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A comparative study of a wind hydro hybrid system with water storage capacity: Conventional reservoir or pumped storage plant?

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ABSTRACT

Hydropower reservoirs (of conventional and pumped storage plants) provide dispatchable power and large-scale energy storage. They are a suitable technology in autonomous power systems with high levels of renewable generation, because of their capacity to buffer intermittencies and high variability of renewable energies such as wind and solar power. This paper presents results of a study comparing the operation of a wind hydro hybrid system including a conventional hydropower with a reservoir and including a pumped storage hydropower plant. This comparative study was carried out based on the adaptation of software Homer (The Micropower Optimization Model) to simulate hydropower plants with water storage capacity and to simulate pumped storage hydroelectric plants. The case study of this paper arose from data related to Rio Grande do Sul, in southern Brazil. The case study is based on a river basin in southern Brazil for which two sites were identified; one below where can be installed the engine room and where there is a reasonable area to implement a water reservoir; other above where a reservoir may also be implemented for the case of pumped storage hydropower plant. The results show that the system with pumped storage plant naturally has the highest initial costs, but the optimal solution of the hybrid system with pumped storage plant require a smaller flooded area than the system with conventional reservoir, thus representing a lower environmental impact.

1. Introduction

Besides environmental benefits, one of the main advantages of some renewable energy technologies (like solar and wind power projects) is their reduced construction time. This enables them to provide a more accurate response to the load growth, while minimizing the financial risk that comes with borrowing millions of dollars to finance other types of plants for several years before they start generating their first kW of electricity [52]. However, autonomous power systems with high levels of renewable generation require adequate measures to overcome the intermittency and stochastic nature associated to most of these energy sources, in order to keep the balance between energy supply and consumption. This balance is important to maintain the quality of the electricity supply by regulating the grid frequency and voltage. A combination of dispatchable technologies and energy storage is one of the most common methods to achieve this equilibrium [45].

Besides providing dispatchable power and operating reserve with short start-up times and lower costs, hydropower reservoirs (of conventional and pumped storage hydro) are the main option for large-scale electricity storage in the form of potential energy, enabling their future consumption when the load exceeds the generation capacity available from the renewable source [16]. The generating capacity of conventional hydropower plants with reservoir (HWR) is constrained by site specific features, such as available head, reservoir capacity and hydrological limitations (stream flow entering the reservoir, rainfall, seasonal weather conditions, additional reservoir uses, etc.). Hydropower plants with pumped storage capabilities partially overcome these issues, by recovering rejected (excess) energy from wind or solar farms to refill an upper reservoir, achieving a maximum exploitation of these intermittent renewable resources.

Pumped storage hydropower (PSH), based on the same principles of conventional hydro, is the most widely used large-scale electrical energy storage technology. According to the International Energy Agency International Energy Agency (IEA) [29], at least 140 GW of large-scale energy storage are currently installed in electrical power grids around the world, with 99% of this capacity coming from PSH technologies, and the other 1% from

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a mix of batteries, compressed air energy storage (CAES), flywheels and hydrogen storage. Barnhart and Benson [3] explain that storage is an attractive load-balancing technology because it increases reliability and flexibility of the power grid (especially in locations with ambitious climate-change policies), while at the same time it helps decreasing carbon emissions by reducing the transmission load and enabling spinning power plants to operate at optimum efficiency.

Regarding energy storage through PSH, Glasnovic and Margeta [25] mention that if site conditions are suitable, the smaller reservoirs and different possible configurations of the PSH plants allow building the different components of the hybrid power system close to energy consumers. This would significantly reduce energy losses due to transport, which could range from 8% to 15%. An important consequence of this possibility is the encouragement of new schemes for use of renewable energy resources, such as solar chimneys [42,36].

Regarding the suitability of water reservoirs for application as PSH, Kucukali [34] proposes a basically qualitative method for assessing reservoirs and establish a ranking for the development of storage capacity through plants in an energy system. The method was applied to Turkey and indicated that the reservoirs are suitable for use as power plants. This method can be a powerful tool for the development of legislation that encourages the implementation of this kind of power plants, suitably overcoming the technical requirements.

Increasing the share of renewable energies in the total energy supply is a priority for many countries, caused by economic, environmental and climate change concerns. Unlike fossil fuel power plants, renewable energy sources have a significant impact on the reduction of greenhouse and pollutant gas emissions. However, there are concerns over the ability to effectively integrate large amounts of intermittent power generation, such as solar or wind power, into the electrical grid [16]. Therefore, the main issue for the successful integration of these technologies is how to best manage the intermittency and stochastic nature associated to most of them. Hydropower reservoirs (of conventional and PSH plants) are the most mature and widely used technology to provide dispatchable power and large-scale energy storage, two of the main solutions implemented for a better integration of renewable energies.

During recent years, a number of papers have been published on the subject of size optimization of hybrid power systems including PSH to recover excess energy from intermittent sources, in order to serve the loads in isolated (stand-alone) or autonomous (independent, but able to connect to the grid) hybrid power systems. These papers are based on the application of computer models that are ready and available on the Internet (commercially or not) or that were written by their authors. This paper is focused on creating and implementing tools that can find universal access and application, contributing to popularize the results.

Some of them are the works on Greek islands written by Anagnostopoulos and Papantonis [2], Kaldellis et al. [31] or Kapsali and Kaldellis [32]. Anagnostopoulos and Popantonis [2] presents a numerical methodology for the design of a pumped storage power plant which allows the recovery of rejected energy from wind farms due to grid limitations. The method was applied in some wind farms on the island of Crete, Greece, and revealed among other conclusions the possibility of recovery of 40–60% of the rejected energy. Kaldellis et al. [31] and Kapsali and Kaldellis [32] perform an energy analysis in order to find a techno economical solution which proves an optimal design for a wind hydro hybrid system with pumped storage capacity. This analysis has been developed for application to the island of Lesbos in the Aegean archipelago.

An interesting parameter to be considered which may contribute to the feasibility of hybrid systems is the possible complementarity between energy resources. It is difficult to manipulate the energetic complementarity considering an isolated place but complementarity can be a tool for managers to decide on the prioritization of projects over a certain region. The optimal sizing of generating units and reservoirs and energy storage devices can take into account the complementarity of energy resources, possibly resulting in reduced costs and increased efficiency, as discussed by Beluco et al. [7], Beluco et al. [8].

An important component in this process is the system design considering market linkages and the works of Bayón et al. [4], Malakar et al. [37] and Souza et al. [51] discuss the wind systems operating with reversible hydro power plants inserted respectively into the Spanish, Indian and Portuguese markets. Bueno and Carta [12] also consider this combination to increase the penetration of renewables in the energy system of the Canary Islands. Dursun and Alboyaci [20] studied the influence of this kind of system to meet the electricity demand in Turkey. Ming et al. [38] present an interesting discussion on the participation of reversible hydro power plants in Chinese integrated system, which experienced a large increase of these plants over the past decade. Nejad [39] and Sangi [47] present similar results for PV systems and solar chimneys in Iran.

Glasnovic and Margeta [25] and Glasnovic et al. [26] explore the Concept-H, based exclusively on the use of renewable resources and predominant use of water reservoirs as energy storage. Foley et al. [22] perform a long term study on the cost of power plants considering their influence to firm large wind farms. His model was fitted with the WASP IV software and applied to the electrical system of Ireland and Northern Ireland. The WASP (Wien Automatic System Planning) is a software tool created for the study of the expansion of energy systems. It is a comprehensive study that takes into account technical, economic and environmental aspects. Among others, it is also possible to cite the publications by Castronuovo and Lopes [15], Krajačić et al. [33], Nyamdash et al. [40] and Chang et al. [16].

