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## Article

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Tmrees, EURACA, 04 to 06 September 2019, Athens, Greece

# Life cycle analysis of a building integrated photovoltaic system operating in Bogotá, Colombia

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## Abstract

In this study, the environmental behavior was characterized for a 840 Wp building-integrated photovoltaic (BIPV) system installed in the Department of Physics of the Faculty of Sciences at the National University of Colombia, Bogota campus. The methodology focused on the application of the international technical standards for Life Cycle Analysis (LCA) from cradle to grave based on the NTC ISO 14040 and NTC ISO 1404 standards, which regulate the methodological procedure. This article is based on comparing the potential of environmental impacts of five power generation scenarios, taking as reference the installation of the photovoltaic system (PV) at the University. During the analysis it was possible to determine that energy generation with coal has a greatest environmental impact compared with photovoltaics: 84% and 6% respectively. This represents 1138.8 gCO<sub>2</sub>eq/kWh for coal, compared to 35 gCO<sub>2</sub>eq/kWh for the PV system.

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**Keywords:** Greenhouse emissions; Life cycle analysis; Photovoltaic systems; Solar cells; Solar energy

## 1. Introduction

In recent years, the need to exploit alternative sources of energy has become an important research objective, especially in order to reduce air pollution and mitigate climate change. This threat must be a sufficient reason to face the high dependence on fossil fuels, which are the main cause of Greenhouse Gases. Although the imperative to acting on climate change has affected almost all sectors, the greatest focus is placed on the electricity sector due to its important contribution to global emissions, which is why different alternatives are being worked on.

Since the development of photovoltaic systems in the world, they have been seen as an alternative to mitigate the greenhouse gases produced by the conventional use of fossil fuels, this has allowed the policies in each of the countries to be more receptive towards renewable energies [1,2].

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## Nomenclature

BIPV	Building integrated photovoltaic system
LCA	Life cycle analysis
PV	Photovoltaic
SIN	Sistema interconectado nacional (in Spanish)
VI	Virtual instrumentation
Wp	Watts peak

Colombia, although it is a country where the majority of its electric power is generated directly by conventional water sources, has also developed new government laws that strengthen the process to face this situation of climate change. However, Colombia is a diverse nation because of the different regions that make it up. In some places, its topography makes it difficult to install conventional electric power generation systems and in others it is very expensive to be transported to remote areas of the country. This is why the systems of distributed generation that allow to integrate the generation capacity of a conventional source with photovoltaic energy are outlined as a feasible solution [3].

The National University of Colombia in its campus located in the city of Bogotá, was one of the pioneers in installing, in 2004, a photovoltaic system integrated with the distribution grid (BIPV — Building-integrated photovoltaic). This system, since that time, plays an important role for the generation of alternative electricity, fulfilling its function continuously; but after 14 years of use it is important through a Life Cycle Analysis based on the standard (ISO 14040, 2006) to determine its behavior during the operation and completion of the system, to know the environmental impacts that have been generated during the years of alternative energy production in that building of the University.

The first part of the article is the introduction to the methodology (LCA) and the approach to the Umberto™ Software is also done, in the second part, the article focuses on the associated environmental impact categories in the CML2001 method, later the article describes the PV operation system, and the results obtained from the (LCA) are presented last.

## 2. Life cycle analysis methodology

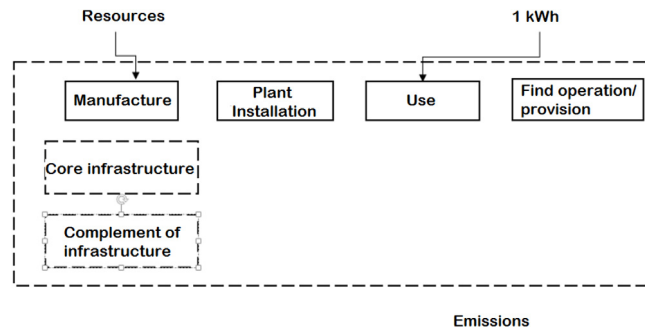
Life cycle analysis, (LCA), is an analytical method that contemplates and makes an interpretation of the potential environmental impacts of a product or service throughout its life cycle [4], this method allows analyzing the phases (Extraction and Manufacturing, Transportation, Use, Transportation available and Final Disposition) from the cradle to the grave with its greatest associated impacts during its process.

