Association of renewable energy technologies

Hybridization case study of small hydropower schemes in mainland Portugal with photovoltaic solar parks

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Abstract

The research carried out aimed to analyze technologically and economically the hybridization of hydro and solar energy sources. The sites under study were the Covas do Barroso and Pinhel hydroelectric plants, which currently operate exclusively based on hydroelectric energy and are limited to a maximum contracted power, that is, grid injection. The historical records of electricity production are not very significant and, for that reason, it was made an attempt to reproduce the operation of those facilities over a longer period of time. Through the analysis of simulated hydroelectric energy data, the production of photovoltaic energy was estimated for different values of installed solar power, from 1 to 7 Megawatt-peak (MWp).

In the technological analysis, the existing hydropower source was prioritized and, observing the results, it was noticed an evident complementarity with the solar source, concluding that the two can coexist. In the economic analysis, the internal rates of return of sequential samples were determined for 30-year cycles and it was concluded that only a pessimistic forecast of revenue from the produced energy would result in the rejection of the project. The optimal solution for Covas do Barroso is determined by the installation between 3 and 4 MWp, and for Pinhel the installation between 4 and 5 MWp.

Key words

Hybridization; hydropower plant; photovoltaic solar park; renewable energies; economic profitability.

1. Introduction

The theme of the master's research carried out falls within the scope of hybridization of renewable energies, which involves the association of two or more technologies for the production of electricity based on renewable sources, sharing the same point of connection with the national electricity grid, to ensure a more stable and competitive supply[1]. More specifically, it was intended to study the applicability of hybridization in existing installations (hydric energy), adding a new module from another source (solar energy) to the electricity generation technology. In that sense, a hydroelectric installation can take advantage of hydroelectric energy during wet periods and photovoltaic energy in dry periods, thus ensuring a more stable and efficient production of electricity. The two proposed study sites are the hydropower schemes (HS) of Covas do Barroso and Pinhel, owned by the company Lusiterg – Projetos Energéticos, Lda., one of the companies of the Hidroerg - Projetos Energéticos, Lda. group. The Covas do Barroso HS is located on the Covas and Couto rivers, in the Tâmega river basin, in the municipality of Boticas, district of Vila Real[2]. The Pinhel HS is located on the Cabras and Pêga streams, in the Côa river basin, in the municipality of Pinhel, in the Guarda district[3]. Thus, it was intended to simulate current hydroelectric production, technically and economically analyze the feasibility of implementing a new energy source to complement the existing one and, in a favorable assessment, identify the optimal conditions for such implementation.

2. Methodology

Methodological strategy

For each case study, the strategy adopted to conduct the present investigation was developed in four main stages: (1) identification of the complementary renewable energy source to be associated with the current hydric energy; (2) facing the lack of records susceptible of being transformed into a long series of turbined flows in the case study, estimation of average daily flows affluent to the HS in order to characterize the conditions of hydroelectric production; (3) the simulation of the production of electric energy from the combination of the two renewable sources limited by the maximum power of connection to the grid that was granted to the case study; (4) and the economic analysis to determine the feasibility of the hybridization project with simultaneous identification of the optimal value of the power to be installed in the complementary hybridization technology.

Identification of renewable energy complementary to the existing one

Hydroelectric production is irregular and profoundly seasonal, with very low or even zero records during long periods of the dry semester of the hydrological year, in perfect complementarity with photovoltaic production[4]. This is also the circumstance of the hydropower schemes that constitute the case studies, which present the opportunity for photovoltaic production in addition to hydroelectric production. In order to fulfill the objective of the investigation, it was assumed that, as close as possible to each HS, there would be availability of land compatible with the installation of a photovoltaic solar park (PV).

The need for proximity to the hydropower scheme derives from the fact that the solar park has to be connected to the currently existing substation in order to use the HS's national electricity grid interconnection. In addition, the control equipment of its exploration will have to be installed in the HS's powerhouse building. Based on the above assumption, the analysis procedure applied is done using a simulation of the joint operation of each hydropower scheme and the solar park.