According to Sinha and Chandel [50], and with thousands of users around the world, Homer is the most widely used tool in research studies related to hybrid power systems, mainly due to its user-friendly interface and detailed documentation. Homer is described by Georgilakis [24] as a computer model that assists in the design of hybrid power systems, including several different power generation technologies for this purpose (PV modules, wind turbines, run-of-river hydropower, batteries, generators, etc.). Homer is mainly an economical model dedicated to system selection and pre-sizing which models the physical behavior and lifecycle cost of a power system. Connolly et al. [17] analyzed 37 different tools for simulation and optimization of hybrid systems and clearly Homer is emphasized among others as one of the most comprehensive tools and simultaneously an easier access tool.

Homer executes three main tasks: simulation, optimization and sensitivity analysis. About the simulation, performing energy balance calculations for each of the 8760 h in a year, Homer estimates the cost and determines the feasibility of a system design. A complete and detailed output is produced for every feasible system configuration in the search space. Regarding optimization, after simulating all the possible system configurations, Homer sorts the feasible projects according to the Net Present Cost (NPC). And, finally, most numerical input variables in Homer (with exception for decision variables) can be sensitivity variables. By assigning more than one value to each input of interest, this capacity of the model is useful to observe how the results could vary, either because the range of values is uncertain or because they represent a variety of possible applications. And one of its greatest advantages is the way the data are presented, allowing full and immediate access to the results.

A weakness of Homer is that the model does not support some renewable technologies, among these, HWR and PSH. However, as explained by Canales and Beluco [13] and Canales et al. [14], one effective way to overcome this shortcoming is to represent the reservoir as an equivalent battery and this approach is used in this document. Future releases or custom versions of Homer might include specific elements to model these components but the Legacy Version, which has universal access, does not have these tools. Even with the limitations of Homer, the adaptations suggested in the above mentioned papers will enable this work to make a comparison of the effects of HWR and PSH on a wind hydro hybrid system.

This paper has four more sections. The next section presents the method used to achieve the optimum size of wind hydro hybrid systems with water storage capacity and the second of these four sections presents a case study. The case study is the evaluation of a wind hydro hybrid system composed of wind turbines on a farm already existing for over ten years (with 150 MW installed) and a pumped storage hydropower plant currently undergoing design studies. This hybrid system was also simulated only with the lower reservoir. The next section presents the simulations carried out with Homer and present the result, discussing these results and forwarding the conclusions presented in the final section.

2. Method

The paper written by Canales and Beluco [13] explained how to model PSH with Homer, an extensively tested tool for assessing the best configuration and performance of hybrid power systems comprising renewable and non-renewable energy sources as well as different devices for energy storage. With a few modifications, the method explained by them can also be used for modeling a conventional HWR, as explained by Canales et al. [14].

Based on these techniques, and besides assessing the optimal system design, this paper compares how a site with potential for both HWR and PSH could be better used in a wind hydro hybrid power system. This objective is achieved by taking advantage of some important features of Homer: the optimization module, its sensitivity analysis capabilities and the detailed output for a simulation period of 8760 h (or one year).

Homer is a software that basically makes an energy balance of the hybrid system being studied, without dynamic considerations, and its applications for feasibility studies and sizing at a basic level do not require calibration and experimental confirmation of the results. Best approaches will be obtained with more appropriate models for power dispatching rules adopted when the system under study have been implemented and are put into operation.

This section has two subsections. The first describes how the hydroelectric power plant will be modeled as a PSH and the second subsection describes how it will be modeled as a HWR.

2.1. Pumped storage hydropower modeling

Hydropower reservoirs and batteries are able to store energy and supply it on demand. This analogy allows the user to create an equivalent battery in Homer for modeling the reservoir. The software considers that the battery properties remain constant during its entire lifetime. According to Canales and Beluco [13], the following equation describes the total stored energy E_S (in kWh) in the active volume of a reservoir Vol (in m^3):

$$E_S = \frac{9.81 \times \eta_{hyd} \times H \times \mathrm{Vol}}{3600} \quad (1)$$

In Eq. (1), H is the effective head (m) and η_{hyd} the efficiency in conversion in turbine mode (%).

Considering a battery with fixed voltage V and with capacity C_B (in Ampere h, Ah) independent of the discharge current, its stored energy is found by the expression:

$$E_S = \frac{V \times C_B}{1000} \quad (2)$$

The power delivered by the battery (in kW) is proportional to the discharge current I (in A), and is calculated by the formula:

$$P_{bat} = \frac{V \times I}{1000} \quad (3)$$

Based on the main features of the pumped hydro site and assuming the gross head as constant, Canales and Beluco [13] explain that PSH can be modeled in Homer through the following three steps: (1) select a reference voltage for the equivalent battery and find the capacity C_B (in A h) of the equivalent battery, proportional to the reservoir volume. The battery must be the only component in the DC bus. (2) In Homer, create an equivalent battery with the previously selected reference voltage and constant capacity found, 100% round trip efficiency and minimum state of charge 0%. The maximum charge current should be proportional to the time required to fill the reservoir. (3) Use the converter to represent the different options for the installed capacity of the hydropower plant. The conversion efficiency in both ways (pump and turbine mode) is controlled via this component.

Besides selecting the required installed capacity from the set of converter sizes to consider, this procedure can be modified to optimize the size of the reservoirs. To do so, a unitary battery is created based on the minimum active volume of the upper reservoir, and different volumes can be assessed by means of a battery bank with more batteries, representing multiples of the reference volume. The cost of the battery must reflect the combined cost of the upper and lower reservoirs.

The method assumes variable speed pump/turbine units. This technology uses asynchronous motor-generators that enable adjusting the pump/turbine rotation speed, regulating the amount of energy absorbed in pumping mode. According to Deane et al. [18], this facilitates energy storage when the grid power levels available are low, and it also reduces the number of starts and stops of the equipment. However, the solutions including synchronous machines and rectifiers are currently more common, as discussed by Hell et al. [28] and Schlunegger and Thöni [48].

2.2. Hydropower plant with reservoir modeling

As described by Canales et al. [14], for each hour of the simulation, Homer uses the following expression to calculate the power output of a hydro turbine:

$$P_{hyd} = \frac{\eta_{hyd} \times H \times \rho_{H20} \times g \times Q}{(1000\mathrm{W/kW})} \quad (4)$$

In this equation, P_{hyd} is the power output of the turbine (kW), ρ_{H2O} the density of water (kg/m^3), g the gravitational acceleration (9.81m/s^2) and Q is the flow rate through the turbine (m^3/s).

With a few modifications, the method described for modeling PSH can be used also for HRW. The procedure requires three components: (1) a DC hydropower turbine, (2) a battery representing the reservoir, and (3) a converter.

For the first component, along with the battery representing the reservoir, this is the only equipment assigned to the DC bus. All losses must be included in the efficiency value, to guarantee that each cubic meter of water, both through the turbines and in the reservoir, represents the same amount of energy. If residual flow is being considered, this should be subtracted before the Homer input. The minimum and maximum flow ratios shall cover the full range of available stream flows. The Homer Legacy version (used in this paper) can consider only one hydroelectric power plant.

