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JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **6**, 043131 (2014)

Modeling pumped hydro storage with the micropower optimization model (HOMER)

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Most renewable energy technologies suffer from an intermittent characteristic due to the diurnal and seasonal patterns of the natural resources needed for power generation; therefore, a complementary energy storage system must be considered. The pumped hydropower plant is a suitable alternative to consider as an energy storage device for hybrid systems. The hybrid optimization model for electric renewables (HOMER) optimization model is widely used around the globe for designing, comparing, or evaluating the performance of hybrid power systems, but it does not include an explicit component to model a pumped hydropower facility. This paper describes a method for representing a pumped hydropower plant by creating an equivalent battery in HOMER, and the procedure was accompanied by a detailed example. An additional example of a wind-hydro hybrid power system with controlled parameters is presented to validate the method. The results support that the procedure explained in this paper adequately represents the pumped hydropower plant as an equivalent battery. © *2014 AIP Publishing LLC*.
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I. INTRODUCTION

One of the main problems with most renewable or low-carbon technologies for power generation is the inflexibility of their operation. This is because their power output generally depends on diurnal and seasonal patterns of the corresponding natural resources (wind, solar radiation, tides, streamflow, etc.) used for generating electricity. For this reason, Yang and Jackson (2011) state that utility-scale electricity storage to maintain balance and prevent blackouts remains a significant barrier to a de-carbonized power system. There are only two large-scale (>100 MW) technologies available commercially for grid-tied electricity storage, pumped hydro energy storage and compressed air energy storage. Of the two, pumped hydro is far more widely adopted.

Pumped hydropower plants use excess or off-peak electricity to pump water from a lower reservoir into an upper one to store energy. When the water stored in the upper reservoir is released, it passes through hydraulic turbines to generate electricity. The off-peak energy used to pump the water can be stored indeterminately as potential energy in the upper reservoir. Thus, two reservoirs in combination can be used to store electrical energy for a long period of time, and in large quantities.

According to Ingram (2009), more than 127 GW of pumped-storage hydropower capacity were operating worldwide in 2009. By that time, solely in China, ten major pumped hydropower plants were under construction for a 12 GW total capacity (Huang and Yan, 2009).

The capability to store great amounts of energy, along with the maturity of the technologies involved in hydropower generation, turns the pumped hydropower plant in a suitable alternative to consider as an energy storage device for hybrid power systems. Some papers related to this subject are the works by Bakos (2002), Castronuovo and Lopes (2004), Anagnostopoulos and Papantonis (2008), and Islam (2012), among many others. For designing, comparing, or evaluating the performance of hybrid power systems, one of the main software used worldwide is the

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Hybrid Optimization Model for Electric Renewables (HOMER), which was developed by the National Renewable Energy Lab, a division of the U.S. Department of Energy.

It is important to mention that, in this paper, using a similar definition as in Lukuyu and Cardell (2014), a hybrid power system is a small and often stand-alone system that produces electricity employing more than one generating technology, usually comprising one or more renewable energy sources and their corresponding storage devices.

The software HOMER, known as "Micropower Optimization Model," is a software that performs an energy balance and a set of cost calculations on a hybrid system assembled from existing internal models. It is possible to simulate systems containing hydro power plants, photovoltaic modules, wind turbines, batteries, diesel gen sets, and other typical components of micro and small hybrid systems. Lambert *et al*. (2006) describe the software, which was originally developed by the National Renewable Energy Laboratory, U.S. Department of Energy. HOMER simulates the system configured for various dimensions of its components and various energy potentials, building a solution space that allows identification of an optimal solution, which will be most suitable for the problem at hand. Unfortunately, HOMER has no internal models for reversible hydro power plants, which has motivated this work.

To overcome the lack of a specific pumped hydro component in HOMER, Islam (2012) used components included with HOMER to account for the pumped hydropower plant in his work, specifically T-105 batteries. However, there are some shortcomings worth mentioning for this approach: (1) For normal batteries their storage capacity depends on the rate at which energy is withdrawn, and that is not the case for an hydropower plant, whose capacity is given by the water balance and size of its reservoir; therefore, it is not as heavily affected by the rate of energy withdrawal. (2) The need of an enormous quantity of batteries to represent large hydropower plants, something that could make hard to keep focus on what information the user is trying to get from the model and its results, or what this quantity means in terms of equivalent units.

