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Variable-Speed Operation of Micro-Hydropower Plants in Irrigation Infrastructure: An Energy and Cost Analysis

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Abstract: Micro-hydropower plants have now become a way to decarbonise the power generation system. Older micro-hydropower plants generally operate at a fixed speed. When there is a lack of rainfall, these plants operate outside their design flow causing various problems (such as the occurrence of the phenomenon of cavitation, decreased turbine performance, and decreased operating hours), especially in micro-hydropower plants installed in irrigation infrastructure, where the priority for water use is crops. This study aims to carry out a comparative evaluation of several indicators (cavitation, investment costs, electricity production and economic benefit) of two types of control system on an asynchronous electric generator (a fixed speed control system (scenario 1) and a variable-speed control system (scenario 2)) at the same micro-hydropower plant. The Rebolluelo micro-hydropower plant (Spain) is used for this purpose as a case study. This micro-hydropower plant uses a semi-Kaplan turbine coupled to an asynchronous electric generator through a gearbox. The results show the advantages of using a variable-speed control system. The use of variable-speed technology: (i) eliminates the possibility of cavitation, (ii) increases the power output ratio (from 35.87% to 93.03%), and (iii) increases the economic benefit (from 29.31% to 108.72%). There are also, of course, disadvantages, such as an 11.96% increase in cost. This work demonstrated the superiority of variable speed technology at micro-hydropower plants for three of the four indicators evaluated. This work could be of assistance when making decisions regarding future micro-hydropower plant installations.

Keywords: micro-hydropower plants; fixed speed; variable speed; cavitation; semi-Kaplan turbine

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1. Introduction

A United Nations report [1] estimates the global population will be 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion in 2100. This significant increase in the world's population will considerably increase demand for food. According to estimates by the Food and Agriculture Organisation of the United Nations (FAO), 60% more food will need to be produced in 2050, than is currently produced [2]. Agriculture will therefore be a key sector for the development of humanity. On the other hand, the agriculture sector is one of the largest consumers of energy and consequently responsible for high amounts of greenhouse gas emissions. For example, it accounted for around 3.2% of the total energy consumed in 2020 in the European Union (EU) [3]. Another fundamental aspect is the notable increase in water consumption. Several research studies have established this water-food-energy nexus [4,5]. In short, the agricultural sector places a heavy burden on the planet's natural resources.

The agriculture sector is the world's largest consumer of water resources, with an estimated average consumption of 70% globally, and even 95% in some developing countries [6]. In order to increase efficiency in the use of water resources, traditional irrigation systems (open surface channels and irrigation ditches) are being replaced by pressurised irrigation techniques (sprinkling or localised irrigation). The implementation of pressurised irrigation techniques has been increasing in recent years. For example, these techniques were being used on 72% of all irrigated cropland in the US in 2018 [7]. The use of these techniques has reached 100% in some Mediterranean countries [8]. This change has altered the electricity consumption profile in the agricultural sector. Renewable energies are a feasible alternative for covering the electricity needs of pressurised irrigation techniques, even in areas where no grid connection is available. Micro-hydropower plants can be used for this purpose.

Hydropower is one of the most widely used renewable sources of electricity generation worldwide. In 2022, the global electricity production from hydropower was 11,300 (TWh) [9]. This represents 6.73% of global electricity generation and 47.38% of global power generation from renewable sources [9]. This technology uses a hydraulic turbine and an electric generator to convert potential energy into electrical energy. The size of the hydraulic turbine classifies the hydropower plant. It can vary from several kW to hundreds of MW [10]: small-scale, medium scale, and large-scale. Small-scale hydropower plants can be further classified into small (up to 10 (MW)), mini (up to 2 (MW)), micro (up to 100 (kW)) and pico (up to 5 (kW)) hydropower plants [10,11]. This classification depends on the country [12].

Micro-hydropower plants have been the subject of study in the European Union in the hopes of increasing the production of renewable energy from this type of hydroelectric power plant [13]. To this end, the RESTOR Hydro project (2012–2015) [14], co-funded by the European Union through the Intelligent Energy Europe Programme, identified and restored water mills, inoperative hydropower plants, dams, and irrigation structures. One of the results of the project was the RESTOR Hydro map [14]. This map shows the location and characteristics of 65,000 possible micro-mini hydropower plants. This web application is free to access and offerts a user-friendly interface.

The focus of this work is on micro-hydropower plants used in irrigation infrastructure. When micro-hydropower plants operate as part of the irrigation infrastructure, electricity generation is a secondary objective. In irrigation infrastructure, priority is given to the use of available water for crop irrigation. With these hydropower plants, the power plant is usually installed as a run-of-the-river system. Therefore, these hydropower plants do not interfere with river flows, making them an environmentally-friendly solution [15]. Micro-hydropower plants require a high initial investment and the estimated lifetime is several decades [16]. The latter characteristic is based on their hydropower potential, which depends on the hydrological regime and thus on local and regional climate characteristics [17]. The estimated lifetime is therefore vulnerable to the potential dangers of climate change. Some micro-hydropower plants have actually seen their lifespan truncated due to low rainfall.

Most twentieth-century micro-hydropower plants were characterised by fixed-speed operation. As the electricity production of a micro-hydropower plant is directly dependent on the amount of water available, two key events occur with regard to the continued operation of a micro-hydropower plant if there ia a decrease in hydropower resources: (i) a dramatic decrease in electricity production over the entire water head range, and (ii) a noticeable decrease in efficiency in partial operation mode or in operation mode outside design conditions [18]. Variable speed operation of a hydraulic turbine using power electronics can prevent these events from occurring. Power electronics allow hydraulic turbine operating modes over a wide range of flow rates and heads outside design conditions, in addition to superior efficiency [19]. However, that the cost of the equipment needed for such a setup is high.

Micro-hydropower plants operating at variable speed can have different topologies depending on the type of electrical generator. If the generator is a synchronous or asynchronous squirrel cage generator, a back-to-back converter can be used. If the generator is a wound rotor asynchronous generator, a double-feed can be used [20]. With both topologies, the main objective is to adjust the speed of the hydraulic turbine so that it operates at the maximum power point (MPP). There are two ways to find this operating point [21]:

indirect and direct. For the former, the maximum power operating point is determined from sensor data and the characteristic curves of the hydraulic machine [22]. For the second, it is based on search algorithms (perturb and observe, artificial intelligent method) [23], which are usually independent of turbine parameters. Although they use sensors, they are not as expensive.

Variable speed hydropower generation began to receive scientific attention several decades ago. Several projects showed the feasibility of variable speed operation in small hydropower plants [24]. Table 1 shows some of the hydropower plants using variable speed technology.

Table 1. Hydroelectric power plants using variable-speed technology.

