOE and the European Parliament is "Net Zero-Energy Buildings" [5]. These buildings produce as much energy as they consume on an annual basis, and they are usually supplied by on-site renewable energy systems.

In May 2010 the Directive 2002/91/EC [6] was rewritten and the Directive 2010/31/EU [7] was approved. The new text adopted by the European Parliament has a greater scope, clarifying, simplifying and strengthening some aspects in order to increase the energy efficiency of buildings and to reinforce the exemplary role played by the public sector. The new Directive proposes that all new residential, office and service buildings built in the EU from 2020 will be nearly zero-energy buildings. This involves generating nearly the same amount of energy as is required, on an annual basis, promoting on-site generation from renewable sources and the incorporation of energy efficient equipment in buildings. The deadline is 2018 for new public buildings.

Although the previous standards are interesting, they are inadequate, failing to consider the indirect impacts of buildings, which means they will not allow eco-efficient buildings in global terms in the medium to long term. Therefore a new standard of "Life Cycle Zero Emission Buildings" (LC-ZEB) [8] should be considered. In this standard, the sum of the annual emissions at the usage stage (associated with demand due to heating, cooling, ventilation, hot water and lighting) and the annualized indirect emissions (including the carbon footprint in building materials and components during the manufacture, transportation, construction, maintenance and final disposal stages) must approach zero. In addition to CO_2 emissions, depending on the environmental priorities, there are other indicators that may be suitable for this standard, such as the primary energy, exergy [9] or the water footprint.

The life cycle approach [10] allows avoidance of trade-offs between life cycle stages of products, impact categories or geographical areas. For example, in cold climates, the demand for heating of a low-energy building can be reduced by up to 10 times that of a conventional building. Nevertheless, as a result of its higher impact in materials and maintenance, the energy demand of the building, considering the life cycle approach, is only reduced by 2 times [11].

At present, the current legislation is leading to the minimization of direct consumption in building use (which now accounts for 60-70% of the total impact, depending greatly on the type of building, construction solutions and climate), so the impact of indirect consumption (which now accounts for 30-40% of the total impact) will increase [12]. In this context, life cycle thinking should aid decision-making in the design and refurbishment of buildings in order to select the best available technologies to minimize the environmental impact of buildings through their entire life cycle.

Nowadays there are several tools and methodologies that assess different aspects of the environmental impact of buildings, such as the procedures for environmental certification LEED [13], BREEAM, ITACA, VERDE [14], etc. However most of these are just qualitative, only considering some aspects or stages of the building's life cycle, and their application is limited to their countries of origin. Consequently the results are often inconsistent, since they are based on different calculation methods, apply different system boundaries and use different criteria (technological, geographical or temporal) for data quality.

Consequently, it is necessary to define and implement a comprehensive and quantitative life cycle methodology for application in buildings that allows assessing first, analyzing in detail later and finally, designing low impact buildings, considering the whole value chain in the construction process.

2. Life cycle assessment methodology applied to buildings

Currently the general method for life cycle assessment is standardized in the ISO regulations [15,16], which describe the principles and the general framework of the LCA, but do not describe the LCA technique in detail, nor state the specific methods for the life cycle stages to be considered.

The method for applying LCA to buildings is currently being developed under the standard "Sustainability of construction works" [17] of the Technical Committee 350 of the European Committee for Standardization (CEN/TC 350).

According to this standard, in this paper a procedure is applied for a quantitative assessment of the impact in a case study of a low impact building. For this assessment, the following life cycle stages [18] are considered: production, construction process, use and end-of-life. Table 1 presents the aspects considered within the system boundaries for the case study analyzed.

Table 1. Life cycle stages and system boundaries considered for the case study
Tablica 1. Stadiji životnog ciklusa i granice sustava uzete u obzir za analizu slučaja

I. Product stage/ Stadij proizvoda	Raw material supply/ Opskrba sirovinom	"Cradle to gate" analysis for all the building materials and the energy equipment (heat/cold generators, equipment for making use of renewable energy). Storage and distribution equipment (such as tanks or piping) are excluded./ Analiza svih građevinskih materijala i energetske opreme "od koljevke do vrata" (generatora topline/hladnoće, oprema za korištenje obnovljivih izvora energije). Oprema za skladištenje i distribuciju (poput spremnika i cjevovoda) su isključeni.
	Transport/ Transport	
	Manufacture/ Proizvodnja	
II. Construction process stage/ Stadij proizvodnog procesa	Transport/ Transport	Transportation of the building materials and energy equipment from the factory gate to the building site./ Transport građevinskog materijala i energetske opreme od vrata tvornice do gradilišta.
	Construction/installation on-site processes/ Izgradnja/instalacija radnje na gradilištu	Energy consumption of machinery and waste management (including transport and final disposal of waste)./ Potrošnja energije strojeva i gospodarenja otpadom (uključujući transport i konačno odlaganje otpada).
III. Use stage/ Stadij korištenja	Operational energy use/ Operativno korištenje energije	On-site RES generation and energy consumption for heating and cooling (including ventilation), hot water and lighting./ Proizvodnja iz obnovljivih izvora energije na lokaciji te korištenje energije za grijanje i hlađenje (uključujući ventilaciju), vruću vodu i rasvjetu.
	Operational water use and wastewater treatment/ Operativno korištenje vode i obrada otpadnih	Water consumption and wastewater treatment./ Potrošnja vode i obrada otpadnih voda.

	voda	
	Maintenance/ Održavanje	Replacement of energy equipment, windows and doors, including stages I & II for new energy equipment and products. The end-of-life stage of the replaced components of the building is also included./ Zamjena energetske opreme, prozora i vrata, uključujući stadije I i II za novu energetsku opremu i proizvode. Kraj životnog vijeka zamijenjenih komponenti zgrade je također uključen.
IV. End-of-life stage/ Kraj životnog vijeka	Deconstruction/ Dekonstrukcija	Demolition of the building, transport of the building materials and energy equipment from the building site to the disposal facilities and final disposal./ Rušenje zgrade, transport građevinskog materijala i energetske opreme od gradilišta do lokacije odlaganja te konačno odlaganje.
	Recycling/re-use/ Reciklaža/ponovno korištenje	
	Transport/ Transport	
	Disposal/ Odlaganje	

The functional unit considered is the building itself, analyzed over a building reference time of 50 years, meeting the conditions of design, thermal comfort, etc. in effect in Spain the year the building was constructed (2009). In addition, the impacts obtained in the study are expressed per occupant, per year and per unit of useful air-conditioned floor area per year.

