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# Rehabilitation or Demolition of Small Hydropower Plants: Evaluation of the Environmental and Economic Sustainability of the Case Study "El Cerrajón"

**Eduardo Vázquez-López [1], Victor Matitos-Montoya [2] and Madelyn Marrero [1,*]**

[1] ArDiTec Research Group, Department of Architectural Construction II, School of Building Engineering, University of Seville, Av. Reina Mercedes 4-a, 41012 Seville, Spain; evazquez6@us.es
[2] School of Engineering, University of Seville, Avenida Camino de los Descubrimientos S/N, 41092 Seville, Spain; victormatitos@gmail.com
* Correspondence: madelyn@us.es; Tel.: +34-95455-66-61

**Abstract:** During the 1950s, numerous small-capacity hydroelectric power plants were built in Spain. Seventy-five years on, it must now be decided whether to continue their operation or demolish them. In order to provide a valid answer, it is necessary to have access to decision-making tools that enable sustainable economic and environmental decision making. The present work proposes a methodology that employs an economic indicator of life cycle cost and environmental indicators of carbon footprint and embodied energy by means of life cycle data analysis. Quantification of the impacts was carried out with the support of construction cost databases and the PREDICE software tool for the quantification of environmental impacts incorporated into maintenance tasks. The case study of the "Cerrajón" power plant was analyzed, where historical hydrological cycles were considered. A life cycle scenario was evaluated in which renovation extended the life of the power plant by a further 75 years. The results show savings in environmental impacts with respect to the impacts of the Spanish energy mix of up to 175 $kgCO_2$ per MWh produced, although no economic benefit was found. It was also shown that in climate change scenarios, the profit price breakeven increases. Rehabilitation appears to present the best choice when combining the two criteria.

**Keywords:** life cycle cost; life cycle assessment; climate change; small hydropower plant



**Citation:** Vázquez-López, E.; Matitos-Montoya, V.; Marrero, M. Rehabilitation or Demolition of Small Hydropower Plants: Evaluation of the Environmental and Economic Sustainability of the Case Study "El Cerrajón". *Environments* **2024**, *11*, 184. https://doi.org/10.3390/environments11080184

Academic Editors: Humayun Nadeem and Warren Batchelor

Received: 28 June 2024
Revised: 5 August 2024
Accepted: 15 August 2024
Published: 22 August 2024



## 1. Introduction

The diversification of energy sources plays a major role in attaining a more robust and sustainable system in both the short and long term [1,2]. One energy source that is often linked to low emissions is that of hydroelectric production, which can be made up of large and small plants. The latter produces 10 MW or less according to the UNICO classification of small hydroelectric plants (SHPs) [3]. However, these plants require a large initial investment in their construction and equipment in addition to their maintenance costs [4]. The global concern regarding the evaluation of their economic and environmental performance justifies their systematic and quantitative assessment [4].

The installed capacity of SHPs has reached 79 GW worldwide, of which 20 GW is in Europe, with 2 GW in Spain [3]. In the particular case of Spain, the country's development has been closely linked to this capacity. In 1940, 92% of Spain's electricity demand was covered by hydroelectric energy. At the end of the 1970s, the Spanish hydroelectric park was one of the largest in Europe, with an installed capacity of 14,000 MW, which represented 50% of the total [5]. However, the continuous decline in the price of electricity led to the abandonment of many SHPs, whose costs exceeded the profit from the sale of the energy produced. This was motivated, on the one hand, by technological improvements in production and distribution (such as thermal, nuclear and combined cycle gas plants) and, on the other hand, by the low cost of fuels used in thermal power plants. The development of hydroelectric production in Spain expanded during the twentieth century to exceed 40,000 GWh in humid years and 25,000 GWh in dry years, with the average of recent years being 32,500 GWh, which represents 17% of annual production [6]. Of the annual hydroelectric production, 88% is provided by conventional plants, including pumped storage plants, which correspond to approximately 29,000 GWh, and 12% is provided by SHP, corresponding to 4000 GWh. There are currently more than 1350 hydroelectric power plants, and of those, 1200 are SHPs [5].

The regulatory framework established by the Spanish Water Law [7] dictates a period of concession of hydraulic production rights of 75 years. Once finished, the infrastructures "will revert to the competent Administration, free of charge, including the costs related to what have been built within the public hydraulic domain during the exploitation of the plant" [7]. Therefore, the concessions of many plants are close to ending [8]. This means that decisions must be made between handing over the infrastructure to the state or renewing it for another concession period.

Although hydroelectric production is the renewable energy with the lowest greenhouse gas emissions [9], there is a discussion regarding the future of these infrastructures [10], the first of which states that the best solution is to dismantle them, thereby allowing the courses of rivers to return to their natural paths without obstacles. This theory is based on the environmental improvements that occur in the biodiversity of the riparian ecosystem [11]. The second discussion estimates that the maintenance, renovation, or restoration of SHPs will have a better environmental impact. This claim is based on the nearly zero greenhouse gas emissions from hydroelectric production [4]. For the evaluation of alternatives, several published studies can help in multivariate decision making [12] or allow for the environmental and social characterization of river barriers [13] using geographical information systems. A further factor to take into account is the impact of climate change on hydroelectric production, with a possible increase in dry cycles that may affect the viability of hydraulic operations [14].

Tools are, therefore, needed to assess the future of SHPs from the point of view of sustainability. The EN-15643 standard [15] establishes a general framework that enables the sustainability of buildings and civil infrastructures to be assessed from an environmental and economic perspective and registers information on impacts throughout the life cycle. Life cycle assessment (LCA) covers the pre-construction, construction, use, and end-of-life phases of infrastructure. This framework has been utilized for environmental and economic assessments of municipal road infrastructures [16], of road paving materials [17,18], and of buildings [19]. Meanwhile, the EN 15978 [20] standard establishes the calculation methods of the environmental assessment, as shown in Rivero-Camacho's research on the LCA in buildings [21]. Moreover, the EN 16627 [22] standard provides a calculation method for the economic assessment, as shown in research by Vázquez-López regarding LCC in buildings [19,23].

In the environmental assessment of construction projects, carbon footprint (CF) and embodied energy (EE) constitute the most commonly assessed indicators according to a review conducted by Bahramian and Yetilmezsoy in 2020 [24]. The CF is the main indicator of the construction sector within the LCA methodology and enjoys demonstrated importance [25] thanks to its direct application in environmental decision making [26], its simple message that reaches the general public [25], and its widespread continuing use today. However, it does present several weaknesses in terms of the transparency of its calculations [27]. Studies that apply this indicator in the construction sector include the work of Schwartz et al. [28], which analyzed the impact of CF on new buildings and their rehabilitation. Furthermore, Chastas et al. [29] evaluated ninety-five residential buildings in Europe and studied the phases of the manufacturing (A1–A3) and construction (A4–A5) life cycles in accordance with the UNE-EN 15978 [20] standard, which lie within a range of 128 to 1350 kg $CO_2eq/m^2$ of the ground floor area. Wolf et al. [30] placed the range between 250 and 750 kg $CO_2eq/m^2$. Also within these ranges, we find the work of Le Den et al. [31], who analyzed more than 700 buildings in Europe with a useful life of 50 years and determined the footprint of the complete cycle of residential buildings as lying between 400 and 800 kg $CO_2$eq/m$^2$, revealing the greater variability in non-residential buildings, where the range is 100–1200 kg $CO_2$eq/m$^2$. Solís-Guzmán et al. [32] also evaluated the CF of different residential projects through an open tool with results that fit the above ranges.