With the objective of allowing a more accurate description of a pumped hydropower plant using the current features of HOMER, this work explains a method for representing the pumped hydro as an equivalent battery. To do so, this paper presents the basics that would allow describing the behavior of a pumped hydro as battery, based on its main characteristics and a few other considerations. An example is also presented of a wind-hydro hybrid power system with controlled parameters to validate the method. The version of the software used for this work was the HOMER Legacy Version 2.68 available at http://homerenergy.com/. Newer versions may be easier for this adaptation, but the Legacy version was chosen because of its universal access.

II. MODELING PUMPED HYDRO AS A BATTERY IN HOMER

A. Concepts and equations

In this paper, following a suggestion made by HOMER Energy (2010), the pumped hydro is modeled as an electrical storage mechanism with a particular capacity and a particular round-trip efficiency. This section will explain the methods and considerations used in the creation of a battery equivalent to a pumped hydropower plant. Some basic definitions and equations are provided next for allowing a better understanding of the relationships established between a battery and a pumped hydropower plant.

In Physics, power is defined as the rate of doing work, or as the rate of transfer of energy. Rizzoni (2009) explains that the electric power P generated by an active element, or that dissipated or stored by a passive element, is equal to the product of the voltage V across the element and the current I flowing through it. It is easy to prove that the units of voltage (J/C, or volts V) times current (C/s, or Amperes A) are actually those of power (J/s, or watts W). This property is particularly important for the representation of pumped hydro as an equivalent battery, where the voltage is considered as fixed and the delivered power is directly proportional to the current. The equation is

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$$P = V \cdot I. \tag{1}$$

For hydropower generation, Loucks and Van Beek (2005) describe that a cubic meter of water, weighing 10^3 kg, falling a distance of 1 m, acquires 9810 J (N·m) of kinetic energy. The energy generated in 1 sec equals the watts of power P produced. Hence, an average flow Q (m^3/s) falling a height H (m) and affected by an efficiency in conversion η, combine in the following equation to calculate the yield in kilowatts of power:

$$P = 9.81 \cdot \eta \cdot Q \cdot H. \tag{2}$$

Multiplying P by the number of hours in period t yields the kilowatt-hours (kWh) of energy produced from an average flow rate of Q, therefore

$$E = P \cdot t. \tag{3}$$

The capacity of a battery C_B is usually specified in Ampere-hours (A·h) units. For example, a battery rated at 100 A·h should be able to supply 100 A for 1 h, 50 A for 2 h, 25 A for 4 h, 1 A for 100 h, or any other combination yielding a product of 100 A·h. In practice, this is not the case because, among other factors, the faster the battery discharges more energy is lost through the internal resistance. An example of this characteristic is given in Figure 1 where the capacity curves of two batteries included in the HOMER library of default components are shown.

The fact that the capacity for hydropower generation is not as heavily affected by its output is the main reason that justifies creating an equivalent battery for modeling a pumped hydro, instead of using one of the battery models supplied with HOMER software. Another good reason is that creating a battery allows the user to define a high capacity, which is convenient, along with a specific voltage, in order that just one battery be enough to model the pumped hydro system, or consider more than one in the design phase, so as to check the effect of different reservoir sizes.

By inspecting the units of Eqs. (1) and (3), it can be observed that, for a battery, with a fixed voltage V, and a capacity C_B (in A·h) independent of its discharge current, its total stored energy E_S (in kW h) can be defined by the following equation:

$$E_S = V \cdot C_B/1000. \tag{4}$$

Similarly, and disregarding inflows and losses due evaporation, withdrawal or infiltration during the generation period, the total stored energy E_S (in kW h) in a hydropower plant can be described by the effective volume of the reservoir (in m^3) and the average power P (kW) produced during the hours needed to empty the reservoir by an average flow rate Q (m^3/s). To do this, the following expression can be used:

$$E_S = (Vol \cdot P(Q))/(Q \cdot 3600). \tag{5}$$

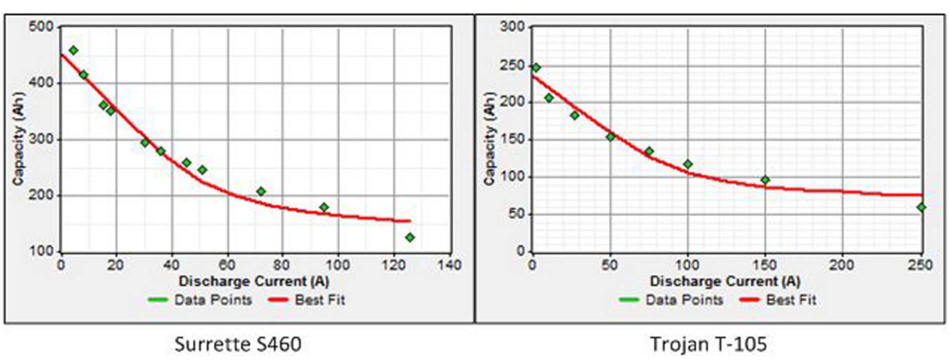

FIG. 1. Capacity curves for two batteries included in HOMER components library.