The software tool used in the case study was SimaPro v7.1.8. The European averages of the Ecoinvent v2.0 database [19-23] were selected for this case study. The LCI in this database have been adapted to the electric mix production in Spain. As we are dealing with average data, its applicability to each European country depends on the level to which its specific characteristics (manufacture technology, origin of the starting materials, energy mix, etc.) vary with regard to these averages. The impact categories considered were the primary energy demand (expressed in equivalent primary energy) according to the CED method [24] and GWP (expressed in equivalent CO_2 emissions) according to the IPPC 2007 methodology [25], considering a time horizon of 100 years.

The study was carried out according to a static LCA approach, so the LCI include intermediate values of the current processes within the system analyzed, without analyzing their variation over time.

3. A case study: LCA of a new university building

The CIRCE building is located on the “Río Ebro” Campus of the University of Zaragoza (Spain). It was built in 2009 with a total budget of €2.7M, co-financed by the ERFD and the Regional Government of Aragón.

The building itself is an R&D project, which aspires to test and establish the scientific and technological bases for the development of LC-ZEB, integrating advanced techniques of bio-construction, energy saving, water, materials and renewable energy, obtaining maximum efficiency from the available resources without compromising thermal comfort.

Figure 1. CIRCE building
Slika 1. Zgrada CIRCE

3.1. Building description

The building consists of a net floor area of 1,743 m^2 with a gross floor area of 1,990 m^2 and a total built volume of 9,550 m^3. The building has a compact shape and is divided into two floors. It clearly shows three elements: a round vestibule with a dome, the offices clustered around it and the laboratories. The laboratories constitute a rectangular building at 36º to the east-west axis, which acts as a barrier to the prevailing wind (North wind). This avoids the considerable temperature drops in the winter months. At the same time, there is a

13-metre high solar chimney, which acts as a passive cooling system.

The building work was carried out following bioconstruction regulations, using eco-efficient materials such as natural cork, timber, natural stone, lime mortar and natural silicate paints, which do not contain harmful or toxic elements and allow the building greater breathability.

The vertical structure consists of load-bearing walls of several thicknesses, which rest on a reinforced concrete slab over compacted gravel and polypropylene sheeting with geotextile for waterproofing and protection. This slab was necessary due to the poor properties of the land, caused by its proximity to the river Ebro. The main exterior walls are cavity walls: the exterior leaf is made of 29 cm lightweight clay blocks, with reinforcing bars along the string line and the inside leaf made of 1' perforated bricks, tied together with stainless steel ties, which gives the building a high thermal inertia. The main part of the horizontal structure is made up of suspended floors and roofing made of laminated timber beams, resting on concrete bands crowning the load-bearing walls.

The building's roofing is planned with landscape systems forming a biotope of indigenous plants that are resistant to the climate and that need minimum irrigation. The green roofs are a very advantageous ecological and economic option: they compensate the use of free surfaces, generate oxygen, act as thermal and acoustic insulation, favor the absorption of pollution and dirt particles, avoid overheating in the summer and reduce extreme temperature variations and dampness.

There is a greenhouse on the ground floor, up against the curved south facade, with a glazed roof and built using laminated timber posts and beams, supported on a low perforated brick wall. This greenhouse is important not only for providing sunlight in the adjacent rooms during the winter months, but also because it functions as heating in winter, even during hours without sunshine, due to the accumulation of heat in the mass of the high thermal inertia of the walls and flooring. It has mobile elements; all the vertical windows of the central part can be opened and there are workable awnings outside over the roof. Thus, in summer it creates a shady porch with ventilation that protects the inside from excess heat and refreshes the adjacent rooms. The greenhouse has single glazing for the vertical enclosure.

The insulation was optimized for each of the thermal areas, depending on how exposed to the exterior it is and the different use of the access spaces, corridors, laboratories or offices, and the correct location of the thermal inertial mass. Sheet and granulated natural cork was used, 2-3 cm thick in the walls, depending on the area.

All the windows and doors have been made in certified pinewood. The windows are double glazed, with an air gap (4/16/4 mm). All are low emissivity, with a high light transmission and low solar factor.

As general paving for offices and corridors, natural linoleum (0.25 cm thickness) has been used, while in the greenhouse and the main entrances of the ground floor, natural dark stone slabs have been laid. These stones are a local product from Calatorao (Zaragoza).

3.2. Input data

3.2.1. Product stage

Table 2 details all the materials that make up the building's structure and enclosure, indicating their volume, density and weight. Due to the poor geotechnical conditions of the terrain, graded aggregate and reinforced concrete were used for the foundations of the building. The total weight of the materials is 14,141.73 t. The graded aggregate makes up 73.7% of the weight, the concrete 14.3%, the bricks 3.4% and the lightweight clay blocks 2.4%.

Table 2. Inventory of building materials
Tablica 2. Popis građevinskog materijala

Category/ Kategorija	Material/ Materijal	Volume/ Volumen (m^3)	Density/ Gustoća (kg/m^3)	Weight/ Težina (t)
Concrete & cement/ Beton I cement	Reinforced concrete/ Armirani beton	1,026.33	1,700	1,744.76
	Concrete without reinforcement/ Beton	175.41	1,525	272.11
	Cement/ Cement	-	-	127.93
	Lime/ Vapno	-	-	71.99
	Graded aggregate/ Šljunak	5,421.16	-	10,427.60
	Adhesive mortar/ Mort za lijepljenje	0.96	1,250	1,20
	Lime mortar/ Vapnena žbuka	130.73	1,250	163.42
	Cement mortar/ Cementni mort	0.01	1,250	0.013
	Ex-clay/ Ekspandirana glina	70.70	538	38.04
	Polypropylene fibres/ Polipropilenska vlakna	-	-	0.044

