Energy and water consumption and carbon footprint of school buildings in hot climate conditions. Results from life cycle assessment.

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ABSTRACT

Optimized energy use and water provision in school buildings play an important role in the sustainability performance of municipalities, and are included in the local sustainable energy policies. Hot climate conditions exacerbate the need for the use of cooling devices and are usually associated to water scarcity problems. Additionally, school buildings in these areas are usually lacking good thermal insulation conditions and energy efficiency measures. This work analyses the energy, material and water requirement activities of two schools located in a hot climate area, and evaluates the aggregated energy and water consumption, the water scarcity exacerbation problems, and the associated carbon footprint through Life Cycle Assessment, which allows the quantification of the impacts along the whole value chain of the school activities per student. Additionally, the effects of different improvement measures, such as the implementation of renewable energy sources and the optimization of energy use based on energy efficiency measures, such as changes in the lighting technologies, are quantified. The results show that schools could reduce the fossil energy demand of the building in the operating and maintenance phase per student between 4.89% and 6.03% by means of the implementation of non-renewable heating measures, between 64.06% and 78.98% by means of the implementation of renewable heating solutions, and between 12.05% and 9.54% by means of the implementation of lighting substitution measures.

KEYWORDS

Life cycle assessment; educational building consumptions; O&M phase building life cycle inventory; energy building demand; water resource depletion; carbon footprint.

HIGHLIGHTS

School buildings in hot climate conditions areas are usually lacking good thermal insulation conditions and energy efficiency measures.

Life Cycle Assessment methodology was used to quantify environmental impacts along the whole value chain of the school activities.

Schools could reduce several environmental impacts by means of the implementation of non-renewable heating and lighting substitution measures.

LCA characteristic could be useful, to drive the analysis towards the identification of hotspots and modifying consumption practices to achieve the goals of environmental impacts decreasing.

1. INTRODUCTION

European policies are focused on achieving a low-carbon economy, proposing by 2030 to reduce its emissions by 40% compared to 1990 levels, 60% in 2040, and an additional reduction from 80 to 95% by 2050, (ECa, 2011; ECb, 2012). Such ambitious goals could be reached through the transition towards a less carbon-intensive global energy system. Particularly, buildings are responsible for 40% of energy consumption and the potential to reduce it is considerable (ECc, 2011). In 2016 the Commission proposed an update to the Energy Performance of Buildings Directive to help promote the use of smart technology in buildings and to streamline the existing rules, including that EU countries make energy efficient renovations to at least 3% of buildings owned and occupied by central government, and draw-up long-term national building renovation strategies (ECc, 2011). In Spain context, according to Ministry of Development (2014), authorities recognizes the cultural and educational use buildings as main priority due to the fact that those buildings represent 11% of the urban area and 2% of the buildings. Moreover, diversity of buildings and their distinct use imply major differences for the adoption of energy conservation strategies. Therefore, single solution or legislative rule can be effective in all cases (United Nations Environment Programme, 2007).Currently, the Life Cycle Assessment (LCA) methodology constitutes the most appropriate framework to adequately assess the environmental impacts of any kind of activity, product or service throughout its life (Isasa et al., 2014; Rodríguez and Porras, 2016). The application of this methodology to the construction sector requires a high complexity in terms to analyse (building design, materials, etc.) due to the particularities of the buildings and the relative lack of information throughout the sector. LCA has been applied for different building research, highlighting Neururer et al. (2016) who found that the operational phase causes 54% up to 83% of negative environmental impacts measured by selected main impacts, including Global Warming Potencial (GWP) and Primary Energy Input. On the other hand, the results from Rodríguez and Porras (2016) concluded 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. LCA is therefore considered as a versatile and useful tool for reducing the energy consumption and associated GHG emissions of the construction sector and establishing the most appropriate environmental improvement measures from a global perspective. The application of LCA to buildings allows considering the environmental impact of all stages of their life cycle, including the product, construction process, use and end of life stages. At present, the current legislative framework is leading to the minimization of the environmental impacts associated to the operating and maintenance (O&M) phase of the building, increasing therefore the relative weight of the remaining phases of the life cycle of the buildings.

Prime factor in any low-carbon building retrofitting consist of the improvement in building use and management, which are aimed at having efficient performance in the use of energy and associated emissions (Ministry of Development, 2014). Public institutions, included educational sector are getting involved in European initiatives and projects related to environmental performance. In particular, many environmental policies and management systems have been established to reduce the environmental impacts of the educational facilities. For example, country initiatives like the ‘Higher Education Funding Council for England’ demands for setting the greenhouse gas (GHG) emission reduction target. Other ongoing examples of European projects are Euronet 50/50 project (Inelligent Energy Europe, 2013) or Eco-schools Programme of Foundation of Environmental Education recognised by United Nations (FEE, 1992).

The global interest in low-carbon economy has promoted studies on the assessment of global warming potential during the life cycle of a building through LCA method. Operational energy consumption data for educational buildings in use can be used to find opportunities to improve efficiency in the public sector. LCA methodology could be used as indicators measure the educational function. Different research works have been identified in the literature and main results are shown in the Table 1. Arena and de Rosa (2003) carried out a LCA and environmental implications study of the implementation of conservation technologies versus traditional technologies for comparing different building technologies which have been applied in a rural school building for obtaining thermal comfort with minimum fossil energy consumption. Varun et al. (2012) presented the environmental impacts in the material manufacturing phase and the operation phase for educational buildings in India. Ozawa-Meida et al. (2011) presented the carbon footprint in the operation phase for United Kingdom universities. Baboulet and Lenzen (2010) presented the environment impact in the operation phase for universities. Jeong et al. (2014) foresees the environmental impact for six impact categories in the project planning phase applying LCA methodology, affecting the whole life cycle of the building focused on educational facilities. Nicolae and George-Vlad (2015) analysed the refurbishment of the buildings as intervention practices in energy saving using a school as a studies case. In Spain, there are works related to this topic (Isasa et al., 2014; Rodríguez and Porras, 2016; Martínez, Oliver and Casas, 2011; Zabalza et al., 2013; Vilches, Garcia-Martinez and Sanchez-Montañes, 2017). As examples, on one hand, Vilches, Garcia-Martinez and Sanchez-Montañes (2017) have made a deep review about the LCA of building refurbishment and they organised and summarised the recent contributions related to the environmental evaluation of building refurbishment and renovation. And the other hand, Isasa et al. (2014) have developed a user-friendly tool associated to an environmental information database of construction products developed which allows calculates the building´s primary energy consumption and the Global Warming Potential measured in CO2 equivalents which use as pilot case educational buildings.

Table 1. Summary of related works to the LCA of educational building and results.

Reference	***Location***	***Analysed impact***	***Result/FU***
Arena and Rosa (2003)	Argentina	GWP, AC, photo-smog, resources consumption, eutroph., toxicity	680 µPE*/m^2 of the whole area of the considered refurbishment technology
Varun et al. (2012)	India	GWP Primary energy	5,3 kg CO2 eq/m^2 usable floor area*year
Ozawa-Meida et al. (2011)	UK	Carbon footprint Energy	65 kg CO2 eq/m^2 gross internal area*year (excluding construction)
Isasa et al. (2014)	Spain/ Portugal	GWP Primary Energy	Use phase: 514 MJ/m^2 acclimatized area*year)

The reviewed works that evaluate the impacts associated to educational buildings are diverse and present a variety of case studies, boundary systems and impact analysis methods. The common characteristic is that all of them include the use phase analysis. The advantages of the application of the LCA methodology on the use phase of the building are that the results show the environmental consequences of the whole chain of production and use of energy and materials consumed in the school. That allows not only the consideration about how much it is consumed, but also what are the impacts of supplying and consuming it.

In spite of the fact that the function of the system is supporting the educational activity; most of the literature reports the results in terms of impacts per unit of area. Furthermore, different studies consider different types of areas (gross area, usable area, floor area, etc.). Therefore, the results of these studies are difficult to compare. Furthermore, some of the methodological assumptions used in the analysis, such as system boundaries and impacts methods, differ between the studies. Each LCA study requires large amount of information about the building architecture or construction characteristics. That could be the main disadvantage of the LCA application to an educational building.