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TABLE I. Main characteristics of the pumped hydro used as example.

Characteristic	Symbol	Value	Units
Size of the reservoir	*Vol*	3600.00	m^3
Available head	H	10.873	m
Flow rate (turbines)	Q	0.10–0.50	m^3/s
Conversion efficiency	η	75%	…
Planning horizon	*Lifetime*	20	yr
Flow rate (pumps)	Q_P	0.2	m^3/s

In the above equation $P(Q)$ means that the average power P is a function of the average flow rate Q, or combining Eqs. (2) and (5),

$$E_S = 9.81 \cdot \eta \cdot H \cdot Vol/3600. \tag{6}$$

In Subsection II B, it will be presented a detailed example of how to create a battery in HOMER equivalent to a pumped hydro based on the previous equations and considerations. It will also include additional details about how to represent the installed capacity and refilling of the reservoir.

B. A detailed example

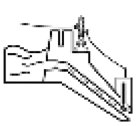
The first thing needed to represent a pumped hydropower system as an equivalent battery is to know the characteristics of the former. As an example, let us consider a pumped hydro with features specified in Table I.

Second, a voltage for the equivalent battery must be selected. For this example, the voltage selected will be 240 V. This value was chosen because it is a voltage that most people can easily relate to, as it is commonly used for residential supply, but any other value could have been selected as well.

With the aforementioned data, it is possible to calculate the values needed to represent the pumped hydropower plant as a battery in HOMER. By using the equations listed previously in this document, Table II shows the relationships between the pumped hydro and its equivalent battery for this example.

When creating a new battery in HOMER, besides the capacity curve, nominal capacity and voltage, the user needs to define a few other parameters. The round trip DC-to-storage-to-DC efficiency of the battery bank is set at 100%, meaning that there are no losses when supplying the stored energy. The minimum state of charge, a measure of the relative state of charge below which the battery bank is never drawn is considered as zero, in order to

TABLE II. Relationship between pumped hydro and its equivalent battery.

	**Pumped hydro** *Vol:* 3600 m^3 *H:* 10.873 m η: 75%	Eq. (1) ≡ Eq. (2) Eq. (4) ≡ Eq. (6)			**Equivalent battery** Voltage: 240 V Round Trip Eff.: 100% Min. state of charge: 0
Q (m^3/s)	*Hours to empty*	E_S (kW h)	P (kW)	C_B (A·h)	I (A)
0.10	10.00	80.00	8.00	333.333	33.333
0.20	5.00	80.00	16.00	333.333	66.667
0.30	3.33	80.00	24.00	333.333	100.000
0.40	2.50	80.00	32.00	333.333	133.333
0.50	2.00	80.00	40.00	333.333	166.667

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represent that the effective volume of the reservoir can be completely depleted for hydropower generation.

To describe the filling of the reservoir on the equivalent battery representation, there are two defining variables. For a battery, the maximum charge current variable imposes an upper limit on the allowable charge current, regardless of the state of charge. The maximum charge rate variable imposes a limit on the rate at which the system can charge the battery bank. That limit is directly proportional to the amount of "unfilled capacity" (headroom) in the battery. As the battery fills up, the headroom decreases, so the maximum charge rate starts to become the limiting factor.

For this example, it was considered that the pumps are able to fill the reservoir (from completely empty to full) in 5 h, which means a maximum $Q_P = 0.2\,\mathrm{m}^3/\mathrm{s}$. For the equivalent battery, it would mean a maximum charge current of 66.667 A, and a maximum charge rate of 0.2 A/A·h, as shown in Figure 2. However, for representing the pumped hydro as a battery, it was found better to use only the maximum charge current as the limiting factor. Therefore, the maximum charge rate used for creating the battery was set in HOMER as 20 times higher than the estimated value of 0.2.