The assessment of the CF is usually accompanied by the calculation of EE. This is the case in Spain. For example, the BEDEC cost database [33], the SOFIAS tool, and E2CO2Cero all allow for the detailed calculation of $CO_2$ emissions accompanied by the calculation of EE from the project budget. BEDEC [33] was developed by the Institute of Construction Technology of Catalonia (ITeC) and uses environmental data on construction materials from the Ecoinvent LCA database. The SOFIAS tool [34] uses data from the OpenDAP database, and E2CO2Cero [35] is software that allows for estimating the EE and CF of a building to be estimated based on the materials consumed. In Southern Spain, the ArDiTec research group defined a methodology that uses the Andalusian Construction Cost Database (ACCD) and is incorporated into the PREDICE tool [36].

Furthermore, the most commonly used LCA indicators in the evaluation of electricity generation plants are embodied energy and the carbon footprint per kWh [9,37] as well as MWh produced [38,39]. The carbon footprint measures the potential contribution to global warming expressed in kg of $CO_2$ equivalent of all greenhouse gas emissions [40], for example, that generated in electricity production [41]. For the evaluation of economic sustainability, the life cycle cost (LCC) indicator is commonly used, defined as the net present value (NPV) of the infrastructure throughout its life cycle, as indicated by the most commonly used standards, EN-16627, ASTM-917, and ISO 15686-5 [22,42,43].

Environmental assessment has been carried out on hydroelectric plants around the world. For example, in Europe, there are small-scale run-of-river hydropower plants and micro-power installations [44,45], while in America, several Amazonian hydropower plants exist [39,46], and in Asia, SHPs from Thailand and China have been evaluated [38,47,48]. Moreover, the economic evaluation of hydroelectric production presents several examples of SHP in the scientific literature [49,50], although studies that contemplate both economic and environmental analyses simultaneously remain scarce [4]. A crucial aspect of the assessment of economic and environmental impacts involves the reliability of databases. From the environmental point of view in the construction sector, the most complete database is Ecoinvent [51,52], while from an economic point of view, it is more appropriate to employ local databases. In Spain, there are numerous regional cost databases [53]. For example, in the region upon which the present study is focused, the Andalusian Construction Cost Database (ACCD) [54] is widely used, as this considers values from its geographical area. There are similar international cost bases, which always follow the same strategy and break down a complex problem into smaller parts. These elements or work units present sufficient entity in their characteristics and performance to be determined independently [19].

There are tools that perform environmental and economic calculations simultaneously. For example, the Retscreen tool has been utilized in previous studies of renewable energy projects by Sandt et al. and by Kosnik et al. [55,56]. Another example in Andalusia is again the PREDICE tool (the “Presupuesto del ciclo de vida del edificio” or the Budget of the building life cycle), which is focused on the construction, maintenance, and end-of-life phases that can simultaneously assess various environmental indicators and the economic cost of construction projects [36].

The main objective of the present work is to design a methodology to answer the question of whether to rehabilitate or demolish SHPs. To this end, it is necessary to have access to tools that enable decisions to be taken objectively and simultaneously while considering economic and environmental aspects of their life cycle. Therefore, reliable information sources and quantifiable variables that can control the answer need to be identified and defined. This study proposes a methodology that uses the LCC economic indicator and the environmental indicators of carbon footprint and embodied energy in the evaluation, based on LCA data from construction materials. A case study is conducted of a dam that ends its operation, “El Cerrajón” in Cordoba, Spain. Another important environmental aspect to consider in SHP assessment is the potential impact that climate change, with long periods of drought, can exert on energy production [57]. The proposed methodology enables a variety of scenarios of rainfall and drought to be visualized and compared, which facilitates decision making. Energy production scenarios and the emissions of the Spanish energy mix are compared.

Environmental and economic assessment is performed within the same framework using the most widely used indicators in the construction sector (carbon footprint and embodied energy). For the first time, the rehabilitation sustainability of small hydroelectric plants is addressed simultaneously from both the environmental and economic perspectives.

## 2. Methodology

This research presents a comprehensive and detailed method for the environmental and economic assessment of dams, intended for small-scale hydroelectric production. Decision making includes the analysis of the economic and environmental viability of the long-term operation of the infrastructure. This section describes the methodology used in the evaluation, the indicators chosen, and the hypotheses or scenarios on which the calculations are made. The evaluation method has been applied to the case study of an SHP in Spain, "El Cerrajón" power plant, Cordoba, Spain [58], the characteristics of which are described in Section 3.

The methodological schema includes the calculation of the hydroelectric production capacity, the quantification of the elements that make up the infrastructure, the estimation of long-term economic and environmental costs, and the analysis of the results for decision making, see Figure 1. To this end, it is necessary to have not only hydrological information on the area where the infrastructure is to be implemented but also project data and the economic and environmental assessment framework.

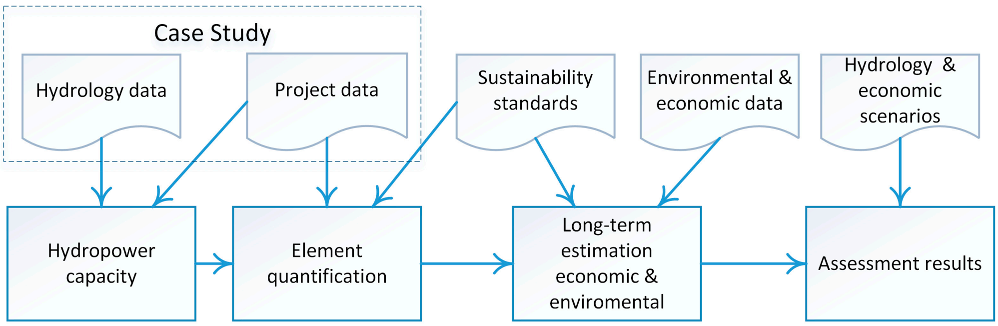


**Figure 1.** Methodological schema.

### *2.1. Hydropower Capacity*

In order to establish the viability of the infrastructure, one of the fundamental items of data required is that of the electricity production capacity of the study area. To attain this, it is necessary to ascertain the flow of water provided by the river, the power of the electricity production equipment to be installed, and, depending on the above, the time that the equipment can be in service, see Figure 2.

To begin with, it is necessary to ascertain the data of normal flows, information that is provided by the hydraulic management agencies. The information available in our case is the depth of the river water level [59] from which the total hydraulic flow (THF) can be calculated by following Manning's formula.

- Total flow calculation with Manning's formula [60], Equation (1),

$$Q = \frac{A}{\eta} \cdot {R_H}^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \tag{1}$$

where Q is the flow rate ($m^3/s$); A represents the water section ($m^2$); η is the Manning number, which represents the amount of resistance to the movement of water in channels (-); $R_H$ is the hydraulic radius, which represents the relation between flow area and perimeter (m); S is the slope of the channel (m/m).