Insulation/ Izolacija	Granulated cork/ Granulirani pluto	-	-	24.99
	Sheet of agglomerated cork/ Ploča aglomeriranog pluta	44.39	115	5.11
	Hemp felt/ Filc od konoplja	42.28	50	2.11
	Ex-clay/ Ekspandirana glina	414.53	538	223.02
Metals/ Metali	Sheet zinc/ Ploča cinka	0.66	7,200	4.74
	Reinforced steel/ Armatura	-	-	69.67
	Rolled steel/ Valjani čelik	-	-	8.67
	Steel pipes/ Čelične cijevi	-	-	0.70
	Steel tips/ Čelični vrhovi	-	-	0.83
Woods/ Drva	OSB panel/ Panel ploča s orijentiranim vlaknima (OSB)	21.90	600	13.14
	Pine timber/ Borovo drvo	30.39	570	17.32
	Indoor laminated timber/ Lamelirano drvo za unutrašnju uporabu	116.97	550	64.33
Others/ Ostalo	Plaster board/ Gips ploče	3.51	900	3.41
	Ceramic floor tiles/ Keramičke pločice	5.30	2,000	10.60
	Limestone/ Vapnenac	2.80	1,895	5.30
	Natural linoleum/ Prirodni linoleum	1.70	1,200	2.04
	EPDM/ Guma EPDM	2.83	1,150	3.26
	Geotextile felt/ Geotekstilni flis	-	-	0.941
	Protective paper/ Zaštitni papir	-	-	0.079
	Airbrick/ Cigla sa šupljinama za zrak	339.93	1,220	414.71
	Hollow bricks/ Šuplja cigla	73.23	920	67.37
	Lightweight clay blocks/ Lagani glineni blokovi	365.93	910	332.99
Category/ Kategorija	**Material/ Materijal**	**Surface/ Površina (m^2)**	**Density/ Gustoća (kg/m^2)**	**Weight/ Težina (t)**
Windows and doors/ Vrata i prozori	Timber window frames/ Drvena prozorska stolarija	60.31	80.20	4.84
	Single glazing (greenhouse)/ Jednostruka glazura (staklenik)	150.31	12.50	1.88
TOTAL WEIGHT/ UKUPNA TEŽINA (t)				14,141.73

The CIRCE building has the following equipment installed for air conditioning and sanitary hot water:

- 1 gas condensation boiler, with a nominal power of 160 kW for heating, with a combustion yield of 98%.
- 1 water-water heat pump with geothermal exchange [26] by means of a panel one meter underground whose temperature is maintained practically constant throughout the year. The pump has a nominal heating capacity of 66.4 kW and a nominal cooling capacity of 54.8 kW and functions with an electric compressor, with a yield of 4.5.
- 2 electric accumulator tanks with a nominal power of 4 kW for sanitary hot water, and a volume of 80 liters.

The heat/cold distribution system uses heated/cooled flooring with independent controls in each room using thermostats. At the same time, the lighting system is composed of high efficiency gas discharge lamps with a total installed capacity of 43 kW. The system includes presence detectors in corridors and some rooms.

During the first year a low-power hybrid wind-photovoltaic system was incorporated, connected to the building's grid, in addition to a low temperature thermal solar system to contribute to heating the building. It has a three-blade wind turbine with a horizontal shaft with nominal power of 6 kW and a total of 55 photovoltaic modules of different technology types, from amorphous silicon capture systems to CIS systems, with a total power of 5.3 kWp. Similarly it has 12 m^2 of thermal solar collectors based on vacuum tubes, with a maximum yield of 74% and a linear heat loss coefficient of 1.06 W/m^2K.

3.2.2. Construction process stage

The materials and equipment were transported from the plant to the construction site mainly by road, and the total transport needs were estimated at 528,074 tkm. For the construction work, the diesel fuel consumption was 13,275 kWh, and the electricity consumption was 2,149 kWh. The total amount of waste (mostly inert waste) generated in the construction of the building was 20 t, which only represents 0.1% of the total weight of the building.

3.2.3. Use stage

The demand and the final energy consumption of the building were calculated using the hourly-based simulation tools Lider and Calener GT [27].

This software is the official tool developed in Spain for the Energy Efficiency Certification of new (medium/large) tertiary buildings according to Royal Decree 47/2007 [28]. Calener GT calculation engine uses a dynamic simulation called DOE 2.2 v4.2a. Calener GT calculates the energy efficiency rating from A to G and provides some results such as the energy demand for heating and cooling based on the definition of the building envelope and the local climate. Then it estimates the final energy consumption for heating, cooling, lighting and hot water, calculated as the ratio of the energy demand and the seasonal efficiency of the facilities [29]. This efficiency calculation is based on the atmospheric conditions and performance curves of these facilities, which are mathematically modeled on the basis of certain variables, such as external temperature and workload. Calener GT considers a heating setpoint temperature of 20°C and a cooling setpoint temperature of 25ºC. The Calener GT calculation engine is validated through tests of the International Energy Agency (BESTEST-Building Energy Simulation Test). Therefore, the results are generally in the same order of magnitude as those obtained with other existing tools for building energy simulation [30].

At the same time, the solar photovoltaic and solar thermal contributions were calculated using the simulation software PvSyst 4.37 [31] and the f-chart method [32,33] respectively. In both cases, climatic data for the location was extracted from Meteonorm. The wind power contribution was calculated using the Weibull distribution and the power curve of the wind turbine. In this case, wind data was obtained from the nearest weather station (Zaragoza airport, distance: 8 km). The total on-site RES generation represents 30.7% of the final energy consumption of the building. When assessing the impact associated with the final energy consumption, the production values of renewable origin were deducted from the consumption of the building.

The results obtained are presented in Table 3. The final energy consumption is about 66% lower than the average consumption of Spanish office buildings.

Table 3. Energy demand, final energy consumption and on-site RES generation in CIRCE building (* the ratio is expressed in useful, air conditioned m^2)

Tablica 3. Potreba za energijom, finalna potrošnja energije i proizvodnja energije iz OIE na lokaciji u zgradi CIRCE (* omjer je izražen u korisnom, klimatizacija m^2)

	kWh/m^2 year */ kWh/m^2 godišnje *	**MWh/year/ MWh/godišnje**	**MWh/life span/ MWh/ životni vijek**
Heating demand/ Potreba za toplinom	38.5	-	
Cooling demand/ Potreba za hlađenjem	11.8	47.86	2,393.19
Heating consumption/ Potrošnja toplinske energije	27.33	7.68	383.81
Cooling consumption/ Potrošnja energije za hlađenje	4.38	0.15	7.64
Hot water consumption/ Potrošnja tople vode	0.09	24.13	1,206.44
Lighting consumption/ Potrošnja rasvjete	13.78	79.82	3,991.06
SUBTOTAL/ UKUPNO	45.58	3.70	185.10
Thermal solar generation (for heating)/ Proizvodnja iz toplinskih kolektora (za grijanje)	2.11	7.32	366.12
PV solar generation (for lighting)/ Proizvodnja iz fotonaponskih panela (za rasvjetu)	4.18	13.47	673.25
Wind generation (for lighting)/ Proizvodnja iz vjetra (za rasvjetu)	7.69	24.49	1,224.47
SUBTOTAL/ UKUPNO	13.98	47.86	2,393.19

The water consumption is estimated at 150 l/day, which implies a consumption of 2.3 l per occupant per day, which is approximately 50 times less than the typical consumption of a residential building in the same location. All of the water consumed by the building ends up in the drain and it is treated as wastewater. A medium-large treatment plant, with a wastewater treatment capacity for 1,200,000 equivalent inhabitants was considered (this corresponds roughly to the wastewater treatment capacity of Zaragoza).