Estimation of average daily flows

The Covas do Barroso and Pinhel hydropower schemes began to be operated in December 1996 and April 2004, respectively, and the corresponding records are available (at 15-minute intervals) from a smart meter system and with some temporal continuity only from 2005 onwards for Covas do Barroso, and a year later for Pinhel. As a result, the historical series of exploration data are too short to support the hybridization study in view. For that reason, taking into account those records and in order to increase the period with hydroelectric production capable of being complemented by photovoltaic production and thus, more consistently concluding on the feasibility of hybridization, it was carried out a simulation of the operation of the power plants of the cases of study based on series of average daily flows affluent to the respective weirs, obtained by transposing those flows from hydrometric stations, according to the flow regionalization model. The actual records of exploration in the hydropower schemes of Covas do Barroso (between 2005 and 2021) and Pinhel (between 2006 and 2021) cover, as mentioned, periods that are too short to support the analysis of the thesis on the feasibility of hybridizing those two sources of energy. For that purpose, and based on the existing real data, it was tried to reproduce the operation of the HS in longer intervals of time, based on the simulation of their exploration. In that sense, it was collected the records of the average daily flows in a hydrometric station as close as possible to each hydropower scheme, very pertinently, in order to guarantee the similarity of the heights of the average annual flow in the hydrographic basins of each scheme and the respective hydrometric station. Considering the average annual volume of water deducted from the upstream consumption of each weir provided by the operating company[2,3] and the average annual volume of the hydrometric station extracted from the Portuguese National Water Resources Information System (SNIRH)[5,6], it was possible to establish the factor to be applied to the flow transposition. In that way and incorporating the records of the average daily flows of each hydrometric station extracted from the SNIRH platform, it was possible to reach an estimate of the series of average daily flows affluent to each hydropower scheme[7]. In this process of calculating the average daily flows affluent to each HS, it was necessary to identify a station located as close as possible to the hydrographic basin dominated by the development in order to ensure similarity of geomorphological characteristics and, very pertinently, of the respective heights of the average annual flow[8]. For the Covas do Barroso HS, the selected hydrometric station was Vale Giestoso (03K/01H), located on the Beça River, affluent of the Tâmega River, in the municipality of Boticas, with continuous records of average daily flows from October 1957 to September 2017, that is, for 60 hydrological years[5]. For the Pinhel HS, the selected station was Cidadelhe (08O/02H), located on the Côa River, affluent of the Douro River, in the municipality of Pinhel, with continuous records of average daily flows for 56 hydrological years, from October 1955 to September 2011[6].

Simulation of hydroelectric production

In each weir, due to the legislation that guarantees the commitment to environmental protection and pre-existing uses, and as stipulated in the licenses for hydropower schemes, the ecological flow and the irrigation flow were removed from the average daily affluent flow on each day, obtaining the value of the average daily effluent flow that can be used in the production of hydroelectric energy.

In each scheme there is a maximum turbine flow, compatible with the installed power, and a minimum limit below which the turbines cannot work. Whenever the effluent flow is greater than the maximum turbine flow, this surplus is stored in the hydraulic circuit (channel, in the case of Covas do Barroso HS, and loading chamber, in the Pinhel HS), contributing to the volume of the lock, up to the limit of its capacity. If this limit is reached, the surplus flow is discharged into the river.

In order to reduce the number of turbine starts, the algorithm for simulating the daily operation of each scheme was designed to minimize the interruptions in the operation of the plants, which occur when the volume of the lock is zero and the affluent flow is less than the minimum starting flow. Thus, when the stored volume is at its maximum capacity and the turbine is working, if the effluent flow is greater than or equal to the minimum starting flow, the turbine uses all that volume of water up to the limit of maximum turbine flow and the lock volume remains at its maximum. On the other hand, when the stored volume is at its maximum capacity and the turbine is running, but the effluent flow is less than the minimum starting flow, the turbine uses water stored in the hydraulic circuit to guarantee that minimum flow and keeps working until the volume reaches a maximum again or empties completely.

In a lock period, when the stored volume is below maximum capacity and the turbine is operating at minimum flow, if the effluent flow is greater than the minimum starting flow, the excess water volume is used to increase the stored volume. On the other hand, when that volume is below the maximum capacity and the turbine is operating at minimum flow, but the effluent flow is less than the minimum starting flow, the turbine uses stored water to guarantee that minimum flow and continues working at that minimum until the volume reaches a maximum again or empties completely. If the effluent flow is equal to the minimum flow, the situation does not change and the storage volume remains constant.