With the aim of identifying main activities and consumption sectors in schools to design efficient low-carbon retrofit solutions according to school performance and needs, this paper assesses through LCA the operating and maintenance phase of school buildings in hot climate conditions. Two schools have been selected as case studies within the ClimACT project[1](ClimACT Project is currently being drawn up under the priority axis ‘Low Carbon Economy’ from Interreg SUDOE program[2]). The paper quantifies the environmental impacts associated with the consumption of energy, materials and water of two located in a central area of Spain (Madrid). Climatic condition responds to continental climatic conditions, cold and hot temperatures along the year and low rainfall. Information collection process was supported by means of a survey, designed according to the scope and boundaries were filled by school’s staff; audits and account books and commercial and public database. The most relevant contribution of this study is an exhaustive life cycle inventory of the O&M phase collected in the audits and surveys made on site in the high schools. Furthermore, we have reported the results per unit of area as well as per student, since we understand that this later reference unit is more relevant for an educational building. Finally, to provide to decision-makers useful information about existing opportunities to enhance the eco-efficiency of educational buildings, the effects of several improvement measures concerning the use of renewable energies and the optimization of energy consumption were assessed.

2. MATERIALS AND METHODOS

The work carried out makes the use of the multi-criteria and holistic approach offered by LCA following the guidelines of ISO 14040 (ISO, 2006) and ISO 14044 standards (ISO, 2006). LCA is a methodology that allows the evaluation of the environmental impacts associated to all the stages of a product's life cycle and encompasses extracting raw materials, processing, manufacturing, transportation and distribution, use, reuse and recycle and final disposal.

The framework of the analysis includes four phases: i) Definition of objective and scope; ii) Inventory Analysis; iii) Impact Assessment and iv) Interpretation of results. Figure 1 show the adaption developed in the original steps in order to apply LCA in this study.

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[1] Additional information: http://www.climact.net/ .

[2] Interreg SUDOE: Cooperation Programme Interreg V-B Southwest Europe

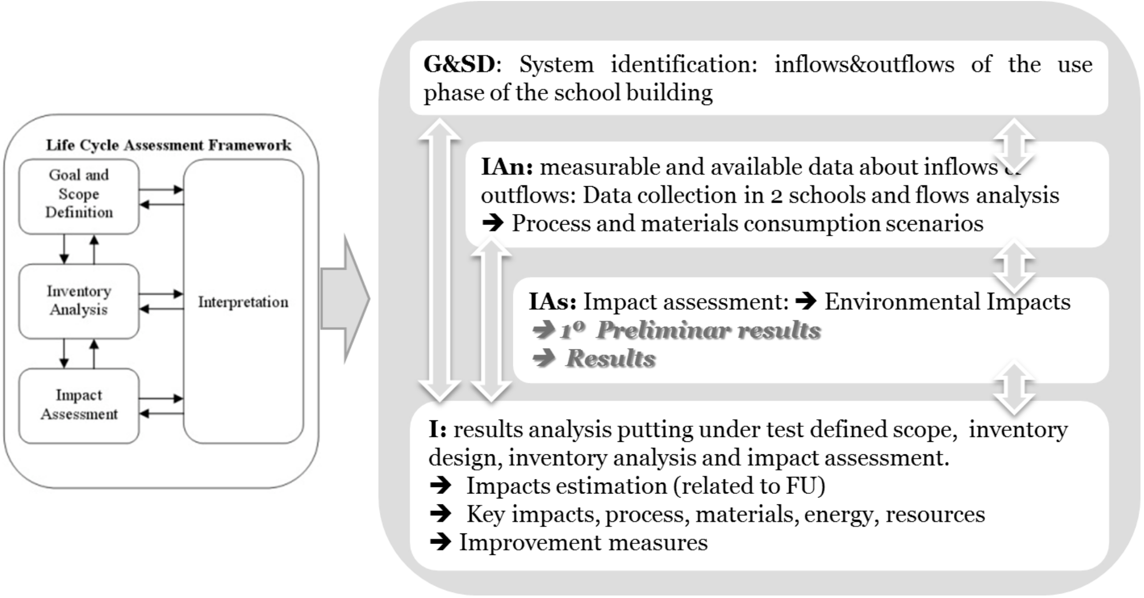

Figure 1. Structure of integrated approach supported in LCA.

2.1. Goal and scope definition

The goal of this LCA was the assessment of the environmental impacts associated with the consumption of energy, materials, and water in two educational centres located in a central area of Spain. This zone presents continental climatic conditions and subject to both cold and hot temperatures along the year as well as low rainfall conditions that may, in some cases, lead to water scarcity problems. Other aspects regarding to functional unit and system limits are shown below.

Functional unit. The function considered in this LCA is the provision of space and conditions for the educational activities during a school season (from September to July). It should be considered that the building is operating during July just to administration activities.

The inventory of the whole energy, materials and water consumption will be referred to this period and results will be expressed per course and per student. Concurrent activities carried out in the building (such as adult education activities or other cultural activities) are excluded from the assessment. Frequently, in LCA of buildings the functional unit is an area unit, but in this study one student was identified as useful functional unit. However, some results are expressed by area in order to compare with the previous results existing in the literature.

Scope and system boundaries. The work is focused on the quantification of the environmental impacts of the O&M of the building for educational activities. The analysis is then restricted to the assessment of energy, raw materials and water consumed by the building itself in order to provide a comfortable space to carry out educational activities. The consumption and environmental loads of materials used in educational activity itself are excluded from the assessment.

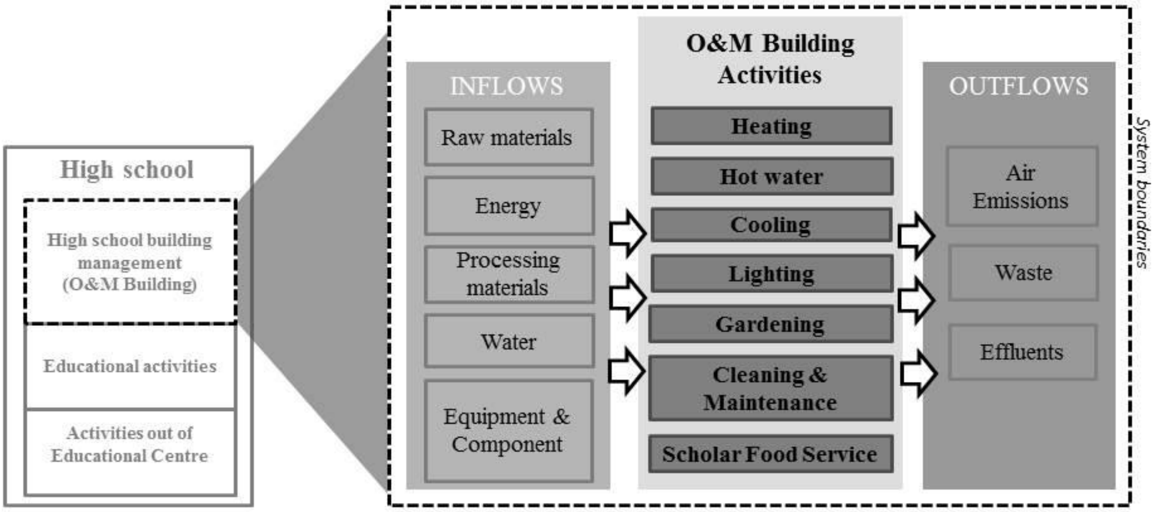

Figure **2** illustrates the system boundaries and the activities explicitly considered.

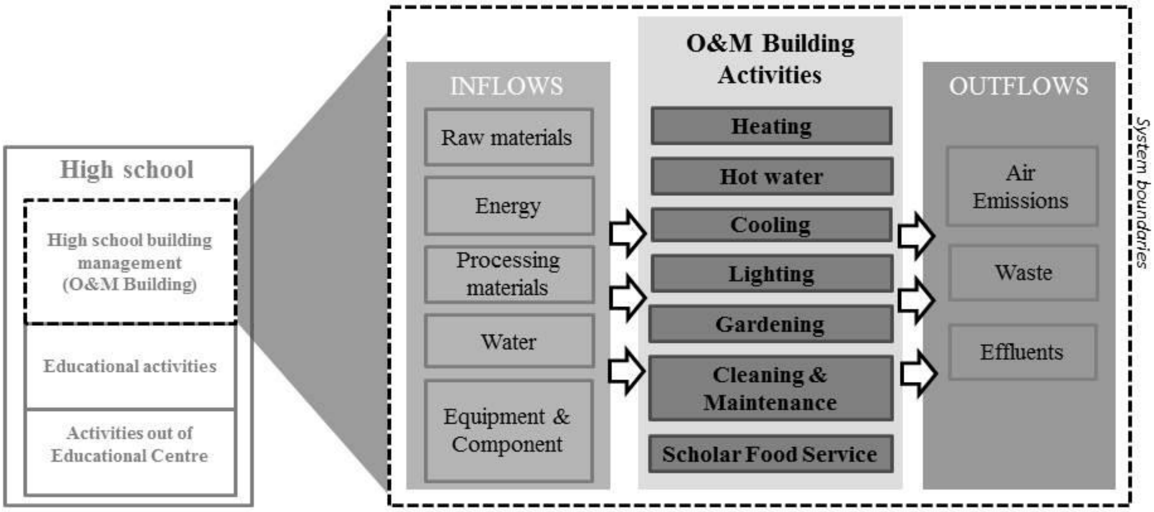

Figure 2. Scope and system boundaries of the system in high schools.