Name	Country	Total Power (MW)	Reference
Avče	Slovenia	180	[24]
Linthal	Switzerland	1000	[25]
Frades II	Portugal	750	[24]
Fengning	China	3600	[24]
Tehri	India	4250	[26]
Nant de Drance	Switzerland	900	[25]

The operating conditions of a micro-hydropower plant integrated into irrigation infrastructure can be highly variable. This flow instability reduces the overall efficiency of the micro-hydropower plant, and can even lead to the phenomenon of cavitation decreasing the lifetime thereof. By implementing a system that varies the rotational speed of the electric generator with respect to its synchronous speed, the turbine can better adapt to the hydrological regime of the river, and thus increase the overall efficiency of the micro-hydropower plant and extend its lifetime. If a micro-hydropower plant operates at synchronous speed, the turbine has a single operating point. In contrast, if it operates at variable speed, the hydraulic power transferred by the fluid can be modified and it can therefore operate at maximum power. This speed variation is made possible by the use of electronic power converters.

This study focuses on the Rebolluelo micro-hydropower plant, located in the north of Spain as part of irrigation infrastructure. It is comprised of a semi-Kaplan turbine coupled to a squirrel-cage asynchronous generator. Both fixed-speed and variable-speed technologies are implemented at this micro-hydropower plant.

The main contributions of this work are as follows:

(i) An analysis of the phenomenon of cavitation when using fixed-speed and variable-speed technologies;
(ii) An analysis of the investment costs for fixed-speed and variable-speed technologies;
(iii) An analysis of the power production for fixed-speed and variable-speed technologies;
(iv) An analysis of the economic benefit of fixed-speed and variable-speed technologies.

In summary, the purpose of this work is to facilitate decision-making when considering future micro-hydropower plant installations.

This paper is structured as follows: Section 2 presents the context of the Rebolluelo micro-hydropower plant with fixed-speed technology. Section 3 describes the Rebolluelo micro-hydropower plant operating at variable speed. The assessment indicators are shown in Section 4. The results are presented in Section 5. Finally, Section 6 summarises the main contributions and conclusions of the paper.

2. The Case Study

Rincón de Soto is an agricultural town in La Rioja (Spain). This town is located on the banks of the river Ebro and its main activity is fruit and vegetables farming. The River Ebro Rincón de Soto Community of Irrigators (*RSCIRE*) uses an important irrigation infrastructure, formed by canals and irrigation channels. Taking advantage of this irrigation infrastructure and the water concession, the *RSCIRE* rebuilt a micro-hydropower plant in 2010.

2.1. The Rebolluelo Micro-Hydropower Plant

The Rebolluelo micro-hydropower plant is located in the town of Rincón de Soto in La Rioja (Spain) (latitude 42°14′04″ N, longitude 1°51′03″ W, and altitude of 261 m. It is a run-of-the-river power plant. The Rebolluelo micro-hydropower plant operates at fixed-speed. Figure 1 shows a Google Earth image of the Rebolluelo micro-hydropower plant location. The Rebolluelo micro-hydropower plant is mainly comprised of the following components: a semi-Kaplan turbine, an asynchronous squirrel cage generator, and a speed multiplier (gearbox). The semi-Kaplan turbine (THEE, model THEE D-644-AET) has an automatic blade drive, fixed guide vanes, and an output of 60.60 kW. The nominal flow rate is 1495 L/s and the minimum start-up flow rate is 200 L/s. The rated speed of the semi-Kaplan turbine is 584 rpm. This type of turbine is a reaction turbo-machine, has a vertical axis and is fed by a penstock connected to the Ebro river upstream. The net head is 4.80 m. The turbine shaft is connected to the generator shaft via a gearbox. The gearbox has a ratio of 1:1.72, to match the speed of the semi-Kaplan turbine to the speed of the electric generator. The characteristics of the electric generator (Leroy Somer, model PLSG280SC-T [27]) are: 70 kW, 1000 rpm and 400 V.

Figure 1. The Rebolluelo micro-hydropower plant.

The mini-hydropower plant uses the difference between the level of the irrigation canal and its outflow into the river Ebro. The flow enters the loading chamber through an automatic screen cleaner that prevents plant debris from entering the turbine. Figure 2 shows the water supply to the micro-hydropower plant.

Figure 2. Irrigation canal. Water supply to the micro-hydropower plant.

There is an oil-hydraulic gate in the load chamber through which the flow enters the turbine. The plant has a side spillway with a hydraulically-operated gate (see Figure 3). The turbined flow is channelled to the river Ebro via a 31 m long outflow channel. Figure 4 shows a diagram of the channel, the load chamber, and the turbine.

Figure 3. Water inlet to the loading chamber and side spillway.

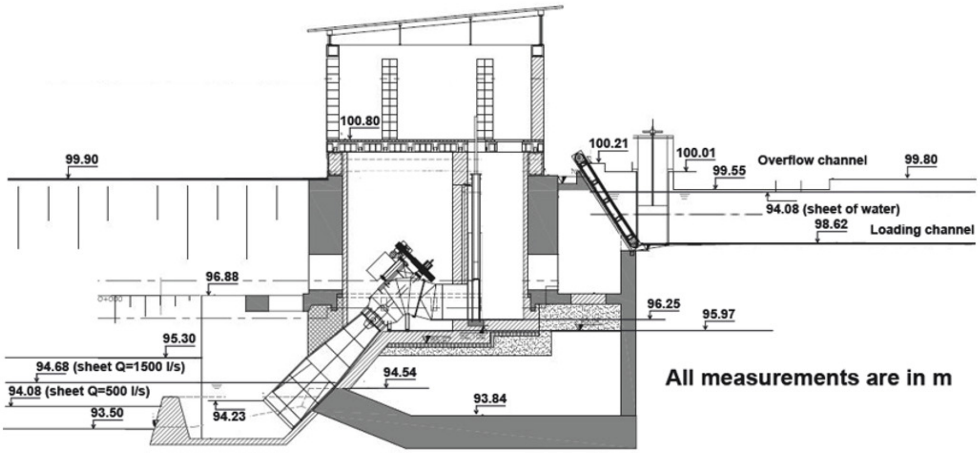

Figure 4. Diagram of the channel, the loading chamber, and the turbine.

The Rebolluelo micro-hydropower plant uses an "all-nothing" type of water level control with hysteresis (3%) and actuation only on the position of the blades. The control algorithm is run every 25 s and the action on the blades applies opening and closing pulses lasting 2 s and 1 s respectively for each control cycle. Although the automatic blade regulation makes it possible to maintain acceptable efficiencies above 40% of the design flow rate, the following problems were observed:

(i) As flow rates below the turbine's design flow were recorded, efficiency became low and even forced shutdowns due to minimal power. Figure 5 shows the efficiency-flow and power-flow curves for the micro-hydropower plant. According to Figure 5a, the efficiency of the turbine significantly decreases at low flow rates;
(ii) The low flows caused the blades to be positioned at minimal angles in order to maintain the water level in the load chamber. The decrease in suction head coupled with the high turbine speed (rated speed) resulted in cavitation.