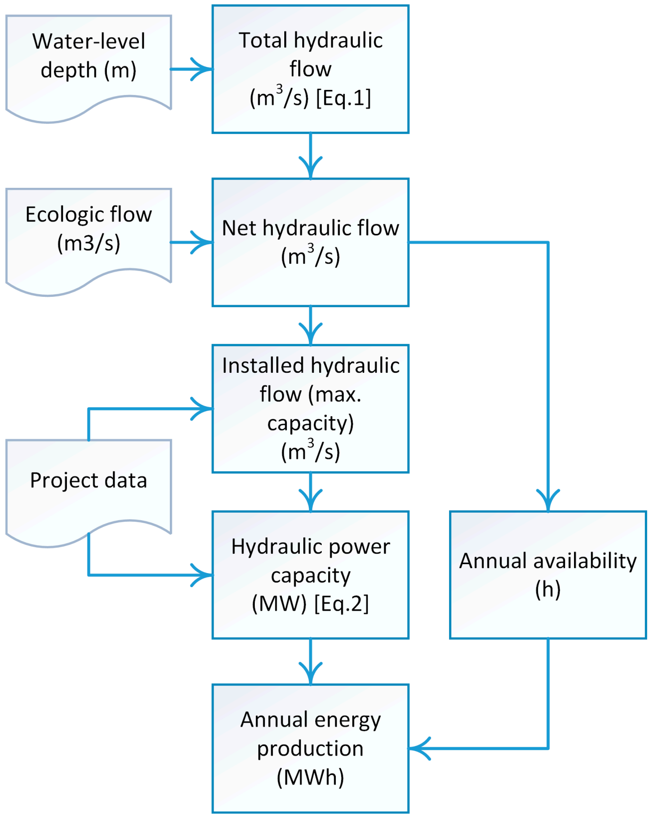


**Figure 2.** Diagram of the calculation of hydraulic use.

The total flow values are classified into monthly average values, and the minimum monthly ecological flow defined by the basin management administration [61] is deduced. The result is the monthly net hydraulic flow. This allows us to evaluate the capacity of the turbine equipment to be installed. Figure 3 present an example: the flow of the river where the case study is located, the Salado river, and its net flow calculation.

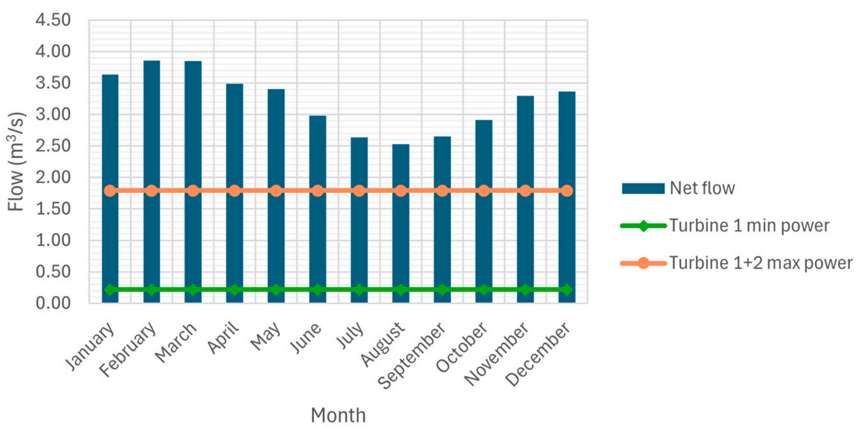


**Figure 3.** Net hydraulic flow, Salado river (average values for 2010–2023).

The next step is to determine the maximum energy power by employing the formula proposed by the European Small Hydropower Association (ESHA) [62], Equation (2), which states,

$$P_{Max} = \eta_T \cdot \eta_A \cdot g \cdot H_{net} \cdot Q_{max} \quad (2)$$

where $P_{Max}$ is the maximum power (kW); $\eta_T$ is the turbine performance for which, due to the years of usage of the hydroelectric plant, losses are considered; and $\eta_A$ is the alternator performance. In the same way, losses are also considered in the alternator performance; g is the gravity constant, 9.81 $m/s^2$; $H_{net}$ is the height of the net head [m]; and $Q_{max}$ is the maximum flow [$m/s^2$].

$Q_{max}$ is the maximum flow that can be generated by the designed turbine equipment and $H_{net}$ is the height of the vertical drop of water flow after deducing the pressure losses of the components of the water circuit, branch channel, and pipes.

In the last step, depending on the flow received and the capacity of the turbines, the produced electricity can be established. With this amount, the total energy produced annually can be calculated. Five percent of annual hours are established as being dedicated to maintenance work.

### *2.2. Environmental and Economic Assessment Framework*

The assessment of economic and environmental sustainability carried out in this research is based on the European standard EN-15643:2021 [15]. This standard shows the conceptual and methodological framework for carrying out the assessment of the social, environmental, and economic sustainability of buildings and civil infrastructure. The standard divides the study of the life cycle of civil infrastructures into the stages of construction (A), use (B), and end of life (C). It also includes the evaluation of benefits and expenses beyond the system limit (D). The latter category includes the assessment of the impacts of electricity generation, see Figure 4.

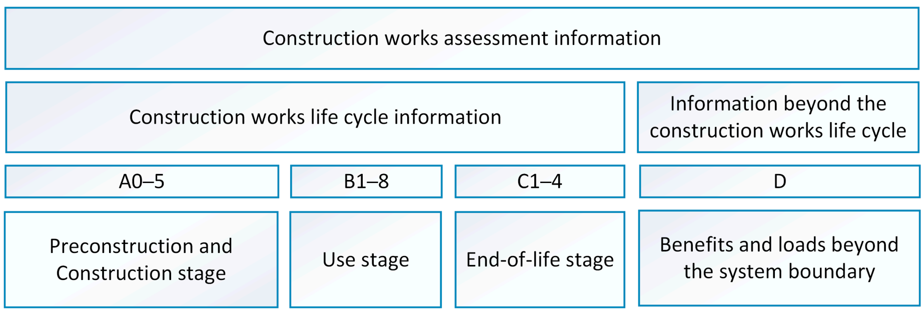


**Figure 4.** Categories distribution based on EN15643 [15].

The boundaries of the present work do not take into account the A0 stage of preconstruction nor the economic costs related to taxes or other expenses of the developer during the construction and end-of-life stages.

The indicator utilized to assess economic sustainability is that of the LCC, as recommended by the EN-16627 standard [22], since it facilitates analysis of the profitability and efficiency of the investment.

For environmental sustainability, this research evaluated the environmental indicators of embodied energy (EE) and carbon footprint (CF) throughout the life cycle, as set out in the EN-15978 standard [20].

The study timespan is 75 years, which coincides with the authorized concession period of energy production. As the objective of this research is to reveal the profitability of the renewal of the energy production authorization, the beginning of the life cycle is established as the time when the comprehensive rehabilitation of the production plant is carried out, see Figure 5.

The boundaries of the problem start with the rehabilitation work of the plant (construction stage). The analysis includes the materials, labor, and machinery. The impacts are assessed with the PREDICE tool. The assessment includes the use stage, where energy production is taken into consideration, and finishes with the end-of-life stage. The latter includes demolition work, and for this, the PREDICE tool is again employed, which considers the impacts of the treatment and transportation of demolition waste. The renewal of electrical production equipment, turbines, alternators, and transformers in the construction phase has also been included, as has its withdrawal in the end-of-life phase.

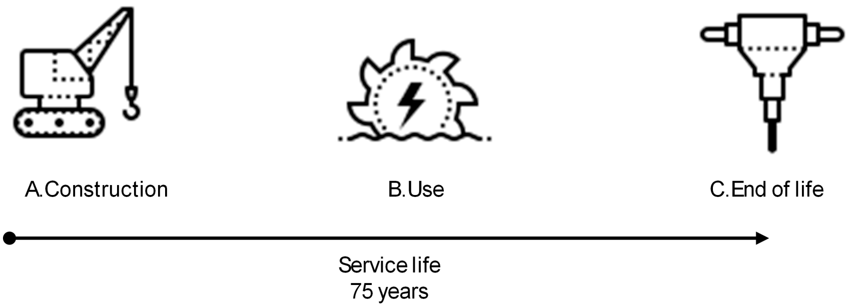


**Figure 5.** Plant life cycle (source: Authors).

The PREDICE tool is formed of 4941 construction elements (materials, machinery, and labor used in the execution of the project's work units). The input data include the measurements of the construction, rehabilitation, and/or maintenance project, expressed in terms of its work units. The tool automatically calculates their environmental cost (CF, EE, water footprint WF, and ecological footprint EF) and construction and demolition waste (CDW) [36]. The tool uses the work breakdown structure of the Andalusia Construction Cost Database (ACCD), which means that each activity in the Bills of Quantities generates carbon footprints and embodied energy, see Figure 6. The analysis covers the entire life cycle of the building and is based on environmental data obtained with Simapro. All construction materials are organized and classified into environmental families and subfamilies, and the tool calculates the weights of the construction materials in each work unit.