The studied system include the next three activities: *management and operation of the building activities*; e*ducational activities* and *activities outside the centre*, which correspond mainly to transport and mobility. So, the analysed system consists of the O&M stage. As far as possible, the consumption of materials of the educational activity itself is excluded from the assessment. The system has some inputs such as raw material, energy, water and outflows as air emissions, wastes and wastewater, as consequence of the building processes and activities. Among them have been identified the high school heating, hot water production, cooling, lighting, gardening, cleaning and facilities maintenance, and scholar food service. Some of more relevant activities are related with the next issues:

i. Cleaning activities refer to the daily cleaning of classrooms, offices, corridors and other dependencies of the school building. They involve the use of cleaning products and machines.
ii. Heating and cooling of the school building requires the use of fuels and electricity. The manufacturing of the heating and cooling system itself is excluded from the analysis.

iii. Lighting involves the use of electricity but also the yearly replacement of spent lamps and their disposal.
iv. Scholar food system considers the equipment and operation time.
v. Gardening activities are those related to the planting, watering and care of trees and other plants present in the school grounds.
vi. Maintenance activities include the annual painting, repairing and other required maintenance of the building elements.
vii. Wastes: wastes produced by annual painting, repairing and other required maintenance of the building elements.

Other activities strictly linked to the education performance in the schools are not included within the scope, such as the use of computers and other electronic equipment, and the resources consumption related to teaching such as pens, books, paper and other materials.

Pilot schools and data sources. Two educational centres for secondary and high school education level were selected for the analysis performed in this paper hereafter called High School 1 (HS1) and High School 2 (HS2). Both centres are located in urban areas within Madrid City, in residential neighbourhoods.

The difference between educational centres in terms of level of education and location could be important influencers in the performance. On the one hand, activities and materials consumption in primary or childhood school as well as schedules are expected to be highly different to those of secondary and high schools. On the other hand, location characteristics such as climactic conditions could determine the fuel consumption for heating or the run out water per year. Consequently, the study cases were selected considering attending to the similarity in these two characteristics, educational level and location. This fact helps to the comparability of cases, since the performance is independent of these two factors.

Table 2. Characteristics of high school case studies

Parameter	***Unit***	***HS1***	***HS2***
Year of construction and refurbishments		1988 (building 1) 2003 (building 2)	1950 Refurbishment in different years
Number of buildings		2	1
Number of floors		3 (building 1) 2 (building 2)	3
Outdoor and indoor area	m^2	14409	5600
Gross building area	m^2	6096	4523
Number of students		907	410
Ratio students-area	students/m^2 of gross area	0.149	0.091

Information source and data quality. The most important sources of information used and the consulted databases were selected. Processes whose contribution to mass and energy flows are known to be important and whose emissions are relevant to the environment were selected and investigated. Data used in this LCA was directly provided or collected in both educational centres for the period between January to March of the year 2017, and are referred to the previous course period (2015-2016). The pilot schools were characterized and quantified according to a collection survey designed to gathering information as inputs to elaborate the inventory. Survey was structured in order to ask about goods and services consumption to achieve an adequate characterization.

Information was obtained in two steps. Firstly, a survey designed according to the scope and boundaries was filled by school’s staff. Secondly, the centres were audited through several visits in which all the important elements were inventoried and characterised. Account books were consulted taking into account bills to quantify actual total consumptions. Ecoinvent database (Wernet et al., 2016) has been used for the background processes such as transport, fuels and basic chemicals. The LCA software used has been SIMAPRO^{TM} (Goedkoop et al., 2016). Occupancy patterns variability for the period were not taken into account. However, both high schools under study present similar patterns referred to scholar activities.

2.2. Inventory analysis

A summary table is presented about the info collected for inventory according to the description below:

i. Water consumption from bills.
ii. Fuels and electricity consumption in heating and cooling systems from bills and device information. The manufacturing of the heating and cooling infrastructure itself is excluded from the analysis. Refrigerant consumption and emission was included.
iii. Lighting involves the use of electricity but also the yearly replacement of spent lamps and their disposal. 4 scenarios have been created.
iv. Gardening activities are those related to the planting, watering and care of trees and other plants present in the school grounds
v. Cleaning activities refer to the daily cleaning of classrooms, offices, corridors and other dependencies of the school building. They involve the use of cleaning products and machines.
vi. Maintenance activities include the annual painting, repairing and other required maintenance of the building elements.
vii. Scholar food system considers the equipment and operation time.

Table 3. Summary table of the inventory data.

Activity	*Description*	*HS1*	*HS2*	*Source of data*
Water	Water consumption from network	m3	m3	Survey, audit and ledge account(bills)
Heating	Boilers, yields, light fuel oil fuel consumption	92.5%	90%	Survey, audit and ledge account(bills)
HW	Electric hot water system	-	1 unit	Survey/ Estimation of time by workers
Cooling	Minisplit electricity consumption Refrigerant air emission	2 unit 3.5 kW	3 units 3.5 kW	Survey/ Estimation of time by workers
Lighting	Energy consumption Lamp replacement FT, FCL, Conventional, Halogen and LED	32453.01 kWh Replacement by type	17159.7 kWh Replacement by type	Survey and audit
Gardening	Water, pesticides and fertilizers, and petrol consumption Water/soil/air emissions	Tetraconazole Domark 0.12 m^3 of water 50 l of petrol	-	Survey, audit and ledge account(bills)

Cleaning and Maintenance	Amount of material consumption and wastes production. Electricity	Chemicals and stuff	Chemicals and stuff	Survey, audit and ledge account(bills)
Scholar Food service	Energy consumption by appliances	Electricity consumption by appliances 19296.9 kWh	-	Audit
Wastes	Waste produced in maintenance and cleaning	Produced wasted of the repairs and maintenance. Wastewater	Produced wasted of the repairs and maintenance Wastewater	Survey to workers

Consumption of water. Water consumption was calculated trough data obtained from bills. Water data consumption was obtained from bills (Table 4).

Heating system. Heat consumption was evaluated by considering the type of fuel and the technical characteristics of the equipment. Both schools have two condensing boilers, with an average yield of 92.5% in the HS1 and 90% in HS2. The fuel used is light fuel oil and total quantities have been obtained from bills. The power capacities of these boilers are different, according to building size. HS1 has two boilers of 300 kW and 116.5 kW, one in each of its buildings. HS2 produce energy using two boilers of 300 kW and 175 kW that work in different areas of the same building. Heating system is operating around 6 months along the year, from November to April. In both cases hot water is produced in a system apart from the heating system. HS1 does not have any system, but HS2 uses an electric water heater located in the clothing room. Consumption of heating according to fuel consumption was calculated during the same period expressed in Megajoules (MJ), using as calorific value of 37.01 MJ/l for light oil (IDAE, 2010).

Table 4. Water and fuel consumption by high school.

	HS1	*HS2*
Water consumption (m^3)	1440	637
Fuel consumption for heating (MJ)	510858	505070

Cooling. For the cooling system in the studied cases, equipment and their use is similar. The equipment used consists of 3.5 kW split units located in specific offices of the educational centre. The electricity consumption of this equipment depends on the operating period. The average operation time was estimated by users (8 hours per day for two months). The information required to calculate energy consumption was the EER. The assumption of the equipment works 80% of the operation time in active mode, 20% stand-by, and 10% in off-mode was made. While HS1 have 2 splits units, the HS2 uses 4 split units. The calculated emissions from equipment elements and refrigerant leakages were based in the report from AC-Sun (Naef et al., 2010), which analyses the carbon footprint of provision of conventional cooling equipment during one year for a Spanish household, taking into account a lifetime of 12 years, in comparison with best available technologies, through LCA methodology. This work provides data about annual refrigerant leakages for most common refrigerants. An average of these values was used, resulting a 13.2% of total refrigerant per year.