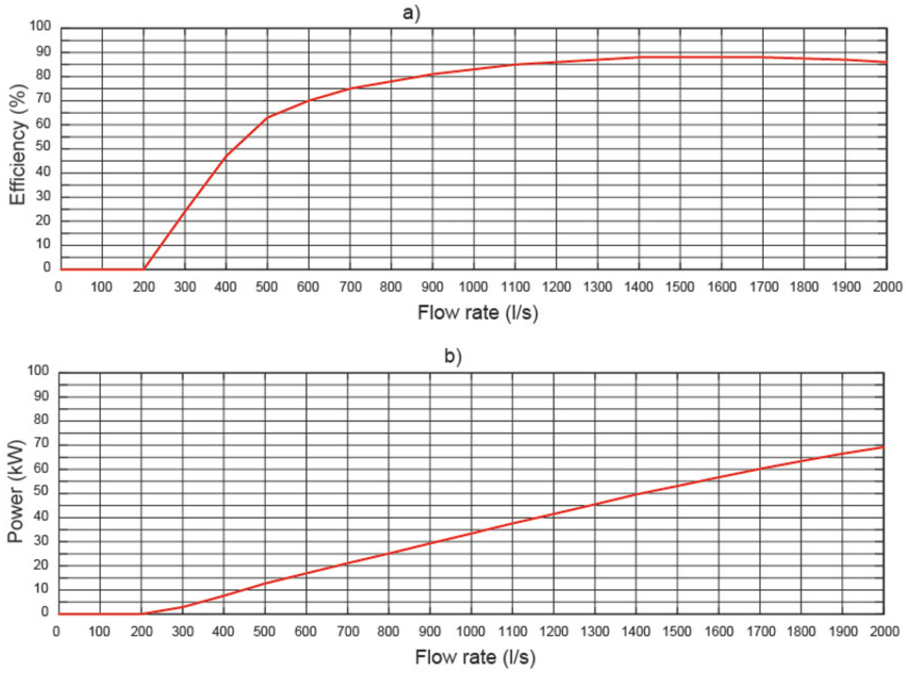

Figure 5. Efficiency-flow and power-flow curves for the micro-hydropower plant. (**a**,**b**) Flow rate (l/s).

2.2. Cavitation Problems in the Turbine

Continuous operation of the turbine in flow ranges far from the design flow caused significant cavitation problems [28]. The phenomenon of cavitation in the turbine caused severe erosion of the blades resulting in increased operating noise, increased vibrations [29], decreased turbine performance [30], decreased power output, and high repair costs [31]. Figure 6 shows images of the surface of the runner blades subjected to cavitation.

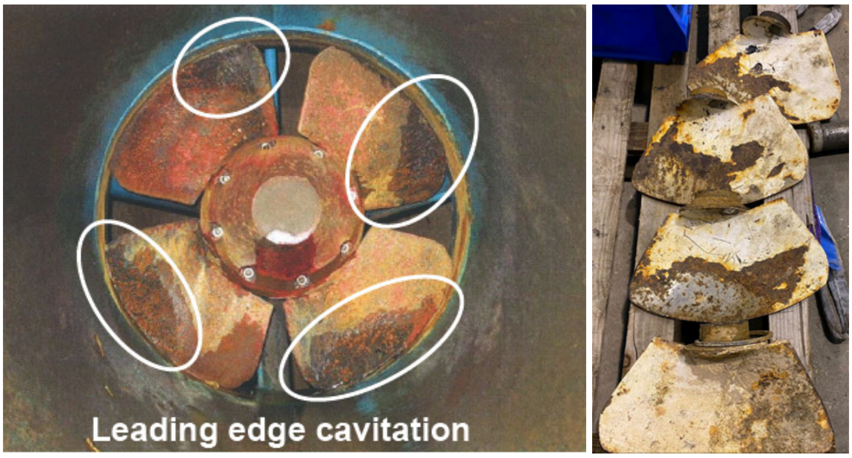

Figure 6. Images of the effects of cavitation on turbine blades.

A significant decrease in the available flow at the micro-hydropower plant while maintaining the rotational speed of the turbine, as the generator is directly connected to the grid, increases the probability of the occurrence of the phenomenon of cavitation. As a result of this cavitation, the Rebolluelo micro-hydropower plant was stopped in March 2017 so the turbine blades could be repaired. After the turbine blades were repaired, the problem of cavitation continued, which led to the decision to change the turbine control system and implement a variable-speed control system.

2.3. Electricity Production

The total maximum flow available is 1.485 L/s. However, on most days the available flow is lower. For example, the system operated for 6018 h in 2014, which represents 68.7% of the total time. In addition, 34.5% of the operating time accounted for around 20% of the nominal power. Therefore, a significant decrease in available flow coupled with the fixed speed mode of turbine operation, as the generator is directly connected to the grid, significantly decreases the operating hours and efficiency of the turbine.

3. The Rebolluelo Micro-Hydropower Plant Operating at Variable Speed

This type of installation is characterised by a significant variation in the flow rate of the flowing water [32], requiring major machine adjustments, which is sometimes not taken into account. The most effective solution is the implementation of a variable-speed control system on the electric generator [33].

The control strategy is to assimilate the semi-Kaplan turbine, as much as possible to a propeller turbine (fixed blades) driven at variable speed, except in cases where additional blade regulation is necessary to keep the water level constant. Therefore, priority is given to water level regulation by varying the speed of the semi-Kaplan turbine as opposed to water level regulation by varying the angle of the blades, with the following advantages:

(i) Decreasing the turbine operating speed decreases the critical cavitation factor, which prevents cavitation problems at low water flow rates;
(ii) For low flows, combining a reduction in turbine speed and blade angle closure can prevent the occurrence of cavitation;
(iii) Since the blades do not need to be kept at minimal opening angles, problems in the blade drive mechanism are avoided;
(iv) Increasing the performance of the micro-hydropower plant for low flows, thus achieving the plant's design efficiency.

The Rebolluelo micro-hydropower plant operated at fixed speed. A back-to-back dual *PWM* converter was added to it, so that it could operate at variable speed. The project has been led by the Spanish company SinFin Energy [34]. Figure 7 shows the system control structure. This structure includes two parts: the generator-side control system and the grid-side control system. The generator-side converter controls the speed of the semi-Kaplan turbine and the grid-side converter regulates the DC bus voltage and controls the currents fed into the grid.

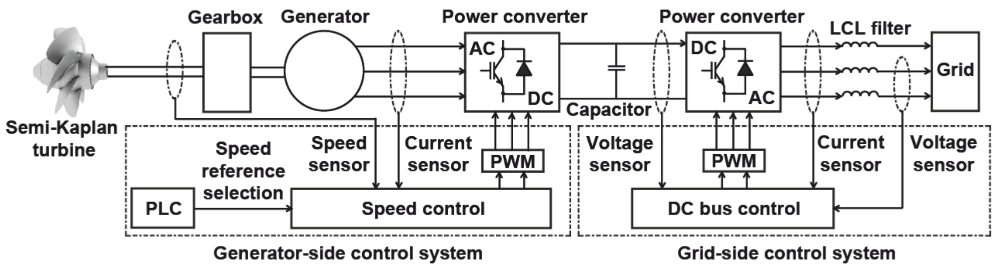

Figure 7. The micro-hydropower grid-connected control system.