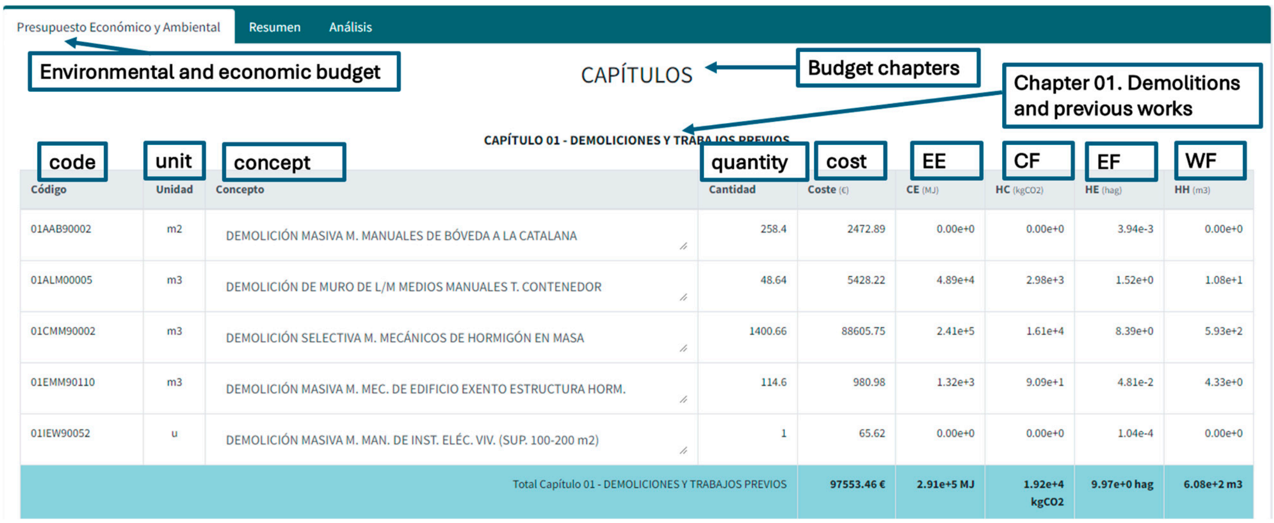


**Figure 6.** The PREDICE tool reports on the budget chapters Sewers and Structures with their corresponding quantities of the work units, along with the economic and environmental impacts of each resource (CF stands for carbon footprint, EE for embodied energy, EF for ecological footprint, and WF for water footprint) (source: Authors).

During the use stage, the useful life of the equipment is equivalent to that of the plant itself, but minor maintenance is considered as per the approximations in ESHA for the economic impact [62] and Varun et al. [48] for the environmental impact. The functional unit is the entire plant, but to facilitate comparison with other authors, the impacts are also calculated per 1 MWh, whereby the impacts are expressed in kg of $CO_2$eq/MWh of energy produced and MJ/MWh of energy produced.

*2.3. Economic Assessment*

The economic costs considered for the assessment of the feasibility of renewing the electricity production concession over the next 75 years are described below, within each category described in EN-15643. Category A (construction costs) either includes the costs of building the plant or the costs of renovation in the case of a comprehensive renovation.

Category B includes the annual costs associated with the operation of the hydroelectric power plant obtained from the Layman's handbook on how to develop a small hydro site [62], where the costs of repairs and maintenance are calculated in accordance with Equation (3),

$$C_{maintenance} = 600 \cdot \sqrt{P_{max}} \quad (3)$$

where $P_{max}$ is the maximum installed power in the hydroelectric power plant (kW).

Other usage expenses, such as insurance, local taxes, auditing, engineering, supervision, administration, and accounting, are calculated in accordance with Equation (4),

$$C_{other\ expenses} = 3385 \cdot \sqrt{P_{max}} \quad (4)$$

Category C includes the costs of demolition and waste management for the dismantling of the production plant, the dam, canals, and gates, and for the landscape restoration of the environment.

Category D of the EN-15643 standard includes the income obtained outside the system and/or the income from the electricity production of the plant. A key piece of information for the assessment of economic sustainability is the price of the energy produced. The average price of electricity in Spain during the period 2010–2023 [63] is employed in its calculation: 62.02 EUR/MWh.

The annual income from the sale of the electricity produced is obtained by applying Equation (5),

$$\text{annual income} = P_{Max} \cdot t \cdot \text{electricity price} \quad (5)$$

where $P_{Max}$ is the maximum power installed in the hydroelectric power plant (kW); t is the turbine working time throughout the year (h); and electricity price is the economic value of the turbine produced energy (EUR/kWh).

The electricity generation tax in Spain, which is 7% of the EUR/kWh produced is subtracted from this income [64].

Since economic data were taken from different years, two cost update inflation rates were applied to homogenize said data [23]. The first updated costs are the construction, use, and end-of-life categories, with the consumer price index in Spain (CPI) [65]. The second updated prices are those of the energy production, with the annual inflation rate of electricity prices in Spain (IPE) [66]. In both cases, the values of the 2007–2023 period have been averaged, whereby the CPI value is 2.16% and the IPE value is 2.82%.

The LCC of the investment is calculated by adding the cash flow of each year updated to the present values using Equation (6),

$$LCC = \sum \frac{C_n}{(1+dr)^n} \quad (6)$$

where $C_n$ is the cash flow of year n; $dr$ is the discount rate; and $n$ is the year.

Discount rates of 5% and 10% are employed in the scenarios. Income and expenses taking place each year of operation are also considered. Finally, the minimum value of kWh production that makes the investment profitable is calculated, LCC = 0, and is named as profit price breakeven (PPB).

*2.4. Environmental Sustainability*

As in the case of economic sustainability, the schema of categories proposed by EN-15643 is followed with the same calculation boundaries as in the previous section. The PREDICE tool [36] calculates the environmental impacts of the elements of the plant life cycle in the categories of construction and end of life. The tool is based on the evaluation of the budget of the construction and the demolition project, specifically on its bill of quantities and project work units. The latter is broken down into basic resources of labor, machines, and materials. The materials used in the project are transformed from their commercial units of measurement, that is, from meters, cubic meters, tons, etc., to kilograms of material. After having been organized into families of materials, their water, ecological, energy, and carbon footprints are all calculated using the tool. $CO_2$ emissions and embodied energy calculations are employed in the present work methodology [54].

The environmental impacts of the energy production machinery, such as turbines, alternators, and transformers, were calculated individually by employing the Ecoinvent database [51] since those elements cannot be found in the PREDICE database. The process used by Varun et al. was used for the environmental costs of the use stage [48]. Once all the impacts of the life cycle stages were calculated, two indicators were used. Firstly, the relationship between total impacts and the maximum power capacity of the plant is established. Secondly, the calculation of avoided emissions in comparison with electric mix emissions of the Spanish mix per kWh produced is determined based on the scenarios found in Rivero-Camacho [21], see Table 1.

**Table 1.** Expected electricity grid emissions in Spain [21].

| | **MJ/kWh** | **kg$CO_2$eq** |
|---|---|---|
| Period | EE | CF |
| 2020–2040 | 5.846 | 0.549 |
| 2041–2060 | 5.835 | 0.283 |
| 2061–2090 | 5.824 | 0.057 |
| 2090–2120 | 5.816 | 0.028 |

### *2.5. Economic and Environmental Data*

Table 2 summarizes the sources of the economic and environmental data used in the calculation.