Lighting. The required environmental information about the life cycle of lighting appliances was obtained from Tähkämö (2013) which estimates environmental impacts through LCA of two light lamps types. The inventory data of manufacturing, package, transport and end-of-life of LED panel luminaire was adapted to the study case according to U.S. Department of Energy (2012). One more case of a conventional tungsten bulb was identified in the database in order to complete the variety of lighting types in the studied buildings. Electricity consumption was calculated considering the estimated occupancy hours per room type (offices, classrooms, toilets, corridors, laboratories, library, gym, and others), the power of lighting type and the luminaires number.

Scholar food service. Just HS1 presents a little scholar food service that requires the use of different appliances. The electricity consumption was calculated considering a working period of 3 hours per day for discontinuous working appliances (dishwasher, oven, kitchen/plate, microwave, coffeemaker), and the whole day for continuous working appliances (freezer and fridge) in the scholar period.

Gardening. In order to asses gardening activities, irrigation, fuel consumption in gardening works and pesticide and fertilizers application were considered. Tap water is the water used for sparkling irrigation, and the used fuel is petrol in combustion machinery. The emissions associated to fuel consumption have been calculated using data from Nemecek and Kägi (2007). The high school cases analysed in this work did not have extensive green areas. Only fungicides are applied in trees. During application, losses could be important. These losses result from volatilization, water runoff or photodegradation. Once applied, the pesticide can be leached and reach the groundwater, or be transported by runoff until surface waters. Atmospheric emissions produced by the application of used pesticides in that studied cases were losses by volatilization of compounds once they have been applied to the vegetation in the school garden and green areas. The document of the EPA AP-42 (EPA) provides some emission factors for volatilization of pesticide based on the method of application and the vapour pressure of the compounds. It also provides an emission factor of volatile organic compounds (VOCs) for the inert fraction of applied compounds. In our case, Tetraconazole and Sulphur have an emission factor of 350 g/kg of active material applied. Tetraconazole is a solution or liquid that corresponds to an average of volatile organic compounds in the inert fraction of 20%, and Sulphur is a granulated formulation type, whose fraction is 25%. Total emissions of VOCs into the atmosphere, produced by the application of pesticides in the garden, are quantified in 0.164 kg/year. Regarding to emissions to water, these compounds are not highly leachable. The Groundwater Ubiquity Score or GUS index (Gustafson, 1989) was calculated finding values between 1.0 and 1.8, which classifies them as low leaching potential pesticides.

In addition, the sequestration of carbon by vegetation is considered. Required inputs to characterize green area are the trees species and number of each one. Vegetation captures CO_2 from the air by photosynthesis process during the growth of the plant. This CO_2 is stored in the structure of plants and soil and therefore it is removed from the atmosphere. However, at the same time losses of CO_2 can occur by mineralization of organic matter by autotrophic respiration of plants and when vegetation is removed. The sequestration and storage of carbon depends on several factors: type and age of species, climatic conditions and management of vegetation, among others. The factor considers that the existing vegetation in school is not going to be cut, but remains during the life cycle of the specie. Data of CO_2 absorption for species planted in the schools' gardens which do not grow naturally in the territory, the study on urban vegetation in the city of Barcelona has been applied (Chaparro and Terradas, 2009).

Green areas of the HS1 present 42 trees (*Platanus*) and green area of the HS2 just 4 trees (*Eriobotrya japonica*).

Cleaning and maintenance. Consumption data during the operation of the building was also collected to identify inputs on the performance. Data was collected from the school bills per year. Cleaning materials consumptions (Table **5**) are referred to chemical products, mops, gloves, cleaning cloths, and clothes of workers. Consumption of maintenance materials (Table **6**) is referred to resources used in repair works and refit operations due to damages in the building (fence substitution, door repairs, locks repairs, paint in bad conditions walls, key duplications, etc.). The information shows a large diversity of material types and quantities consumed in the school building maintenance per year, depending on the building requirements. To improve the maintenance performance, a diagnosis of the building situation is required, as well as to investigate the operation of the buildings. Electricity consumption by machinery and appliances was calculated considering the estimated hours per year and the power.

Table 5. Cleaning inventory.

Material/Energy	*HS1*	*HS2*	
Textile Cotton	12.2	4.7	kg
Textile Polyester	0.2	12.00	kg
Cleaning paper	418.00	n.d.	kg
Ammonium	102.00	210.00	kg
Detergent	117.00	240.00	kg
Bleaching	68.40	n.d.	kg
Soap	153.00	n.d.	kg
Latex	0.82	0.576	kg
Electricity of machinery/appliances	n.d.	n.d.	kWh

Table 6. Maintenance inventory

Material/Energy	*HS1*	*HS2*	
Adhesive	5.00	3.20	kg
Sealant	n.d.	n.d.	kg
Paint (water solvent)	111.00	158.00	kg
Paint (acrylic solvent)	26.70	n.d.	kg
Other paint	18.00	n.d.	kg
Wood	n.d.	156.00	kg
Glass	6.25	10.00	kg
Rubber	1.25	0.62	kg
Leather	0.24	n.d.	kg
Metal	0.13	0.5	kg
Steel	72.00	347.00	kg
Aluminium	n.d.	n.d.	kg
Concrete	n.d.	n.d.	kg
Plaster/gypsum	n.d.	n.d.	kg
Sand	n.d.	n.d.	kg
Plastics (ABS included)	n.d.	0.06	kg
Polyethylene (PE)	15.30	n.d.	kg

Polyvinyl chloride	n.d.	24.90	kg
Polystyrene	n.d.	4.16	kg
Electricity of machinery/appliances	128.00	n.d.	kWh

Wastes. Schools produce waste which is a mix between typical waste from offices activities and houses. The identified wastes are produced in the performance of the O&M. Note that the municipal mixed wasted produced in the high schools has been excluded of the scope due to the fact that this king of wastes are not produced by O&M stage. Finally, the wastewater treatment has been estimated considering a 75% ratio between water consumption and wastewater production based on bibliography (Marín Galvín, 2015).

Table 7. Wastes inventory.

Input (Material/stuff)	***Unit***	***HS1***	***HS2***
Batteries	Kg	0,6	0,8
WEEE [1]	Kg	n.a.	99,8
Fluorescent tubes	Units	200	121
Compact fluorescent lamps	Units	112	10
Incandescent bulbs	Units	5	n.a.
Plastics mixed	Kg	144	3.43
Aluminium	Kg	n.a.	10.5
Metal	Kg	n.a.	10
Glass	Kg	1,5	n.a.
Hazardous waste	Kg	18,6	n.a.
Water treatment	m^3	1170	478

[1] WEEE: waste electrical and electronic equipment to recycling.

3. RESULTS AND DISCUSSION

Results of this work involve three aspects. First of all, results of the effect of the selected system boundaries and scope are presented and analyzed. Secondly, a summary of the more relevant observed results for the assessed impacts is presented. Finally, results of the evaluation of the more remarkable effects of the identified and proposed improvement measures are shown.

The impacts associated to these consumptions have been assessed with the impact categories, cumulated energy demand (CED), water resource depletion (WRD) and global warming potential or carbon footprint (CF).

Cumulated Energy Demand (CED)

CED represents the direct and indirect energy use throughout the life cycle including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials (VDI, 1997).

Water Resource Depletion (WRD)

Water consumption has been evaluated using the method recommended by ILCD for freshwater scarcity based on the Ecological Scarcity Method developed by Frischknecht et al (2008) (European Commission, 2012). In this method, each country is assigned a factor reflecting the degree of water scarcity compared to an average European value. For the impact assessment, the water consumption in the activity is related to local scarcity, in order to indicate how important the effect is.

Carbon Footprint (CF)

Global warming potential or carbon footprint (CF) has been assessed in terms of kilogram equivalent of carbon dioxide (kg CO2eq), and the results were calculated using the characterization factors proposed by IPPC methodology (IPCC, 2007).

3.1. Effect of the system boundaries and scope

In order to clarify the assumptions and what the results shows, we must highlight the limits of the system. One of the most important characteristic of the application process of the LCA methodology is the iterative pathways between phases to establish the system boundaries and the final scope to study the system, to drive the analysis towards the key activities and relevant consumption to achieve the goal of the study.