The water level threshold for blade angle regulation was set at 80% of the available head. A maximum and minimum possible value for the blade angle was established where the operation of the hydraulic mechanism had been observed to be stable. Similarly, a maximum and minimum value for the generator speed was determined, avoiding turbine overspeeds and heating problems in the electric generator due to low speed drive.

The micro-hydropower plant will operate most of the time regulating the water level, with a set point of 98% (100% corresponds to the spillway overflow) and varying the turbine speed with the blade angle at a fixed value set at the configured maximum limit. When the speed regulation is not sufficient to maintain the level corresponding to the nominal head, automatic blade regulation begins until the situation is corrected, at which time the micro-hydropower plant again comes under control with the blade opening at a fixed value. A diagram of the optimal water level control system is shown in Figure 8.

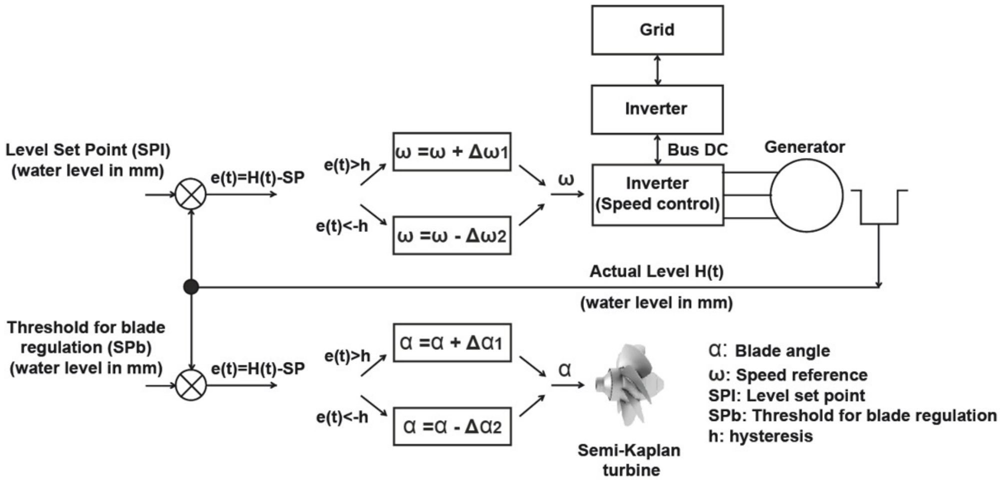

Figure 8. Diagram of the optimal water level control system.

The operating range of the turbine is 584 rpm. and 233 rpm. This means the generated electric current will have frequencies of 50 Hz and 20 Hz, respectively. Speeds lower than 233 rpm are not operated so that the operating temperature of the electrical generator does not rise to values that would be detrimental to the insulation of the electrical circuit.

The Rebolluelo micro-hydropower plant is equipped with a *PLC* (Programmable Logic Controller) control system and Scada system supervision. The control strategy with this type of micro-hydropower plant consists of keeping the water level in the load chamber (turbine inlet) constant at the maximum possible level prior to the overflow to the spillway, thus obtaining the maximum head for any operating situation. Figure 9 shows a photograph of the hardware used. Scada system supervision is shown in Figure 10.

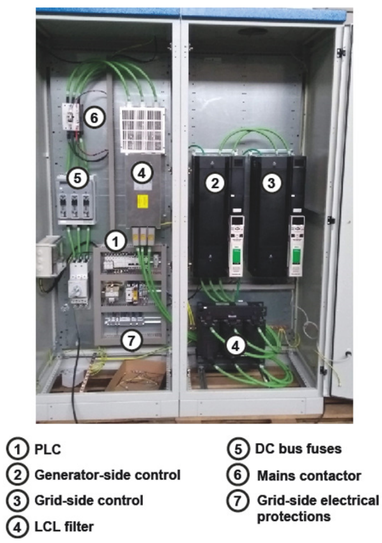

Figure 9. Photograph of the hardware used.

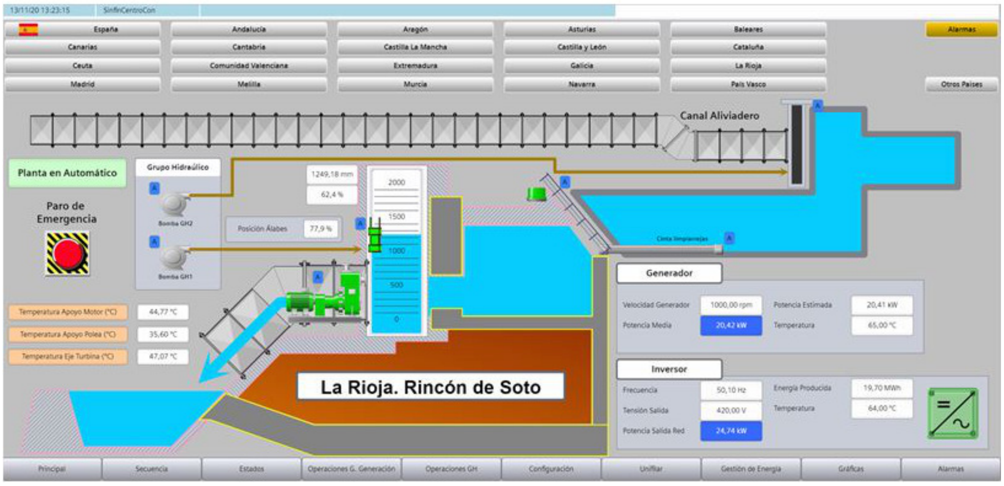

Figure 10. Scada system supervision.

4. Assessment Indicators

In order to analyse how the implementation of variable-speed technology affects a micro-hydropower plant, assessment indicators need to be defined. Four assessment indicators are proposed: the phenomenon of cavitation, investment costs, electricity production, and economic benefit.

4.1. The Phenomenon of Cavitation

Several numerical [35] and experimental [36] studies have been carried out on the operating flows of hydraulic turbines under off-design conditions. These studies were carried out as a function of the Thoma number (Thoma's cavitation factor), and demonstrated its influence on the generation of the phenomenon of cavitation. Therefore, the Thoma number is an essential factor to be taken into account for the stable operation of a hydraulic turbine. Thoma's cavitation factor is a dimensionless number that represents the cavitation properties of a fluid and it can be calculated using Equation [37]:

$$\sigma = \frac{H_a - H_s - H_v}{H} \tag{1}$$

where σ is the Thoma number (*dimensionless*), H_a is the atmospheric pressure head (m), H_v is the vapor pressure of water corresponding to the water temperature (m), H_s is the suction head of the hydraulic turbine (m), and H is the head of the hydraulic turbine (m).

The critical cavitation factor (σ_c) was used to evaluate the phenomenon of cavitation. Equation (2) shows an empirical relationship for the determination of the critical cavitation factor for a Kaplan turbine [38,39]:

$$\sigma_c = 1.1 \cdot \left[0.28 + \left[\frac{1}{7.5} \cdot (N_s/380.78) \right]^3 \right] \tag{2}$$

where σ_c is the critical cavitation factor (*dimensionless*), and N_s is the specific speed of the turbine (rpm). The specific speed can be calculated as [40]:

$$N_s = \frac{N \cdot \sqrt{P_t}}{H^{5/4}} \tag{3}$$

where N is the speed of the turbine (rpm), P_t is the power output of the turbine (kW), and H is the head of the hydraulic turbine (m).