Within building maintenance, only the replacement of the windows, doors and the energy generation equipment every 25 years has been considered in the calculations with a static LCA approach [34].

3.2.4. End-of-life stage

Within this stage, the impacts related to building demolition, transportation and the most probable final disposal scenario in Spain for all the materials from the building and from the energy equipment were taken into account.

In order to simplify the analysis, only 2 options were considered: direct recycling and direct final disposal without recycling (landfilling or incineration). Direct recycling at the building site was only considered for the metals. In this case, only burdens due to dismantling (energy consumption and particulate matter emissions) were included. The processes of recycling and external evaluation are beyond the limits of the system analyzed. Thus, its positive effects were considered only in the new products created using this waste. Except for the metals, a direct final disposal without recycling was considered. The burdens due to dismantling, the transport from the building site to the final disposal site, and the final disposal in a landfill or a municipal solid waste incinerator are accounted for within the system boundaries.

It is important to note the high level of uncertainty when considering an end-of-life stage scenario, as it will occur in more than 50 years' time.

3.3. Results and discussion

Analyzing the indicator CED, the use and production stages have a similar impact (46%), and the impact in the construction and end-of-life stages are lower, at 5% and 3% respectively. Nevertheless, when analyzing the indicator GWP, the end-of-life represents 14% of the total impact. This is because the scenario considered for the final disposal of all the biomass materials of this building was their energy valuation by incineration.

The poor properties of the land where the CIRCE building is located increase its structural needs and entail an increase in emissions in the production, construction and end-of-life stages, which would otherwise be even lower. In fact, if we eliminate the reinforced concrete slab and the layer of compacted graded aggregate, the total heating potential of the whole life cycle decreases by 23% with respect to the value in Table 4.

Table 4. Cumulative primary energy demand and CO_2 equivalent emissions in the different stages of the building's life cycle (* the ratios are expressed in useful, air conditioned m^2)

Tablica 4. Ukupna potreba za primarnom energijom i emisije ekvivalenta CO_2 u svim stadijima životnog ciklusa zgrade (* omjer je izražen u korisnom, klimatizacija m^2)

	Cumulative Primary Energy Demand/ Kumulativna potreba za primarnom energijom		**Global Warming Potential/ Potencijal globalnog zatopljenja**	
	GJ-Eq	**kWh-Eq/ m^2 year */ kWh-Eq/ m^2 godišnje ***	**t CO_2-Eq**	**kg CO_2-Eq/m^2 year */ kg CO_2-Eq/m^2 godišnje ***
Product stage/ Stadij proizvoda	17,588.40	55.80	911.75	10.41
Construction process stage/ Stadij proizvodnog procesa	2,182.41	6.92	129.71	1.48
Use stage/ Stadij korištenja	17,605.14	55.85	909.07	10.38
End-of-life stage/ Kraj životnog vijeka	1,259.30	3.99	309.64	3.54
TOTAL/ UKUPNO	38,635.25	122.57	2,260.17	25.81

Figure 2 disaggregates the GWP impact into the most relevant aspects analyzed in the different stages of the life of the building. The materials in the category "Concrete & Cement" make up 32% of the total impact, followed by the energy consumption for lighting (31%) and for heating (28%). The on-site RES generation compensates for 42% of the impact associated with the direct consumption of the use stage, avoiding the emission of 624 tCO_2-Eq throughout the building's useful life. Similarly notable is the absorption of 83 tCO_2-Eq associated with the timber used in the structure and joinery of the building, which makes the building a significant CO_2 store.

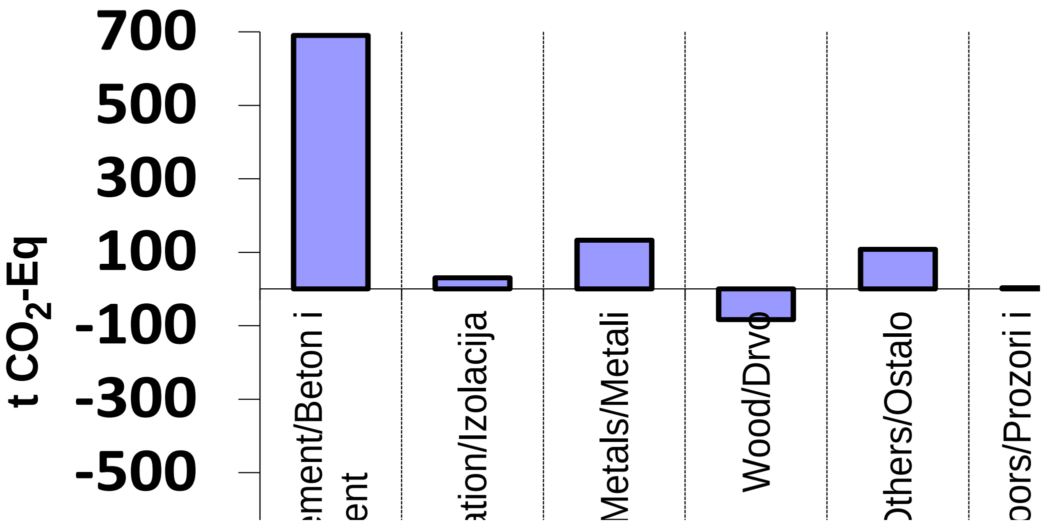

Figure 2. Global Warming Potential of the different aspects of the building's life cycle
Slika 2. Potencijal globalnog zatopljenja različitih aspekata životnog ciklusa zgrade

3.4. Sensitivity Analysis and Scenarios

3.4.1. System boundaries

3.4.1.1. Simplified LCA

This section compares the results obtained in the complete LCA (as defined in paragraph 2) with those obtained by simplifying the analysis. The simplified LCA proposal involves:

- Selecting only the cumulative primary energy and the global warming potential as impact categories.
- Leaving the construction and end-of-life stages out of the system boundaries.
- Limiting the aspects included in the building production stage to the construction of the structure and enclosure.
- Limiting the aspects included in the building use stage to the final energy consumption for the building operation.

