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A Comparative Life Cycle Assessment and Costing of Lighting Systems for Environmental Design and Construction of Sustainable Roads

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Abstract: The management of the life cycle of the transport network is one of the main challenges of sustainable mobility. Roads and highways cause significant damage to the ecosystem. Specifically, lighting systems contribute to climate change, energy consumption, and human health effects. In this context, this work proposes the combination of life cycle assessment (LCA) with life cycle costing (LCC) to analyze the eco-efficiency of the life cycle of a road, including evaluation of the relative contribution of the lighting system to the total impact. Four scenarios were included in the model: (S1) high-pressure sodium lamps with ballast powered from the grid; (S2) halogen lamps powered from the grid; (S3) light-emitting diode lamps powered from the grid; and (S4) light-emitting diode lamps powered from a standalone photovoltaic system. The life cycle stages of raw material extraction, construction, use, maintenance, and end of road life were included in the analysis. The results show that scenarios S3 and S1 are the most eco-efficient relative to the less favorable S2 scenario (80% and 74% lower, respectively). Scenarios with the least environmental impact are the most economically viable.

Keywords: life cycle assessment; life cycle costing; eco-efficiency; roads; environmental cost-effectiveness; road light; alternative lighting

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1. Introduction

The construction sector is one of the main sources of environmental impact around the world. In 2021, it was responsible for 30% of energy consumption, 37% of carbon dioxide emissions, and one-third of greenhouse gases emitted globally, 11% of which was due to the manufacture of construction materials and products such as steel, cement, and glass [1,2]. Specifically, road construction projects consume large amounts of resources. The use of virgin raw materials and the extraction of natural aggregates remain predominant, causing landscape modifications and ecosystem alterations [3], despite the growing trend of the use of waste materials with similar or superior performance compared to conventional practices [4]. The impacts associated with the consumption of fossil fuels, energy, and the emission of greenhouse gases linked to the services and facilities of roads—such as telecommunications or lighting—are also noteworthy. Therefore, this infrastructure causes significant direct damage to the ecosystem (e.g., effects on wildlife, habitat fragmentation, alterations in water-flow patterns, noise or pollution) and, indirectly, contributes to climate change, resource depletion, and negative impacts on human health, among others.

Consequently, the design, construction, and management of road transport networks have become major challenges for sustainable mobility. Currently, as a priority on roadmaps within the 2030 Horizon, R&D programs have set the objective of reducing greenhouse gas emissions by 20% compared to 1990 levels, increasing energy efficiency by 20%, and achieving 20% of energy consumption from renewable energy [5]. To achieve this, public administrations in the European Union are moving towards the search for regulatory environmental requirements, focusing their efforts on achieving a balance between the economic interests of the transport sector and environmental limitations. This implies guiding the previous phases of the project with a life cycle approach and ensuring that the strategies for the prevention and minimization of impacts do not focus exclusively on their useful life (operation phase), but also on the extraction and use of raw materials, construction, maintenance, and end of life. This perspective will help identify the most impactful sources and will allow prioritization of those constructive solutions that reduce the carbon, water, energy, or habitat footprints. In the near future, public administrations will guide Green Public Procurement (GPP) with carbon impact requirements or new Environmental Product Declarations (EPDs) for buildings, infrastructure, and other constructions [6], with the aim of achieving a carbon-neutral transport sector by 2050 [7]. These strategies enable improvement of the circular economy in other economic sectors [8]—for example, the use of industrial byproducts for road stabilization [9,10], and using municipal incinerated bottom ash [3,11] or plastic waste on road pavements [12].

The optimal way to achieve these objectives and implement more sustainable constructive solutions is only possible from the early stages of road planning and design, considering all phases of its lifecycle. The fundamental principle is to propose different alternatives and select the one with the best environmental performance [13]. Thus, the prediction of environmental impacts should be carried out from the project's initial phase, making use of accurate information and comparing alternatives in order to select the most eco-efficient solution. In this scenario, the environmental performance of roads must be evaluated to support decision-making with new holistic methods of life cycle analysis. Today, several environmental analysis tools are available. Life cycle assessment is one of the most widely used and accepted methods.

In the life cycle of a road, the lighting system contributes to climate change, energy consumption, and human health effects, as well as incurring high investment costs. In EU28 countries, around 2.35 million km (43%) of the 5.5 million km of roadways are lit, including 12% of motorways, 12% of national roads, and 18% of regional roads. In 2005, the energy consumption for road lighting was approximately 35 TWh (1.3% of total electricity consumption) [14,15]. Up to 25% of the overall budget of the road network is allocated to lighting costs, which corresponds to approximately 3850 million euros equivalent in current costs [16].

Today, the most widely used outdoor lighting technology on roads is high-pressure sodium (HPS), followed by light-emitting diodes (LEDs) and, less frequently, high-pressure mercury (HPM), low-pressure sodium (LPS), fluorescent, and metal halide or incandescent lamps. The percentages of use are very variable, depending on the adaptation of the regions to the different lighting technologies [17–21]. LED lamps have developed rapidly in recent years, because of the increasing replacement of HPS and incandescent lamps in countries such as India, Japan, China, or the Unites States of America [22]. It should be noted that the systems currently used are based on a continuous service of lighting in time slots, which generates an over-illumination of the road (in periods of non-use) [23]. In contrast to traditional systems, adaptive lighting [24,25] maximizes the useful life of lamps and other elements, with an autonomous process that activates road lighting according to needs. These solutions improve the efficiency of the system in terms of costs, energy consumption, and environmental impact. For these reasons, the development of new road lighting technologies and optimization of existing ones are active lines of research at present.

In this context, it is important to analyze the lighting technologies from a life cycle perspective. Methodologies such as LCA or LCC provide useful results for decision-making in the system design. Reviewing the scientific literature, a larger number of publications analyze the economic impact of lighting systems [26–33], while works that apply LCA individually or also integrate LCC for the quantification of environmental and economic impact are less frequent [34–44]. Only a limited number of studies consider comparative LCA of different lighting technologies on roads. In general, these studies usually consider two technologies exclusively, whereas most of the literature analyzes streetlight technologies and luminaires [14,16,18,27,28,40,45,46]—and, less frequently, road lighting [14,40,47]. LCA studies of lighting typically only consider the lamps, and not the entire system (such as bulbs, luminaires, ballast, columns, circuits, wire connections, and energy supply). The study of the relative environmental impact of lighting systems with respect to the overall life cycle of the road has not yet been carried out, neither the balance between the economic and environmental results of the technologies most commonly used today.

This work proposes the combination of life cycle assessment in its environmental dimension (LCA), economic dimension with life cycle costing (LCC), and the analysis of the eco-efficiency of the life cycle of a road. The integration of these methods improves decision-making: the combination of LCA and LCC allows analysis of the overall sustainability of the road, whereas the analysis of eco-efficiency contributes to minimizing the environmental impact, improving the economic performance, and reducing the life cycle costs of the system. Furthermore, the relative contribution of the lighting system to the total impact of the road is analyzed. Four scenarios were included in the model: (S1) high-pressure sodium lamps with ballast powered from the grid; (S2) halogen lamps powered from the grid; (S3) light-emitting diode lamps powered from the grid; and (S4) light-emitting diode lamps powered from a standalone photovoltaic system.