For the second component, the battery is the only other equipment on the DC bus. A reference voltage for the equivalent battery must be selected to find a C_B value proportional to the active storage volume of the reservoir. In the same way as in pumped hydropower modeling, the equivalent battery should have a round trip efficiency of 100% and minimum state of charge 0%, with a maximum charge current proportional to the maximum stream flow expected. Losses from withdrawal, evaporation or infiltration are disregarded.

For the third component, the efficiency of the inverter must be 100% and all losses should have been already incorporated in the hydro inputs. By setting the rectifier capacity relative to inverter as zero, the excess electricity from the hydro becomes the only source for refilling the reservoir. Additionally, the inverter must be able to operate in parallel with another AC power source, and the maximum converter size must match the maximum power that could be produced by the hydropower plant.

3. Case study presentation

This section describes the hypothetical autonomous system used as case study in this paper. It was created from real data related to Rio Grande do Sul, a southern state of Brazil. It is important to mention that the wealth of water resources in Brazil allowed the construction of many big hydropower plants with huge reservoirs in the past decades. These plants are the core of the Brazilian National Interconnected Power System (Sistema Interligado Nacional—SIN), which demands a complex operation plan and a transmission grid of approximately 100,000 km.

About 90% of the total energy production of the SIN comes from hydropower [45]. The region complementarity of hydrological and wind regimes, efficiency of the SIN and the abundance of resources are the main reasons why pumped storage hydropower is practically inexistent in Brazil. Environmental concerns related to flooding vast areas (mainly in the Amazonia) and air pollution, as well as incentives for diversifying the electricity generation mix might require the future use of PSH or other energy storage technologies in Brazil [23].

Wind power is used as the intermittent renewable energy source for this case study. As with the majority of renewable technologies, grid planning analysis must take into consideration the fact that most of the time the generation of these plants is lower than the installed nominal power.

The application of Homer, considering the adaptations made to simulate HWR and PSH, in conjunction with the characteristics of the case studied will enable a comparison of the effects of using only one of the reservoirs without pumping and the use of two reservoirs with pumping.

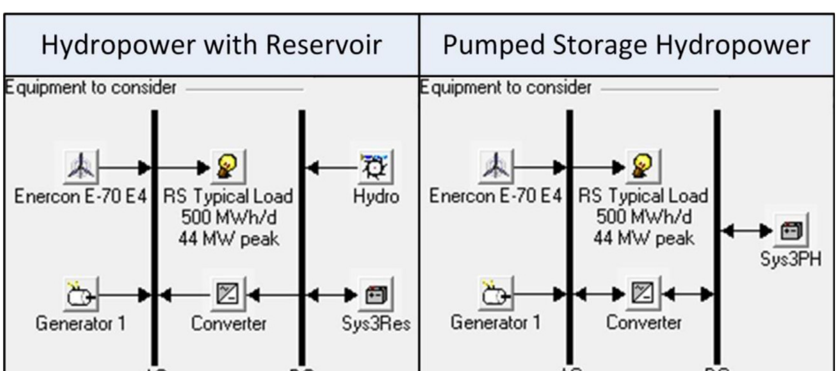
This section has six subsections. The first presents the system configuration. The second and third present respectively hydropower generation and wind turbines. The next two subsections present respectively the diesel gen set and the consumers load. The last subsection makes some additional comments.

3.1. System configuration

Homer simulates the system operation and is able to determine the best long-term configuration of a power system. Its optimization algorithm looks for the system configuration that minimizes the total Net Present Cost. For this case study, the following options were considered to serve an AC load: a set of AC wind power turbines, an AC diesel generator, and one of two options: a HWR or a PSH.

For this paper, the AC load was created from information related to Rio Grande do Sul, and it was scaled to 100MW h/d and 500MW h/d, to validate the model under different demand conditions. Fig. 1 displays the schematic diagram for both systems to consider and its corresponding search space.

To estimate the capital cost of these generating units, two main information sources were used: Pasquali [43] and Braciani [10]. The currency exchange rate used is USD$ 1 = R$ 2.



Search Space							Sensitivities	
	E-70		GEN1	Sys3PH		Converter	AC Load	Diesel
For Hydropower plant with reservoir:	(Quantity)		(kW)	(Quantity)		(kW)	(MWh/d)	Price ($/L)
	0	45	-	0	10	0	100	1
610kW run-of-river hydro installation	10	50	500	1	12	4,600	500	5
722kW converter (No rectifier capacity)	20	55	1,000	2	15	11,500		
1 Sys3Res battery = 1,206,303 kWh	25	60	5,000	4	18	23,000		
	30	65	10,000	5	23	34,500		
	35	70	20,000	7		46,100		
	40	75	30,000			69,100		
			40,000			92,200		
			50,000			115,250		

Fig. 1. Schematic diagrams and search space.

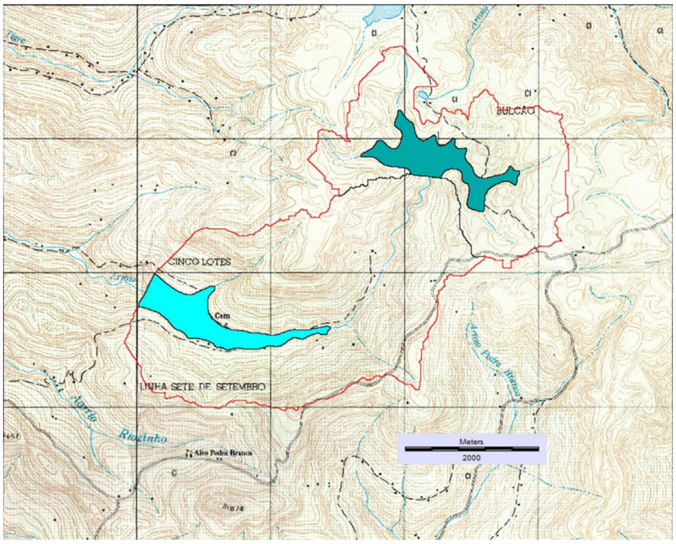


Fig. 2. Basin contour for “System 3” or “Linha Sete” upper and lower reservoirs (adapted from DSG, 1979).

3.2. Hydropower generation and resource

For this case study, only one from two options could be considered for hydropower generation: a HWR or a PSH plant. The basic features and the stream flows used to estimate the power generation capacity are explained in the following subsections. This subsection has three parts: description of the site and the hydroelectric resource, modeling as a HWR and modeling as a PSH.

3.2.1. Location and hydro resource

The representation of the hydropower projects for this case study was made according to the location described by Beluco [6] for “System 3” or “*Linha Sete*”. Fig. 2 shows the basin contour for both reservoirs. This figure was adapted from a small region (~80 km^2) of the Barra de Ouro map sheet (SH.22-X-C-V-1), scale 1:50000, made by the Brazilian Army's Geographic Service Directorate Diretoria de Serviço Geográfico (DSG), 1979 [19].

The estimation of the average monthly stream flow available was based on hydrological methods, as explained for example by [11]. It was used a contiguous basin, assuming that it has the same hydrological characteristics of the one in which the system is located. Since the basins are nearby and very close, no significant errors occur with the adoption of this method. The discharge data series for the Encantado river were obtained from the website of the National Water Agency (Agência Nacional de Águas) of Brazil (http://hidroweb.ana.gov.br/, Station: 86720000).