In the inventory data collection and analysis, the electricity consumption of the devices and equipment's was calculated for each O&M activity identified as a network electricity consumer. Calculated electricity was compared with the electricity consumed according to the electricity bills. As a result, it was found that there was an amount of electricity consumed in the high schools, apart from the amount calculated for O&M activities. This electricity, which has been excluded from the limits of the system, has been called "other electricity consumption" (OEC). In order to show the contribution of OEC to the impacts, it has been represented in comparing it with the contributions of the activities included in the system (Figure 3).

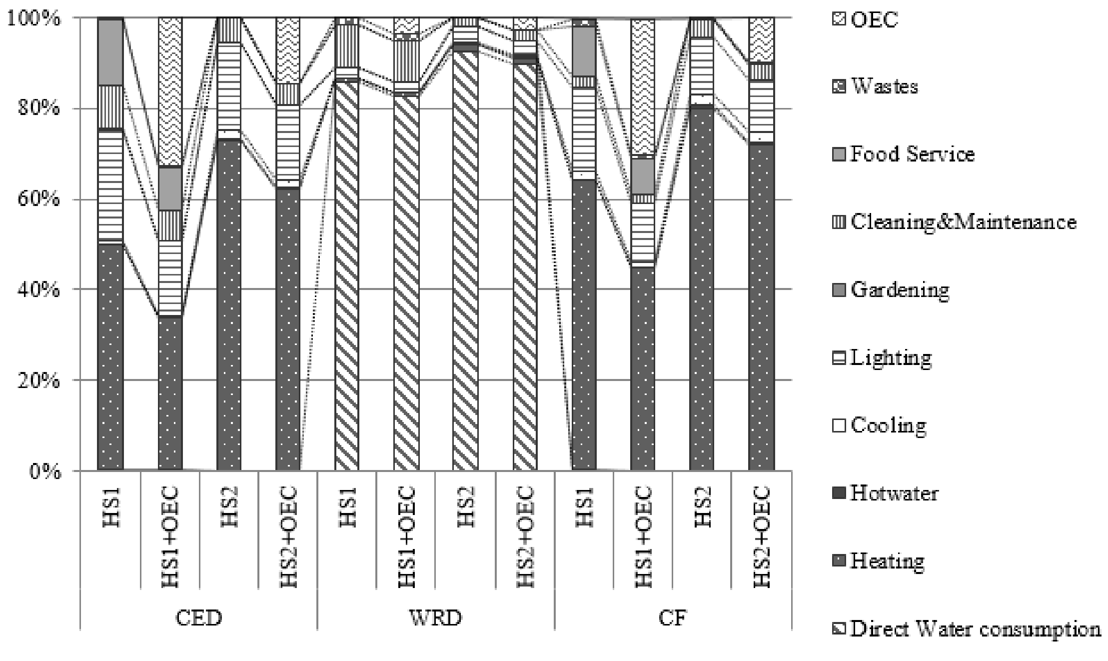

Figure 3. Contribution of each activity in the system (HS1, HS2), and the system and OEC (HS1+OEC, HS2+OEC)

For purposes of interpretation, it is stated that there are activities outside of the activities identified in the O&M area of the school building that entail an electrical consumption. That electricity is higher or lower depending on the high school, with the consequential contribution to the impacts, mainly for CED and CF impacts. Note that CED of the OEC in the HS1 reach around the 30% of the CED and CF. In spite of the relevance contribution, activities responsible for OEC have not been identified, so it has been assumed that this electricity is strictly linked to student activity and it is out of the boundaries system.

Concerning to the rest of activities included in the system, Figure 3 shows that both heating and lighting are the activities with the greatest impact. In the case of depletion of the water resource, the direct impact of water is the most shocking activity.

Taking into account the Spanish Authorities exposes in (Ministry of Development, 2014) referred to the energy consumption in administrative and educational buildings, a minimum value of 10% of energy consumption should be considered as varying subject to use and management. This can even commonly represent values around 30% of consumption. So, to assess the results of the impact analysis and savings achieved by the application of improvement measures in the study cases buildings would be useful the collection of data during a representative period.

3.2. Results of the Impact Assessment

Impact assessment was developed in terms of the selected impacts, as such was described in goal and scope definition step. These impacts are related to energy and water consumption and their consequences due of energy demand, water scarcity and the carbon footprint.

The summary of the environmental impact assessment is presented in Table 8. Impacts are referred to two functional units: per student and gross area. HS2 shows a worse performance in all three categories. However, if the results are expressed per unit of gross area, the results present a reverse tendency and HS2 shows a better performance. This is due to the number of students per unit of gross building area, since HS1 provides space for almost double number of students per gross area, as it is reflected by the ratio student-area shown in Table 2.

Table 8. Results of system analysis by impact categories.

		Unit per student		*Unit /m^2 gross building area*	
	Unit	HS1	HS2	HS1	HS2
CED	MJ	1445	2163	215	196
WRD	m^3 eq	3.75	2.91	5.59	2.64
CF	kg CO_2 eq	76	133	11	12

CED: direct and indirect energy use throughout the life cycle; **WRD**: based on the Ecological Scarcity Method. *[Frischknecht et al (2008)];* **CF:** IPPC methodology.

Regarding to CED results, HS2 shows a higher energy demand than HS1, taking into account analysis per student. This is reasonable result since HS2 is an older building and the gross built area per student in average is higher in HS2 (11 m^2/student) than in HS1 (7 m^2/student).

As stated by Lizana et al. (2016) there is a great potential for energy retrofitting even in mild and hot climatic areas, where the energy demand in winter is very high due to the low quality of the thermal envelopes of the buildings and their inefficient systems, and where the cooling demand is significant and is increasing. CED per gross building area has been calculated as well. The results are within the range of other LCA results for energy in high schools in Spain carried out by Isasa et al. (2014), for building use stage. When CED results are analysed taking as a functional unit the gross area of the buildings, HS2 presents the lowest energy demand. Possible reasons could be the type of construction, the building envelope and geometrical characteristics of the building. The results of research on energy efficiency opportunities of existing buildings have showed that energy use in existing buildings can be significantly reduced through proper retrofitting actions, which is described as work required to upgrade an aged or deteriorated building (Nicolae and George-Vlad, 2015).

Water consumption has been evaluated using the method recommended by ILCD for freshwater scarcity. Spain is a dry country with water scarcity problems and quantification of water consumption should reflect this situation. Table 8 includes results for water resource depletion impact category. HS1 presents a higher impact than HS2. Apparently, 3.75 m^3 and 2.91 m^3 equivalent per student and year, could be high, but we have to taking to account that direct consumption is 1.72 m^3 and 1.55 m^3 per year and student, respectively. Considering that consumption values and the fact of the selected indicator takes into account water scarcity situation in each area of the world to show the potential impact calculating results in terms of m^3 equivalents, it makes the results are into the expected range.

For CF impact category, the results show that HS2 present a higher value of CF per student than HS1 (Table 8). The same reasons exposed before regarding to energy consumption applies here. HS2 is an older building (probably with worse thermal efficiency) and with fewer students per square meter. However, when looking at the results per square meter, results are very similar. A more detailed contribution analysis in each impact category has been carried out showing the contribution of each analysed building activity.

As well as the results are shown in Figure 3 in relative terms for HS1 an d HS2, once time the scope is explained, the Figure 4 represents the impact and contribution of each activity in the system, by high school and impact.