As seen in Table I, the planning horizon (lifetime) of the project was set as 20 yr. Thus, by considering that the reservoir can be depleted daily, it can be defined the following values for the equivalent battery:

- Lifetime throughput: The total amount of energy that can be cycled through the battery before it needs replacement.
  - Lifetime throughput = 20 yr × 365 days/yr × 80 kW h/day = 584 000 kW h.
- Cycles to failure versus depth of discharge: Just one value is needed, according to the previous considerations.
  - Cycles to failure at 100% discharge = 20 yr × 365 cycles/yr = 7300 cycles.

Once all the required data have been calculated, the pumped hydro can be represented by creating an equivalent battery in HOMER, as displayed in Figure 3 for the example presented in this section.

Finally, with the aim of representing the installed capacity of the hydropower plant, the converter used in HOMER to connect the DC Bus to the AC Bus must be created following some considerations:

- Inverter inputs: Lifetime should be the same as in the equivalent battery, 100% efficiency.
- Rectifier inputs: 100% capacity relative to inverter, 100% efficiency.
- The installed capacity of the hydropower plant (in kW) must be specified as one of the sizes to consider for the converter. If the installed capacity value is defined by the user as the only size to consider, HOMER could issue a warning indicating that the "converter search space may be insufficient," but this message can be disregarded.

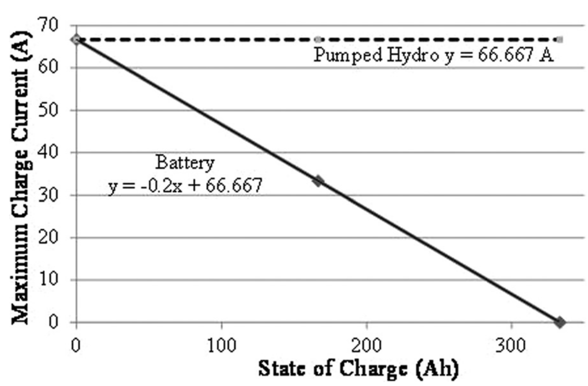

FIG. 2. Maximum charge current vs. maximum charge rate to represent reservoir filling.

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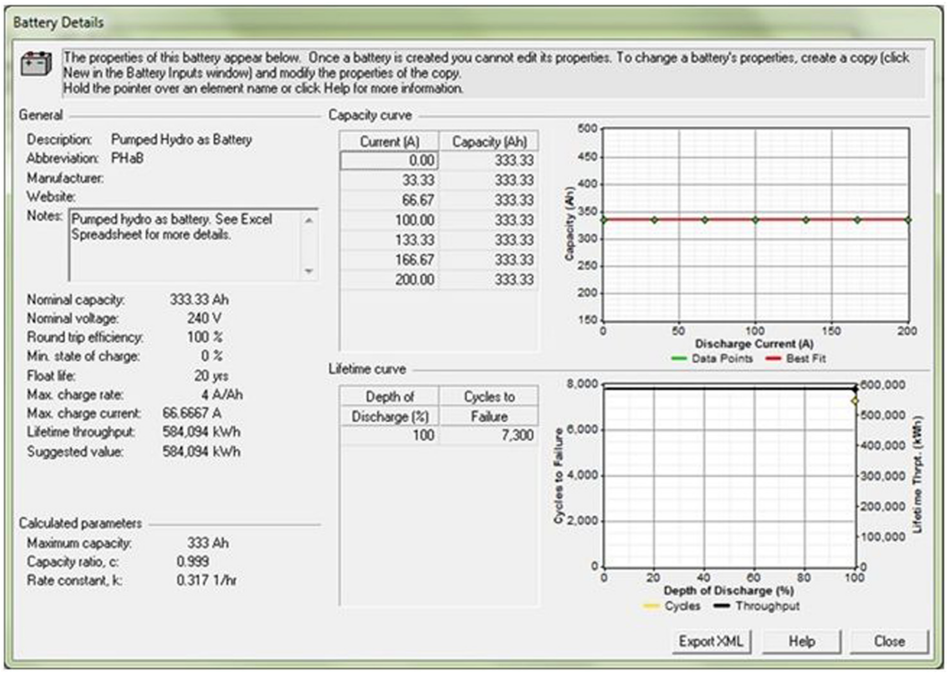

FIG. 3. Example Representation of a pumped hydropower plant as an equivalent battery.