The cavitation factor can also be determined as a function of the specific speed:

$$\sigma = \frac{(0.01 \cdot N_s - 0.54)^2}{45} + 0.035. \tag{4}$$

Equation (4) can be used for specific speeds in the range 70 to 800 rpm.

To assess this indicator, the ratio between σ and σ_c was used. If the value of σ is greater than σ_c the phenomenon of cavitation will not occur [38]:

$$\sigma \succ \sigma_c. \tag{5}$$

Therefore, decreasing the specific speed of the turbine decreases the probability of cavitation.

4.2. Investment Costs

The cost of installing a micro-hydropower plant varies from one location to another. It depends on several factors, such as the existing infrastructure [41] and the distance to the grid connection point, etc. Generally, for equal performance, the cost of a low head plant is higher than that of a higher head plant [41].

Hosseini et al. [42] proposed guidelines for determining the costs of a small hydropower plant. These costs are:

(i) Civil engineering costs. Civil engineering costs are related to the construction and hydro-structural costs of the project. In our study, these costs include the water conveyance system, the water penstock structure, and the tailrace structure;
(ii) Electro-mechanical equipment costs. These costs include the turbine, the generator, the gates, the control system, the power substation, and the electrical and mechanical auxiliary equipment;
(iii) Power transmission line costs. These costs include the electricity transmission line to connect the power substation to the power transmission grid;
(iv) Indirect costs. These costs mainly include engineering and design (E&D), supervision and administration (S&A), as well as inflation during the construction period (I).

This procedure has been used in several studies [43,44].

Due to the characteristics of our study, we were most interested in estimating the cost of electro-mechanical equipment as all other costs are considered constant. Graphs are available to determine the approximate cost of the electro-mechanical equipment [44]. However, the drawback is that these graphs have not been recently updated [44]. Moreover, as each installation is different, turbine and alternator manufacturers do not provide any cost information.

To determine the electro-mechanical equipment costs ($EMEC$),many studies use equations based on the power output of the turbine (P_t) and the head of the hydraulic turbine (H) of a small hydropower plant [44,45]. Ogayar and Vidal propose the following cost function for a semi-Kaplan turbine [46]:

$$EMEC = a \cdot P_t^{b-1} \cdot H^c \tag{6}$$

where a, b, and c coefficients depend on the geographical, space or time field in which they are used. For the determination of these parameters, in [46] a best-fit analysis (applying logarithms) was carried out. The value of the constants for semi-Kaplan turbines obtained in [46] is:

$$EMEC = 19498 \cdot P_t^{-0.58338} \cdot H^{-0.113901} \tag{7}$$

where $EMEC$ is the electro-mechanical equipment costs (€/kW), P_t is the power output of the turbine (kW), and H is the head of the hydraulic turbine (m). Equation (7) has been used in several studies [47,48]. The use of Equation (7) incurs errors within a fluctuation band between 19.52% and −9.50% [46].

The equations for the determination of costs refer to a distant period of time, as they are more than 10 years old. Moreover, these costs vary considerably from one location to another. Therefore, the actual costs of the Rebolluelo micro-hydropower plant will be used for this study [34].

To assess this indicator, the ratio between the micro-hydropower plant cost ($MHPC$) of the two technologies was used. The $MHPCR$ can be calculated as the difference between the costs of using both technologies:

$$MHPCR = \frac{MHPC_2 - MHPC_1}{MHPC_1} \cdot 100 \quad (8)$$

where subscript 1 represents the Rebolluelo micro-hydropower plant with fixed-speed technology, and subscript 2 represents the Rebolluelo micro-hydropower plant with variable-speed technology.

4.3. Electricity Production

Equation (9) can be used to determine the power generated by the micro-hydropower plant [49]:

$$P_g = P_t \cdot \eta_g = \eta_t \cdot \rho \cdot g \cdot H \cdot q_t \cdot \eta_g \quad (9)$$

where P_g is the power output of the electric generator (W), P_t is the power output of the turbine (W), η_g is the electric generator efficiency (%), η_t is the turbine efficiency (%), ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), H is the head (m), and q_t is the turbined flow rate (m^3/s).

Actual electricity generation data are available for this study [34].

The power output ratio (POR) will be used to compare the two technologies. This relationship is defined as:

$$POR = \frac{P_{g2}^{year2} - P_{g1}^{year1}}{P_{g1}^{year1}} \cdot 100 \quad (10)$$

where subscript 1 represents the Rebolluelo micro-hydropower plant with fixed-speed technology, and subscript 2 represents the Rebolluelo micro-hydropower plant with variable-speed technology. The superscript $year1$ represents the year of operation of the Rebolluelo micro-hydropower plant with fixed-speed technology, and the superscript $year2$ represents the year of operation of the Rebolluelo micro-hydropower plant with variable-speed technology.

4.4. Economic Benefit

The Rebolluelo micro-hydropower plant operates in the day-ahead Iberian Electricity Market ($MIBEL$) [50], comprising the Portuguese and Spanish electricity systems.

The economic benefit ratio (EBR) has been used in similar studies to evaluate various power plant operation modes [51]. The EBR can be calculated as the difference between the economic benefit using both technologies [51]:

$$EBR = \frac{EB_2^X - EB_1^X}{EB_1^X} \cdot 100 \quad (11)$$

where subscript 1 represents the Rebolluelo micro-hydropower plant with fixed-speed technology, and subscript 2 represents the Rebolluelo micro-hydropower plant with variable-speed technology. The superscript X represents the year chosen from the day-ahead Iberian Electricity Market.

5. Results and Discussion

Two scenarios will be analysed in this section to illustrate how the implementation of variable speed affects a micro-hydropower plant. Scenario 1 is the operation of the Rebolluelo micro-hydropower plant with fixed-speed technology, and scenario 2 is the operation of the Rebolluelo micro-hydropower plant with variable-speed technology. In addition, several years will be used in each scenario in this study:

(i) Scenario 1. 2016 was chosen as the best year for electricity production, and 2017 was chosen as the year in which the operation of the micro power plant was stopped due to the cavitation phenomenon;
(ii) Scenario 2. The Rebolluelo micro-hydropower plant started operating at variable speed in July 2020. The years 2021 and 2022 were chosen, as they are the only years for which all the data are available.

In order to compare the two scenarios, several assessment indicators were used, such as: cavitation phenomena, investment costs, electricity production, and economic benefit.

5.1. The Phenomenon of Cavitation

Table 2 shows the cavitation number results for various flow rates. As can be seen in Table 2:

(i) For a flow rate of 1495 L/s (100% of the nominal flow rate) no cavitation occurs in any of the scenarios. The value of the cavitation factor obtained agrees with the value obtained in ref. [52];
(ii) For a flow rate of 598 L/s (40% of the nominal flow rate) cavitation occurs in scenario 1. In contrast, for the same flow rate no cavitation occurs in scenario 2.