The watershed area above the gauging Station is 19,200 km^2, above the upper reservoir dam is approximately 6.15 km^2 and 18.5 km^2 above the lower reservoir. Because of the small area above the upper dam, only the lower one is considered feasible for building a hydropower plant with reservoir. As a simplification, the proportion between these areas (0.0964%) was used to determine the monthly average flow for the watershed above the dam, as presented in Fig. 3. The annual average flow was calculated to be 0.539 m^3/s.

Based on the Tennant method described by Benetti et al. [9], 10% of the annual average flow was adopted as the instream or residual flow. Once subtracted this residual flow, the top column with dashed line contour in Fig. 3 shows the stream flow available to the turbines each month.

3.2.2. Representing the hydropower plant with reservoir

As previously explained in the method section, representing a hydropower plant with reservoir in Homer requires three elements: a DC hydropower turbine, a battery representing the reservoir and a converter.

The design flow rate of the hydro turbine was set at 0.70 m^3/s ± 75%, which allows including the whole range of available stream flows given in Fig. 3, as explained in the method section. A variation between 0.248 m^3/s and 0.825 m^3/s is sufficient. The available head used is H = 105 m, based on the assumption that the active volume (Vol) of the reservoir is that contained between elevations 360 m and 350 m, and the turbine is at elevation 250 m. Consequently, the chosen nominal power for the hydro installation is 610 kW. By dividing the average energy available in the run-of-river energy by the corresponding volume discharged during one hour, it yields 0.2432kW h/m^3. The overall efficiency was assumed to be η_{hyd} = 85%, including conversion and pipe head losses.

Regarding the battery representing the reservoir, based on the information at [6], the Vol = 4,960,000 m^3. The total volume is 18,730,000 m^3, and it would take about 15 months to fill based on the estimated average flow. By selecting 10 kV as reference voltage in Eqs. (1) and (2), a total stored energy E_S = 1,206,303 kW h and a capacity C_B = 120,630 A h are found. It can also be observed that dividing the stored energy by the active volume results in the same

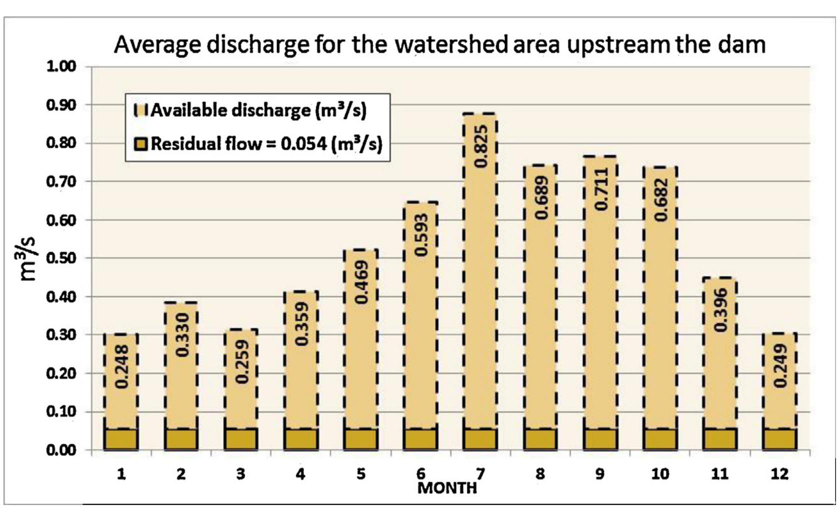


Fig. 3. Average discharge for the watershed area upstream the lower reservoir dam.

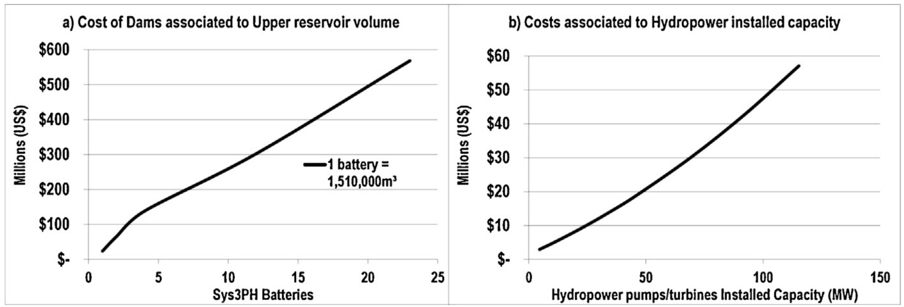


Fig. 4. Relationship between costs and PSH components: (a) Dams; (b) Pumps/turbines installed capacity.

yield of 0.2432 kW h/m^3 found for the hydro installation. The maximum charge current was defined as 100 A, and the maximum charge rate as 100 A/Ah.

The converter represents the maximum power that could be produced by the hydropower plant. For this case study, the size of this component is the one that corresponds to P_{hyd} (Q = 0.825 m^3/s) = 722 kW. The converter will be used only as a converter.

According to Braciani [10], the average cost per installed kilowatt of HWR in Brazil is around USD$ 1324/kW. Around 45% of this cost corresponds to the civil works. In this case study, the capital cost of the project was divided equally among the three Homer components required for representing the hydropower plant with reservoir.

3.2.3. Representing pumped storage hydropower

The "System 3" described by [6] is used as the PSH plant for this case study. The length of the pipes connecting both reservoirs was calculated as 4.5 km, and the available head, taken as a fixed value, is the difference between the lower elevations of both dams. According to [13], PSH plants can be modeled in Homer as a combination of a battery bank and a converter. For this case study, the set of cost functions presented by [43] was used for estimating the PSH cost.

The upper reservoir volume of 1,510,000 m^3, corresponding to elevation 740 m in [6], is used to create the unitary battery for this case study. For the unitary battery, using 10 kV as the reference voltage in Eqs. (1) and (2) produces E_S = 1,933,932 kW h and C_B = 193,393 A h. Dividing the stored energy in the upper reservoir by its volume results in 1.28 kW h/m^3. The maximum charge current was defined as 15,000 A, and the maximum charge rate as 15,000 A/A h. The length of each dam at different elevations, required for cost estimation, was assessed using GIS software. Depending on storage capacity, this case study evaluates several reservoir combinations, represented by the quantity of Sys3PH batteries to consider in the model, as shown in Fig. 1. For this case study, Figure 4a shows the relationship between the dams costs and the storage capacity of the upper reservoir.

This case study will consider several options for the installed capacity of the pumped hydropower plant represented in Homer, as listed in Fig. 1. The conversion efficiency for pumps (rectifier) and turbines (inverter) is set at 85% for both. Except for the dams, all the other PSH costs are included in the converter cost. Fig. 4b shows the relationship between these costs and the installed capacity of the hydropower pumps/turbines for this example.

3.3. Wind turbine and resource

The Osorio Wind Park is used as the template for this case study. According to their website (http://www.ventosdosulenergia.com.br), the installed capacity of the project is 150MW, corresponding to 75 identical ENERCON E-70 E4 wind turbines. The power curve for this equipment is offered in the product overview brochure at the ENERCON website (http://www.enercon.de/en-en/88.htm), accessed on September 2014.