**Table 2.** Data source and tools used in each category of the infrastructure lifecycle in accordance with EN-15643 [15].

| **Categories** | **Economic Data** | **Environmental Data** |
|---|---|---|
| A Construction | ACCD [54] | PREDICE [36] |
| B Use | ESHA [62] | Varun, et al. [48] |
| C End of life | ACCD [54] | PREDICE [36] |
| D Benefits and loads beyond the system boundaries | NEMO [63] | Rivero-Camacho C. [21] |

## **3. Case Study**

### *3.1. Infrastructure Description*

Since 1858, there has been evidence of the existence of a flour mill called El Cerrajón that remained in operation until 1954 when the hydroelectric power station was installed. This plant was designed and built by the civil engineer Miguel Aubet Iturbe. The current weir and the water diversion channel of the Salado river were built at the same time as the high-voltage transformation center and the electrical transport to the towns of Camponubes and Zamoranos, Cordoba, Spain [58], see Figure 7.

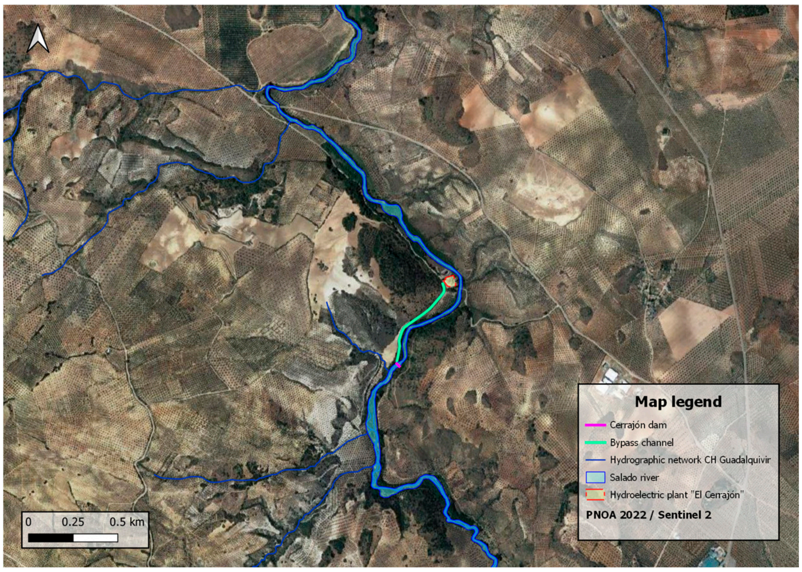


**Figure 7.** Location of the "El Cerrajón" in Cordoba, Spain.

The use of electricity was intended to supply these towns and to drive numerous nearby olive oil and flour mills. The authorization for the generation of electricity was granted in 1954 with a duration of 75 years [7]. The plant has not produced electricity since 2008.

El Cerrajón weir is a gravity dam, being of a straight profile with a length between abutments of 15 m and a height of the dam of 7 m, and it is classified as a small dam according to the "Technical Regulation on Dam and Reservoir Safety" [67] but as a weir in the "Hydrological Planning Instruction" [68]. The weir is entirely made of mass concrete, see Figure 8. This type of installation does not completely interrupt the passage of water and is best suited for seasonal rivers due to the intermittence of water flow during periods without rainfall or long periods of drought [50]. It is of the run-of-river typology and classified as SHP since it has an installed capacity of less than 10 MW [3].

**Figure 8.** Downstream of the El Cerrajón weir and diversion channel of the ecological flow (source: Technical documentation of the set of waterwheels, watermills and river mills in the province of Cordoba [69]).

The upstream face is vertical with a circular increase of 1 m at the crown, while the downstream face is inclined with a 100% slope. It has a fixed-lip spillway over the entire crest of the dam that allows for the evacuation of the surplus of the reservoir water by overflowing. The water overflows and circulates over the downstream face to an intermediate berm of 2.5 m in length that dissipates the energy by means of a launching element.

On the right-hand bank of the river, there is a channel that allows for the ecological flow, through a screw-operated passage gate. The canal is 2 m deep and approximately 1 m wide and has a steep slope. Its thickness is 0.3 m, and it is composed of masonry and concrete.

On the left-hand bank is the diversion channel that transports the water a length of 561 m following the slope of the land. The channel has a rectangular section with a depth of 1.2 m, a width of 1.6 m, and a slope of 0.0001 m/m. The channel is made of mass concrete. The water enters the diversion channel through a pass-through gate operated by wrought-iron toothed gears.

The diversion channel ends in a pressure pipeline with a height of 6 m and a diameter of 1.5 m, allowing for the flow of water in free sheet to enter the load. From the base of the balance chimney, there are two penstocks of 0.6 m diameter that narrow until they reach the turbines. The water inlet to the turbines is regulated with butterfly valves operated by a handwheel for the indiscriminate use of each turbine and for its maintenance.

The existing turbines are of the Francis type. Turbine 1 has a flow rate of 1.25 $m^3/s$ and an alternator of 140 kVA, and Turbine 2 has a flow rate of 0.54 $m^3/s$ and an alternator of 50 kVA. The turbines are placed in parallel to allow for progressive operation according to the incoming flow. The electrical energy produced is transformed from 220 V to 6000 V by means of a transformer for its transport to the grid [58].

Lastly, the turbine water is redirected to the riverbed through a drainage gallery that is 72 m long. This gallery has a rectangular section of 3 m width and 0.8 m height with a vault on the ceiling with a 0.7 m rope. The drainage channel is composed of concrete on the floor, ordinary masonry with interior plaster for the gables, and sardine masonry with cement mortar for the vault. There are two buildings for electricity production, the turbine and alternator room and the control and transformation room.

To establish the water flows for the power capacity of the plant, data have been taken from the M17-107 gauging station [59], see Table 3. This station is located 2 km downstream from the facility since the riverbed has no new contribution on that route.

**Table 3.** Features of the M17-107 control frame [59].

| Code | Type of Station | River | ETRS89-UTM H30 | | Frame Features |
|---|---|---|---|---|---|
| | | | X | Y | |
| M17-107 | Frame | Salado | 395,206 | 4,156,782 | • Width: 4 m<br>• Height: 4 m |

### *3.2. Hydraulic Exploitation Scenarios*

Since the objective of this research is to decide whether to renew the authorization for electricity production, three hypotheses of water flow are applied. With these three, the scenarios of dry, humid, and medium flows can be studied regarding how they affect economic profitability and environmental impact.

H1 corresponds to the average flows of the period (2010–2023). In the H2 and H3 scenarios, the hydraulic flows have been modified by CGCM2-FIC and ECHAM4-FIC climate change estimations made by CEDEX based on IPCC predictions [70]. The estimated flow fractions according to climate change scenarios are divided into three periods, 2010–2040, 2041–2070, and 2071–2100, and into the four seasons, as shown in Table 4 [71].

**Table 4.** Percentage of flow reduction for climate change estimations [71].

| | CGCM2-FIC | | | ECHAM4-FIC | | |
|---|---|---|---|---|---|---|
| | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 |
| Winter (January, February, March) | 0.91 | 0.8 | 0.489 | 0.73 | 0.5 | 0.68 |
| Spring (April, May, June) | 0.93 | 0.79 | 0.571 | 0.86 | 0.71 | 0.57 |
| Summer (July, August, September) | 0.8 | 0.8 | 0.6 | 0.6 | 0.6 | 0.6 |
| Autumn (October, November, December) | 1.22 | 0.94 | 0.556 | 0.53 | 0.33 | 0.37 |

### *3.3. Hydraulic Flow Scenario*

Following the methodology set out in Section 2.1, the monthly flows supplied in the three proposed scenarios are calculated, and the results are extrapolated to monthly flows, see Figures 3, 9 and 10.