Table 2. The results of the cavitation number for various flow rates.

Scenario	Flow Rate (L/s)	Cavitation Factor	Critical Cavitation Factor
1	1495	0.8	0.32
1	598	0.27	0.31
2	1495	0.8	0.32
2	598	0.32	0.31

5.2. Investment Costs

For this paper, the civil engineering and power transmission line costs are the same for the two scenarios under study. The indirect costs can also be considered the same, as these types of costs due to scenario 2 will increase the costs of the control equipment. This is not the case for the electro-mechanical equipment costs in the two scenarios. The costs of the turbine, generator, gates, power substation, and mechanical auxiliary equipment are the same. In contrast, the costs of the control system and electrical auxiliary equipment increase in value in scenario 2.

With regard to the costs of electro-mechanical equipment, as each installation is different, turbine manufacturers do not provide generic information on these costs which can be extrapolated to other installations. In contrast, the costs of the generator, the control system, the power substation, and the electrical auxiliary equipment are easier to determine.

All costs used have come from ref. [34] for the Rebolluelo micro-hydropower plant. Table 3 shows the costs of the Rebolluelo micro-hydropower plant with fixed-speed technology (costs updated as of 8 November 2023). The micro-hydropower plant cost is EUR 493,802.15. Equation (7) shows a large difference in comparison to the actual costs.

Table 3. The cost of the Rebolluelo micro-hydropower plant with fixed-speed technology.

Cost Type	Cost (€)	(%)	Reference
Civil costs	112,430.64	22.77	[34]
Electro-mechanical equipment costs	319,686.62	64.74	[34]
Power transmission line costs	47,302.30	9.58	[34]
Indirect costs	14,382.59	2.91	[34]

As can be seen in Table 3, the electro-mechanical equipment costs account for a very high percentage of the total cost of the micro-hydropower plant. This trend is consistent with several studies [46,48].

The control system of the Rebolluelo micro-hydropower plant with variable speed technology has a cost of EUR 59,078.75 (costs updated as of 8 November 2023) [34]. Table 4 shows the costs of the Rebolluelo micro-hydropower plant with variable-speed technology (costs updated as of 8 November 2023). The micro-hydropower plant cost is EUR 552,880.9.

Table 4. The cost of the Rebolluelo micro-hydropower plant with variable-speed technology.

Cost Type	Cost (€)	(%)	Reference
Civil costs	112,430.64	20.33	[34]
Electro mechanical equipment costs	378,765.37	68.51	[34]
Power transmission line costs	47,302.30	8.55	[34]
Indirect costs	14,382.59	2.61	[34]

Evidently, the implementation of variable-speed control meant an increase in the total cost of the Rebolluelo micro-hydropower plant. Specifically, the $MHPCR$ is 11.96%.

5.3. Electricity Production

Figure 11 shows the rainfall at Ricón de Soto (Spain) for the years under study.

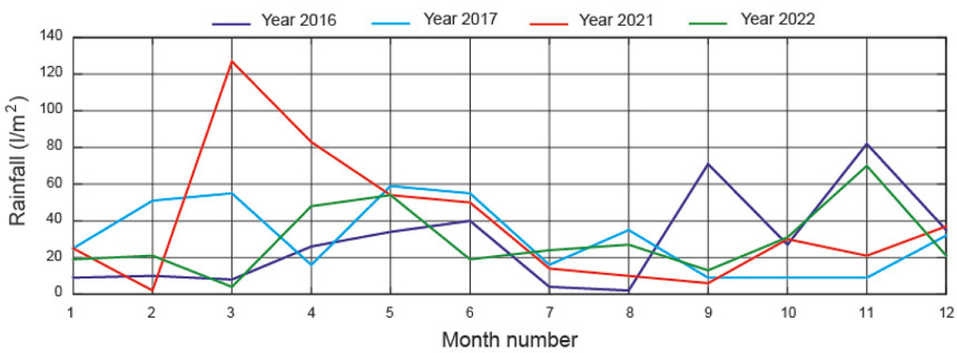

Figure 11. Rainfall at Ricón de soto (Spain) for the years under study.

In addition to the level of rainfall, the need for water for irrigation in each year should be taken into account. Taking into account that the area of land used for cultivation has not changed and that the type of crop has not changed either, the water needs for irrigation in the four years can be considered to be similar and allow for an acceptable comparison.

Figure 12 shows the monthly energy generated by Rebolluelo micro-hydropower plant with fixed-speed technology during 2016 and 2017 [34].

As can be seen in Figure 12, since March 2017 the Rebolluelo micro-hydropower plant has not produced any electricity. The semi-Kaplan turbine broke down due to severe cavitation problems.

Figure 13 shows the monthly energy generated by the Rebolluelo micro-hydropower plant with variable speed technology during 2021 and 2022 [34]. Even when using variable-speed technology, the micro-hydropower plant was not operational during some months of the year due to the low flow available. This situation would have been even worse if fixed-speed technology were used.

Figure 14 shows the annual power generated by the Rebolluelo micro-hydropower plant with both technologies. The micro-hydropower plant operated with fixed speed technology in 2016 and 2017, and it operated with variable-speed technology in 2021 and 2022.

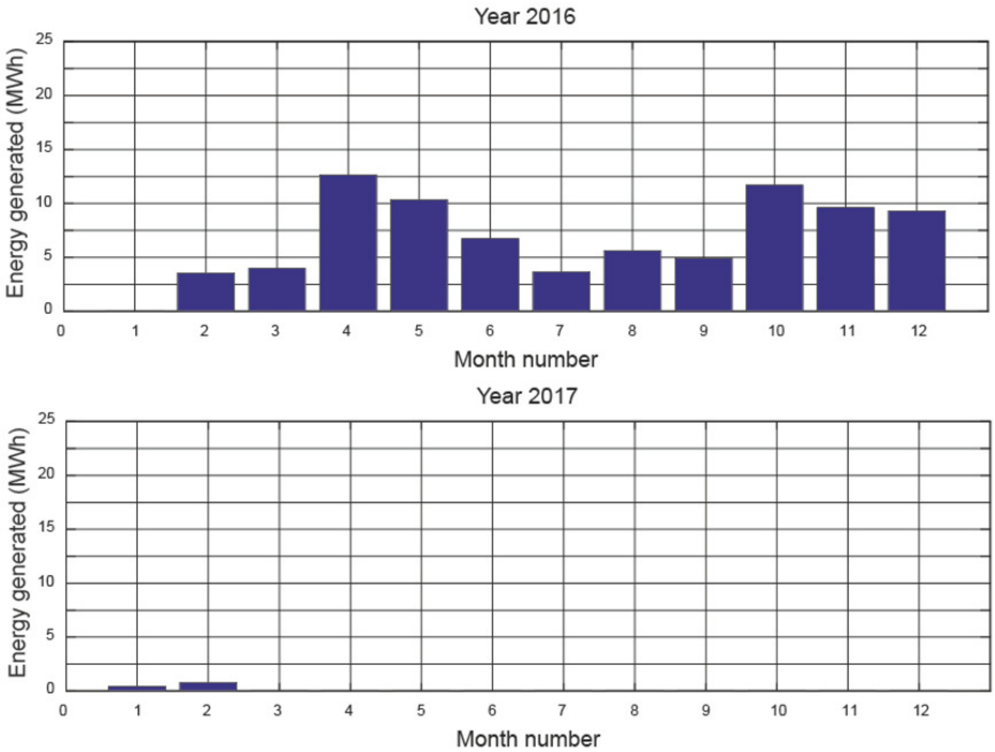

Figure 12. Monthly energy generated by the Rebolluelo micro-hydropower plant with fixed-speed technology.