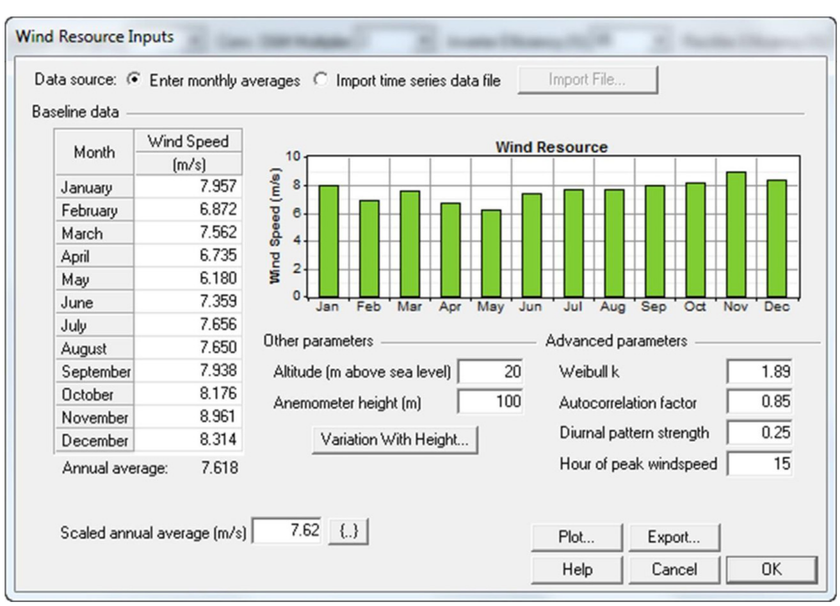


Fig. 5. Wind resource inputs in Homer for the case study.

Fig. 5 shows the wind resource inputs used in Homer. The monthly average wind speed in the Osorio Wind Park at 100m above ground was extracted from Silva [49]. These data were used to generate a synthetic series of hourly wind speed data to the operation site of the wind turbines of the Osorio Wind Park. The synthetic series was generated by Homer.

According to Silva [49], measures of wind velocity made by the wind park operator found an average annual Weibull shape factor equal to 1.89, with the hour of peak wind speed at 15 h. The Weibull shape factor, with a typical range from 1.5 to 2.5, refers to the shape of a distribution of wind speeds, with higher values indicating that wind speed tend to stay within a narrow range.

Based on [10], the average cost per installed kilowatt in wind farms in Brazil is around USD$ 2156.50/kW. By using this value, the initial cost of each E-70 turbine was set at USD$ 4313,000 in Homer.

3.4. Diesel generator set

For this case study, an AC diesel generator with Homer's default settings is considered as one of the options to serve the load. Two different diesel prices were evaluated in the sensibility analysis: U $5/L and U$1/L. Several generator sizes were considered, as described in Fig. 1, with the technical minimum load ratio set at 30%, according to Kaldellis et al. [31] for heavy oil and diesel engines.

No cost penalties for emissions were assigned in this case study. However, along with the price of fossil fuels, the greenhouse and pollutant gas emissions usually play a significant role in the viability of renewable energy projects. As cited by Glasnovic and Margeta [25], it is estimated that coal power plants emit 0.955 kg CO_2/kWh, oil driven power plants emit 0.893 kg CO_2/kWh and gas power plants 0.599 kg CO_2/kWh.

For cost calculations in Homer, the average cost per installed kilowatt for a thermoelectric plant in Brazil is set at USD$ 1073.50/kW, according to Braciani [10].

3.5. Load

The AC load profile used as baseline for this case study was created from data related to Porto Alegre, capital city of Rio Grande do Sul. For non-touristic cities of the state, the behavior of electricity demand trough the seasons is likely to be similar.

Fig. 6a presents the scaled monthly load profile, represented as a percentage of the average daily load. This graph was created based on the information reported by [27] regarding the total monthly load consumption in Porto Alegre for the years 1997 and 1998. As for the daily profile, [44] obtained the typical daily load curve for the residential customer (151–300 kW h/month) in Porto Alegre. These hourly values were converted so that they represent the loads in terms of percentage of the total daily load, as shown in Fig. 6b.

In order to be used as data source by Homer, the information from both graphs in Fig. 6 was combined to create a load profile with the average electric demand (in kW) for the 8760 h in a year. The average baseline demand was set at 100 kW h/d. As previously mentioned, this baseline was scaled to 100MW h/d and 500MW h/d, to assess the optimal system configuration for different scenarios by means of the Homer software features.

3.6. Additional considerations

Besides the information and parameters described before, some other considerations and assumptions were made for modeling the system described in Homer.

For the operating reserve, the 10% Homer default value is used, indicating that the system must operate with enough spare capacity to serve an abrupt 10% increase in the load. The maximum acceptable capacity shortage was set at zero and the dispatch policy is the load-following strategy.

The wind power operating reserve was set at 50%, representing that the system must keep enough spare capacity operating to serve the load even if the wind turbine output suddenly decreases 50%. Besides working as spinning reserve, the importance of this reserve is supported by Sovacool [52], who mentions that, even though is possible to forecast the wind generator output a day in advance, forecast errors of 20%-50% are not unusual.

The project and equipment lifetime was set at 20 years, with an annual real interest rate of 6%. For estimating the operating and maintenance (O&M) cost of the different components, the following values were adopted: (1) for a conventional hydropower installation and the hydropower reservoirs (represented as batteries), the O&M annual cost was set as 3% of the capital cost of the equipment, according to [30]; (2) for a pumped storage hydropower installation (not including the reservoir), represented in Homer by means of the converter, it was assumed an O&M annual cost of 6% of the capital cost, based on the observations made by [46], who indicates that the overhauling is twice more frequent than in HWR; (3) for the wind turbines, it was adopted an O&M annual cost of 4%, a conservative estimate based on [35]. They state that for new large turbines, costs for service, consumables, repair, insurance, administration, lease of site, etc. range from 2 to 3.5% of the capital cost; (4) the operating and maintenance cost for the AC diesel generator was set at USD$ 0.01/kW per hour.

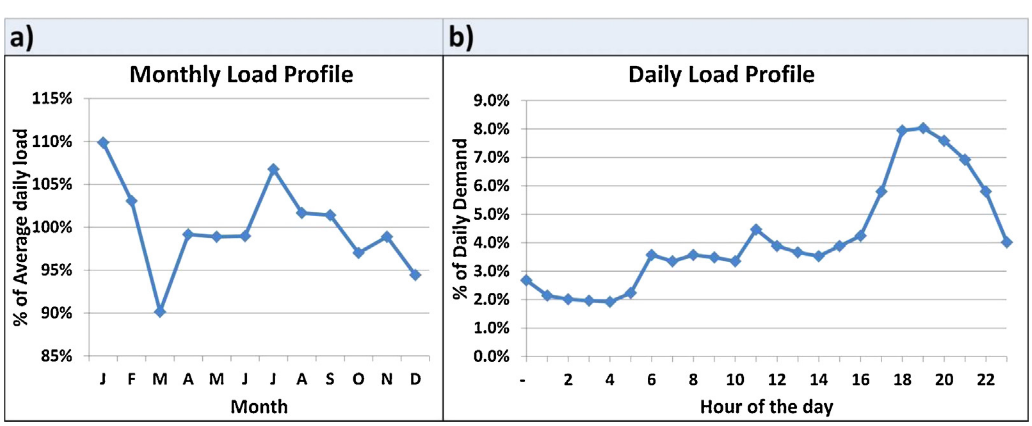


Fig. 6. Scaled load profiles for the case study.