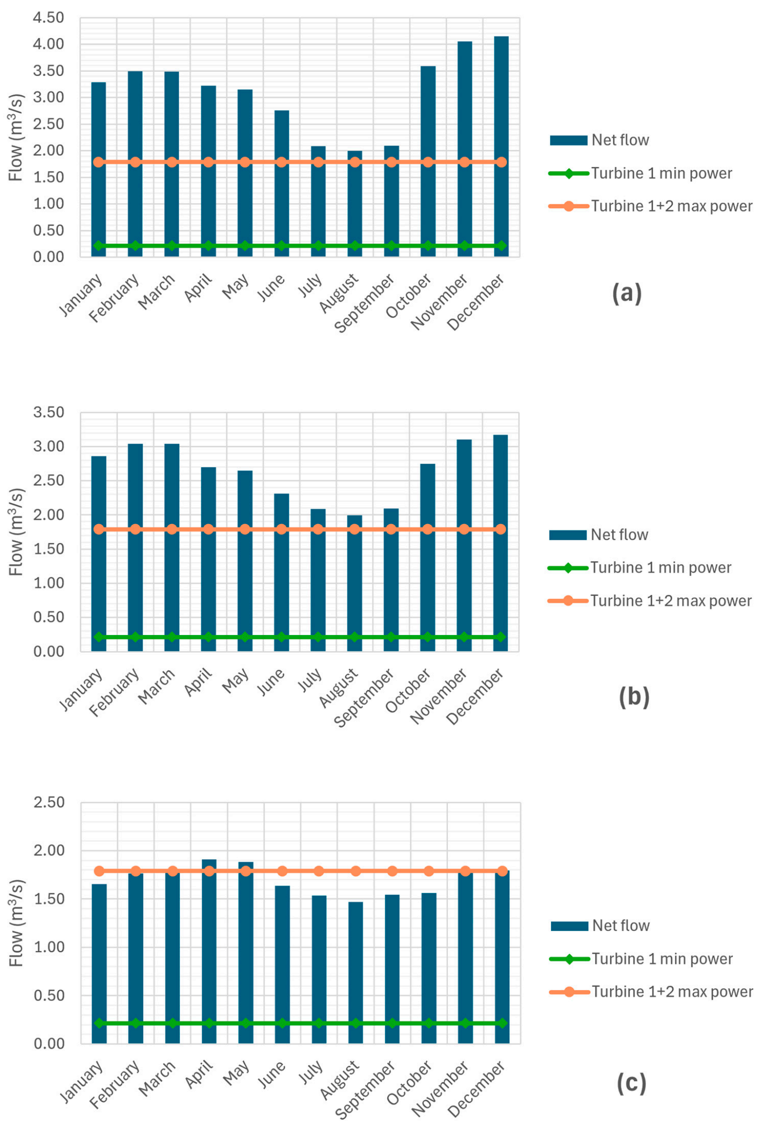


**Figure 9.** Net hydraulic flow of Salado River H2 scenario based on CGCM2-FIC predictions: (**a**) 2010–2040, (**b**) 2041–2070, and (**c**) 2071–2010.

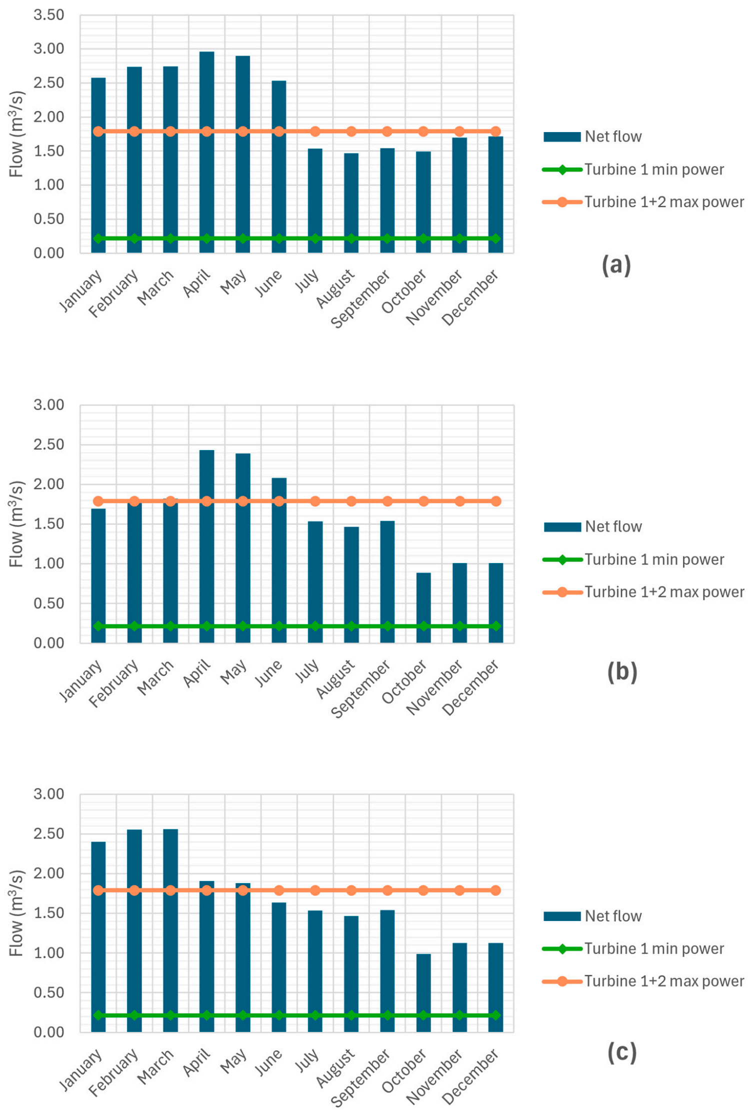


**Figure 10.** Net hydraulic flow of Salado River H3 scenario based on ECHAM4_FIC predictions: (**a**) 2010–2040, (**b**) 2041–2070, and (**c**) 2071–2010.

It can be observed that the flow values of the H1 scenario allow the turbine to work at full power, whilst in the H2 scenario, the flow is under the limit for several months (June to December), during the period 2071 to 2100. Scenario H3 shows a similar behavior to H2 but during all periods. In the latter scenario, the turbine needs to be regulated and adapted to the incoming flow. In all scenarios and periods, the plant can operate above the minimum, defined as 40% of the plant's minor turbine, at 0.216 $m^3/s$.

## 4. Results

In this section, the proposed methodology is applied to the case study of the hydroelectric power plant of El Cerrajón. The economic and environmental costs of the construction and end-of-life stages have been calculated with the PREDICE tool. The results per budget chapter are summarized in Tables 5 and 6, and a detailed breakdown can be found in Appendix A, Table A1.