Finally, if the lock volume is empty and the turbines are stopped, water storage becomes a priority and the entire effluent flow, obviously already deducted from the ecological and reserved flows, is allocated to this objective, without any energy production until the moment when that volume is filled[2,3].

Based on the previously explained operating rules, the daily exploration simulation procedure used the *Visual Basic* programming language incorporated into the *Microsoft Office Excel* program, for which a given time interval or calculation step was adopted. Since that interval is shorter than the day and only average daily values of the affluent flows were available, the flow on each day was considered constant. In each step, as a result of the simulation, it was obtained the turbined flow, the corresponding turbined water volume, and the hydroelectric energy produced[9].

Simulation of photovoltaic production

The production of photovoltaic energy depends, in the first instance, on the peak power of the system installed in the PV. The peak power of a module corresponds to the maximum electrical energy that can be generated under ideal conditions. In that sense, it is essential to obtain accurate preliminary estimates of photovoltaic energy production in the geographical context of the place under analysis. Those estimates can be presented, among other alternatives, through the dimensionless unitary photovoltaic production relative to a location and a period of time. That unit production, expressed in MWh/MWp, refers to the electrical energy produced by a photovoltaic equipment for each megawatt-peak installed[10]. Thus, in a PV equipped with a maximum power corresponding to n MWp, the energy from that solar equipment produced in a certain time interval is obtained by the product between n and the unit production.

In this study, since, under the terms of the applicable legislation, the production of hydroelectric energy has priority, the production of photovoltaic energy can only occur in periods when the hydroelectric equipment is not operating at full load, that is, in periods when the hydroelectric power is lower than the installed power of 6.40 MW at the Covas do Barroso HS and 6.76 MW at the Pinhel HS (concessioned power and which is permitted in connection to the grid)[2,3]. The power available for photovoltaic production is, therefore, given by the difference between the power installed in the power plant in question and that which, in fact, is being supplied by the respective turbine.

Once it is chosen to install a certain capacity in the PV, the power at which the production of photovoltaic energy will actually occur is given by the minimum value between the available power and the power supplied by the solar park. Finally, based on the previous assumptions, the analysis procedure applied used the simulation of the joint operation of each HS and the PV for which different installed photovoltaic powers were admitted, between 1 and 7 MWp, in order to optimize the joint production.

Economic analysis

Among several economic indicators, and due to its ease of interpretation and visualization, the internal rate of return (IRR) was defined as the measure of evaluation of economic viability to be used in this study. That simplicity is due to the fact that the IRR is a relative indicator that measures the profitability of the project in terms of rate, thus allowing a hierarchy of options[11]. The project is viable if the internal rate of return is higher than the discount rate. The higher the IRR, the more favorable the project will be.

The economic feasibility analysis of the project, carried out through the IRR and relative to an analysis period of d years, considered equal to the useful life of the PV installation, will have an approach similar to the calculation of moving averages, used to characterize trends in time series. In that sense, based on the simulation results of the joint exploration of hydroelectric and photovoltaic energy during a period, the various IRR values will be calculated, resulting from the subdivision of that period into smaller cycles, with a duration of d years[12].

The subdivision of the simulation period into consecutive periods of *d* years, differing only in the starting and ending years, was not only conditioned by the objective of identifying possible trends in the IRR values, but also intended to resolve the question of which period the economic analysis should focus on, so that their results could support a decision on whether or not to invest in hybridization. Taking into account the expected effects of climate change, in terms of reducing surface water availability in mainland Portugal, it was considered successive sub-periods with a sufficiently long d dimension, desirably in the order of magnitude of the useful life of the photovoltaic panels, which could be considered representative of the hydrological variability and that, at the same time, give consistency to the results of the economic analysis, as they allow to verify if eventual changes in the hydrological regime over time influenced the IRR values[13].