HYBRID POWER SYSTEM CONSIDERING HYDROPOWER WITH RESERVOIR

E-70	Hydro (kW)	GEN1 (kW)	Sys3Res	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	GEN1 (hrs)
10	610	10000	1	722	$ 54,675,000	14,528,280	$ 221,313,232	0.529	0.78	8,890,770	5,365
10	610	10000		722	$ 54,405,000	15,089,922	$ 227,485,216	0.543	0.77	9,294,270	5,561
10		10000			$ 53,865,000	15,762,546	$ 234,660,160	0.560	0.75	9,801,867	5,779
	610	10000	1	722	$ 11,545,000	22,317,564	$ 267,525,712	0.639	0.10	15,567,108	8,760
	610	10000		722	$ 11,275,000	22,672,540	$ 271,327,264	0.648	0.09	15,930,185	8,760
		10000			$ 10,735,000	23,321,624	$ 278,232,192	0.665	0.00	16,595,468	8,760

HYBRID POWER SYSTEM CONSIDERING PUMPED STORAGE HYDROPOWER

E-70	GEN1 (kW)	Sys3PH	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	GEN1 (hrs)
10		1	11500	$ 72,096,096	2,751,166	$ 103,651,752	0.248	1.00		
10	500	1	11500	$ 72,632,848	2,736,866	$ 104,024,488	0.248	1.00		0
10	10000			$ 53,865,000	15,762,546	$ 234,660,160	0.560	0.75	9,801,867	5,779
	10000			$ 10,735,000	23,321,624	$ 278,232,192	0.665	0.00	16,595,468	8,760

Fig. 7. Homer optimization results for both hydropower options. Load: 100 MWh/d; diesel price: USD$ 1/L.

4. Simulation results and discussion

By using the procedures and case study data previously described, the main results obtained by the simulation with Homer are presented and discussed in this section.

The procedures explained in the method section allow determining the best use of a site with potential for both HWR and PSH in a hybrid power system. An example of this is shown in Fig. 7, where the best options are sorted in terms of the NPC of the feasible system designs.

Using the conditions described in the case study presentation, with a scaled annual average primary load of 100 MW h/d and diesel price of USD$ 1/L, some remarks can be made:

(1) With capacity of less than half of each wind turbine, it was clear since the case study presentation that the HWR with reservoir would probably not be much appealing for a system of this size or bigger. While including this component is the best option in terms of NPC and increases the renewable fraction in 3%, this also does not reduce the size of the required generator or its total run time during the year. This is evident when the system design does not include wind power and the generator must operate 100% of the time.

(2) A pumped hydropower scheme, while not necessarily adding more renewable electricity to the system, it would enable further integration of variable (or intermittent) sources of renewable energy. For both hydropower options, the best system design for this scenario would include ten E-70 wind turbines. For this load scenario, the difference between them is that the scheme with PSH (with 11.5 MW of installed capacity) does not require a diesel generator, allowing a 100% renewable generation to serve the AC load of 100MWh/d. The estimated excess energy for the system with pumped hydro is 33.6%, and 56.2% for the scheme with the small hydropower plant (Table 1).

(3) The initial capital cost of the system including PSH would be 33% higher when compared to the one with HWR, mostly because of the additional reservoir and the pump/turbine units of greater capacity. However, after 20 years and with the parameters already defined, the NPC of the system with PSH is only 47% of the other configuration, mainly because the savings on fuel, with less emissions of greenhouse gases as an additional benefit.

(4) Among the considered sizes for the upper reservoir of the PSH plant, the minimum volume is enough to serve the AC load, as it can be seen in Fig. 7 at the column with the number of Sys3PH batteries. According to [6], the flooded area and volume of both PSH reservoirs combined (0.225 km^2; 4.0hm^3) would be less than the one of the HWR (0.561 km^2; 18.7 hm^3).

Limited by the geographic and hydrological constraints at this site, the impact of the conventional hydropower plant in the system decreases as the average primary load increases, and thus the number of wind turbines and size of the diesel generator becomes a function of the fuel price and cost of each wind turbine.

Mainly because of the small watershed area above the lower reservoir dam and the corresponding available stream flows, the HWR potential for this case study is only a fraction of what can be installed for pumped hydropower. The capacity to perform this kind of comparison is particularly important because single dams of hydropower plants can be transformed into pumped hydro if a site suitable for a second reservoir is available. This suitability requires two main conditions: being vertically separated a few hundred meters, but not too distant in the horizontal direction from the existing reservoir. As cited by [21], this transformation of single reservoirs is perhaps the simplest way to add energy storage capacity to the grid, has lower costs than new pumped hydropower systems and lower environmental impacts than new hydropower plants with reservoir.

The range of COE values obtained for the different system configurations of this case study is higher than the range published

Table 1
Output summary for the best system design for 500 MWh/d AC load with different diesel prices.

	Description	Units	With diesel price = USD$1/L	With diesel price = USD$5/L	Additional notes
(1)	ENERCON E-70	Units	40	45	2 MW capacity each wind turbine
(2)	Volume of the reservoir	m^3	1,510,000	3,020,000	1.51×10^6 m^3 = 1 battery = 1.93 GWh
(3)	Hydropower pumps/turbines	MW	46.1	46.1	85% efficiency for both operating modes
(4)	AC diesel generator	MW	40.0	–	Min. load ratio 30%
(5)	Energy from wind power	GWh	249.6	280.8	Including excess electricity
(6)	Energy consumed by pumps	GWh	91.1	93.2	Rectifier input in Homer simulation
(7)	Energy produced by hydro turbines	GWh	66.0	67.5	Inverter output in Homer simulation
(8)	Energy from diesel generator	GWh	5.5	–	
(9)	Excess electricity	GWh	47.5	72.5	
(10)	Total AC Load	GWh	182.5	182.5	
(11)	Net energy from reservoir	GWh	0.2	0.1	
(12)	Final% of volume in the reservoir	%	89.6	96.5	Final state of charge of the battery in Homer
(13)	Net Present Cost	USD$	$379,705,696	$402,920,160	Best system in terms of NPC for each situation

by the Electric Energy National Agency (Agência Nacional de Energia Elétrica—ANEEL) of Brazil. According to Agência Nacional de Energia Elétrica (ANEEL) (2008) [1], and using the same currency exchange rate applied before, the COE in Brazil ranges from USD$ 0.05/kWh (small hydro and biomass) to USD$ 0.25/kWh (diesel). Besides the considerations made about the cost of the components, the main reasons for this difference are: (1) The simplification of assuming 20 years as the project lifetime and of all its components; (2) The wind profile characteristics, with a maximum attainable capacity factor of 35.6% for the wind turbines. A more uniform wind profile and a more accurate lifetime of each component would reduce the COE values found by Homer (e.g., the adopted lifetime of civil works in hydropower projects is usually between 30 and 40 years).

Another factor affecting the COE value is the amount of excess electricity, which could be sold to another grid or used to supply power to deferrable loads, instead of rejecting it by leaving wind turbines offline. [41] indicate that there are several large-scale industrial and commercial deferrable loads that might use this excess electricity, such as thermal storage, heating, air conditioning, pumps, agitators, smelters, wastewater and desalination plants, among others. The plug-in electric vehicles are also an emerging source of flexibility which could revolutionize the ability to incorporate intermittent renewable energy sources, with some test projects in Denmark and California in the process of implementation.