Figures 3 and 4 show the life cycle impacts obtained from the above considerations versus the results obtained for the whole LCA.

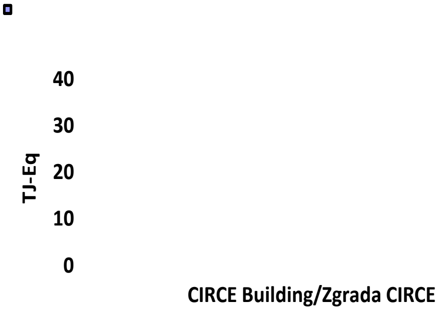

Figure 3. Comparison of the embodied energy impact (in TJ-Eq) in the CIRCE building using the complete LCA and the simplified LCA
Slika 3. Usporedba utjecaja ukupne energije (u TJ-Eq) u zgradi CIRCE koristeći cjelokupnu analizu životnog ciklusa i pojednostavljenu analizu životnog ciklusa

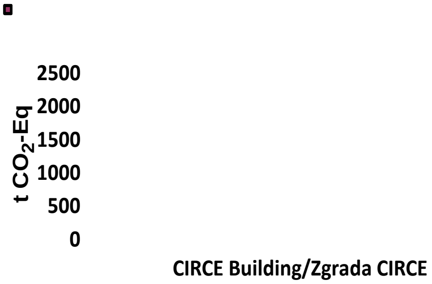

Figure 4. Comparison of the GWP impact (in tCO_2-Eq) in the CIRCE building using the complete LCA and the simplified LCA

Slika 4. Usporedba utjecaja potencijala globalnog zatopljenja (u ekvivalentnim tonama CO_2) u zgradi CIRCE koristeći cjelokupnu analizu životnog ciklusa i pojednostavljenu analizu životnog ciklusa

From these figures, an error of between 14% and 23% is estimated for the simplified analysis. The proposed simplification reduces the data and calculations, also reducing the time required to carry out the study, which is essential in order to achieve universality in the use of the LCA between the key players in the construction sector. However the generalization of this simplification proposal to other buildings (of similar types) would require a greater number of studies to draw relevant conclusions.

3.4.1.2. Broadening the system boundaries: incorporating urban mobility

This section compares the results obtained in the entire LCA (as defined in paragraph 2) with those obtained by incorporating urban mobility needs into the limits of the building's use stage.

All the urban mobility data were extracted from an internal staff survey conducted in 2010 (first year of the building use). All of the occupants responded correctly to the survey and a total of 65 valid surveys were obtained with 100% reliability. The results show that most staff members make daily short journeys: 58% of staff travel between 5 and 20 km/day, and the average distance travelled by each person is 13.5 km/day. It is important to note that in only 2% of trips do 2 employees of the CIRCE building travel in the same vehicle. In the remaining 98%, these trips are made individually. As shown in Table 5, the total number of kilometers travelled per year amount to almost 292,939 km/year, which implies an average of 4,507 km per person per year.

Table 5. Total number of kilometers per year by vehicle type

Tablica 5. Ukupni broj kilometara godišnje po tipu vozila

Means of transport/ Vrsta prijevoza	**Mileage (km/year)/ Kilometraža (km/godišnje)**	**Percentage/ Udio**
Car/ Automobil	199,855.35	68.2%
- Diesel car/ Dizel automobile	132,791.10	45.3%
- Petrol car/ Benzinski automobile	67,064.25	22.9%
Bus/ Autobus	42,205.40	14.4%
Bicycle/ Bicikl	23,450.20	8.0%
Van/ Kombi	10,021.20	3.4%
- Diesel van/ Dizel kombi	9,791.70	3.3%
- Petrol van/ Benzinski kombi	229.50	0,1%
Motorcycle/ Motocikl <=125CC	6,956.70	2.4%
Motorcycle/ Motocikl >125CC	6,405	2.2%
On foot/ Pješke	4,044.80	1.4%
TOTAL/UKUPNO	292,938.65	100%

The impact associated with mobility was evaluated using the data available in the Ecoinvent v2.0 database, like the rest of the study. The impact of the trip itself and the corresponding impact related to the vehicle and the necessary infrastructure were also considered. In total, the global warming potential associated with mobility is estimated at 41.53 tCO_2-Eq/year. As shown in Figure 5, the impact in equivalent CO_2 emissions associated with mobility is 2.3 times greater than the impact in the usage stage of the building which includes water consumption, energy and maintenance.