For the evaluation of the photovoltaic system at the National University of Colombia, the ISO 14040 and 14041 standards based on the software application Umberto NXT LCATM [5]. This software package has a graphical interface that allows defining the flows of materials or energy according to the model to be analyzed, and also to establish the environmental impact in a quantitative way during the process. Additionally, this software has linked the largest global databases with the inputs and outputs for many products throughout their life cycle, among which are GaBi and Ecoinvent [6]. The environmental impact analysis was developed with the CML2001 methodology [7].

### 2.1. Research scope

The functional unit is defined as the kWh of electricity produced by a photovoltaic plant connected to the grid on a large scale from the photovoltaic installation (840 Wp) at the National University of Colombia, considering 3.90 kWh/m<sup>2</sup>-day of radiation over an inclined plane of 45°, with a projection of 30 years of life expectancy. The limits of the system are described in Fig. 1.

The study is based on comparing the environmental impacts under the methodology of the CML2001, from 1 kWh generated with a photovoltaic system, compared to 1 kWh of conventional energy generation systems (Coal, Diesel, Natural Gas and Hydroelectric). The evaluated impact categories present a systems-oriented approach,



**Fig. 1.** Scheme of system limits.

Source: Adapted from [8].

grouped into four damage categories: human health, ecosystem quality, climate change and resources, which determine their greatest impact during the life cycle or from the cradle to the grave of the system [9].

### 3. BIPV system description

The BIPV system, installed in the National University of Colombia (Fig. 2), includes a photovoltaic generator with 12 modules of monocrystalline silicon (BP Solar-270F), each of 70 Wp and a DC/AC inverter Xantrex model Sun Tie-1000 of 1000 W.



**Fig. 2.** BIPV system installed in the terrace of the Department of Physics of the National University of Colombia, Bogotá.

Source: Authors.

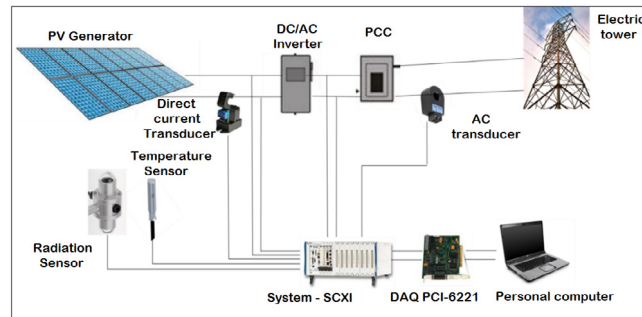
The BIPV system is fully monitored to evaluate and analyze the general behavior and power quality of the photovoltaic installation [10]. Fig. 3 shows the block diagram of the PV System together with the Monitoring System implemented with virtual instrumentation (VI).

The main raw materials to manufacture a photovoltaic panel are:

- AlMg3 alloy
- Photovoltaic silicon sheet
- Low Steel Alloy

### 4. Results

The models of conventional generation systems (Coal, Diesel, Natural Gas and Hydroelectric) were produced through the Umberto<sup>TM</sup> software directly with the Ecoinvent 3.1 database. Systems with similar capabilities were projected to the conventional ones in Colombia, taking into account that life cycle analysis data sets are available



**Fig. 3.** Monitoring system implemented to monitor the performance of the BIPV System.  
Source: Authors.

through the interface and mainly European data. The generation model of the BIPV system is configured for the generation of one (1) kWh, evaluating from the cradle to the grave and is composed of the following phases:

- Extraction and Manufacturing: the impacts associated with materials and processes to manufacture a solar panel are found in this phase.
- Transportation: taking into account environmental impacts related to the transportation, from the place of origin of the photovoltaic system to its destination (The import of the photovoltaic panel system is assumed to arrive by boat from England to a port in Colombia (Cartagena) 7,984.71 km in distance; then this is transported by land 944.9 km until arriving to Bogota. The use of cables is supposed for connecting with the SIN because the energy that is not used by the University is injected into the National grid).
- Use: in the use phase, electric cables are considered for connection and injection of electric power to the local and national connection.
- Disposal transportation: the system material will be taken to final disposal at an average distance of 40 km.
- Disposal: for the disposal phase after 30 years of service a landfill will be used for its disposal. A distance of 40 km is assumed for the final disposal of waste.

For the interpretation of the inventory in the LCA, the Recipe procedure was important, allowing the interpretation of the data by reducing the size of the inventory. The main objective of Recipe is to take the impacts to the same unit of measurement (1 kWp), which allows an assessment of all the impacts.

Fig. 4 shows the model for the generation of 1 kW from a thermal source. For this case, coal is used from the Ecoinvent 3.1 database, loaded in the Umberto NXT LCA software, where by expanding the activities, it is possible to load the impacts from the extraction of raw materials to the emissions for the production of electricity.

In Fig. 5 the same procedure is carried out (generation of 1 kW) but this time for Natural Gas.

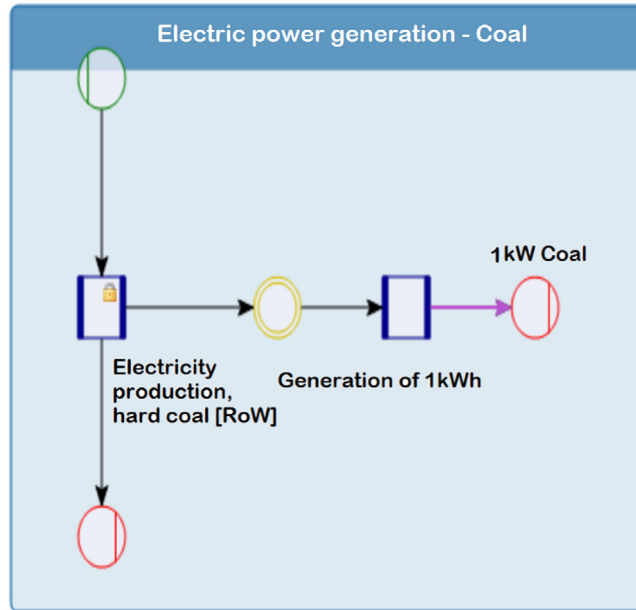
In Fig. 6 the fuel used for the generation of 1 kW is Diesel.

Fig. 7 presents the model of the Hydroelectric Generation System for the generation of 1 kW. This system is considered in the analysis of results because Colombia has between 70%–90% of generation capacity by hydroelectric power within its energy matrix.