Therefore, this article is structured as follows: Section 2 describes the methodology. Section 3 applies the integrated LCC-LCA method and eco-efficiency analysis of a standard road model, analyzing the four most used lighting technology scenarios at present, and the results are discussed in Section 4. Finally, the conclusions are formulated in Section 5.

2. Materials and Methods

2.1. Life Cycle Assessment Approach

The standard LCA methodology is implemented for this study with the ISO 14040 procedure [48]. The life cycle assessment (LCA) and life cycle costing (LCC) methods are integrated with the aim of obtaining an indicator of the eco-efficiency of the road's life cycle. Figure 1 summarizes the stages, adapted to the objectives of the study. In the first step—goal and scope definition—the case study and data collection procedure are defined, together with the functional units, system boundaries, main assumptions for calculation, impact categories, and calculation methodology. Life cycle inventory analysis (the second step) involves the collection of data and calculation procedures (validation of the functional unit and its relationship with unit processes and the reference flow) to quantify the relevant inputs (i.e., energy, raw material, auxiliary inputs, products, co-products) and outputs (i.e., products, co-products, waste, emissions to atmosphere, hydrosphere and lithosphere, and other environmental aspects) of the system. The third step—life cycle impact assessment (LCIA)—integrates the life cycle assessment (LCA) and life cycle costing (LCC) methodologies to analyze the eco-efficiency of the life cycle of a road, including the evaluation of the relative contribution of the lighting system to the total impact. The environmental LCIA is focused on the characterization of 18 midpoint and 3 endpoint categories based on ISO series 14040. LCC is carried out according to the standard procedure ISO 15686-5:2017 Buildings and constructed assets—Service life planning—Part 5, including the calculation of environmental costs with the Eco-Cost methodology. Eco-efficiency is determined by the ratio between the environmental and economic impacts. Finally, in step 4, the results of phases 2 and 3 are interpreted, drawing conclusions and recommendations to improve the environmental performance of the system.

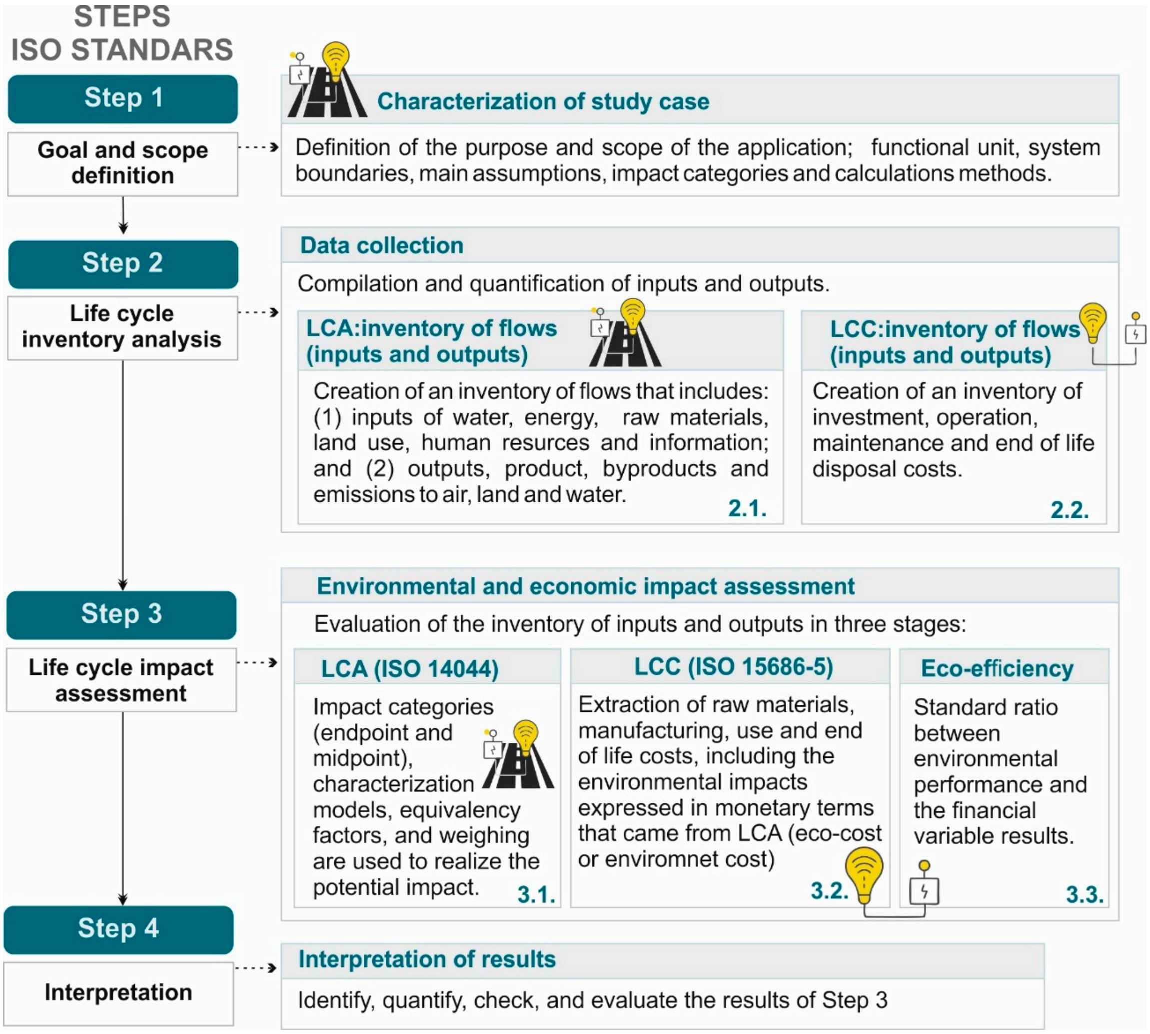


Figure 1. Life cycle assessment approach.

2.2. Case Study and Data Collection

The case study includes the construction project of a local road that connects an industrial estate with the central nucleus of a town in southern Spain (Huelva). The examined road offers a solution to local traffic, improving communications, and dividing traffic between both locations.

The system analyzed is a paved road with standard characteristics consisting of a single lane of traffic in each direction, hard shoulders, and a pedestrian area (10 m in total width). The road's drainage system (see Figure 2, [a]), sewerage system (see Figure 2, [b]), and the auxiliary pipes for drinking water supply, electricity distribution, and telecommunications complete the infrastructure. Figure 2 shows a typical cross-section.

The lighting network (see Figure 2, [c]) consists of 30 lighting columns, control panels, and power supply wiring (see Figure 2, [d]). Four scenarios with different outdoor lighting systems using current street lighting technologies were included in the model:

- Scenario 1 (S1—HPS): High-pressure sodium lamps (HPS) with ballast powered from the grid.
- Scenario 2 (S2—HA): Halogen lamps powered from the grid.
- Scenario 3 (S3—LG): Light-emitting diode (LED) lamps powered from the grid.
- Scenario 4 (S4—LPH): Light-emitting diode (LED) lamps powered from a standalone photovoltaic system.