To conclude this section, it was considered useful to summarize the steps required to model a pumped hydro as an equivalent battery in HOMER, according to the methods explained before:

(1) List the main characteristics of the pumped hydro site: size of the reservoir, efficiency, available head, and flow rate.
(2) Select a reference voltage for the equivalent battery.
(3) Find the capacity C_B (in A·h) of the equivalent battery, proportional to the reservoir volume.
(4) In HOMER, create an equivalent battery with a the following characteristics:
   (a) Constant capacity C_B (in A·h) found in step 3, for any discharge current (A).
   (b) The reference voltage selected in step 2.
   (c) Round trip efficiency 100% and minimum state of charge 0%.
   (d) A maximum charge rate proportional to the time needed to fill the reservoir (based on Q_P), and a maximum charge rate much greater than the estimated value.
   (e) Relate the float life and cycles to failure of the equivalent battery to the planning horizon and operation regime of the pumped hydro, or use other considerations.
(5) To represent the installed capacity of the hydropower plant, the converter should be created with the following characteristics:
   (a) Inverter inputs: Lifetime the same as in the equivalent battery, 100% efficiency.
   (b) Rectifier inputs: 100% capacity relative to inverter, 100% efficiency.
   (c) The installed capacity of the hydropower plant must be specified as one of the sizes to consider for the converter.

III. AN EXAMPLE: A WIND-HYDRO HYBRID SYSTEM WITH CONTROLLED PARAMETERS

An appropriate application of a pumped hydro is in wind-hydro hybrid power systems. As explained by Castronuovo and Lopes (2004), wind power generation suffers from an intermittent characteristic due to the own diurnal and seasonal patterns of the wind behavior; therefore, a complementary energy storage system must be considered. Using storage energy strategies will help wind generators to follow closely a given production plan, to improve their participation in the market, or just for the optimization of their operation.

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In order to validate the methods presented in this paper for modeling a pumped hydro as an equivalent battery in HOMER, this section details an example of a wind-hydro hybrid power system with controlled parameters and considering two scenarios:

(a) Complete depletion and refill of the reservoir.
(b) Verifying the installed hydropower capacity constraint.

Before describing these two scenarios, the hypothetical wind turbine and other parameters, constraints and inputs common to both cases, are presented. It is worth mentioning that the only really significant cost for this example is the one of the diesel fuel, because the goal is to maximize the renewable fraction, hence, avoiding the non-renewable generation.

It is important to state that the scenarios presented in this example are practically impossible to happen in the real world (same wind and load profile every day), but these assumptions were made aiming to check if an equivalent battery in HOMER is a feasible representation of a pumped hydropower plant.

Hypothetical wind turbine and wind resource

As all the parameters and constraints in this example, an AC hypothetical wind turbine was created to check if the hybrid system performs as expected. Its power curve and assumed cost info, as well as the wind profile (exactly equal for every day), are given in Figures 1 and 4. The anemometer and hub (the center of the rotor) were defined as being at the same height.

An important thing to be mentioned is that the equivalent battery representation of a pumped hydro, in a wind-hydro hybrid power system, is observed better with AC Wind turbines, with the aim of leaving only the equivalent battery connected to the DC Bus with a huge, free, and 100% efficient converter, as it was also suggested by HOMER Energy (2010), and implemented on the method presented in this paper.

AC generator and diesel inputs

In HOMER, a "generator" is defined as a device that consumes fuel to produce electric (and sometimes thermal) energy. Generators can be dispatched, meaning the system can turn them on as necessary. When given a choice of generator sizes, HOMER will invariably choose the smallest one that meets the maximum annual capacity shortage constraint, since smaller generators typically cost less to operate than larger generators. For example, a few sizes for an AC generator will be considered, using the default parameters.

For diesel inputs, with the objective of maximizing the generation renewable fraction, it will be assumed an extremely high fuel price ($15/l), in order to avoid as much as possible the use of the generator. The AC Generator main features and the diesel inputs are shown in Figure 5.

Economic and emissions inputs

The project lifetime will be set at 20 yr, as it was set for the pumped hydro and wind turbine. All the other economic inputs will remain as default.

No emissions penalties or limits were considered for this example, but the high price to pay for diesel deters the use of this type of energy production.