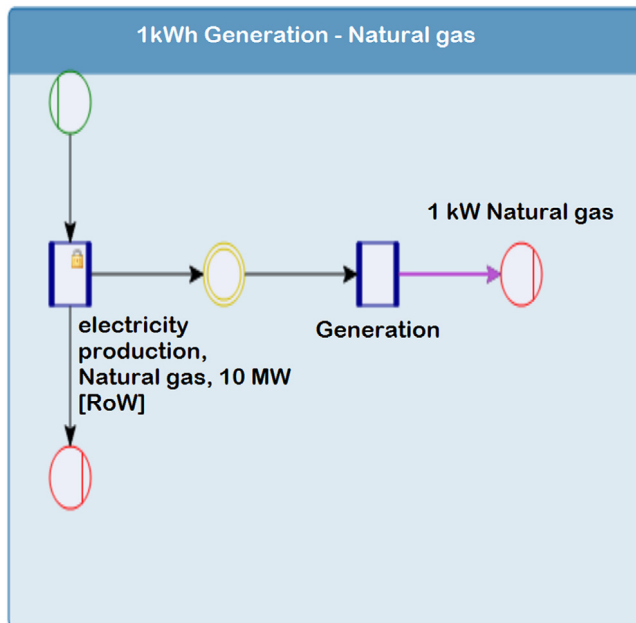
#### 4.1. ReCiPe analysis

Ecopoints are based on the concept of ecological singularity. These evaluate the contribution of the various pollutant compounds to the different categories of impact considered, such as: greenhouse effect, stratospheric ozone, acidification, eutrophication, photochemical fog, heavy metals, carcinogenic substances, ionizing radiation, generation of waste, radioactive waste and exhaustion of energy resources. The total impact is the sum of the ecopoints associated to the whole set of emitted substances considered under each category of impact. Fig. 8 presents the result of each of the models studied for the generation of 1 kW.

The generation of energy through coal presents a greater number of ecopoints with a total of 0.225. In second place, natural gas with 0,13 ecopoints and in third place the diesel generation with 0,98 ecopoints. The production of 1 kW using photovoltaic solar energy only produces a total of 0.011 ecopoints.



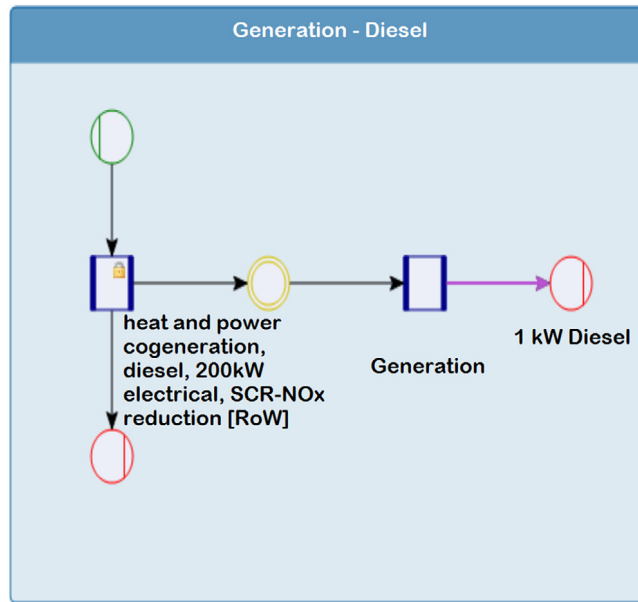
**Fig. 4.** Model of the thermal generation system with coal.  
Source: Umberto NXT LCA™.



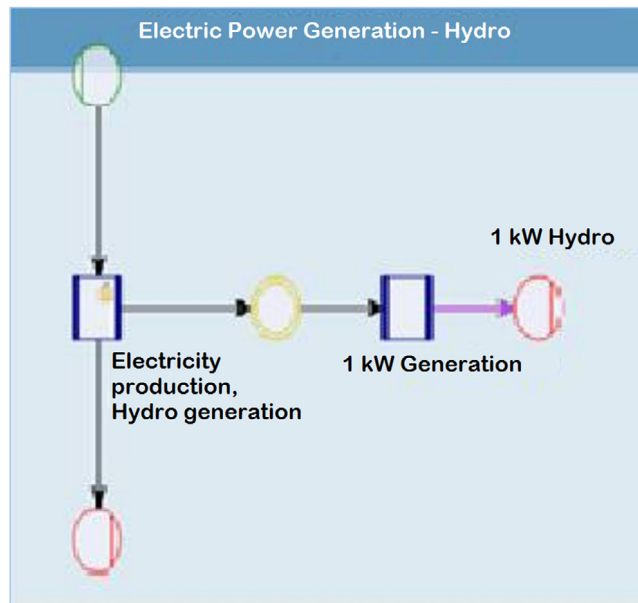
**Fig. 5.** Model of the generation system with natural gas.  
Source: Umberto NXT LCA™.