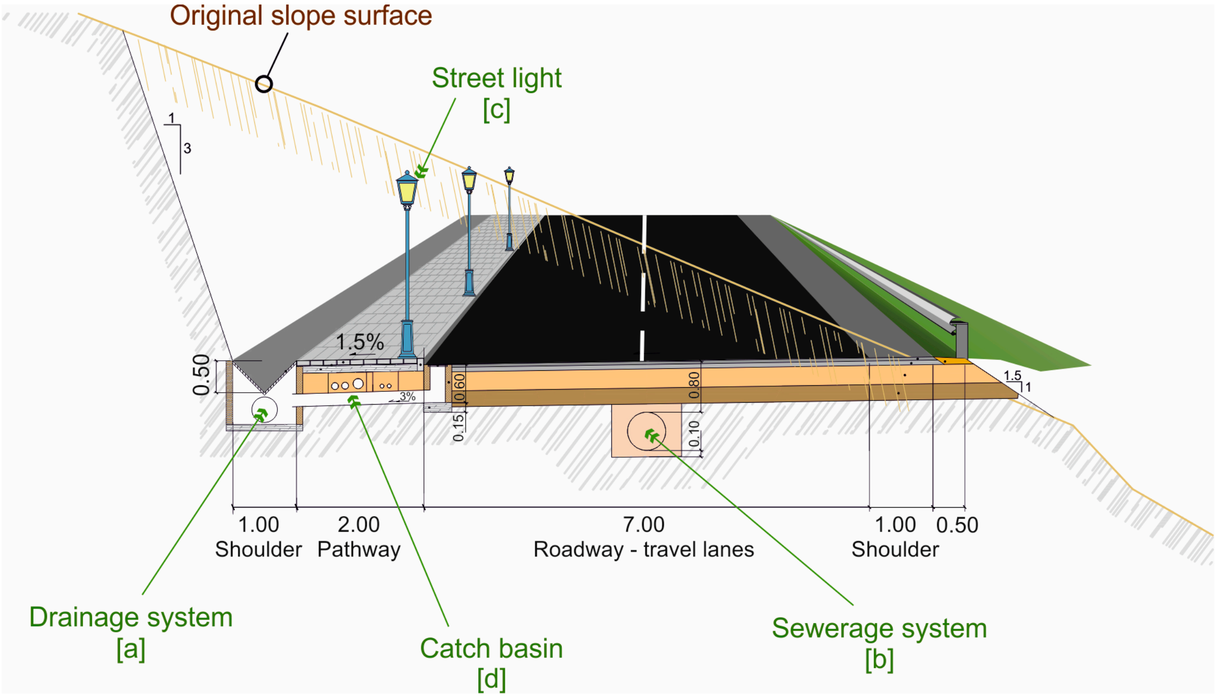


Figure 2. Section of the road.

The design of the installation considers the equidistant distribution of the luminaires on the pavement and the following requirements of the European standards EN 13201 and Regulation Of Energy Efficiency In Outdoor Lighting [49,50]: (1) lighting classes ME6 for motorized traffic (road traffic circulating at 30 km/h and an intensity of less than 7000 vehicles per day); (2) minimum values of lighting parameters for the road type (see Table 1); (3) selection of the most suitable luminaire family (including different lamp powers, optics, and reflectors) and the establishment of generic parameters of the system geometry (distances, heights and inclinations) (see Table 2, column a); and (4) simulation of lighting systems with DIALUX software [51] for each scenario (see Table 2, column b), determining auxiliary devices for the appropriate power supply of each system (see Table 3).

Table 1. Minimum values of lighting parameters for the road type (M6).

Parameter	Metrics (Units)	Requirement
Road surface luminance (dry)	Luminance (cd/m^2)	0.30
	Average luminance, L_{av} (cd/m^2)	0.30
	Overall uniformity, U_o	0.35
	Longitudinal uniformity U_l	0.40
Disruptive glare	Threshold increment, TI (%)	15
Lighting of the surroundings	Edge illuminance ratio R_{EI}	No requirements

Table 2. Lighting simulation results.

Geometric Parameters (a)		Light Indicators (b)	
Distance between columns(m)	23	Lm (cd/m^2)	1.15
Light point height (m)	6	U_o	0.36
Light projection (m)	−0.5	U_t	0.62
Inclination (°)	0	TI (%)	12
Distance between column and carriageway (m)	0.3		

Table 3. Results of lighting system alternatives.

Scenario	S1-HPS	S2-HA	S3-LG	S4-LPH
Tension (V)	100	230	90	24
Power (W)	100	500	68	83
Light flux (lm)	10,700	10,250	11,200	10,160
Color (K)	2000	2900	3000	4000
Lifespan (h)	23,500	2000	50,000	50,000
Ballast/Controller	SI	NO	SI	SI

3. LCA Model Development

3.1. Goal and Scope Definition

The goal of this assessment is to identify the most eco-efficient scenario of lighting systems in the global environmental impact of a road. The environmental and economic impact were calculated with a life cycle assessment (LCA) model, and a life cycle costing (LCC) model respectively.

3.1.1. Functional Unit

The useful life of a road more suitable for studies of these characteristics is established between 20 and 75 years [52–55], depending on the type of road—regional roads, local roads, municipal street networks, highways, bicycle lanes, bridges, or tunnels [56]—and traffic density. In addition, a standard length of 1 km is usually considered. For this study, the functional unit was a 1 km road composed of a 7 m wide single carriageway with two vehicle lanes (one in each direction), a 1 m hard shoulder, and 2 m for sidewalk zones (representing a road surface of 10,000 m^2). The LCA included the extraction and production of raw materials, construction, operation and maintenance, withdrawal from service, and end of life, with a 20-year period of road service.

3.1.2. System Boundaries

The life cycle of a road can be divided into different stages. The raw material extraction and construction phase covers all unit processes related to the extraction and transport of raw materials, the reuse or recycling of materials, and the activities derived from their handling and installation at the final site, including operational work (traffic signs, lighting system, telecommunications, and road markings). The operation phase covers the use of the road, its maintenance, and the renovation of facilities (surface and services); during its useful life, routine maintenance of the asphalt surface is carried out, consisting of reaming of the tread layer and the extension of a new layer with the same characteristics (for this study, a frequency of 7 years was estimated). Due to the study location (southern Spain), the tasks related to winter service (i.e., road salting and snow clearance) were not included in the system boundaries. In addition, in its operation phase, the road makes use of additional services, such as traffic signs, road safety, and systems (lighting, sewerage, electricity, and telecommunications). Finally, the end-of-life stage includes demolition and waste disposal activities; these are often integrated into the maintenance phase, as most roads do not reach the end of their useful life and are usually not dismantled [52,57,58]. In this study, considering 20 years as the analysis period, dismantling was not included within the system boundaries; however, for the rest of the subsystems, the end-of-life stage was considered. The boundaries of the lighting system comprise cradle-to-grave life cycle processes, including the extraction of raw materials, manufacturing of elements (lightbulbs, luminaires, ballasts, columns, circuits, wire connections, and energy supply), electrical installation, use, maintenance, and end of life. Figure 3 represents the simplified process flow and system boundaries of the study case. The main assumptions listed in Table 4 were considered. The definition of the life cycle stages is in accordance with the European standard EN 15804 [59].