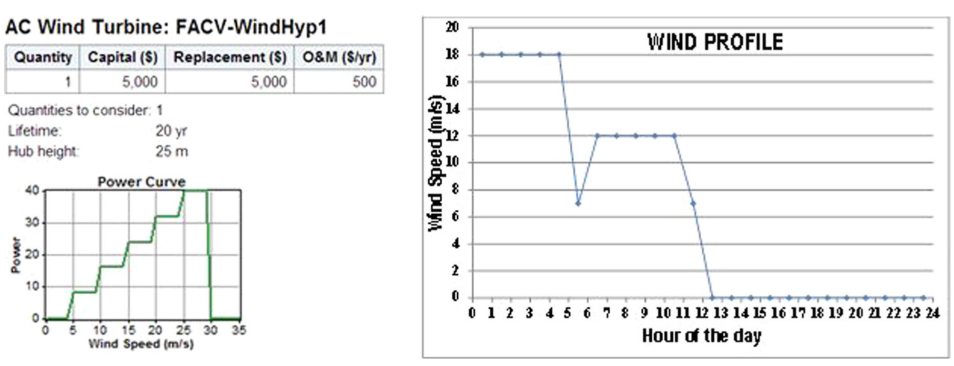

FIG. 4. Hypothetical wind turbine characteristics and wind profile for both scenarios.

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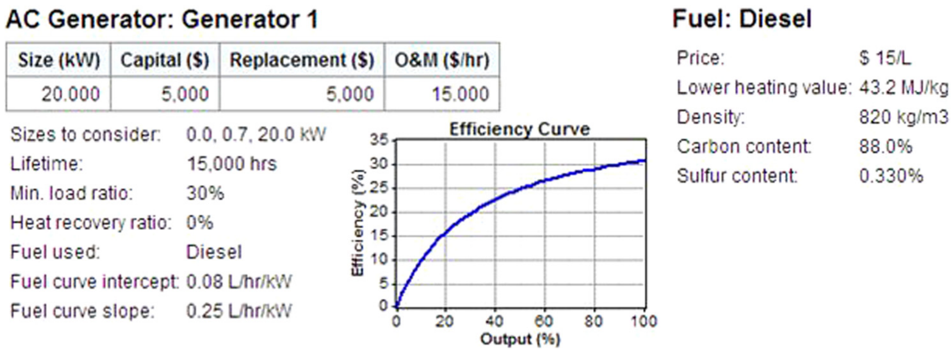

FIG. 5. AC generator main features and diesel inputs.

System control and constraints

In HOMER, the system control inputs define how the software models the operation of the battery bank and generators. For the example presented in this paper, the load following strategy will be the control policy. This means that whenever a generator is needed it will produce only enough power to meet the demand. Another important control setting considered is that the system allows using of a generator with capacity less than the peak load.

For this example, all the constraints take their default values, except for the operating reserve. This operating reserve is surplus operating capacity that ensures reliable electricity supply even if the load suddenly increases or renewable power output suddenly decreases. For both scenarios of this example this value will be set as zero.

A. Scenario 1: Complete depletion and refill of the reservoir

The load profile used for this scenario (Figure 6) in combination with the wind profile previously shown in Figure 4, allows verifying if the equivalent battery representation of a pumped hydropower plant follows the expected behavior, according to the information displayed in Table II.

This scenario can be divided into three stages each day: (1) During the first 6 h of the day there is no load to serve, allowing using the power generated by the wind turbines to "recharge the battery" (refill the reservoir); (2) From 06:00 to 11:00, there is a primary load of 16 kW followed by a quiet period of 1 h; (3) From 12:00 to 22:00, there is a primary load of 8 kW that must be met and no wind to produce energy, meaning that this load must be supplied by the pumped hydro and/or the AC Generator. During the last 2 h of each day, there is no load to serve or wind to produce electricity.

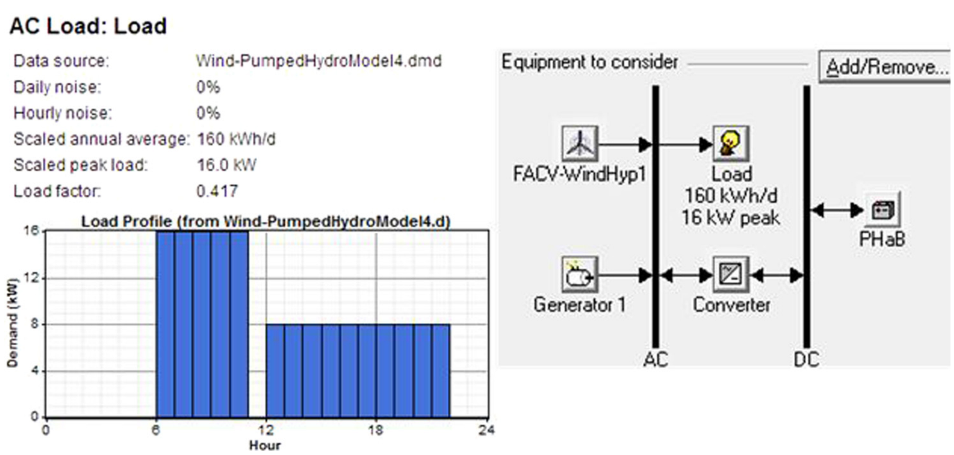

FIG. 6. Load profile and equipment to consider for system configuration for Scenario 1.