Fig. 9 shows the impacts associated to each one of the categories: affection to the resources, affection to the health and affection to the ecosystems, where clearly the highest impact occurs in the affection to the health in all the generation systems. In this figure the hydroelectric generation system is not considered, since the impacts are similar to the pv system, its impact only occurs in the initial phase.

Fig. 10 shows a detail of the ecopoints on the category of health affection.



**Fig. 6.** Model of the generation system with diesel.  
 Source: Umberto NXT LCA™.



**Fig. 7.** Hydroelectric generation system model.  
 Source: Umberto NXT LCA™.

The impact with a greater contribution is human toxicity, for all the models studied. However, the generation of one thermal kW from coal has the highest. According to the results of the Umberto NXT LCA software, the emissions generated by elements such as Selenium, Manganese and Barium represent 84% of the total emissions that affect human toxicity, being this category the most representative in the study.

The results of the study on climate change are shown in Fig. 11. The model with the greatest environmental impact is the generation from the use of coal due to the type of fuel: this shows that to generate 1 kW, the pollution is

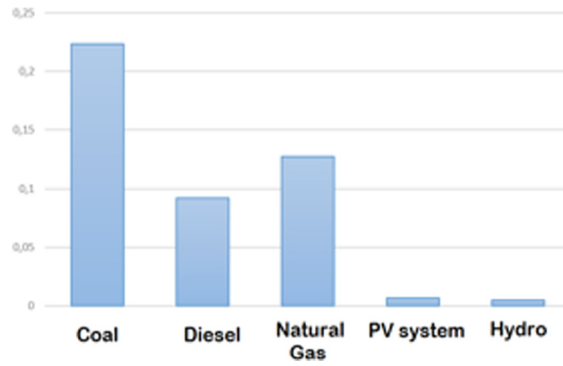


Fig. 8. Total ecopoints for a 1 kW generation using the sources analyzed.  
Source: Umberto NXT LCA™.

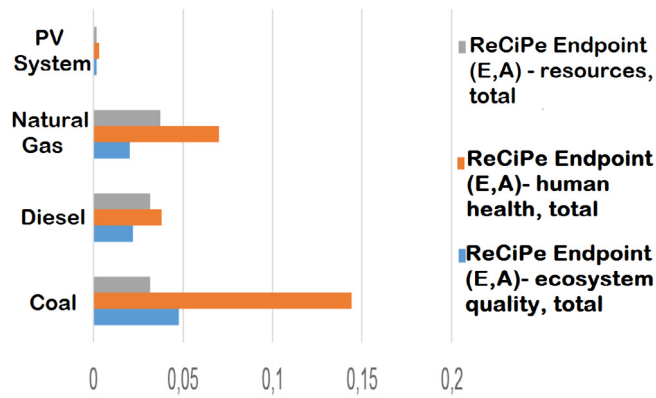


Fig. 9. Total ecopoints by category.  
Source: Umberto NXT LCA™.

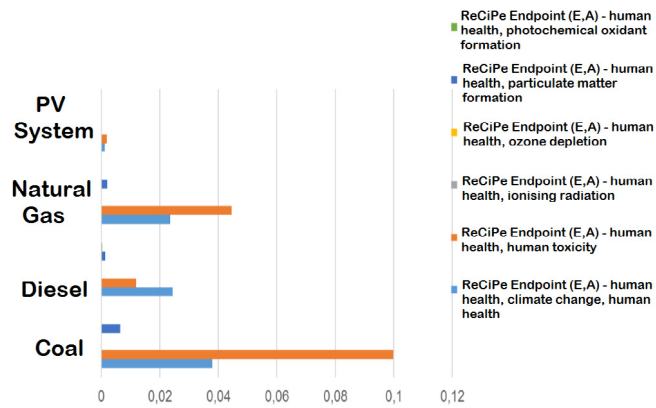
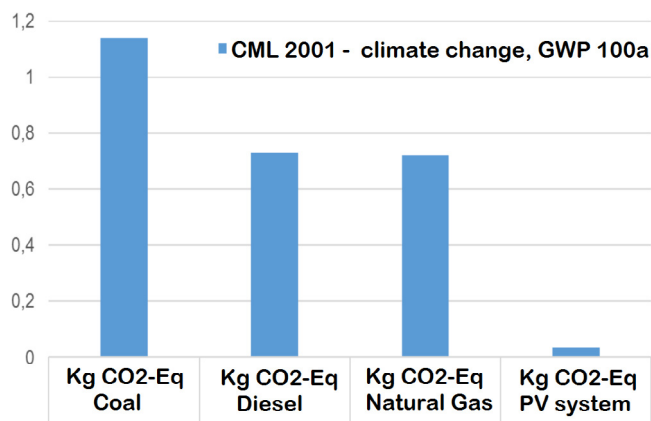