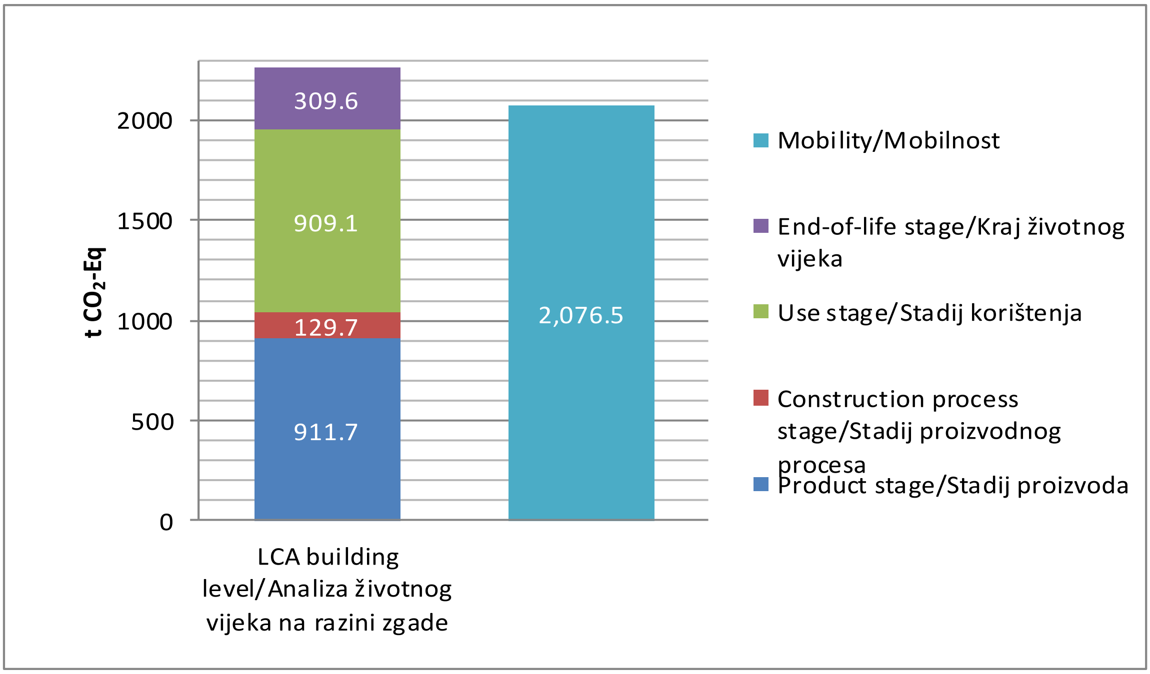

Figure 5. Impact of mobility on the life cycle of the CIRCE building, evaluated in terms of GWP

Slika 5. Utjecaj mobilnosti na životni ciklus zgrade CIRCE, ocijenjeno na temelju potencijala globalnog zatopljenja

Therefore, including mobility within the limits of the LCA of the CIRCE building, this would provide 48% of the building's global warming potential. Similar figures are obtained if we analyse in terms of embodied primary energy.

3.4.2. Lifetime of the building

The building's lifetime is an important parameter in the LCA calculations. The lifetime usually considered is 50 years. However the lifetime presents significant differences depending on the country and the type of building.

In this section a sensitivity analysis for the building's lifetime is presented. Different lifetime values have been considered: 25, 50, 75, 100 and 125 years. In order to achieve comparability of the results, the annualized impact (in terms of GWP) was assessed. In this analysis, the maintenance intervals (for windows, doors and the energy generation equipment) were maintained. In order to simplify the analysis, the lifetimes of the remaining building components were considered the same as the building lifetime value (25, 50, 75, 100 and 125 years).

As Figure 6 shows, the impact reduction is very significant as the building's lifetime is increased. In fact if we compare a lifetime of 25 years with a lifetime of 50 years, a total reduction of 36% in the annualized GWP impact is obtained. The reduction is particularly significant in the production stage.

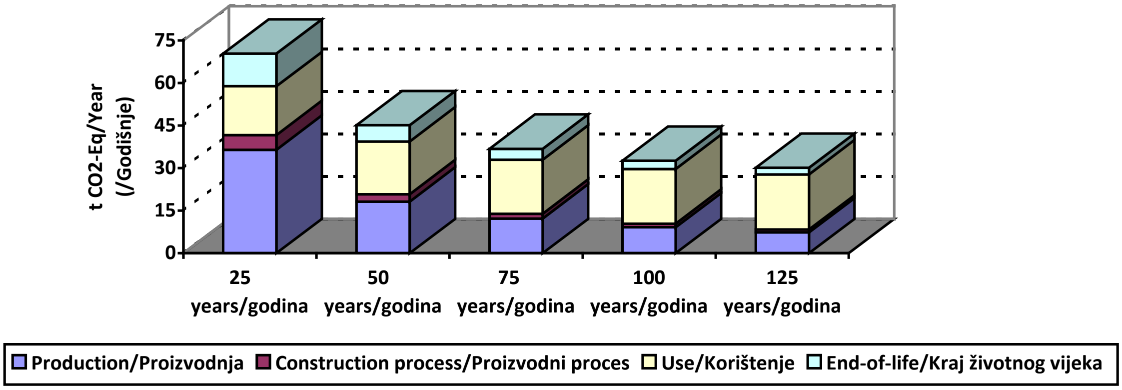

Figure 6. Comparison of the annualized GWP impact (in tCO$_2$-Eq) during the building's life cycle with different building lifetime values

Slika 6 Usporedba utjecaja potencijala globalnog zatopljenja na godišnjoj razini (u tonama ekvivalentnog CO$_2$) za vrijeme životnog ciklusa zgrade s različitim trajanjima životnog vijeka

Obviously the impact of the building operation (including the operational energy use and the operational water use and wastewater treatment) is the same for the different building lifetime values. Consequently only the maintenance impact is increased in the usage stage, as shown in Figure 7.

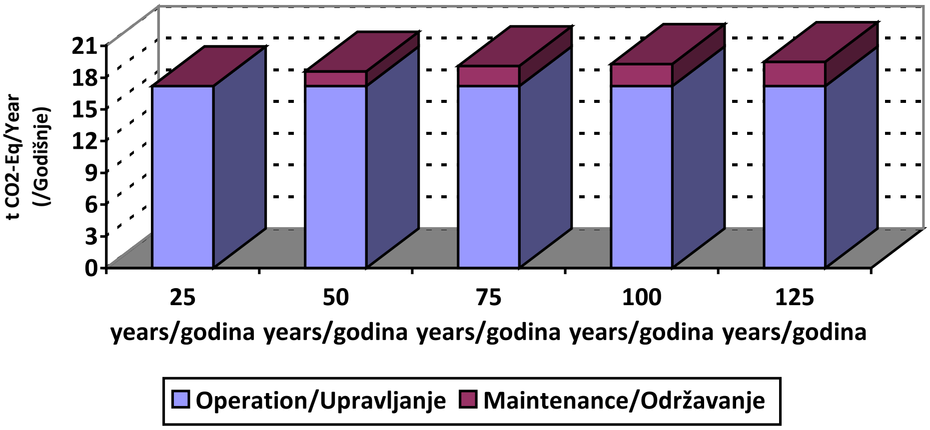

Figure 7. Comparison of the annualized GWP impact (in tCO_2-Eq) during the use stage of the CIRCE building with different building lifetimes

Slika 7. Usporedba utjecaja potencijala globalnog zatopljenja na godišnjoj razini (u tonama ekvivalentnog CO_2) za vrijeme korištenja zgrade CIRCE s drugačijim vremenima gradnje

3.4.3. Electricity mix

This section evaluates the influence of the electric mix considered in LCA calculations on the results of the GWP. To this end, 4 different electricity mixes were compared: the Spanish electricity mix, the average electricity mix in Europe (see Figure 8) estimated according to the statistics of the UCTE (Union for the Co-ordination of Transmission of Electricity member countries) – actually the ENTSO-E European Network of Transmission System Operators for Electricity, and 2 other electricity mix scenarios.