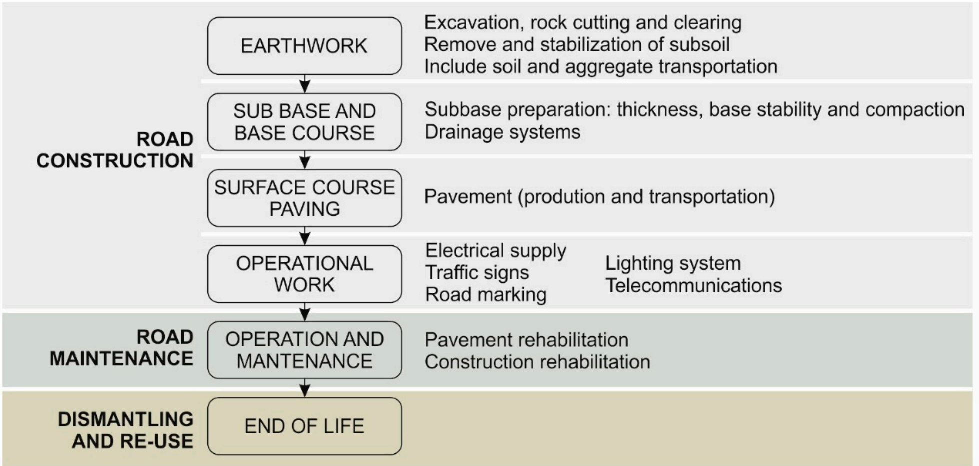


Figure 3. System boundaries.

Table 4. Main assumptions for calculation.

Life Cycle Phases	Main Assumptions for Road	Main Assumptions for Lighting System
Extraction and production of raw materials, fuel, and products	Includes transportation of materials and use of heavy machinery. Reuse of raw materials from construction processes.	Includes the extraction and processing of raw materials for the manufacture of lighting system components.
Construction	Includes transportation of materials and use of heavy machinery. Reuse of raw materials from construction processes.	The manufacturing process for components is considered. Logistics (packaging and transport) is excluded.
Operation and maintenance (20 years) *	Road traffic is not considered. Tasks related to winter service (i.e., road salting and snow clearance). Cleaning of roads and sewers is not considered.	Same range of luminescence for all scenarios. Includes the number of bulb replacements. Corrective and preventive maintenance of the lighting system is considered (i.e., regular check-ups, cleaning of luminaires, and replacement of lamps and auxiliary equipment at the end of their useful life). Includes a grid or a standalone photovoltaic system.
Disposal and end of life	Demolition or dismantling of the road is not included.	Landfill. Recycling (reuse, recycling, and incineration).

* A study period of 20 years was considered, as this is the estimated lifetime of an outdoor road lighting system.

3.1.3. Impact Categories and Calculation Methodology

The results of the life-cycle impact assessment were calculated using the ReCiPe methodology [60] in SimaPro 8 [61] according to the European standard. The impact categories considered included 18 midpoint indicators (climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion) and 3 endpoint indicators (human health, biodiversity, and resource scarcity). For the analysis of environmental costs, the following midpoint methodologies were used: potential 100-year IPCC, USEtox, ReCiPe, the EF method, and the method of Boulay et al. (2011) (water scarcity) [62].

3.2. Scenarios in the Life Cycle Inventory

This study was structured with two levels: (I) a macro-level analysis for the life cycle of the road infrastructure, and (II) a micro-level analysis for the operation stage. To compile the inventory of the inputs and outputs of the unitary processes of the road's life cycle, data were collected using the technical documentation of the construction project, scientific publications, and the breakdown of existing products on the market and their suppliers. To simplify the structure of the life cycle inventory (LCI), the system was broken down into different groups: earthworks, drainage, pavement, and operational works (including the sidewalk zone and systems, lighting, sewerage, electricity, and telecommunications). The Ecoinvent 3 database was used to develop the LCI. Inputs available for Western European dates were given preference in the selection; for unavailable processes, other entries were selected or adapted from similar records.

Finally, to calculate the relative contribution of lighting systems to the total environmental impact of the road, the four scenarios described in Section 2.2 were considered: S1—HPS, S2—HA, S3—LED-G, and S4—LEDPV. According to the functional unit of the studio, the sub-lifecycle of the lighting system fulfills the following function: to illuminate 1 km of a local road of lighting category ME6 for motorized traffic [49,50], with a 7 m wide carriageway divided into two lanes (one for each direction), a 1 m wide hard shoulder, and a 2 m wide pavement for foot traffic, for a useful life of 20 years and an annual use of 4069 h. In order to carry out a comparative LCA, an equivalent service was established for the four scenarios in terms of light flux and color quality (see Tables 2–4) and the selection of accessories, i.e., luminaires, columns, reflectors, position, angle, and wiring, dimensioned according to the lamp requirements. Table 5 shows the reference flows of the lighting systems in terms of the number of bulbs and the electricity consumption.

Table 5. Lighting inputs for each scenario and functional unit.

Scenario	Technology/Powered	Power	Electricity Consumption (kWh/year)	Number of Items (Bulbs) *
S1	HPS/grid	100 W	14,851 (from de grid)	120
S2	HA/grid	500 W	65,307 (from the grid)	630
S3	LED/grid	68 W	10,671 (from de grid)	60
S4	LED/standalone photovoltaic system	83 W	10,671	60

* Lifespan: HPS bulbs (23,500 h); halogen bulbs (2000 h); LED light bulbs (50,000 h).

3.3. Life Cycle Impact Assessment (LCIA)

The LCIA phase was focused on the characterization step according to ISO series 14040, with the following impact indicators: 18 midpoint categories in the CML method (Hierarchist) and 3 endpoints in the Eco-indicator 99 method (Hierarchist). The LCIA results were calculated using SimaPro 8 [61]. Specifically, and as an objective of this work, the impact of the life cycle of the lighting system was analyzed within the "systems" group for four scenarios (S1, S2, S3, and S4). Table 6 shows the results of the road life cycle analysis, and Table 7 presents the results obtained for the life cycle of each lighting system.

Table 6. Road life cycle impact analysis results.

Impact Category *	Unit	Earthwork	Drainage	Pavement	Sidewalk Zones	Systems	Total
Climate change	kg CO_2 eq	2.5×10^5	3.1×10^4	4.9×10^4	5.0×10^4	3.3×10^5	7.1×10^5
Ozone depletion	kg CFC-11 eq	4.1×10^{-2}	1.9×10^{-3}	2.3×10^{-2}	2.7×10^{-3}	3.8×10^{-2}	1.1×10^{-1}
Terrestrial acidification	kg SO_2 eq	1.4×10^3	9.1×10^1	3.1×10^2	1.6×10^2	1.7×10^3	3.7×10^3
Freshwater eutrophication	kg P eq	3.5×10^1	3.4×10^0	6.0×10^0	6.0×10^0	9.6×10^1	1.5×10^2
Marine eutrophication	kg N eq	1.7×10^2	1.6×10^1	4.3×10^1	2.6×10^1	7.8×10^2	1.0×10^3
Human toxicity	kg 1,4-DB eq	8.4×10^4	5.2×10^3	1.2×10^4	9.8×10^3	1.3×10^5	2.4×10^5
Photochemical oxidant formation	kg NMVOC	1.7×10^3	9.8×10^1	3.6×10^2	1.4×10^2	1.3×10^3	3.6×10^3
Particulate matter formation	kg PM10 eq	6.6×10^2	3.9×10^1	2.0×10^2	6.7×10^1	5.8×10^2	1.6×10^3
Terrestrial ecotoxicity	kg 1,4-DB eq	1.0×10^2	1.3×10^1	1.3×10^1	1.1×10^1	2.7×10^1	1.7×10^2
Freshwater ecotoxicity	kg 1,4-DB eq	2.3×10^3	1.5×10^2	3.7×10^2	3.1×10^2	9.0×10^3	1.2×10^4
Marine ecotoxicity	kg 1,4-DB eq	2.7×10^3	1.5×10^2	3.9×10^2	3.2×10^2	8.0×10^3	1.2×10^4
Ionizing radiation	kBq U235 eq	2.6×10^4	1.8×10^3	9.6×10^3	2.6×10^3	1.0×10^5	1.4×10^5