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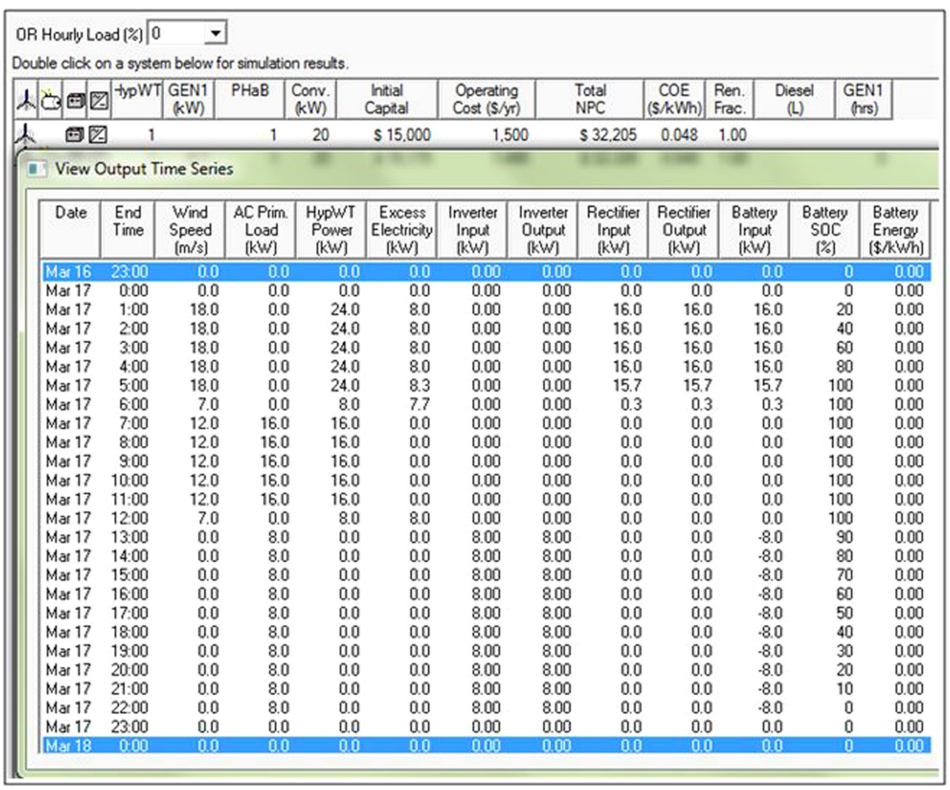
After running the simulations in HOMER, with all the parameters and inputs described previously for this scenario, the optimization results indicate that the best option (according to net present cost (NPC)) does not even include an AC generator. For a 24 h period in Scenario 1, a screen capture of the output time series is shown in Figure 7.

Based on the information shown in Figure 7, the following observations can be made for Scenario 1:

- Even if the wind turbines are able to generate more power (as it can be seen in the excess electricity column), the maximum battery input is 16 kW/h. This corresponds to the battery maximum charge current of 66.667 A, equivalent to a maximum 0.20 m^3/s average pumping flow Q_P for refilling the pumped hydro reservoir. As expected from the information displayed in Table II, it can be observed that the battery goes from empty to completely full in 5 h, as there is enough power available to serve the pumps.
- During the period from 12:00 to 22:00, there is a primary load of 8 kW. The equivalent battery is able to supply the required 80 kW h at a constant rate, going from full charge at the beginning of this period, to total depletion at the end of it. This performance matches the information displayed in Table II, where the pumped hydro is expected to produce 8 kW of power for an average flow $Q = 0.1$ m^3/s, and the reservoir is anticipated to empty in 10 h at this rate.
- For this scenario the renewable fraction is 100%, the excess electricity 26%, the unmet electric load 0%. The equivalent battery is able to serve 50% of the total primary load (58.4 MW h/yr).

B. Scenario 2: Verifying the installed hydropower capacity constraint

The load profile for this scenario (Figure 8) and converter setting inputs used in HOMER were designed in order to verify if installed capacity of the pumped hydropower plant can be accurately represented. This capacity will be defined as 24 kW. The wind profile is the same as in the previous scenario (Figure 4).