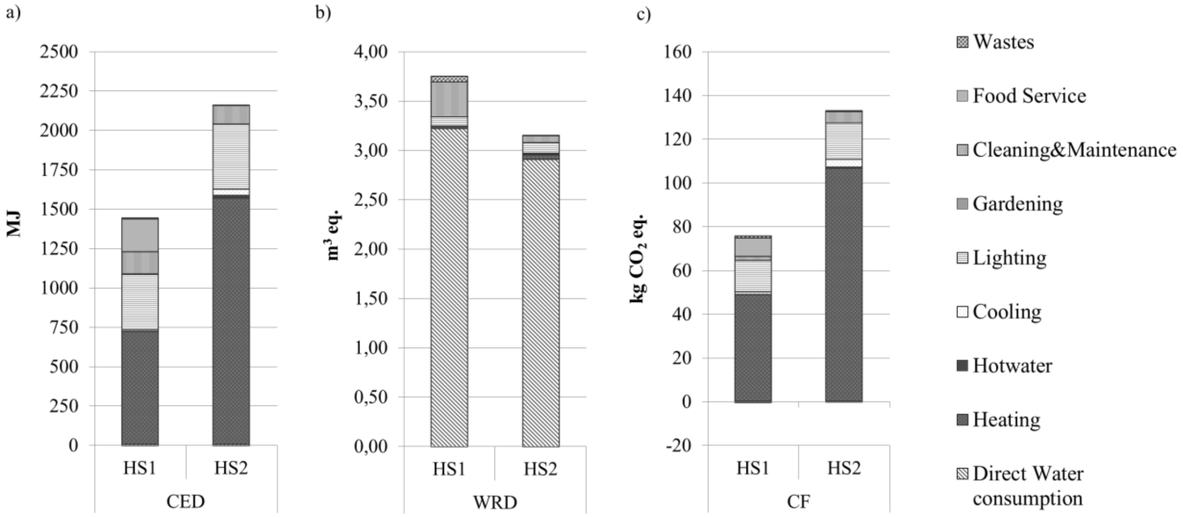

Figure 4. Impact results per activities and high school in terms of CED (a), WRD (b) and CF (c).

As it was expected, the results show that heating is the activity with the highest energy demand in the O&M of the high schools building per student, followed by lighting in the whole high school. Food service presents also a higher energy requirement. Cooling system energy demand in high school’s offices is comparatively high especially considering the short period of use (2 months per year). CF follows the same trends as CED. However, heating contribution to CF is larger in both high schools. Cleaning and maintenance contribution to CF impact is lower that the contribution to CED. Also in this case, the contribution of food service is significant due to electricity consumption.

Water resource depletion impact is dominated by the direct use of water in the high schools, followed by the use of water in lighting. This lighting contribution is due to the use of water of electricity generation technologies in the Spanish electricity grid. Cleaning and maintenance also contributes significantly to water depletion impacts. Water use in the school centres can be minimized by using faucet aerators to reduce the flow of water.

In contrast to the reviewed literature, in this study the educational building performance is evaluated according to the specific function of the building in the use phase as discussed above, providing results which are more meaningful. Even if the findings are difficult to compare with published literature, they can be used to contrast the results of the present study. Ozawa-Meida et al. (2011) found 65 kg CO_2 eq/m^2 of gross internal area per year, excluding construction, analysing the university; and Varun et al (2012) obtained 5,3 kg CO_2 eq/m^2 usable floor area per year. The values obtained in this study are considerably different although the order of magnitude is similar. Differences in scope, educational level and location are the reasons behind these differences. Apart from carbon footprint results, this study provides information about energy use and water footprint of these educational activities which is an added value to the existing findings. Results are also calculated per student. These results are much easier to communicate to the school community in order to engage them in implementing low-carbon retrofit measures.
Additionally, the results are calculated using primary data collected on site in the high schools under study which makes the results highly reliable.

3.3. Effects of the Improvement Measures

In this session the results regarding main identified opportunities in order to reduce energy, inflow material, or environmental impacts at each stage of the studied system life-cycle, are summarised. One of most relevant aspects of conducting an LCA is the possibility to identify iterative pathways for different phases of the activities. In order to drive the analysis towards the identification of key activities and modifying consumption and use practices to achieve the goals of environmental impacts reduction.

As it is expressed in Nicolae and George-Vlad (2015), savings are measured as the difference in energy consumption before and after the efficiency improvement has taken place. So, the results of the measures application on the system through the scenario development are expressed in term of saving in the each analysed system impacts. The ‘energy savings’ means an amount of saved energy determined by measuring and/or estimating consumption before and after implementation of an energy efficiency improvement measure, whilst ensuring normalization for external conditions that affect energy consumption (Article 2.5 of the Energy Efficiency Directive (ECb, 2012)). Specifically, energy savings are defined as the result of improvements of energy efficiency.

As results indicate, much of impacts are related to heating and lighting in the analysed high schools. Thus, two potential improvement measures that could improve energy efficiency and increase environmental benefits were analysed. One of these measures is referred to the implementation of renewable energies in heating supply, and another one consists of the optimization of energy consumption by changing the lighting technology.

Measure 1: Changes in heating production technology.
Energy demand of heating accounts for about 40% in HS1 scenario and 70% in HS2 scenario. Both cases use light fuel oil boilers. In order to reduce energy demand and CO_2 emissions, the effects of two variations were analysed. Heating Measure 1a (HM1) consists in changing the

used fuel by natural gas, and Heating Measure 1b (HM2) consists of the substitution of the heating system with a hybrid biomass/solar thermal system. On the one hand, with an individual biomass boiler, a reduction of around 17% of primary energy demand and 53% of CO_2 emissions can be reached (Lizana et al., 2016). On the other hand, solar thermal energy has potential opportunities for being integrated into heating systems. Additionally to potential environmental benefits, a hybrid configuration can eliminate the discontinued operation of traditional solar collectors (IDAE, 2015). The process used in HM2 scenario for heating operates with a share of energy supply from 76% of biomass and 34% of solar.

Figure 3 shows how the contribution of the heating to the total impact of the system in each category varies considering the application of HM1 and HM2, compared to the reference scenario. The replacement of the fuel oil boiler by a system based on natural gas as fuel generates a slight reduction of the impact in all the considered categories with respect to the results found in the reference scenarios of both high schools. The substitution by the hybrid system presents an increase of energy demand due to the fact that CED includes both renewable and non-renewable energy. For the analysis of heating measures, the CED impact category has been expanded to also take into account the fossil CED. In other words, fossil CED impact indicator considers the energy demanded from primary energy of fossil origin instead of global CED values. HM2 implementation achieves huge fossil fuel reductions compared to the heating reference scenario. Similar results are found in CF impacts. The result of the application of the HM2 causes a significant decrease in the amount of CO_2 much higher than the HM1 application. WRD savings are not highlighted, since results are often below than 2% referred to heating activity, but it is underlined that HM1 decreases the water depletion more than HM2 in both high schools. It is known that solar collectors show disadvantages in terms of biochemical oxygen demand to water (Dones et al., 2007).

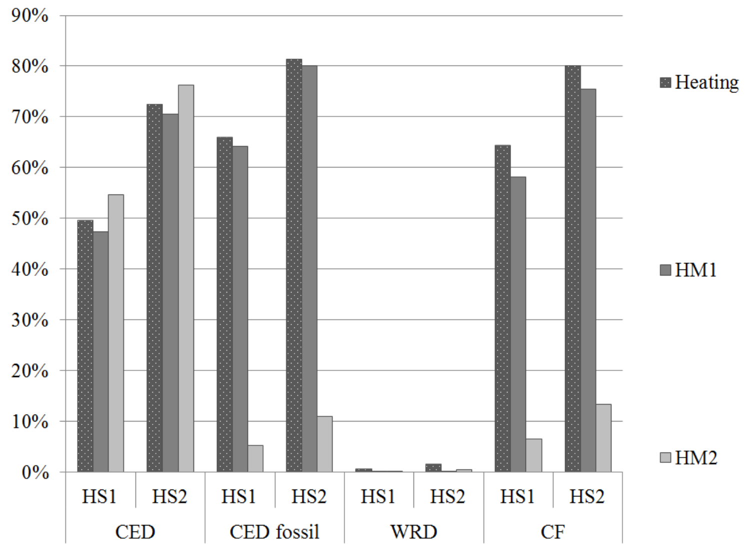

Figure 5. Comparison of contribution of heating in each studied high school building (HS1 and HS2), without (Heating) and with measures (HM1 and HM2), by impact category.

In summary,
Table **9** shows the savings results of the application of measures HM1 and HM2 with respect to the reference scenario. The application of HM1 is beneficial in all cases, reaching a higher percentage of savings in HS2 than in HS1. The reason is the difference in the number of students. Even though in the reference scenario the impact per student was affected by the

lower number of students in HS2, in this case the savings are also affected, but are positive, since achieved saving is distributed among fewer students in HS2 than in the case of HS1.

Regarding to HM2 implementation, note the CED results for both high schools are negative, which means that instead of savings, the impact has grown due to energy demand of the system application. The reason is that the system needs a lot of renewable biomass to produce the same amount of energy as fossil fuels. Although, CED fossil and CF system savings are remarkable in both high schools, being more severe the influence in HS2 by the reasons stated in previous paragraph. Savings in CED are reaching between 64.06% and 78.98%, and savings in the CF present values between 61.92% and 76.90%.