Table 6. *Cont.*

Impact Category *	Unit	Earthwork	Drainage	Pavement	Sidewalk Zones	Systems	Total
Agricultural land occupation	m^2a	4.8×10^3	2.3×10^3	7.4×10^3	1.8×10^3	1.4×10^4	3.0×10^4
Urban land occupation	m^2a	1.6×10^4	5.3×10^2	4.2×10^3	5.7×10^2	2.2×10^3	2.4×10^4
Transformation of natural land	m^2	1.7×10^2	1.1×10^1	2.2×10^2	9.4×10^0	4.2×10^1	4.5×10^2
Water depletion	m^3	1.9×10^4	4.4×10^2	3.8×10^2	1.4×10^4	6.8×10^3	4.0×10^4
Metal depletion	kg Fe eq	1.6×10^4	1.1×10^3	2.2×10^3	6.3×10^3	3.0×10^4	5.6×10^4
Fossil depletion	kg oil eq	8.6×10^4	4.8×10^3	4.4×10^4	8.6×10^3	1.1×10^5	2.5×10^5
Human health	DALY	5.9×10^{-1}	5.7×10^{-2}	1.3×10^{-1}	9.4×10^{-2}	3.4×10^{-1}	5.9×10^{-1}
Ecosystems	Species.yr	2.7×10^{-3}	3.1×10^{-4}	9.8×10^{-4}	4.5×10^{-4}	1.4×10^{-3}	2.7×10^{-3}
Resources	USD	1.5×10^4	8.7×10^2	7.4×10^3	1.9×10^3	9.7×10^3	1.5×10^4

* ReCiPe midpoint (H)/Europe ReCiPe H. Indicator: characterization. ReCiPe endpoint (H)/Europe ReCiPe H/A. Indicator: damage assessment.

Table 7. Impact contribution of each lighting system.

Impact Category *	Unit	S1-HPS	S2-HA	S3-LG	S4-LPH
Climate change	kg CO_2 eq	1.7×10^5	7.1×10^5	1.2×10^5	1.7×10^5
Ozone depletion	kg CFC-11 eq	2.7×10^{-2}	1.1×10^{-1}	2.1×10^{-2}	6.6×10^{-1}
Terrestrial acidification	kg SO_2 eq	9.5×10^2	3.9×10^3	7.2×10^2	9.4×10^3
Freshwater eutrophication	kg P eq	5.0×10^1	1.8×10^2	4.4×10^1	1.5×10^2
Marine eutrophication	kg N eq	5.4×10^2	2.3×10^3	3.9×10^2	2.2×10^2
Human toxicity	kg 1,4-DB eq	7.3×10^4	2.5×10^5	6.8×10^4	2.3×10^5
Photochemical oxidant formation	kg NMVOC	5.2×10^2	2.2×10^3	3.9×10^2	1.3×10^3
Particulate matter formation	kg PM10 eq	3.0×10^2	1.2×10^3	2.3×10^2	2.1×10^3
Terrestrial ecotoxicity	kg 1,4-DB eq	1.3×10^1	4.5×10^1	1.1×10^1	5.4×10^1
Freshwater ecotoxicity	kg 1,4-DB eq	7.1×10^3	3.0×10^4	5.4×10^3	7.6×10^3
Marine ecotoxicity	kg 1,4-DB eq	6.3×10^3	2.6×10^4	4.8×10^3	7.2×10^3
Ionizing radiation	kBq U235 eq	8.1×10^4	3.5×10^5	5.9×10^4	1.9×10^4
Agricultural land occupation	m^2a	6.3×10^3	2.6×10^4	4.8×10^3	7.6×10^3
Urban land occupation	m^2a	1.0×10^3	4.0×10^3	8.0×10^2	1.9×10^3
Natural land transformation	m^2	2.6×10^1	1.1×10^2	1.9×10^1	3.0×10^1
Water depletion	m^3	7.9×10^2	3.2×10^3	6.8×10^2	2.3×10^3
Metal depletion	kg Fe eq	2.1×10^4	5.4×10^4	1.9×10^4	1.4×10^5
Fossil depletion	kg oil eq	5.1×10^4	2.2×10^5	3.8×10^4	4.0×10^4
Human health	DALY	3.7×10^{-1}	1.5×10^0	2.8×10^{-1}	9.5×10^{-1}
Ecosystems	Species.yr	1.5×10^{-3}	6.3×10^{-3}	1.1×10^{-3}	1.6×10^{-3}
Resources	USD	1.0×10^4	4.0×10^4	7.6×10^3	1.7×10^4

* ReCiPe midpoint (H)/Europe ReCiPe H. Indicator: characterization. ReCiPe endpoint (H)/Europe ReCiPe H/A. Indicator: damage assessment.

3.4. Life Cycle Costing (LCC)

Life cycle costing (LCC) includes all relevant costs, income, and externalities of the system's life cycle. This approach considers the costs or cash flows that result from acquisition through operation to disposal. A comparison of alternatives or an estimate of future costs at the project or component level is also frequently included in LCC [63,64]. The analysis was carried out according to the standard procedure ISO 15686-5:2017 Buildings and constructed assets—Service life planning—Part 5: Lifecycle costing, which divides the life cycle cost inventory as shown in Figure 4.

For the four scenarios analyzed, the selected functional unit was taken into account, with a study period of 20 years and an annual luminaire usage of 4069 h. A discount rate of 5% and an annual inflation rate of 3%—both constant—were considered. Regarding the boundary system, and based on the cost distribution identified in Figure 4, the following stages of the road's life cycle were included:

1. Construction: The initial investment of the project and the cost of the work required to get the lighting system into service.
2. Operation: Costs derived from the energy consumption of the installation, which depend on the installed power, the number of operating hours, and the energy costs.

3. Maintenance and end of life: Includes (1) preventive maintenance, corresponding to scheduled maintenance operations, regular checks, cleaning of luminaires, replacement of lamps and auxiliary equipment at the end of their useful life cycle; and (2) corrective maintenance, which covers operations to replace lamps and auxiliary equipment that have deteriorated or have inadequate performance during their useful life, due to manufacturing defects, voltage peaks, among others. Replacement of 1% of the installed lamps and 0.5% of the auxiliary equipment was considered for each year of the installation's operation.