5. Conclusions

This paper presented a comparative study on the use of a HWR or a PSH applied to a wind hydro hybrid system. A case study in southern Brazil was the basis for this study. The procedures described in this paper are based on the work by Canales and Beluco [13] and Canales et al. [14], where they modelled a hydropower reservoir as an equivalent battery in Homer.

Among the main findings of this study, the results show that the procedures explained are useful to define the best use of a site with potential for both conventional HWR and PSH in a hybrid power system, and that the selection and optimal sizing of one of these options depends on many factors such as hydrological constraints, average load to serve and costs of other energy sources.

Additionally, under some conditions and combined with intermittent renewable sources, it was observed that PSH is an efficient way to minimize costs with additional environmental benefits when compared to fossil fuel power plants (PSH produces less emissions) or conventional HWR (PSH can have more installed capacity with less area and reservoir volume).

The comparison made between wind hydro hybrid systems containing HWR and PSH led to an interesting conclusion. The hybrid system containing PSH naturally has the highest initial costs, but present lower operation costs and the optimal solution of the hybrid system with PSH require a smaller flooded area than the optimal solution of the hybrid system with HWR, thus representing a lower environmental impact.

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References

[1] Agência Nacional de Energia Elétrica (ANEEL), 2008. Atlas de energia elétrica do Brasil, Brasília DF, 3rd ed. Available at: http://www.aneel.gov.br/arquivos/PDF/atlas3ed.pdf.

[2] J.S. Anagnostopoulos, D.E. Papantonis, Simulation and size optimization of a pumped—storage power plant for the recovery of wind-farms rejected energy, Renew. Energy 33 (2008) 1685–1694, doi:http://dx.doi.org/10.1016/j.rser.2010.12.016.

[3] C.J. Barnhart, S.M. Benson, On the importance of reducing the energetic and material demands of electrical energy storage, Energy Environ. Sci. 6 (2013) 1083–1092, doi:http://dx.doi.org/10.1039/c3ee24040a.

[4] L. Bayón, J.M. Grau, M.M. Ruiz, P.M. Suárez, Mathematical modelling of the combined optimization of a pumped storage hydro plant and a wind park, Math. Comp. Model. 57 (2013) 2024–2028, doi:http://dx.doi.org/10.1016/j.mcm.2012.03.007.

[6] Beluco A., 2012. Três locais para implantação de usina hidrelétrica reversível ao sul dos Aparados da Serra, no litoral norte do RS, PCH. Notícias & SHP News 52, 32–37. Available at: http://www.cerpch.unifei.edu.br/exibir_rev.php?id=52.

[7] A. Beluco, P.K. Souza, A. Krenzinger, A method to evaluate the effect of complementarity in time between hydro and solar energy on the performance of hybrid hydro PV generating plants, Renew. Energy 45 (2012) 24–30, doi:http://dx.doi.org/10.1016/j.renene.2012.01.096.

[8] A. Beluco, P.K. Souza, F.P. Livi, J. Caux, Energetic complementarity with hydropower and the possibility of storage in batteries and water reservoirs, in: B. Sørensen (Ed.), Solar Energy Storage, Academic Press, Amsterdan, Netherlands, 2012 doi: 10.1016/B978-0-12-409540-3.00007-4 (Chapter 7).

[9] A.D. Benetti, A.E. Lanna, M.S. Cobalchini, Metodologias para Determinação de Vazões Ecológicas em Rios, Rev. Bras. Rec. Hídricos 8 (2003) 149–160. http://www.abrh.org.br/SGCv3/index.php?PUB=1.

[10] Braciani U., 2011. Estrutura de Custos para Implantação das Usinas de Geração de Energia Elétrica no Brasil, BSc. Thesis in Economic Sciences, Universidade Federal de Santa Catarina—UFSC, Florianópolis.

[11] W. Brutsaert, Hydrology, An Introduction, Cambridge University Press, 2005 p. 618.

[12] C. Bueno, J.A. Carta, Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands, Renew. Sustain. Energy Rev. 10 (2006) 312–340, doi:http://dx.doi.org/10.1016/j.rser.2004.09.005.

[13] F.A. Canales, A. Beluco, Modeling pumped hydro storage with The Micropower Optimization Model (Homer), J. Renew. Sust. Energy 6 (2014) 043131, doi:http://dx.doi.org/10.1063/1.4893077.

[14] F.A. Canales, A. Beluco, C.A.M. Mendes, Modeling a hydro power plant with reservoir with The Micropower Optimization Model (Homer), Int. J. Sust. Energy (2015) approved for publication.

[15] E.D. Castronuovo, J.A.P. Lopes, Optimal operation and hydro storage sizing of a wind-hydro power plan, Int. J. Electr. Power Energy Syst. 26 (2004) 771–778, doi:http://dx.doi.org/10.1016/j.ijepes.2004.08.002.

[16] M.K. Chang, J.D. Eichman, F. Mueller, S. Samuelsen, Buffering intermittent renewable power with hydroelectric generation: a case study in California, Appl. Energy 112 (2013) 1–11, doi:http://dx.doi.org/10.1016/j.apenergy.2013.04.092.

[17] D. Connolly, H. Lund, B.V. Mathiesen, M. Leahy, A review of computer tools for analyzing the integration of renewable energy into various energy systems, Appl. Energy 87 (2010) 1059–1082, doi:http://dx.doi.org/10.1016/j.apenenergy.2009.09.026.

[18] J.P. Deane, B.P. Gallachóir, E.J. McKeogh, Techno-economic review of existing and new pumped hydro energy storage plant, Renew. Sust. Energy Rev. 14 (2010) 1293–1302, doi:http://dx.doi.org/10.1016/j.rser.2009.11.015.

[19] Diretoria de Serviço Geográfico (DSG). Barra de Ouro, Rio Grande do Sul, FOLHA SH.22-X-C-V-1, Scale 1:50000, Ministério do Exército, Brasil, (1979).

[20] B. Dursun, B. Alboyaci, The contribution of wind hydro pumped storage systems in meeting Turkey's electric energy demand, Renew. Sustain. Energy Rev. 14 (2010) 1979–1988, doi:http://dx.doi.org/10.1016/j.rser.2010.03.030.

[21] N. Fitzgerald, A. Lacal, R. rantegui, E. McKeogh, P. Leahy, A GIS-based model to calculate the potential for transforming conventional hydropower schemes and non-hydro reservoirs to pumped hydropower schemes, Energy 41 (2012) 483–490, doi:http://dx.doi.org/10.1016/j.energy.2012.02.044.

[22] A.M. Foley, P.G. Leahy, K. Li, E.J. McKeogh, A.P. Morrison, A long-term analysis of pumped hydro storage to firm wind power, Appl. Energy 137 (2015) 638–648, doi:http://dx.doi.org/10.1016/j.apenergy.2014.07.020.

[23] C.R. Galhardo, Os desafios para implantação de usinas hidrelétricas reversíveis no Brasil, PCH, Notícias & SHP News 55 (2012) 32–33. http://www.cerpch.unifei.edu.br/exibir_rev.php?id=55.

[24] P.S. Georgilakis, State-of-the-art of decision support systems for the choice of renewable energy sources for energy supply in isolated regions, Int. J. Distr. Energy Resour. 2 (2006) 129–150.