**Table 5.** Construction stage: cost, CF and EE.

| Chapter | Cost (EUR) | EE (MJ) | CF ($kgCO_2eq$) |
|---|---|---|---|
| 01. Demolition | 20,574.89 | 61,441.889 | 4043.908 |
| 03. Foundation | 16,732.02 | 410,979.969 | 74,309.54 |
| 06. Masonry | 16,494.12 | 55,859.983 | 5082.017 |
| 17. Waste management | 967.00 | 37,993.394 | 2313.564 |
| 19. Health and security | 1842.83 | 29,067.011 | 1885.411 |
| 20. Electric production equipment | 116,310.00 | 334,742.4 | 19,169.9 |
| CD | 172,920.86 | | |
| CI (7% CD) | 13,833.67 | | |
| GG + BI (19% (CD + CI)) | 35,483.36 | | |
| | 222,237.89 | 930,084.646 | 106,804.34 |

**Table 6.** End-of-life stage cost, CF and EE.

| Chapter | Cost (EUR) | EE (MJ) | CF ($kgCO_2eq$) |
|---|---|---|---|
| 01. Demolition | 108,337.35 | 314,462.765 | 20,719.299 |
| 02. Land treatment | 1485.61 | 74,851.773 | 9739.260 |
| 15. Environmental restoration | 10,623.63 | 127,009.744 | 10,228.735 |
| 17. Waste management | 58,652.79 | 2,270,601.137 | 138,265.656 |
| 19. Health and security | 3285.90 | 51,538.927 | 3090.920 |
| 20. Electric production equipment | 10,300.00 | 8800.012 | 524.306 |
| CD | 192,685.28 | | |
| CI (7% CD) | 15,414.82 | | |
| GG + BI (19% (CD + CI)) | 39,539.02 | | |
| Total | 247,639.12 | 2,847,264.36 | 182,568.18 |

### *4.1. Life Cycle Cost (LCC)*

The LCC has been calculated in the three scenarios by dividing the results according to the life cycle categories proposed by EN-15643 and by considering two discount rates: 5% and 10% (see Table 7). The LCC is also expressed per kW of plant capacity. Moreover, the PPB has been determined for the electricity price that produces an LCC equal to 0.

**Table 7.** Life cycle costs (LCC) by employing 5% and 10% discount rates (dr) and the corresponding profit price breakeven (PPB).

| dr | Scenario | A. Construction | B. Use | C. End of Life | D. Income | LCC (D-A-B-C) | LCC/kW | PPB (EUR/kWh) |
|---|---|---|---|---|---|---|---|---|
| 5% | H1 | 212,337.69 | 1,805,537.82 | 30,261.97 | 2,015,694.70 | −32,442.78 | −271.56 | 0.0630 |
| | H2 | | | | 1,982,131.30 | −66,006.18 | −552.51 | 0.0641 |
| | H3 | | | | 1,860,082.81 | −188,054.67 | −1574.12 | 0.0719 |
| **dr** | **Scenario** | **A. Construction** | **B. Use** | **C. End of life** | **D. Income** | **LCC (D-A-B-C)** | **LCC/kW** | **PPB (EUR/kWh)** |
| 10% | H1 | 176,284.27 | 622,548.42 | 767.06 | 640,183.54 | −159,416.20 | −1334.40 | 0.0775 |
| | H2 | | | | 638,014.23 | −161,585.52 | −1352.56 | 0.0777 |
| | H3 | | | | 594,193.74 | −205,406.01 | −1719.36 | 0.0861 |

All scenarios show negative returns, although the PPBs are very close to the current average electricity price in Spain (0.062 EUR/kWh). If the discount rate increases, then the PPB increases, but not in the same proportion.

Figure 11 presents the percentage of each stage in the LCC. The use stage is the most significant due to the long 75-year life span established. The construction stage is significantly lower due to the intensity of the work; the old installation is rehabilitated instead of constructed anew. Also, the influence of the discount rate on the LCC can be appreciated, since the construction costs have more influence when a higher discount rate is employed [23].

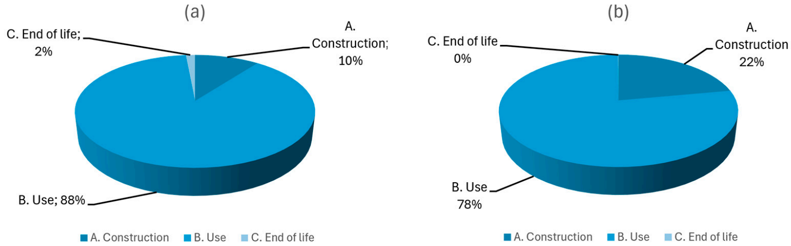


**Figure 11.** Cost percentage of A, B, C life cycle stages when, the discount rate is (**a**) 5% and (**b**) 10%.

### *4.2. Life Cycle Assessment*

Following the methodology described in Section 2.5, the calculation of the environmental indicators, embodied energy, EE, and carbon footprint, CF, has been applied to the case study. The results of the three scenarios are shown in Table 8. The avoided impact is the difference between the "Mix" column and the "El Cerrajón" column. Furthermore, the percentages corresponding to each stage of the life cycle are presented.

**Table 8.** Environmental impacts during the plant life cycle. Embodied energy (EE) and carbon footprint (CF).

| **EE** | **A. Construction** | **B. Use** | **C. End of Life** | **Total EE** | **"El Cerrajón"** | **Mix** | **Avoided Impact** |
|---|---|---|---|---|---|---|---|
| Scenario | GJ | | | | GJ/MWh | GJ/MWh | GJ/MWh (%) |
| H1<br>H2<br>H3 | 930.1 | 29,149.9 | 2847.3 | 32,927.2 | 0.448<br>0.460<br>0.516 | 5.829<br>5.829<br>5.831 | 5.382 (92%)<br>5.369 (92%)<br>5.315 (91%) |
| **CF** | **A. Construction** | **B. Use** | **C. End of life** | **Total CF** | **"El Cerrajón"** | **MIX** | **Avoided impact** |
| Scenario | $tCO_2eq$ | | | | $kgCO_2eq/MWh$ | $kgCO_2eq/MWh$ | $kgCO_2eq/MWh$ |
| H1<br>H2<br>H3 | 106.80 | 2365.15 | 182.57 | 2654.52 | 36.08<br>37.12<br>41.58 | 193.16<br>197.40<br>203.11 | 157.08 (81%)<br>160.28 (81%)<br>161.53 (80%) |

The results show that embodied energy lies between 0.45 and 0.52 GJ/MWh, and emissions are between 36 and 42 $kgCO_2eq/MWh$, with the use stage as the most significant in that it accounts for approximately 90% of the total, see Figure 12. The environmental impacts avoided due to the reuse of the plant are 91% of EE and 80% of CF.

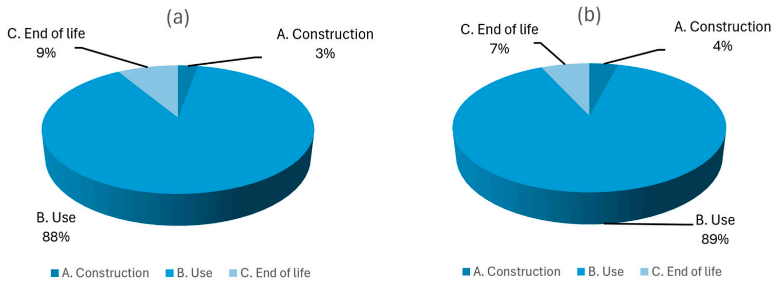


**Figure 12.** Percentage of environmental impacts per life cycle stage, (**a**) embodied energy, (**b**) carbon footprint.

## 5. Discussion

From the point of view of economic sustainability, this study shows that the investment in the rehabilitation of the "El Cerrajón" plant is not profitable. All references consulted [50] have a positive LCC, except in the study by Anagnostopoulos, 2007 [72], which indicates negative values of the LCC in a plant of 0.86 kW capacity. This indicates that plants with low capacity may not be profitable. According to Alonso Tristán et al., in 2010, electricity was generated at a cost of 0.05 EUR/kWh and, in a period of 10 years, the generation of 607.2 t$CO_2$ per year can be avoided.

The environmental sustainability results are compared with the existing literature for similar plant typology, that is, run-of-river and installed power between 0.05 and 2 MW, as shown in Table 9.