3. Description of the collected data

Preliminary estimate of photovoltaic energy production

The evaluation of geographic features and the rigorous determination of solar availability at the areas under study is an important step in the development of any hybridization project with solar photovoltaic energy as a complementary technology. For that purpose and for each case study, *Lusiterg – Projetos Energéticos, Lda*. provided the information it had acquired from *Megajoule*, relating to a series of 8760 hourly photovoltaic productions in an average year, expressed MWh/MWp, in a location as close as possible to the case study[14,15]. Once a given peak power of photovoltaic origin to be installed is chosen, the corresponding energy production is obtained by multiplying the object values of the previous series by that peak power. The options considered for the photovoltaic power to be installed vary between 1 and 7 MWp, with an increment of 1 MWp, in a total of seven alternatives. For the purposes of economic analysis based on consecutive sub-periods, each with a duration of *d*, the previous series were considered constant, adopted year by year. It is important to note that the unitary productions object of these series correspond to gross theoretical values, that is, not yet discounted from the losses related to the initial and annual degradation of the photovoltaic modules, as specified in the following item. The maximum hourly production on average over the years is approximately 0.9 MWh for each installed solar MWp occurring in the summer. On the other hand, the smallest productions refer to the months between November and January.

Photovoltaic equipment

The photovoltaic equipment considered for this study is the model *144 Half-Cell Monofacial Module 530-550W* commercialized by *Suntech Power Holdings Co., Ltd*. This panel has a lifespan of 30 years, an initial degradation of 1.25%, and a maximum annual degradation of the rated power of 0.55%, reaching the lowest performance of about 80% in the thirtieth year after its start of operation[16]. In accordance with the expected useful life for the photovoltaic panels, it was considered that each consecutive sub-period of the economic analysis would have a duration, *d*, of 30 years.

Economic parameters

After the technological analysis and verification of the compatibility of the two renewable energy sources, it was necessary to verify the economic viability of the project and, in a positive conclusion, to determine the optimal power to install. In order to do so, it was necessary to have information on investment and operation and maintenance costs, relative to market values for the beginning of the current year, and information on some of the constraints associated with the implementation of photovoltaic solar parks in association with the case studies considered. Such information was also provided by *Lusiterg – Projetos Energéticos, Lda*. It is important to clarify that it was considered that the constant costs considered would apply to the cash flows inherent to each of the consecutive sub-periods with a duration of d = 30 years, as if such sub-periods always started in the present year. For the same photovoltaic power to be installed, the monetary flows between consecutive sub-periods of 30 years will differ, fundamentally because they are concerned with different photovoltaic energy productions resulting from the different hydrological characteristics of the series and the fact that some of the costs are indexed to these productions.

Starting from the base cost of solar panels of 650 €/kWp, it was decided to carry out a sensitivity analysis with a 10% increase in such cost, leading to the cost of investment in photovoltaic modules of 715 €/ kWp. In an economic period as uncertain as the current one, it was also decided to incorporate three different scenarios into the analysis to define the sale price of electricity from photovoltaic energy, which will contribute to the project's revenue. The pessimistic, optimistic, and intermediate scenarios were then explored, which determine the energy price for subsequent years according to each perspective[17].

Then, the strategy adopted is to calculate the IRR values, resulting from the subdivision of the energy simulation period into smaller cycles (with a duration of d fixed at 30 years). Thus, at the Covas do Barroso HS, the first object of the joint simulation used the flow data between the hydrological years of 1957/1958 and 1986/1987 (i.e., from October 1957 to September 1987) and the last sub-period of the period, the data between 1987/1988 and 2016/2017 (i.e., between October 1987 and September 2017), making a total of 31 sub-periods of 30 years. In the Pinhel HS, the first subperiod had flow data between the hydrological years of 1955/1955 and 1984/1985 (i.e., from October 1955 to September 1985) and the last subperiod, the data between 1981/1982 and 2010/2011 (i.e., between October 1981 and September 2011), making a total of 27 sub-periods of 30 years. In that way, the analysis of economic profitability was carried out by combining all sub-periods of 30 years of simulated hydroelectric and photovoltaic productions, with the two-unit costs adopted for the equipment of the parks, with three scenarios of valorization in the market for the revenue of photovoltaic energy production, and with seven alternatives for the installed power (1 to 7 MWp).

4. Results

Hydroelectric energy

From the transposition of average daily flows in the hydrometric stations, it was possible to simulate and group the data related to the daily hydroelectric energy produced in each scheme. For the Covas do Barroso

HS, 60 years of energy production were simulated, between October 1957 and September 2017. For the Pinhel HS, the simulation period was 56 years, between October 1955 and September 2011.