[25] Z. Glasnovic, J. Margeta, Vision of total renewable electricity scenario, Renew. Sustain. Energy Rev. 15 (2011) 1873–1884, doi:http://dx.doi.org/10.1016/j.rser.2010.12.016.

[26] Z. Glasnovic, M. Rogošić, J. Margeta, A model for optimal sizing of solar thermal hydroelectric power plant, Solar energy 85 (2011) 794–807, doi:http://dx.doi.org/10.1016/j.solener.2011.01.015.

[27] A.M.D. Hansen, Padrões de consumo de energia elétrica em diferentes tipologias de edificações residenciais, em Porto Alegre, MSc. Thesis in Civil Engineering, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, 2000.

[28] J. Hell, A. Lechner, M. Egretzberger, R. Schürhuber, Y. Vaillant, Frequency Converter Solutions for more flexible Pumped Storage Applications, A case study, Proc. HydroVision (2013) . pennwell.websds.net/2013/Moscow/rp-hvr/slideshows/T3S3O4-slides-en.pdf.

[29] International Energy Agency (IEA), Technology Roadmap: Energy Storage, IEA, Paris, 2014. http://www.iea.org/publications/freepublications/publication/technology-roadmap-energy-storage-.html.

[30] T. Jiandong, Z. Naibo, W. Xianhuan, H. Jing, D. Huishen, Mini Hydropower, John Wiley and Sons, Chichester, 1997.

[31] J.K. Kaldellis, M. Kapsali, K.A. Kavadias, Energy balance analysis of wind-based pumped hydro storage systems in remote island electrical networks, Appl. Energy 87 (2010) 2427–2437, doi:http://dx.doi.org/10.1016/j.apenergy.2010.02.016.

[32] M. Kapsali, J.K. Kaldellis, Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms, Appl. Energy 87 (2010) 3475–3485, doi:http://dx.doi.org/10.1016/j.apenergy.2010.05.026.

[33] G. Krajačić, N. Duić, M.D.G. Carvalho, How to achieve a 100% RES electricity supply for Portugal? Appl. Energy 88 (2011) 508–517, doi:http://dx.doi.org/10.1016/j.apenergy.2010.09.006.

[34] S. Kucukali, Finding the most suitable hydropower reservoirs for the development of pumped storage schemes: an integrated approach, Renew. Sustain. Energy Rev. 37 (2014) 502–508, doi:http://dx.doi.org/10.1016/j.rser.2014.05.052.

[35] J. Lemming, P.E. Morthorst, N.E. Clausen, P.H. Jensen, Contribution to the chapter on wind power energy technology perspectives 2008, Risø, National Laboratory for Sustainable Energy, Denmark, 2009 http://www.risoe.dk/rispubl/reports/ris-r-1674 pdf.

[36] J. Li, P. Gui, Y. Wang, Effects of collector radius and chimney height on power output of a solar chimney power plant with turbines, Renew. Energ. 47 (2012) 21–28, doi:http://dx.doi.org/10.1016/j.renene.2012.03.018.

[37] T. Malakar, S.K. Goswami, A.K. Sinha, Optimum scheduling of micro grid connected wind pumped storage hydro plant in a frequency based pricing environment, Electr. Power Energy Syst. 54 (2014) 341–351, doi:http://dx.doi.org/10.1016/j.ijepes.2013.07.021.

[38] Z. Ming, Z. Kun, L. Daoxin, Overall review of pumped hydro energy storage in China: status quo, operation mechanism and policy barriers, Renew. Sustain. Energy Rev. 17 (2013) 35–43, doi:http://dx.doi.org/10.1016/j.rser.2012.05.024.

[39] R.M. Nejad, A survey on performance of photovoltaics systems in Iran, Iran. J. Energy Environ. 6 (2015) 77–85, doi:http://dx.doi.org/10.5829/idosi.ijee.2015.06.02.01.

[40] B. Nyamdash, E. Denny, M. O'Malley, The viability of balancing wind generation with large scale energy storage, Energy Policy 38 (2010) 7200–7208, doi:http://dx.doi.org/10.1016//j.enpol.2010.07.050.

[41] A. Papavasiliou, S.S. Oren, Coupling wind generators with deferrable loads, Energy 2030 Conference, ENERGY 2008, IEEE 1 (7) (2008) 17–18, doi:http://dx.doi.org/10.1109/ENERGY.2008.4781058.

[42] S.V. Panse, A.S. Jadhav, A.S. Gudekar, J.B. Joshi, Inclined solar chimney for power production, Energy Convers. Manag. 52 (2011) 3096–3102, doi:http://dx.doi.org/10.1016/j.enconman.2011.05.001.

[43] L.M. Pasquali, Estudo sobre a influência da reservação hidráulica em sistemas de geração eólica isolados, MSc. Thesis in Water Resources, Universidade Federal do Rio Grande do Sul ?UFRGS, Porto Alegre, 2006 p. 67.

[44] S.B. Rahde, J.W.M. Kaehler, Modelagem da Curva de Carga das Faixas de Consumo de Energia Elétrica Residencial a partir da aplicação de um programa de Gerenciamento de energia pelo Lado da Demanda, M.V.A. Bianchi, S.L.G. de Andrade, M. Metz (Eds.), ENCIT 2000: Proceedings of the 8th Brazilian Congress of Thermal Engineering and Sciences (2000) Brazilian Society of Mechanical Sciences, Rio de Janeiro, 2000, S09P18. [Available at: http://www.abcm.org.br/pt/wp-content/anais/encit/2000/arquivos/s09/s09p18 pdf]..

[45] L.B. Reis, Geração de energia elétrica: Tecnologia, inserção ambiental, planejamento, operação e análise de viabilidade, 1st ed., Barueri, Manole, 2003.

[46] B.E. Sadden, Maintenance of pumped storage plants, in: pumped storage, Proceedings of the conference organized by the Institution of Civil Engineers at Imperial College of Science, Technology and Medicine, Douglas T.H. (1990) 117–141.

[47] R. Sangi, Performance evaluation of solar chimney power plants in Iran, Renew. Sustain. Energy Rev. 16 (2012) 704–710, doi:http://dx.doi.org/10.1016/j.rser.2011.08.035.

[48] H. Schlunegger, A. Thöni, 100 MW full-size converter in the Grimsel 2 pumped-storage plant, Proc. 2013 HYDRO Conference (2013) . www.grimselstrom.ch/home/download/1291.

[49] J.S. Silva, Viabilidade de geração de energia elétrica através de ondas oceânicas no litoral norte do Rio Grande do Sul: estudo de um sistema híbrido de energias renováveis, MSc. Thesis in Water Resources, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, 2012.

[50] S. Sinha, S.S. Chandel, Review of software tools for hybrid renewable energy systems, Renew. Sustain. Energy Rev. 32 (2014) 192–205, doi:http://dx.doi.org/10.1016/j.rser.2014.01.035.

[51] J.A.M. Souza, F. Teixeira, S. Faias, Impacto f a price maker pumped storage hydro unit on the integration of wind energy in power systems, Energy 69 (2014) 3–11, doi:http://dx.doi.org/10.1016/j.energy.2014.03.039.

[52] B.K. Sovacool, The intermittency of wind, solar and renewable electricity generators: Technical barrier or rhetorical excuse? Utilities Policy 17 (2009) 288–296, doi:http://dx.doi.org/10.1016/j.jup.2008.07.001.