**Table 9.** Comparison of life cycle environmental impacts.

| Reference | Power (MW) | Life Span | CF (kg$CO_2$eq/MWh) | | | |
|---|---|---|---|---|---|---|
| | | | A | B | C | Total |
| El Cerrajón | 0.12 | 75 | 1.45 | 32.15 | 2.48 | 36.08 |
| Varun [48] | 0.10 | 30 | 23.84 | 31.58 | n/a | 55.42 |
| Varun et al. [48] | 0.05 | 30 | 37.74 | 36.98 | n/a | 74.88 |
| Suwanit [47] | 1.15 | 50 | n/a | n/a | n/a | 16.28 |
| Gallagher et al. [44] | 0.10 | 50 | n/a | n/a | n/a | 7.39 |
| Pang et al. [38] | 1.60 | 30 | 27.3 | 1.10 | 0 | 28.40 |

The results vary widely since conditions such as transporting materials to remote locations can exert a significant impact. In smaller plants, such as those studied in Thailand [47], the authors only consider the electricity and water employed in the use stage and, therefore, impute only 8% of the $CO_2$eq of the 50-year lifespan. In Gallagher's research [44], it remains unclear what proportions of the emissions are due to the usage, construction stage, and end-of-life stage.

The differences in emissions with respect to Pang et al. [38] may be due to the fact that, in the use stage, they only consider the expenses in lubrication oil of the mechanical components and the loss of production of power when the plant is shut down for maintenance work. At the end-of-life stage, they consider that 20% of the materials are recyclable and assume a weight loss of 2% due to corrosion, as well as that the dam and buildings are not demolished. In Pang et al. [38], the use stage is 3% of the cost due to maintenance work, and the end-of-life stage is less than 1%.

For the calculation of the impacts of the use stage, the Varun hypotheses [48] are employed. The annual maintenance cost is 3% of the total civil work cost, and the electromechanical equipment cost is also 3%. This implies that the civil works and equipment are changed every 33.33 years. Their annual electricity consumed on-site is 5% of the annual electricity output. No other authors take these expenses into consideration.

For the calculation of the impact of the reservoir, the amount of flooded biomass per unit of reservoir area can vary from 500 Mg/ha for a tropical forest to 100 Mg/ha for a boreal climate [47], whereas the carbon content of different ecosystems varies from 18.8 kg of $CO_2$eq/$m^2$ for tropical forests to 0.3 kg of $CO_2$eq/$m^2$ for desert shrub. In the present SHP studied herein, there is no water storage, and, hence, no change in terrestrial ecosystem is considered.

In the period from 2070 to 2100, following Rivero-Camacho's predictions [21], the plant would produce emissions exceeding the average emissions of the Spanish energy mix: 36.08 vs. 28 kg $CO_2$eq/MWh.

## 6. Conclusions

During the 1950s, numerous hydroelectric power plants of small capacity were built in Spain. After 75 years of concession, a decision must be made as to whether to continue in operation or to demolish the plant. A methodology was tested for the simultaneous evaluation of the environmental and economic impact of small hydroelectric plants. The present work combines the assessment of an economic indicator, that of the life cycle cost, and two environmental indicators (carbon footprint and embodied energy) by means of LCA data. The data sources were established as the regional construction cost databases and generic environmental databases for the LCA information. The quantification of the impacts was supported by the PREDICE software tool, which simultaneously assesses economic and environmental impacts incorporated in the project quantity surveying of the maintenance tasks.

The case study of "El Cerrajon" plant is analyzed, where different historical hydrological cycles are contemplated based on climate change scenarios. A life cycle scenario was evaluated, whereby the energy production of the plant was extended by a further 75 years. The results show savings in environmental impacts through the reuse and repair of the plant with respect to the impact of the current Spanish energy mix. However, in the 2070–2100 period, the emissions will be higher than those in the predicted scenarios of the Spanish energy mix.

On the cost side, run-of-river hydroelectric plants with low power production are more likely to be unprofitable. The cost of SHP energy production is always slightly higher than that of the Spanish mix in all scenarios evaluated, ranging between 2% and 24% (drought scenario) more expensive.

Even though the investment is not profitable, minor public economic incentives could render these sites profitable, and their electricity production involves much lower emissions than the current Spanish mix, where savings reach 175 $kgCO_2$ per MWh produced.

From the point of view of environmental impacts, there is no doubt that this type of electricity production is highly beneficial, since its emissions are much lower than those produced by the electricity mix (grid) in Spain, and it also helps reduce dependence on fossil fuels. Nevertheless, the choice regarding rehabilitation or demolition of the power plant of the case study remains unclear since it is economically unprofitable.

In future work, a study could include the evaluation of a greater sample that includes larger plants and their reservoirs in order to attain a complete understanding of the carbon and energy footprint of this energy source. The use stage can also be studied in greater depth. Lastly, the economic and environmental impacts of SHPs on the region and the electric mix could be assessed for the definition of incentive policies for their restoration.

**Author Contributions:** Conceptualization, E.V.-L.; methodology, V.M.-M., M.M., and E.V.-L.; software, V.M.-M., M.M., and E.V.-L.; validation, M.M. and E.V.-L.; formal analysis, V.M.-M. and E.V.-L.; investigation, V.M.-M., and E.V.-L.; resources, V.M.-M., M.M., and E.V.-L.; data curation, V.M.-M. and E.V.-L.; writing—original draft preparation, E.V.-L.; writing—review and editing, M.M. and E.V.-L.; visualization, V.M.-M. and E.V.-L.; supervision, M.M. and E.V.-L.; project administration, E.V.-L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

**Acknowledgments:** We thank José Enrique Povedano Molina for providing the project documentation provided on the "Cerrajón" hydropower plant, which was crucial in undertaking this.

**Conflicts of Interest:** The authors declare there to be no conflicts of interest.

## Abbreviations

| | |
|---|---|
| ACCD | Andalusian Construction Cost Database |
| CEDEX | Center for studies and experimentation of Public Works (Centro de estudios y experimentación de Obras Públicas, in spanish) |
| CPI | Consumer Price Index |

| | |
|---|---|
| ESHA | European Small Hydropower Association |
| CF | Carbon footprint |
| IPCC | Intergovernmental Panel on Climate Change |
| IPE | Inflation Price of Electricity |
| LCA | Life cycle assessment |
| LCC | Life cycle cost |
| NEMO | Nominated Electricity market Operators |
| NPV | Net Present Value |
| PPB | Profit Price Breakeven |
| SHP | Small Hydropower plant |
| THF | Total Hydraulic Flow |

## Appendix A

**Table A1.** Example of PREDICE calculation in construction stage.

| Code | Unit | Concept | Quantity | Cost (EUR) | EE (MJ) | CF ($kgCO_2$) |
|---|---|---|---|---|---|---|
| | | CHAPTER | | | | |
| | | 01. Demolition | | | | |
| 01AAB90002 | $m^2$ | Massive demolition dome | 51.68 | 494.58 | 0 | 0 |
| 01ALM00005 | $m^3$ | Manual demolition brick wall | 9.73 | 1085.87 | 9781.219 | 595.616 |
| 01CMM90002 | $m^3$ | Selective demolition concrete | 300.26 | 18,994.45 | 51,660.67 | 3448.292 |
| | | Total Chapter 01. Demolition | | 20,574.89 | 61,441.889 | 4043.908 |
| | | 03. Foundation | | | | |
| 03ERM80080 | $m^2$ | Wall formwork | 9.73 | 400.88 | 3525.338 | −140.033 |
| 03HMM00002 | $m^3$ | Concrete HM-20/P/40/I | 300.26 | 16,331.14 | 407,454.631 | 74,449.572 |
| | | Total Chapter 03 Foundations | | 16,732.02 | 410,979.969 | 74,309.54 |
| | | 06. Masonry | | | | |
| 06AEE00002 | m | Semicircular arch. Brick | 206.72 | 15,040.95 | 51,879.023 | 4165.654 |
| 06CMO80010 | $m^3$ | Stone wall 50 cm. | 9.73 | 1453.18 | 3980.96 | 916.364 |
| | | Total Chapter 06. Masonry | | 16,494.12 | 55,859.983 | 5082.017 |

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