With the goal of validating the models for transposing hydrometric information and simulating the operation of hydroelectric plants, the productions of both energies were compared at monthly and annual levels and for the periods with operating data available. Regarding the Covas do Barroso HS, the average annual energy resulting from the simulation of its exploration was 16.47 GWh, while the real average annual energy, that is, actually produced, was 15.20 GWh (between October 2005 and September 2021, excluding the period from October 2011 to September 2012 due to lack of complete data). Based on the energies, on the one hand, real according to the exploration data and, on the other hand, obtained by simulating the daily operation of the HS, it was obtained the correlation between them at monthly and annual levels for the time periods in that simultaneously it was possible to analyze both energies, that is, between March 1999 and September 2017. The correlations obtained were 0.956 and 0.997, at monthly and annual levels, respectively.

Regarding the Pinhel HS, the average annual energy calculated for the simulation period was 16.39 GWh, while the real average annual energy was 16.50 GWh (between October 2006 and September 2021). In a similar way to the procedure adopted in Covas do Barroso, it was calculated the correlation between the real energies and those obtained by simulating the daily operation of the plant, at monthly and annual levels for the time periods with simultaneous energy recordings, that is, between April 2004 and September 2011. The correlations obtained at monthly and annual levels were 0.961 and 9.979, respectively.

In the case of both the Covas do Barroso and Pinhel HS, the high correlations between simulated and effectively recorded monthly and annual energies lend credibility to the models used for this purpose, that is, the transposition of hydrometric information and the simulation of the HS production. Thus, it was considered sufficiently reliable to apply the economic analysis to productions in consecutive sub-periods of 30 years in order to assess the effect of hydrological variability, possibly already combined with the consequences of climate change, in assessing the feasibility of investing in hybridization.

Photovoltaic energy

Through the analysis of the simulated values of hydroelectric energy, and as mentioned above, in order to optimize the joint activity of the two renewable sources of electricity production, the simulation of energy production from the solar park admitted different installed photovoltaic powers, between 1 and 7 MWp, allowing the analysis of a greater number of alternatives.

In Covas do Barroso, and for each of those hypotheses of nominal installed power, it was simulated the photovoltaic energy production for 60 years, between October 1957 and September 2017, based on the values of hydroelectric energy simulated in that period, and between October 2005 and September 2021, originated from real values of hydroelectric production (again excluding the period from October 2011 to September 2012 due to lack of records).

In Pinhel, under the same analysis conditions described above, it was simulated 56 years of photovoltaic energy production, between October 1955 and September 2011, based on the simulated hydroelectric production, and between October 2006 and September 2021, related to the real values of hydroelectric energy produced in the corresponding period.

When evaluating those results, it was verified the relevance of analyzing the evolution of photovoltaic energy production as a function of the PV power, not only in gross terms, but also in relative terms. As it would be expected, when the installed power in the solar park increases, the total energy produced through that source also increases. However, when the focus is on photovoltaic energy produced by MWp, it was noticed a decrease as the installed capacity in PV increases. This is due to the fact that, despite the increased availability for the generation of photovoltaic energy, it is not always reflected in its production due to the prioritization of the use of the water source.

Hybrid energy

By selecting some key years, it was possible to verify the low production of hydroelectric energy in dry years, allowing to take advantage of almost all the photovoltaic energy production capacity. In average years, there were wet periods in which the production of hydroelectric energy reached the maximum contracted power, resulting in the occurrence of periods of wastage of available photovoltaic energy. In wet years, the hydroelectric production operated at full load in both HS in most of the time. In those years, the time during which there was no production of photovoltaic energy was very substantial and considerably affected its overall performance. Nevertheless, it was possible to verify the complementarity between the two sources of electricity production in most of the periods analyzed, with a strong water component in the wet periods and a very important solar component in the dry periods.