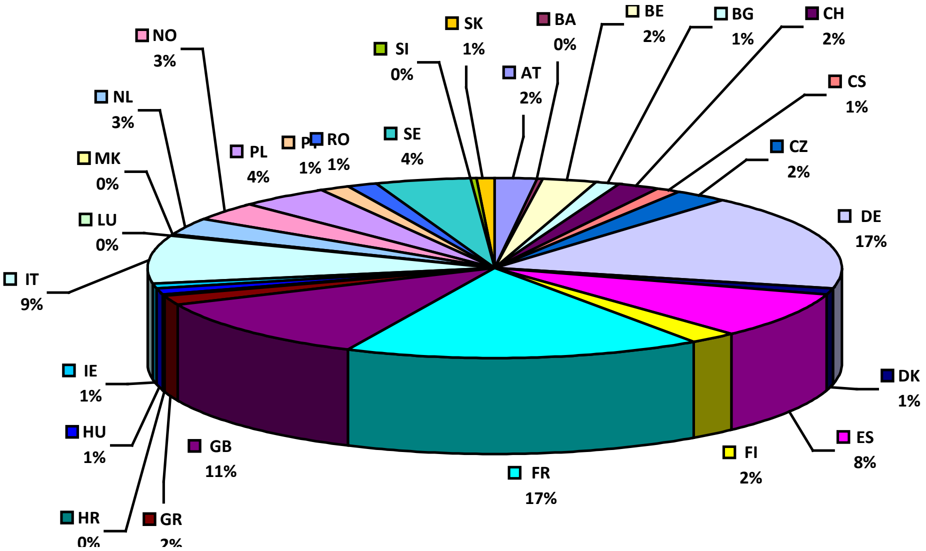

Figure 8. Electricity mix for the production of 1 kWh in Europe (average values of UCTE member countries in Ecoinvent database)

Slika 8. Udjeli proizvodnje 1 kWh električne energije u Europi (**prosječne** vrijednosti zemalja članica UCTE iz baze Ecoinvent)

Table 6 presents two futures scenarios for the electricity mix. The first scenario considers a share of RES of 40% in the electricity mix, whereas the second scenario takes into account a share of RES of 80%.

As shown in Figure 9, considering the average European electricity mix instead of the Spanish electricity mix, there is virtually no variation in the total GWP of the building (the increase of the impact is less than 1%).

Considering scenario 1, the decrease in total GWP is 8.1%. This decrease is greater in the use stage, where the reduction is 15%. In the production stage, the reduction is 5%, whereas in the other stages there is virtually no variation.

Moreover, considering scenario number 2, the total GWP reduction is 15%. Again, in the usage stage, the decrease obtained is higher (29%). While the decrease in the production stage is 9%, and in the other stages there is no variation.

Table 6. Electricity mix for the production of 1 kWh in Scenarios 1 & 2
Tablica 6. Udjeli proizvodnje 1 kWh električne energije za scenarije 1 i 2.

Source/Izvor	Scenario 1 /Scenarij 1 40% RES (kWh)	Scenario 2 /Scenarij 2 80% RES (kWh)
Natural gas/Prirodni plin	0.30	0.10
Nuclear/Nuklearna	0.20	0.07
Hard coal/Antracit	0.10	0.03
Wind power/Vjetar	0.20	0.40
Hydropower/Hidro energija	0.18	0.36
Photovoltaic production/ Fotonapon	0.02	0.04

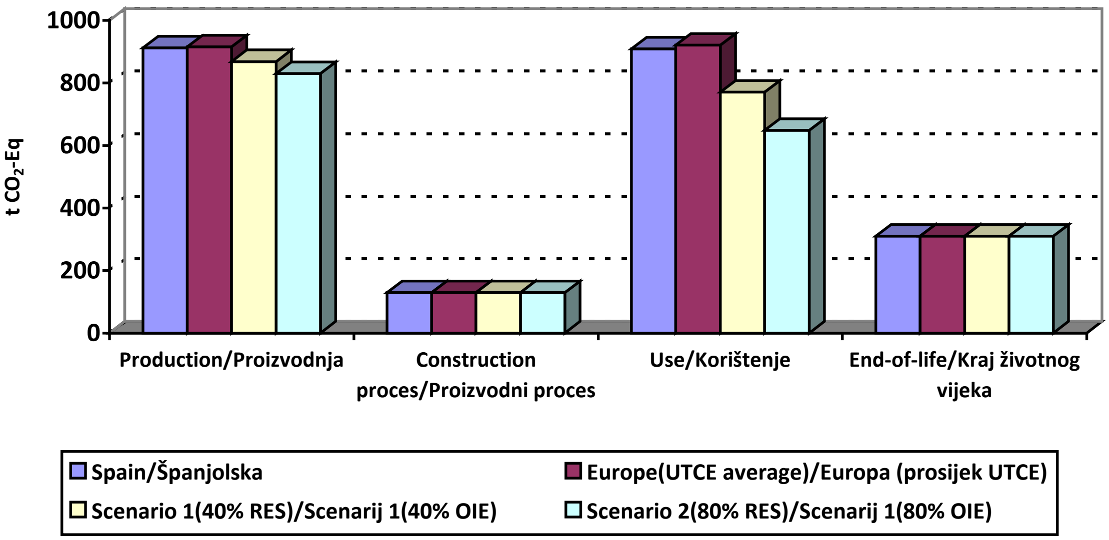

Figure 9. Comparison of the GWP impact (in tCO_2-Eq) during the building's life cycle with different electricity mixes
Slika 9. Usporedba utjecaja potencijala globalnog zatopljenja na godišnjoj razini (u tonama ekvivalentnog CO_2) za vrijeme životnog ciklusa zgrade s različitim udjelima u proizvodnji električne energije

3.4.4. GWP time horizon

The GWP value depends on how the gas concentration decays over time in the atmosphere. Since this is often not precisely known and hence the values should not be considered exact, it is very important to give a reference to the calculation when quoting a GWP. A time horizon of 100 years is commonly used by regulators, although other time intervals (e.g. 20 years, 500 years) can also be considered.

Figure 10 presents the results of the GWP impact of the building, considering time horizons of 20, 100 and 500 years. Assuming a time horizon of 20 years, the GWP is increased by 10% compared to the common approach (100 years). However, if a time horizon of 500 years is considered, the GWP is decreased by 4% compared to the usual approach.