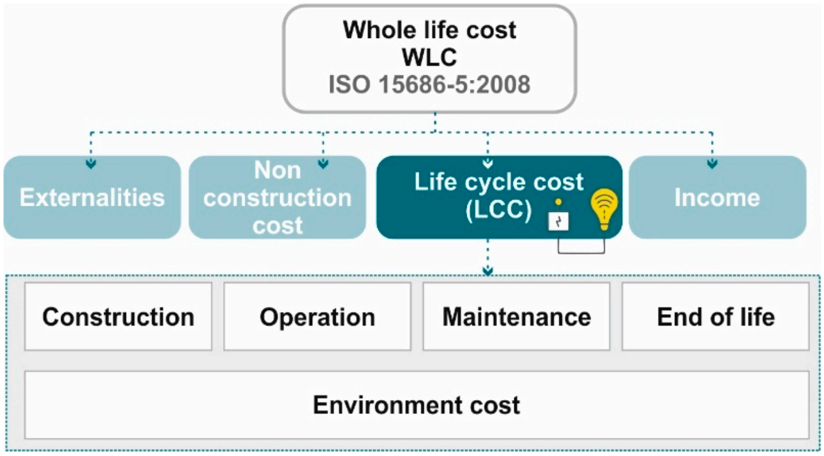


Figure 4. ISO 15686-5, life cycle cost.

Subsequently, the net present value (*NPV*) was calculated with Expression (1). This index is the discounted monetary value of the expected net benefit during the analysis period, where I is the initial cost, b_t is the size and timing of future net benefits, r is the discount rate, and T is the length of the time period. Subsequently, this value was incorporated into the analysis of the eco-efficiency of the system. Table 8 shows the results for the four lighting scenarios.

$$NPV = -I + \sum_{t=1}^{T} b_t \left(\frac{1}{1+r} \right)^t \quad (1)$$

Table 8. Costs of lighting life cycle scenarios.

	Initial Cost (EUR)	Energy Consumption (EUR)	Preventive Maintenance (EUR)	Corrective Maintenance (EUR)	Total Cost (EUR)	NPV (EUR)
S1	3775.98	50,839.83	14,512.74	364.35	69,492.90	14,191.27
S2	5347.83	223,545.93	54,260.16	216.84	283,370.76	56,844.19
S3	8257.98	36,531.36	13,798.62	1596.51	60,184.47	12,825.92
S4	32,403.90	0.00	11,616.09	1563.06	45,583.05	16,430.39

Finally, environmental costs were quantified [63,64] with the eco-cost methodology [62]. This methodology includes a single aggregated score of prevention-based indicators. Eco-costs express the environmental load of a system on the basis of impact prevention. They are the (marginal) costs necessary to counteract or reduce environmental pollution and resource depletion, taking into account the regenerative capacity of the ecosystem.

Eco-costs are useful to compare the environmental performance of different systems with the same functionality. They can be considered as virtual costs, as they are not integrated into the real costs (i.e., life cycle costs). In this case study, eco-costs were calculated for the lighting systems (see Table 9, "total eco-cost"), and they are also a measure of the financial risk associated with noncompliance with future governmental regulations. The following midpoint methodologies were selected: potential 100-year IPCC, USEtox, ReCiPe, EF method, and Boulay et al. 2011 (Water Scarcity) [62].

Table 9. Environment costs for lighting life cycle scenarios for year.

Eco-Cost Categories	S1	S1	S1	S1
Human health (EUR)	294	1205	225	1571
Ecosystems (EUR)	1167	4766	916	5406
Resource scarcity (EUR)	1522	5768	1195	4877
Global warming	1047	4452	776	1034
Total eco-cost (EUR)	4031	16,192	3111	12,889

3.5. Eco-Efficiency Analysis

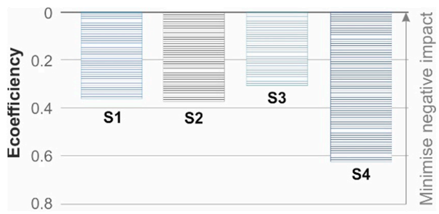
Eco-efficiency is achieved by the "delivery of competitively priced goods and services that satisfy human needs and improve quality of life, while progressively reducing ecological impacts and resource intensity" [65]. It is analyzed through an eco-efficiency indicator—that is, the ratio between an environmental and a financial variable. The concept of eco-efficiency relates environmental and economic performance, allowing the interpretation of the results of an activity, product, process, or service by identifying the most appropriate challenge or improvement strategy for the organization's environmental performance and reducing management's efforts. For this case, the standard eco-efficiency indicator defined in Expression (2) was applied [66].

$$\text{Eco} - \text{efficiency} = \frac{\text{environmental performance}}{\text{financial performance}} = \frac{\text{Impact value}}{\text{Net present value}} \quad (2)$$

where NPV is the net present value calculated in the LCC analysis, and the impact value or "single score" is obtained through the ReCiPe methodology (Endpoint, Europe ReCiPe H/A, single score). Table 10 shows the results of the eco-efficiency analysis.

Table 10. Eco-efficiency analysis for lighting scenarios.

Scenario	Impact Value (Pt)	NPV (EUR)	Eco-Efficiency Index
S1	16,992.08	46,831.19	0.36
S2	69,642.34	187,585.83	0.37
S3	12,964.96	42,325.54	0.31
S4	33,310.54	54,220.29	0.61



4. Results and Discussion

Figure 5 compares the impacts of the road's life cycle. For all categories considered, the main contributors to the environmental impact are "earthworks", "system", and "pavements", which represent 46%, 27%, and 16% of the total impact of the system, respectively. The high impact contribution for the earthworks group is due to the orography and land leveling operations up to the baseline of the final path, which include unit processes such as excavation, rock cutting, stabilization, embanking, and material transportation (soil and aggregates). These processes use heavy equipment with high carbon dioxide and nitrogen oxide emissions as a result of the combustion of fossil fuels. They also require the use of materials (natural aggregates and crushed rock extracts), prefabricated elements, and other supplies linked to the "pavements" group, such as cement manufacturing or hot-mix asphalt production. On the other hand, the "systems" group—which includes the electrical supply, traffic signs, road marking, lights, telecommunications, and sewage system—makes use of large quantities of plastic materials in pipelines. These aspects have a significant environmental impact related to the consumption of virgin materials, petroleum-derived products, and the modification of the ecosystem. For impact mitigation in "earthworks", it would be interesting to optimize the compensatory movement of the soil [67,68], which could reduce the cost and time of these works while minimizing waste and emissions. Environmental performance could also be improved by replacing virgin raw materials with byproducts from industry and other sectors, e.g., asphalt pavement recycling techniques with reclaimed asphalt pavement (RAP) aggregates [69], municipal incinerated bottom ash [3,11], plastic waste [12], agricultural waste products such as sugarcane ash [70], or blast-furnace slag [71] on road pavements, or low-temperature materials instead of hot-mix asphalts embedded in the road to reduce energy consumption [72].