Table 9. Results of heating measure application by impact and studied high schools.

	CED		*CED fossil*		*WRD*		*CF*	
Unit per student	*MJ*		*MJ fossil*		*m^3 eq*		*Kg CO2 eq*	
	HS1	*HS2*	*HS1*	*HS2*	*HS1*	*HS2*	*HS1*	*HS2*
System	1445	2165	1064	1888	3.76	3.15	76	133
System with HM1	1382	2028	1012	1774	3.74	3,11	64	108
% saving	4.35%	6.34%	4.89%	6.03%	0.49%	1.27%	15.06%	18.70%
System with HM2	1605	2516	383	397	4	3	29	31
% saving	-11.10%	-16.20%	64.06%	78.98%	0.38%	0.99%	61.92%	76.90%

Measure 2: Changes in lighting technologies.

Lighting system technologies have an important influence on the electricity consumption. Tubular fluorescent lamps and compact fluorescent lighting are the most common type of lighting in studied high school buildings. Lighting Emission Diode (LED) represents a sustainable solution for lighting, presenting the highest energy efficiency and lifetime (Tähkämö and Halonen, 2015). In the case study, most of luminaires are different types of fluorescent technologies, a minor number of conventional tungsten bulb lamps and a small number of LEDs. In order to optimize the energy consumption in school buildings, making them more environmentally friendly, the effects of whole lighting substitution with LED's are analysed (LM). LED lighting substitution could reduce electricity consumption by around 47-60% (Avella, Souza, and Silveira, 2015) as well as the environmental impacts related to production phase. The improvement measure considers that all non-LED lamps are replaced by several types of LED lamps. The equivalence between the power and durability of the lamp types has been considered using commercial information of usual market products (OSRAM, 2017). For instance, fluorescent lamp of 55W and 20.000 hours of lifetime has been replaced by a LED panel of 30W and 50.000 hours of lifetime. With the lighting measure configuration, the electricity savings in lighting activity are around 50% (Tähkämö, 2013).

Figure 6 represents the contribution of lighting activities per student and year in HS1 and HS2 for each analysed impact category. The contribution of lighting activity is reduced by approximately half in both high schools after the implementation of the measure. Those results are consistent considering that the most important impact in the use of lighting is electricity consumption. Welz et al. (2011) confirms that the O&M phase electricity consumption is the main contributor to this impact of lighting, independent on the actual lamp type examined.

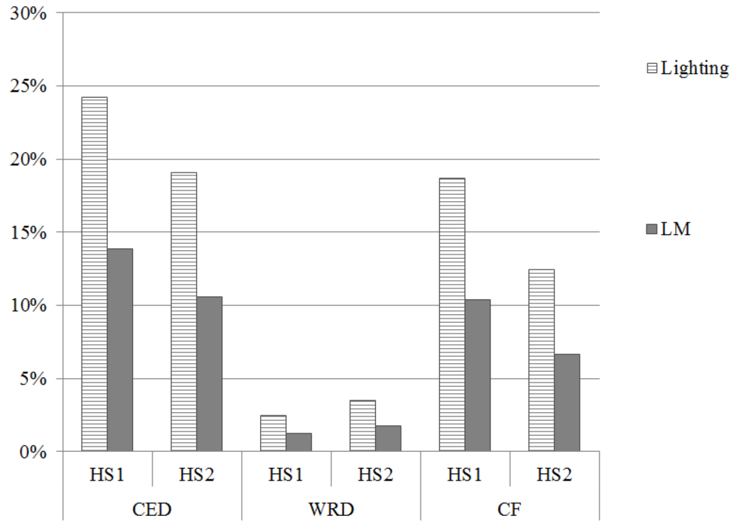

Figure 6. Comparison of contribution of lighting in each studied high school building (HS1 and HS2), without (Lighting) and with measures (LM), by impact category.

The contribution of the lighting improvement measure to global CED, WRD and CF can be evaluated in terms of the total system. Although contributions of lighting in both high schools have experienced similar reductions, savings have different size in each case, achieving better results when measure is implemented in HS1 than HS2. In fact, the differences in the CF are pronounced in savings rates as consequence of relative contribution in the system. In current scenario, in HS1 lighting has a higher contribution to the total system impact than HS2, thus, efficiency measures in lighting has a larger effect in HS1. WRD savings are caused by indirect electricity savings, achieving values up to 1.25% for HS1 and up to 1.75% for HS2.

Table 10. Results of lighting measures application by impact and studied high schools.

	CED		*WRD*		*CF*	
Unit per student	*MJ*		*m3 eq*		*kg CO2 eq*	
	HS1	HS2	HS1	HS2	HS1	HS2
Current System	1445	2165	3.76	3.15	76	133
LM	1271	1959	3.71	3.10	69	125
% saving	12.05%	9.54%	1.25%	1.75%	9.27%	6.23%

As is presented by Ministry of Development (2014), scenarios which get savings in educational buildings between 5% and 10% are foreseen to achieve the overall government buildings reduction target of the 3% (ECc, 2011). That could be achieve through the implementation of energy efficient measures focused in key activities of the educational buildings, similar to the proposed measures in that work.

4. CONCLUSIONS

Operating and maintenance phase of schools has been assessed through Life Cycle Assessment in a hot climate area. Two schools have been selected as case studies within the Interreg SUDOE ClimACT project.

The impacts in Cumulated Energy demand CED, Water Resource Depletion (WRD) and Carbon footprint (CF) for different activities in two pilot schools located in Madrid (Spain) were presented. Impacts are presented per student and per built gross area in order to compare the impact in both schools. One of the most relevant aspects of LCA development is the possibility to get iterative pathways between stages. This characteristic could be useful, to drive the analysis towards the identification of key activities and modifying consumption practices to achieve the goals of decrease environmental impacts.

According to the results, high schools under study have to drive efforts to increase efficiency in conditioning and lighting in order to reduce global warming impacts and energy consumption. Water depletion impact is mainly due to direct consumption and also indirectly by electricity consumption in lighting.

Apart from carbon footprint results, this study provides information about energy use and water footprint of these educational activities which is an added value to the existing findings in literature. Results are also calculated per student which can be considered as much more meaningful functional unit. These results are easier to communicate to the school community in order to engage them in implementing mitigation measures. Additionally, results are calculated using primary data collected on site in the high schools under study which makes the results highly reliable.

Proposed measures, related to most significant activities bearing in mind contribution to considered impacts, reach variable savings. The results show that schools could reduce the cumulated fossil energy demand of the building in the O&M phase per student between a 4.9% and 6% by means of the implementation of non-renewable heating measures, the cumulated energy demand between 64.06% and 78.98% by means of the implementation of renewable heating measures, and between 12.05% and 9.54% by means of the implementation of lighting substitution measures. If CED and WRD per student are to be reduced, the substitution of luminaires in lighting is the best action, finding larger advantages in HS1 than in HS2. CF per student is best reduced when HM2 is implemented, changing the light fuel oil heating system by hybrid biomass-solar heating system, being the reductions higher in HS2 than HS1.

There is an important effect of student number in the analysis. Using student as a functional unit HS2 always present higher impacts in terms of CED, WRD and CF. Using area as functional unit, the situation is the opposite, but the CED difference between both high schools are not as intense as when student is the functional unit. However, using only an area unit as functional unit lose the link to the educational activity.

Additionally, results of the impact analysis and savings achieved by the application of the measures HM1 and HM2 in the study cases buildings could be more useful involving the collection of data during a representative period time.

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ABBREVIATIONS

AC	Acidificacion
CED	Cumulative Energy Demand
CED fossil	Cumulative Fossil Energy Demand
CF	Carbon Footprint
EPA	Environmental Protection Agency if United States
GHG	Greenhouse Gas
GUS index	Groundwater Ubiquity Score Index
GWP	Global Warming Potential
HM1	Heating Measure 1
HM2	Heating Measure 2
HS1	High school 1
HS2	High school 2
ILCD	International Reference Life Cycle Data System
IPPC	Intergovernmental Panel on Climate Change
ISO	International Stantarization Organization
kg	Kilogram
kg CO2 eq	Kilogram of CO2 equivalent
kW	Kilowatt
KWh	Kilowatthour
l	Litre
l eq	Litre equivalent
LCA	Life cycle assessment
LED	Light Emission Diode
LM	Lighting measure
m^2	Square meter
m^3	Cubic meter
m^3 eq	Water cubic meter equivalent
MJ	Megajoule
n.d.	No data
OEC	Other electricity consumption
O&M	Operating and Maintenance
U.S.	United States
PE	Person equivalent
VOCs	Volatile Organic Compounds
WRD	Water Resource Depletion

REFERENCES

Arena, A., & de Rosa, C. (2003). *Building and Environment*(38), 359 – 368.