Fig. 10. Results in health affectionation category.  
Source: Umberto NXT LCA™.



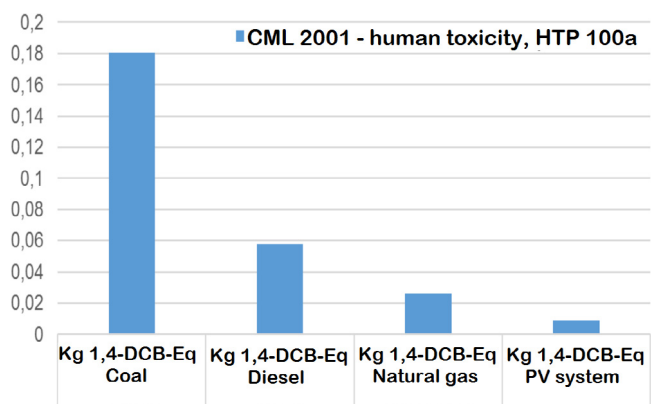
equivalent to 1138, 8 gCO<sub>2</sub>eq/kWh compared to the photovoltaic system which equals 35 gCO<sub>2</sub>eq/kWh, equivalent to 3% compared to coal generation. The contribution of Diesel is 730 gCO<sub>2</sub>eq/kWh and the Natural Gas of 722 gCO<sub>2</sub>eq/kWh. Currently, it is under discussion, how hydroelectric generation contributes to climate change.



**Fig. 11.** Results of the impact on climate change.

Source: Umberto NXT LCA™.

The results of the study on human toxicity are shown in Fig. 12.



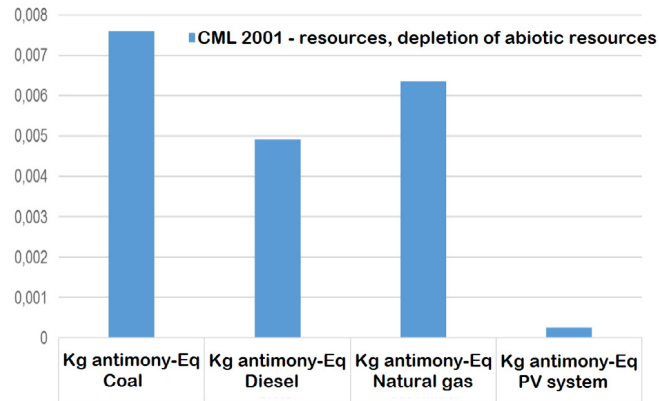
**Fig. 12.** Results of the impact on human toxicity.

Source: Umberto NXT LCA™.

The impacts on human health show a similar tendency to impacts on climate change, both in terms of impact and global comparison. These are referred to the impacts of toxic substances in terrestrial and aquatic ecosystems. The characterization factors are calculated describing the destination, exposure and the effects of the toxic substances for an infinite time horizon expressed as 1,4-dichlorobenzene equivalents/kg of emissions, due to the fact that the first three models require hydrocarbon base raw material and/or its derivatives. The generation with incomplete combustion generates gases of CO<sub>2</sub>, CO, NO<sub>x</sub> and SO<sub>2</sub>, their contributions to the generation systems represent for the coal 66%, diesel 20% and natural gas 9.5% of the impact. The photovoltaic system also presents emissions to the atmosphere related to aluminum at the time of production (due in particular to the needs of electricity mainly emitted in the country of origin of the aluminum) representing 3% of the total impact on human health for the model.