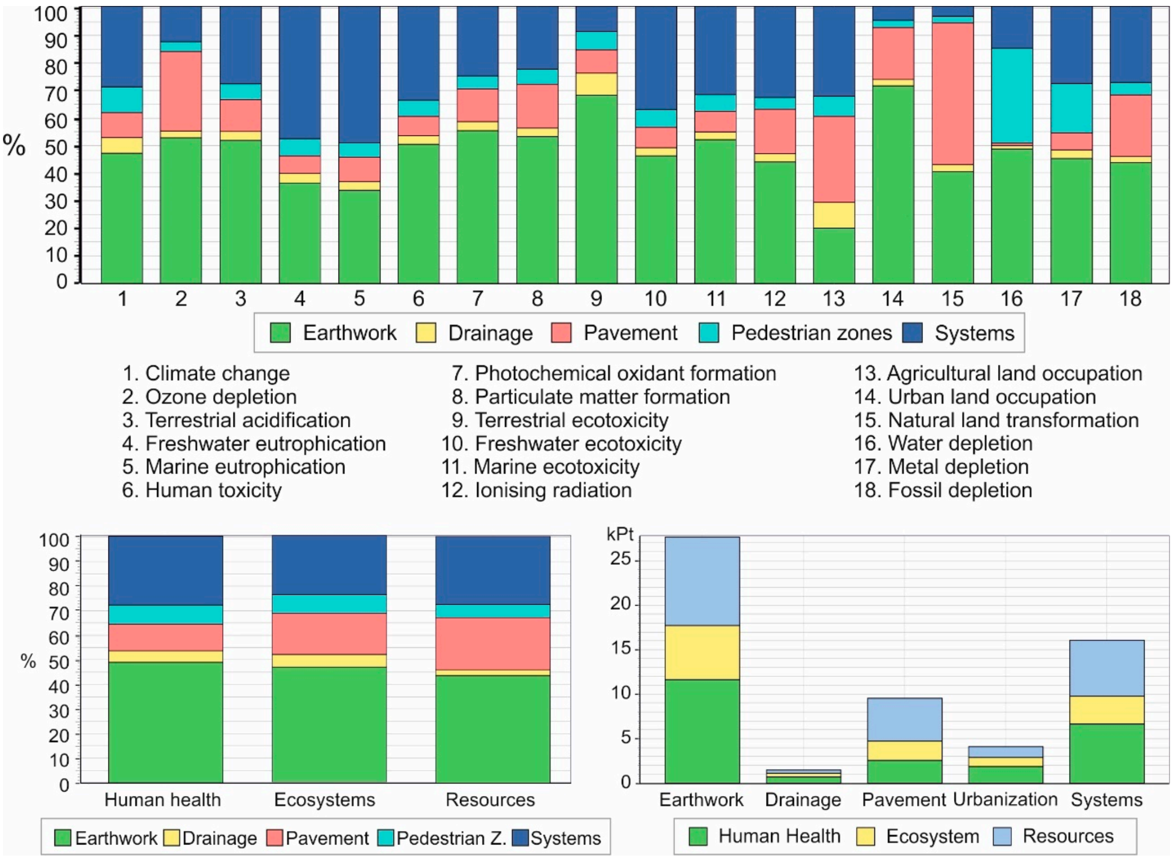


Figure 5. Life cycle environmental impacts of the road.

The results of the ELCA of the lighting system are shown in Figure 6. Scenario S3 (light-emitting diode lamps powered from the grid) showed the best indicators from an environmental point of view, followed by scenarios S1 (high-pressure sodium lamps powered from the grid) and S4 (light-emitting diode lamps powered from a standalone photovoltaic system). Solutions with the lowest environmental impact are the most economically viable in the LCC. Analyzing the results of the weighing indicator endpoint (single score) for scenarios S3 (16.99 kPt) and S4 (33.31 kPt), connecting the lamps to the electricity distribution network represents 61% less environmental impact than installing a self-sufficient system for each of the luminaires. Although this situation may differ between territories (based on the energy mix of the geographical area analyzed), in this study case scenario S3 is environmentally and economically beneficial—firstly, due to the fact that in the Spanish market the contribution of energy plants based on renewable sources or those that do not emit CO_2 equivalent is significant; secondly, because the energy costs are mainly linked to the use phase of the lighting system (during the night hours there are surpluses in the electricity system; in this period, the economic cost of energy is lower). On the other hand, the manufacturing cost of batteries with sufficient autonomy to maintain the S4 system's operation is high. Moreover, these storage devices are not efficient enough to adapt to the most climatically unfavorable times of the year (such as winter, with few hours of daylight). This situation means that the system requires large-capacity/size photovoltaic panels; consequently, the manufacturing stage of the elements (lamps, controllers, photovoltaic panels, and batteries) in scenario S4 generates a higher environmental impact (10.09 kPt) compared to the full life cycle (3.92 kPt) in scenario S3, where the use stage (grid energy consumption) generates the highest impact (84%).

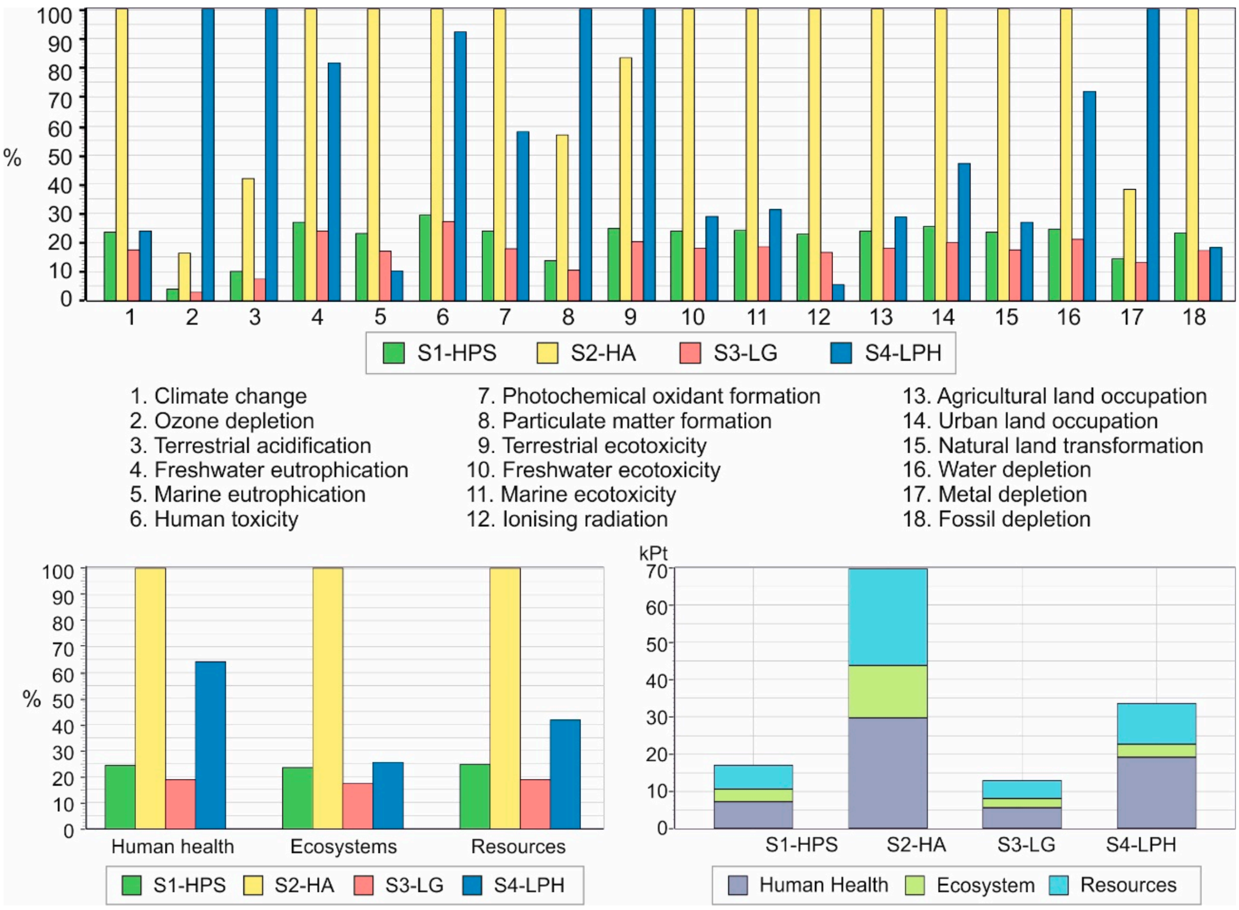


Figure 6. Comparative analysis of the environmental impact of the lighting system.