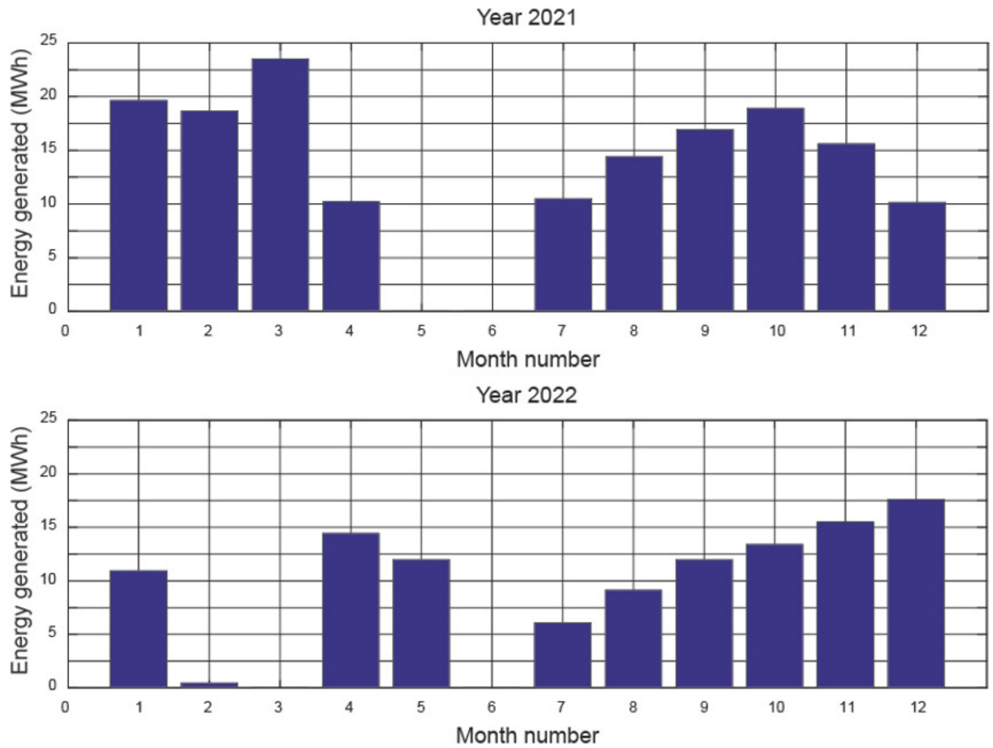

Figure 13. Monthly energy generated by the Rebolluelo micro-hydropower plant with variable-speed technology.

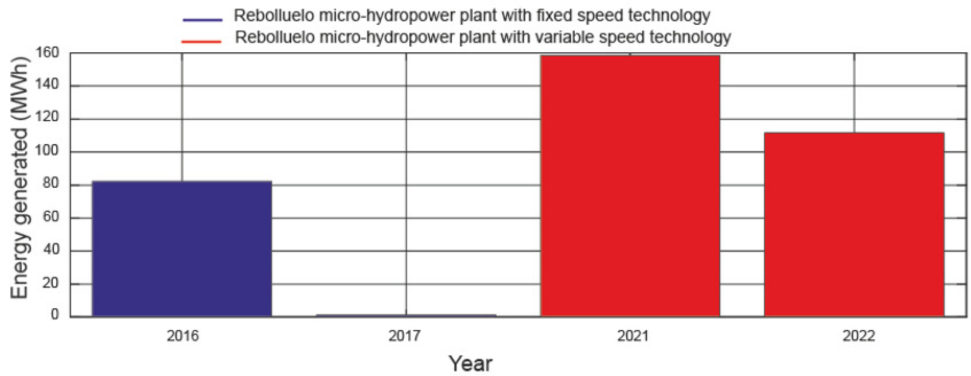

Figure 14. Annual energy generated by the Rebolluelo micro-hydropower plant with both technologies.

The year 2016 was used as the basis for comparison in order to determine the *POR*. Compared with 2016, the power output ratio increased by 93.03% and 35.87% in 2021 and 2022, respectively. Therefore, the implementation of variable-speed control significantly increased the generation of electrical energy.

5.4. Economic Benefit

To analyse the economic benefit of each scenario, the day-ahead Iberian Electricity Market price for the year 2022 was chosen. As an example, Figure 15 shows the hourly day-ahead price on the Iberian Electricity Market and the energy generated for 16 April 2022. The product of these two curves determines the economic benefit on that particular day.

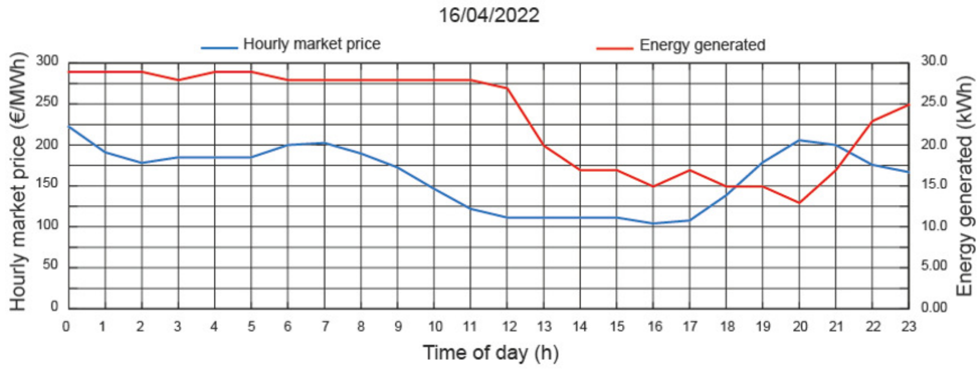

Figure 15. Hourly day-ahead price on the Iberian Electricity Market and the energy generated for 16 April 2022.

Figure 16 shows the monthly economic benefit of the Rebolluelo micro-hydropower plant with both technologies. The micro-hydropower plant operated with fixed speed technology in 2016 and 2017, and it operated with variable-speed technology in 2021 and 2022.

The year 2016 was used as the basis for comparison to determine the *EBR*. Compared with 2016, the economic benefit ratio increased by 108.72% and 29.31% in 2021 and 2022, respectively. Therefore, the implementation of variable-speed control significantly increased the economic benefit.