The results of the study regarding the depletion of the abiotic resource are shown in Fig. 13.

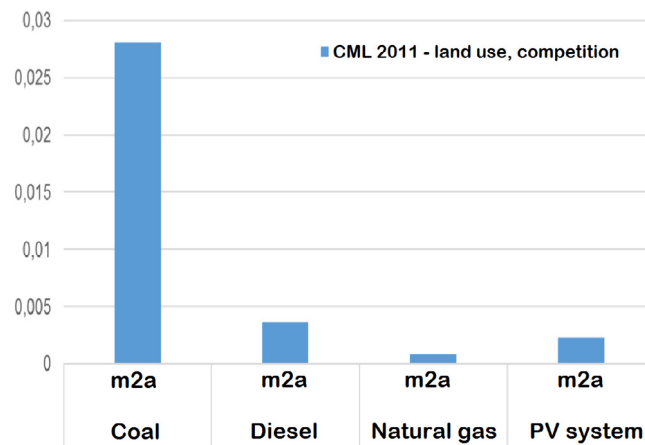
The abiotic depletion factor was determined for each extraction of minerals and fossil fuels according to the proposed models. The result determined that in coal generation this equals 7.5; diesel 4.9; natural gas 6.3 and



**Fig. 13.** Results of the impact on abiotic resource depletion.  
Source: Umberto NXT LCA™.

with the photovoltaic system 0.2 kgADF/Kg-Emission on the basis of concentration reserves and the rate of deaccumulation. Likewise, long-term trends in the reduction of the quality of resources are taken into account.

The results of the study regarding the use of the soil are shown in Fig. 14.



**Fig. 14.** Results of the impact on land use.  
Source: Umberto NXT LCA™.

The use of the soil is a determining factor for the generation of energy in each of the models. This category establishes the area of use of natural resources, and it can generate shortages depending on the exploitation of the land. The result of the analysis of the use of the soil generated from the thermal source with coal needs a 57% area, diesel 11% and the photovoltaic system 4.5%. It should be noted that natural gas is negligible. In hydroelectric generation, due to its nature, it requires large areas of land.

## 5. Conclusions

For the photovoltaic system at the National University of Colombia, based on the life cycle analysis, it was determined that the phase with the lowest environmental impact was that of “Use”, the environmental burdens are low. The environmental impact was reflected in the phases of extraction and manufacturing, transport, disposal transportation, disposal of the photovoltaic panels, due to the manipulation of materials and use of fuel to mobilize the materials.

The hydroelectric plants and the PV system present the same environmental impacts, according to the environmental burdens during the life cycle analysis (LCA); but it should be noted that their burdens should also be considered in the analysis of costs, social impact and public order, where their different impacts could vary.

Both systems are positive and sustainable, however, geographic and meteorological factors must be taken into account in order to define which system is more viable.

The secondary data taken from Ecoinvent V.3.1, facilitated the model of the conventional generation scenarios (Coal, Diesel, Natural Gas and Hydroelectric): the inventory was covered by 83% of the world electricity production in 2017, which allowed obtaining greater reliability of data and reducing the uncertainties in the study of stroke; also, contribute to a more accurate estimation of environmental burdens.

The behavior of the LCA in the four scenarios using the methodology CML 2001, determined that the categories with the greatest environmental impact are human toxicity and climate change, for the thermal source from Coal with 1803 gr-DBC-Eq/kg on the quality of the ecosystem and 1138.8 gCO<sub>2</sub>eq/kWh for the production of 1 kW, significantly impacting human health.

## Acknowledgment

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