Table 11 shows the improvement in environmental performance that could be achieved on a road if the HPS-based lighting system (S2) were replaced. The results indicate that scenario S3 would reduce the impact by 80%, while S1 would reduce it by 75%. Scenario S4 would reduce the impact by 45% in most categories; this percentage (lower than that of S1 and S3) is due to the manufacturing of the photovoltaic panel system and energy storage devices, for which some impact categories—such as acidification or metal depletion—decrease the overall environmental performance results; these circumstances make S4 the third-best option for substitution.

The LCC results of the lighting system show a situation similar to that obtained in the environmental performance analysis. Scenario S2 is the least optimal environmentally and economically because of the short lifespan of the halogen lamps (2000 h, compared to 23,500 h for HPS bulbs and 50,000 h for LED bulbs), which implies a high replacement rate in the maintenance stage, as well as high energy consumption (84% and 77% higher than alternatives S3 and S1, respectively). Table 12 shows a comparative analysis where the four scenarios are prioritized from an environmental and economic point of view.

Table 11. Comparative best scenarios: impact mitigation by replacing the HA system.

Indicators *	Units	S2-HA	S1-HPS	S3-LG	S4-LPH
Climate change	kg CO_2 eq.	7.1×10^5	−76%	−83%	−77%
Terrestrial acidification	kg SO_2 eq.	3.9×10^3	−76%	−82%	138%
Freshwater eutrophication	kg P eq.	1.8×10^2	−73%	−76%	−18%
Marine eutrophication	kg N eq.	2.3×10^3	−77%	−83%	−90%
Human toxicity	kg 1,4-DB eq.	2.5×10^5	−71%	−73%	−9%
Photochemical oxidant formation	kg NMVOC	2.2×10^3	−76%	−82%	−42%
Particulate matter formation	kg PM10 eq.	1.2×10^3	−76%	−81%	76%
Terrestrial ecotoxicity	kg 1,4-DB eq.	4.5×10^1	−70%	−76%	20%
Freshwater ecotoxicity	kg 1,4-DB eq.	3.0×10^4	−76%	−82%	−75%
Marine ecotoxicity	kg 1,4-DB eq.	2.6×10^4	−76%	−81%	−72%
Ionizing radiation	kg U235 eq.	3.5×10^5	−77%	−83%	−94%
Agricultural land occupation	m^2a	2.6×10^4	−76%	−82%	−71%
Urban land occupation	m^2a	4.0×10^3	−75%	−80%	−54%
Natural land transformation	m^2	1.1×10^2	−76%	−83%	−73%
Water depletion	m^3	3.2×10^3	−75%	−79%	−28%
Metal depletion	kg Fe eq.	5.4×10^4	−62%	−66%	161%
Fossil depletion	kg oil eq.	2.2×10^5	−77%	−83%	−82%

* ReCiPe midpoint (H)/Europe ReCiPe H.

Table 12. Comparative analysis of environmental and economic results.

	LCA	LCC
1, S3-LG	12.96 kPt (19%)	EUR 42,326 (23%)
2, S1-HPS	16.99 kPt (24%)	EUR 46,831 (25%)
3, S4-LPH	33.31 kPt (48%)	EUR 54,220 (29%)
4, S3-HA	69.64 kPt (100%)	EUR 187,586 (100%)

The results in Table 12 are consistent with the analysis of the eco-efficiency index, which relates environmental and economic metrics. In this case, the optimal solution for the lighting system is the S3-LG scenario, followed by S1-HPS and S2-HA, while S4-LPH is the least favorable. The reason for this situation is that the S1, S2, and S3 systems do not require an initial investment in the energy generation system, as they are powered from the grid, which is also shared in the geographical area (energy mix)—a strategy that contributes to reducing the environmental impact. A possible solution to improve the eco-efficiency of scenario S4 would be to install a control system or sensor system that activates the lighting system on demand, i.e., deactivates or reduces the intensity of the lamps when there is no movement on the road; this would reduce the capacity of the S4 system. These results raise the question of whether photovoltaic technology is currently sufficiently developed to be installed on the transport network in urban areas when the energy distribution network becomes available.

5. Conclusions

Using life cycle assessment, this study analyzed a standard model of a road composed of a 7 m wide single carriageway with two vehicle lanes—one in each direction—a 1 m hard shoulder, and 2 m for sidewalk zones. Four different scenarios for the lighting system were analyzed in order to determine the eco-efficiency of the road—S1, with high pressure sodium lamps powered from the grid; S2, with halogen lamps powered from the grid; S3, with light-emitting diode lamps powered from the grid; and S4, with light-emitting diode lamps powered from a standalone photovoltaic system—in order to determine the relative contribution of the lighting system to the total impact of the road. The results show that scenarios S3 and S1 are the most eco-efficient, in comparison to the less favorable S2 scenario (80% and 74% lower, respectively). The solutions with the least environmental impact are the most economically viable. Furthermore, the most negative stages in the life cycle of the road in terms of environmental impact are “earthworks” and “pavements”.

Today, LCA is a widely used methodology for assessing the environmental, economic, and social impacts of any product, process, or service throughout its life cycle. The standards allow a structured application of the procedure in any sector, although the current trend is to adapt these standards to different economic activities, i.e., the development of specific guidelines is supported in order to adapt the impact calculation models to each product system and facilitate the application of the methodology. Analyzing the established LCA procedure and the calculation model necessary to obtain the results, it can be concluded that it is a long and complex process linked to an exhaustive study of the system analyzed. The characteristics of the process make it difficult for sectors with early experience in LCA, as in the case of its application to the life cycle of roads. The multidisciplinary nature of the stages and unit processes that comprise this type of system, the extensive inventory of raw materials and products from a variety of manufacturers and suppliers, the scarcity of specific methods and tools that facilitate their application, and the investment of time and economic resources necessary to carry them out make the application of LCA to roads an important challenge at present. Furthermore, the quality of LCA studies is limited by the small number of specialized databases, as well as by the temporality, geographic origin (regional/local), and accuracy of inventory data, influencing the accuracy and validity of the results. Therefore, one of the main future challenges facing the scientific and professional community is the expansion of existing LCA tools and the development of databases specialized in the construction of transport networks.

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