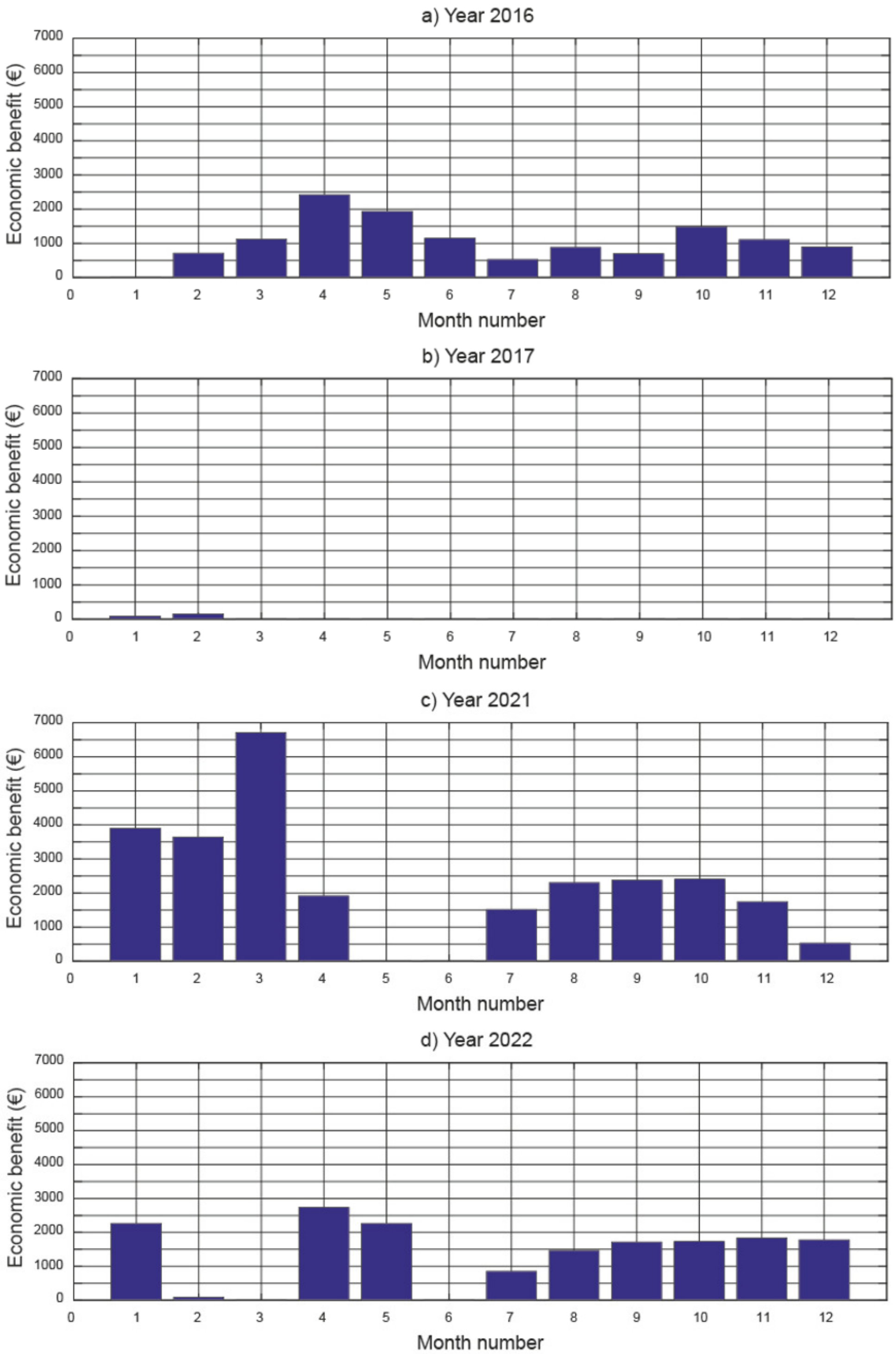

Figure 16. Economic benefits of each scenario.

6. Conclusions

In this paper, a comparative evaluation was carried out on several indicators (the phenomenon of cavitation, investment costs, electricity production and economic benefit) for the same micro-hydropower plant, located in the north of Spain, in an irrigation infrastructure (the Rebolluelo micro-hydropower plant) featuring two types of asynchronous electric generator control system (a fixed-speed control system (scenario 1) and a variable speed control system (scenario 2)). The assessment indicators were analysed for four different years: 2016, 2017, 2021, and 2022. In scenario 1, the year 2016 was chosen as it was the best year for electricity production, and the year 2017 was chosen because the operation of the micro-hydropower plant was halted due to the phenomenon of cavitation. The Rebolluelo micro-hydropower plant started operating at variable speed in July 2020. Therefore, in scenario 2 the years 2021 and 2022 were chosen as these are the only years for which all data are available. This micro-hydropower plant uses a semi-Kaplan turbine coupled to an asynchronous electric generator through a gearbox. Older micro-hydropower plants operate at fixed speed. When there ia a lack of rainfall, irrigation infrastructure prioritises the use of water for crops, which leads to these micro-hydropower plants operating outside their design flow and, thus, to various problems (such as cavitation, reduced turbine efficiency, and reduced operating hours). In summary, the following conclusions can be drawn:

(i) The use of variable-speed technology eliminated the possibility of cavitation. It allowed operation in a speed range of 584 rpm (when the flow rate is high) to 233 rpm (when the flow rate is low);
(ii) Evidently, the use of variable-speed technology increased the total cost of the Rebolluelo micro-hydropower plant. The micro-hydropower plant cost ratio is 11.96%;
(iii) The use of variable speed technology significantly increased the power output ratio. Using 2016 as a basis for comparison, the power output ratio increased by 93.03% and 35.87% in 2021 and 2022, respectively;
(iv) The use of variable-speed technology significantly increased the economic benefit. Using 2016 as a basis for comparison, the economic benefit ratio increased by 108.72% and 29.31% in 2021 and 2022, respectively.

This work shows the superiority of variable-speed technology in micro-hydropower plants for three of the four indicators assessed. Although the cost is higher, the rest of the indicators recommend the implementation of this type of control system in micro-hydropower plants. This work could be used to help make decisions with regard to future micro-hydropower plant installations.

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Nomenclature

EBR	Economic benefit ratio (*dimensionless*)
$EMEC$	Electro-mechanical equipment costs (€/kW)
g	Acceleration of gravity (m/s^2)
H	Head of the hydraulic turbine (m)
H_a	Atmospheric pressure head (m)
H_s	Suction head of the hydraulic turbine (m)
H_v	Vapor pressure of water (m)
$MHPC$	Micro-hydropower plant cost (€)
$MHPCR$	Micro-hydropower plant cost ratio (*dimensionless*)
N	Speed of the turbine (rpm)

N_s	Specific speed of the turbine (rpm)
P_g	Power output of the electric generator (W)
P_t	Power output of the turbine (kW)
POR	Power output ratio (*dimensionless*)
q_t	Turbined flow rate (m^3/s)
η_g	Electric generator efficiency (%)
η_t	Turbine efficiency (%)
ρ	Water density (kg/m^3)
σ	Thoma's cavitation factor (*dimensionless*)
σ_c	Critical cavitation factor (*dimensionless*)

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