Economic indicators

In the economic analysis, it was determined the internal rate of return of sequential samples, each with a duration of 30 years, resulting from the subdivision of the total period of records of photovoltaic production into smaller cycles. It was possible to observe a growing trend in the value of IRRs over time, suggesting a natural evolution for investment in that renewable source. It is possible that this trend may be related to a decrease in surface water resources, a fact, however, that has not been investigated. For each HS, it was noticed that the IRRs related to a value of energy revenue in the pessimistic perspective were the ones that registered the lowest values, and the IRRs based on optimistic values registered the highest IRRs. It was concluded that only a pessimistic forecast of revenue from the sale of electricity would result in the economic unfeasibility of the project. The worst results fell mainly on the extreme values of the analyzed powers, between the alternatives of 1 and 7 MWp. Finally, the optimal solution for Covas do Barroso is based on installation between 3 or 4 MWp, and for Pinhel on installation between 4 and 5 MWp.

Bibliografy

[1] Energia elétrica por hibridização: quando a união das energias renováveis faz a força. Disponível em: https://www.iberdrola.com/inovacao/energia-hibrida. (data da consulta: 19/08/2022)

[2] Dados técnicos. (1996). *Aproveitamento hidroelétrico de Covas do Barroso*. Harpenerg – Gestão e Projetos Energéticos, Boticas.

[3] Dados técnicos. (2004). *Aproveitamento hidroelétrico de Pinhel*. Harpenerg – Gestão e Projetos Energéticos, Pinhel.

[4] Beluco, A.; Souza, P. K.; Krenzinger, A. (2003). A Complementariedade no Tempo entre as Energia Hidrelétrica e Fotovoltaica. *Revista Brasileira de Recursos Hídricos*. **8** (1): 99-109.

[5] Caudal médio diário. (2017). Estação hidrométrica de Vale Giestoso (R.E.) (03K/01H). Dados de monitorização da rede hidrométrica. Sistema Nacional de Informação de Recursos Hídricos (SNIRH). Amadora, Portugal.

[6] Caudal médio diário. (2011). Estação hidrométrica de Cidadelhe (R.E.) (08O/02H). Dados de monitorização da rede hidrométrica. Sistema Nacional de Informação de Recursos Hídricos (SNIRH). Amadora, Portugal.

[7] Portela, M. M. (2014). *Da Regionalização de Informação Hidrométrica ao Dimensionamento de Albufeiras de Regularização e à análise de Incertezas*. Lição correspondente ao Sumário a que se refere a alínea c) do Artigo 5º do Decreto-Lei n.º 239/2007, de 19 de junho. Unidade curricular Modelação e Planeamento de Recursos Hídricos, Mestrado em Engenharia Civil, 54 pp., IST, Lisboa.

[8] Quintela, A. C. (1967). *Recursos de águas superficiais em Portugal Continental*. Tese de Doutoramento, Instituto Superior Técnico. Lisboa, Portugal.

[9] Quintela, A. C. (2011). *Hidráulica*. 12ª Edição. Fundação Calouste Gulbenkian. Lisboa, Portugal.

[10] Veríssimo, P. et al. (2020). Area and LCOE consideration in utility-scale, single-axis tracking PV power plant topology optimization. Solar Energy. **211**: 433-445.

[11] Rebelo, S. et al. (2007). *Métodos de Avaliação da Decisão de Investimento: A Realidade Empresarial do Algarv*e. ESGHT, Universidade do Algarve. Faro, Portugal.

[12] Campos, M. D.; Filho, L. S. (2021). O uso da média móvel como indicador de tendência: do mercado financeiro ao acompanhamento dos casos de covid-19. *Negócios em Projeção*. **12** (2): 73-81.

[13] Silva, R. G. et al. (2018). Application of a demand forecasting model in a rental company of billiard tables. *Journal of Engineering and Technology for Industrial Applications*. **4** (15): 53-58.

[14] Costa, R. (2021). *Estimativa preliminar de produção de energia para a Central FV Vila Covas do Barroso*. Megajoule. São Mamede de Infesta.

[15] Costa, R. (2021). *Estimativa preliminar de produção de energia para a Central FV Pinhel*. Megajoule, São Mamede de Infesta.

[16] Suntech Ultra V Series: 144 Half-Cell Monofacial Module 530-550W (2021). Suntech Power Holdings Co., Ltd. Xinwu District, China.

[17] Solar PV: Capture price per unit of resource available – high, central & low. (2021). Hidroerg - Projetos Energéticos Lda, Lisboa.