Avella, J. M., Souza, T., & Silveira, J. L. (2015). A Comparative Analysis between Fluorescent and LED illumination for Improve Energy Efficiency at IPBEN Building. The Xi Latin-American Congress Electricity Generation And Transmission. Clagtee.

Baboulet, O., & Lenzen, M. (2010). Evaluation the environmental performance of a. *Journal of Cleaner Production*(18), 1134e1141.

Bull, J., Gupta, A., Mumovic, D., & Kimpian, J. (2014). Life cycle cost and carbon footprint of energy efficient refurbishments. *International Journal of Sustainable Built Environment*(3), 1-17.

Chaparro, l., & Terradas, J. (2009). *Serveis Ecològics del Verd Urbà a Barcelona.* Centre de Recerca Ecològica i Aplicacions Forestals. Universitat Autònoma de Barcelona. Bellaterra.

Dones, R., Bauer, C., Bolliger, R., Burger, B., Faist Emmenegger, M., Frischknecht, R., Tuchsmid, M. (2007). *Life Cycle Inventories of Energy Systems: Results for Current in Switzerland and other UCTE Countries. ecoinvent report No. 5. Paul Scherrer Institut Villigen.* Swiss Centre for Life Cycle Inventiories, Dübendorf, CH.

ECa. (2011). European Comission. Communication from the Commission to the European parliament, the Council, the European Economic and Social Committee and the Committee of the regions. A roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112 final.

ECb. (2012). Eusropena Comisson. DIRECTIVE 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.

ECc. (2011). *European Commission, Energy, Topics, Energy Efficiency, Buildings*. (European Commission) Recuperado el 2017, de http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

EPA. (1995). *Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: Stationary Point and Area Sources.* Environmental Protection Agency of United Estates. https://www3.epa.gov/ttn/chief/ap42/ch09/final/c9s02-2.pdf

European Commission, J. R. (2012). *Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information.* Luxemburg: Publications Office of the European Union.

FEE. (1992). *Ecoschools Programme*. Recuperado el 2017, de http://www.ecoschools.global/

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., & Meijer, E. (2016). Introduction to LCA with SimaPro. PRé Consultants.

Guerra-Santin, O., & Tweed Aidan, C. (2015). In-use monitoring of buildings: An overview and classificationof evaluation methods. *Energy and Buildings*(86), 176–189.

Gustafson, D. (1989). Groundwater ubiquity score: A simple method for assessing pesticide leachability. *Environmental Toxicology and Chemistry, 8*(4), 339 - 357.

IDAE. (2010). *Guía técnica de diseño de centrales de calor eficientes.* Madrid.

IDAE. (2015). *Análisis de potencial y oportunidades de integración de energía solar térmica en redes de climatización.* Madrid.

INE. (2015). *Survey on Water Supply and Sewerage.* Obtenido de http://www.ine.es/en/prensa/np934_en.pdf

Inelligent Energy Europe. (2013). *50/50 Euronet MAX Project*. Obtenido de http://www.euronet50-50max.eu/en

IPCC, I. P. (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.BAveryt, M. Tignor and H.L. Miller (eds.). Cambridge, UK, and New York, NY, USA,: Cambridge University Press.

Isasa, M; Gazulla, C, Zabalza, I; Oregi, X; Partidário, P; Duclos, L. (2014). EnerBuiLCA: life cycle assessment for energy efficiency in. *WORLD SB4.* Barcelona.

ISO. (2006). *14040. Environmental management. Life cycle assessment. Principles and framework.*

ISO. (2006). *14044. Environmental management. Life cycle assessment. Requirements and guidelines.*

Jeong, K., Ji, C., Koo, C., Hong, T., & Park, H. S. (2014). A model for predicting the environmental impacts of educational. *Journal of Cleaner Production*(In Press), 1-12. doi:http://dx.doi.org/10.1016/j.jclepro.2014.01.027

Lizana, J., Barrios-Padura, Á., Molina-Huelva, M., & Chacartegui, R. (2016). Multi-criteria assessment for the effective decision management in residential energy retrofitting. *Energy and Buildings*, 284-307.

MAPAMA. (2015). *Ex ante Carbon Dioxide Absorption Calculator* . Recuperado el 2017, de http://www.mapama.gob.es/es/cambio-climatico/temas/mitigacion-politicas-y-medidas/proyectos-absorcion-co2.aspx

Marín Galvín, R. (2015). El ciclo integral del agua en Córdoba. Flujos de materia implicados y huella de carbono. *IV Jornadas de Ingeniería del Agua*. Cordoba.

Martínez, A. G., Oliver, C. L., & Casas, J. N. (2011). Life cycle assessment of three dwellings in Andalusia (Spain): The significance of building type and materials selection. *2011 International Conference on Electrical and Control Engineering*. Yichang.

Ministry of Development. (2014). *Long-Term Strategy for Energy Renovation in The Building Sector in Spain pursuant to Article 4 of Directive 2012/27/UE.*

Naef, S., Kristina Merrild, H., & Hedal Kløverpris, N. (2010). *Carbon Footprint of AC-Sun.* Force Technology.

Nemecek, T., & Kägi, T. (2007). *Life Cylce Inventories of Agricultural Production Systems. Final Report Ecoinvent V2.0 No.15a. Agroscope Reckenholz-Taenikon Reserch Station ART.* Zurich and Dübendorf: Swiss Centre for Life Cycle Inventories.

Neururer, C., Smutny, R., Treberspurg, M., & Sellner, G. (2016). Environmental life cycle assessment of office buildings - Analysis of determinants. *Central Europe towards sustainable Building - Decision-support tools and assessment methods.*

Nicolae, B., & George-Vlad, B. (2015). Life cycle analysis in refurbishment of the buildings as interventionpractices in energy saving. *Energy and Buildings*(86), 74–85.

OSRAM(2017). *Product Lifecycle Management.* Obtenido de http://www.osram-group.com/en/sustainability/environmental/product-lifecycle-management

Ozawa-Meida, L., Brockway, P., Letten, K., Davies, J., & Fleming, P. D. (2011). Measuring carbon performance in a UK University through a consumption-based carbon footprint: De Montfort University case study. , 56, pp. 185-198. *Journal of Cleaner Production*(5), 185-198. doi:http://dx.doi.org/10.1016/j.jclepro.2011.09.028

Rodríguez, A., & Porras, S. (2016). 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. *Sustainability, 8,* 287.

Tähkämö, L. (2013). *Life cycle assessment of light sources - Case studies and review of the analyses.* Aalto University publications series - Doctoral Dissertations 111/2013.

Tähkämö, L., & Halonen, L. (2015). Life cycle assessment of road lighting luminaires - Comparison of light-emitting diode and high-pressure sodium technnologies. Journal of Cleaner Production. *Journal of Cleaner Production*, 234-242.

U.S. Department of Energy. (2012). *Life Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 2: LED Manufacturing and Performance.*

United Nations Environment Programme. (2007). *Buildings and climate change. Status, Challenges and Opportunities.*

Varun, S. A. (2012). Life cycle environmental assessment of an educational building in Northern India: a case study. *Sustainable Cities and Society*(4), 22-28. doi: 10.1016/j.scs.2012.03.002

VDI. (1997). Cumulative Energy Demand - Terms, Definitions, Methods of Calculation. In: VDI-Richtlinien 4600. .

Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy and Buildings, 135,* 286-301.

Welz, T., Hischier, R., Hilty, & Lorenz, M. (2011). Environmental impacts of lighting technologies - Life cycle assessment and sensivity analysis. *Environmental Impacts Assessment Review, 31*, 334-343.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, [online] Available at:, 9*(21), 1218–1230. Recuperado el March de 2017, de <http://link.springer.com/10.1007/s11367-016-1087-8>

Zabalza, I., Scarpellini, S., Aranda, A., Llera, E., & Jáñez, A. (2013). Use of LCA as a Tool for Building Ecodesign. A Case Study of a Low Energy Building in Spain. *Energies* , *6*, 3901-3921.