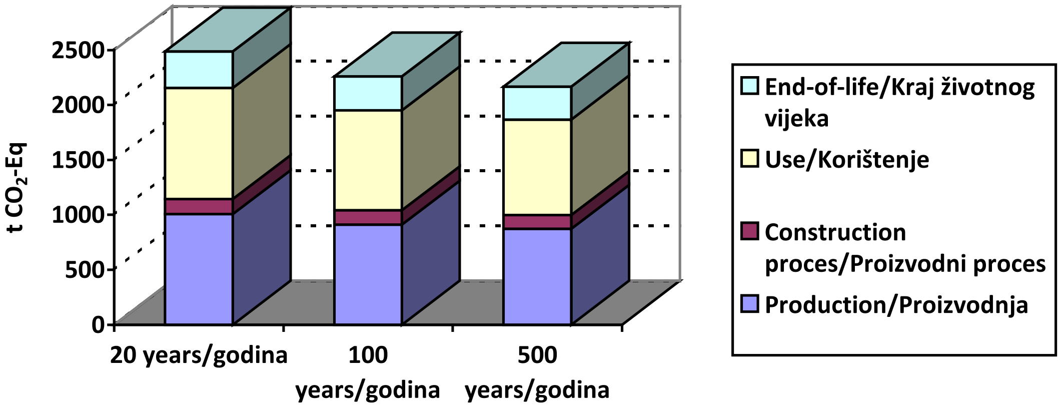

Figure 10. Comparison of the GWP impact (in tCO$_2$-Eq) with different time horizons during the building's life cycle
Slika 10. Usporedba utjecaja potencijala globalnog zatopljenja na godišnjoj razini (u tonama ekvivalentnog CO$_2$) s različitim horizontima za vrijeme životnog ciklusa zgrade

3.4.5. Transport distance from the factory gate to the building site

In order to evaluate the impact of transporting 1 tonne by several means of transport, the following linear correlation was applied:

Transport impact = $\Sigma_i\, m_i \times d_i$ (1)

- d_i: distance travelled by each form of transport (in km).
- m_i: coefficients applied to each form of transport (in tCO$_2$-Eq/km). [35].

A sensitivity analysis for the transport distance of the building components is carried out. To this end, the building's life cycle impact is evaluated in terms of GWP, assuming that all the building materials (except for the graded aggregate) and energy equipment are transported by a 20-28 t lorry at half load covering different distances from the factory gate to the building site (from 50 km to 5,000 km). For the graded aggregate, a distance of 15 km was maintained.

As can be seen in Figure 11, if the transport distance from the factory gate to the building site is lower than 200 km, the construction process stage involves an impact of less than 10% of the total life cycle impact. However, if the distance is greater than 2,000 km, the construction process stage has the highest impact and reaches more than 40% of the total impact.

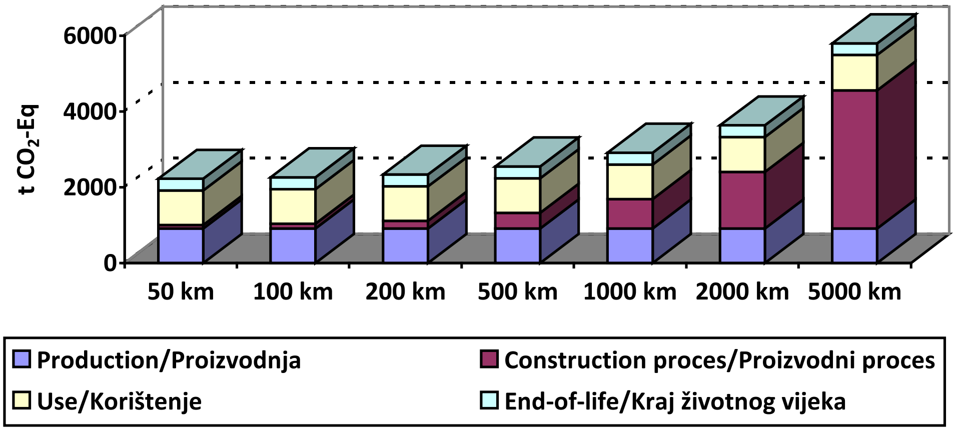

Figure 11. Comparison of the GWP impact (in tCO$_2$-Eq) with different transport distances from the factory gate to the building site
Slika 11. Usporedba utjecaja potencijala globalnog zatopljenja na godišnjoj razini (u tonama ekvivalentnog CO$_2$) s različitim udaljenostima od vrata tvornice do gradilišta

4. Conclusions

The indirect environmental impact of buildings is greater than the direct impact of buildings built to the current building standards. Specifically, the indirect impact associated with the urban mobility of a building's occupants is more than double the direct impact associated with the energy consumption for air conditioning and lighting and with water consumption. In addition, this situation will grow in the future due to the ever more stringent standards focused on reducing energy and water consumption in the daily use of the buildings. The reduction of urban mobility entails opting for compact urban planning designs, and promoting car sharing and car pooling, through subsidies or tax exemptions.

The environmentally-friendly design of the building analysed, with good insulation, adequate orientation, passive conditioning and integrated renewable energies, allows us to achieve a low energy consumption building, decreasing the relative impact of the use stage and increasing the relative significance of the production stage.

In the case analysed it was observed that the global impact of the life cycle (including mobility) expressed in global warming potential is very much lower than that of other university buildings. Despite this, the figures obtained indicate the complexity of achieving a life cycle zero-emissions building. For this reason this standard must be considered an ambitious challenge to be met in the medium to long term.

As can be deduced from the results of the sensitivity analysis, there are many parameters (system boundaries, lifetime, electricity mix, GWP timeframe and transport distances) which have a decisive influence on the LCA results. As this influence can be different depending on the type of building and the location, more studies should be carried out in order to establish definitive conclusions.

Acknowledgements

This paper has been developed from the results obtained within the framework of the EnerBuiLCA Project "Life Cycle Assessment for Energy Efficiency in Buildings" [36] and the ECOURBAN project "Methodology for assessing energy and environmental impacts to assist the eco-design of housing developments" both coordinated by the CIRCE Foundation. The EnerBuiLCA project is co-financed by the European Regional Development Fund (Territorial Cooperation Programme SUDOE – Interreg IV B, file number: SOE2/P2/E367), whereas the ECOURBAN project is financed by the Spanish Ministry of Science and Innovation (Spanish National Plan for Scientific Research, Development and Technological Innovation 2008-2011 - Contract ENE2010-19850).

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