HypWT	GEN1 (kW)	PHaB	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	GEN1 (hrs)
1		1	20	$ 15,000	1,500	$ 32,205	0.048	1.00		

Date	End Time	Wind Speed (m/s)	AC Prim. Load (kW)	HypWT Power (kW)	Excess Electricity (kW)	Inverter Input (kW)	Inverter Output (kW)	Rectifier Input (kW)	Rectifier Output (kW)	Battery Input (kW)	Battery SOC (%)	Battery Energy ($/kWh)
Mar 16	23:00	0.0	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0	0.00
Mar 17	0:00	0.0	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0	0.00
Mar 17	1:00	18.0	0.0	24.0	8.0	0.00	0.00	16.0	16.0	16.0	20	0.00
Mar 17	2:00	18.0	0.0	24.0	8.0	0.00	0.00	16.0	16.0	16.0	40	0.00
Mar 17	3:00	18.0	0.0	24.0	8.0	0.00	0.00	16.0	16.0	16.0	60	0.00
Mar 17	4:00	18.0	0.0	24.0	8.0	0.00	0.00	16.0	16.0	16.0	80	0.00
Mar 17	5:00	18.0	0.0	24.0	8.3	0.00	0.00	15.7	15.7	15.7	100	0.00
Mar 17	6:00	7.0	0.0	8.0	7.7	0.00	0.00	0.3	0.3	0.3	100	0.00
Mar 17	7:00	12.0	16.0	16.0	0.0	0.00	0.00	0.0	0.0	0.0	100	0.00
Mar 17	8:00	12.0	16.0	16.0	0.0	0.00	0.00	0.0	0.0	0.0	100	0.00
Mar 17	9:00	12.0	16.0	16.0	0.0	0.00	0.00	0.0	0.0	0.0	100	0.00
Mar 17	10:00	12.0	16.0	16.0	0.0	0.00	0.00	0.0	0.0	0.0	100	0.00
Mar 17	11:00	12.0	16.0	16.0	0.0	0.00	0.00	0.0	0.0	0.0	100	0.00
Mar 17	12:00	7.0	0.0	8.0	8.0	0.00	0.00	0.0	0.0	0.0	100	0.00
Mar 17	13:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	90	0.00
Mar 17	14:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	80	0.00
Mar 17	15:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	70	0.00
Mar 17	16:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	60	0.00
Mar 17	17:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	50	0.00
Mar 17	18:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	40	0.00
Mar 17	19:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	30	0.00
Mar 17	20:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	20	0.00
Mar 17	21:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	10	0.00
Mar 17	22:00	0.0	8.0	0.0	0.0	8.00	8.00	0.0	0.0	-8.0	0	0.00
Mar 17	23:00	0.0	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0	0.00
Mar 18	0:00	0.0	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0	0.00

FIG. 7. Output time series for a 24 h period in Scenario 1.

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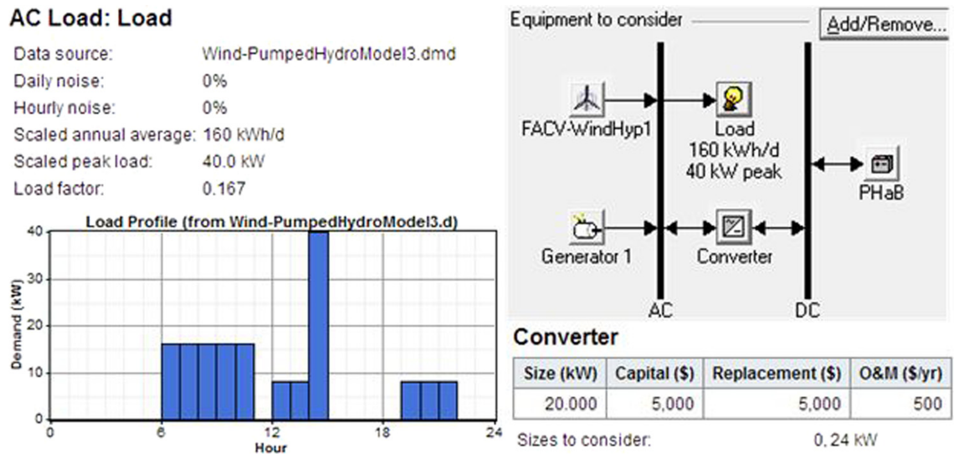
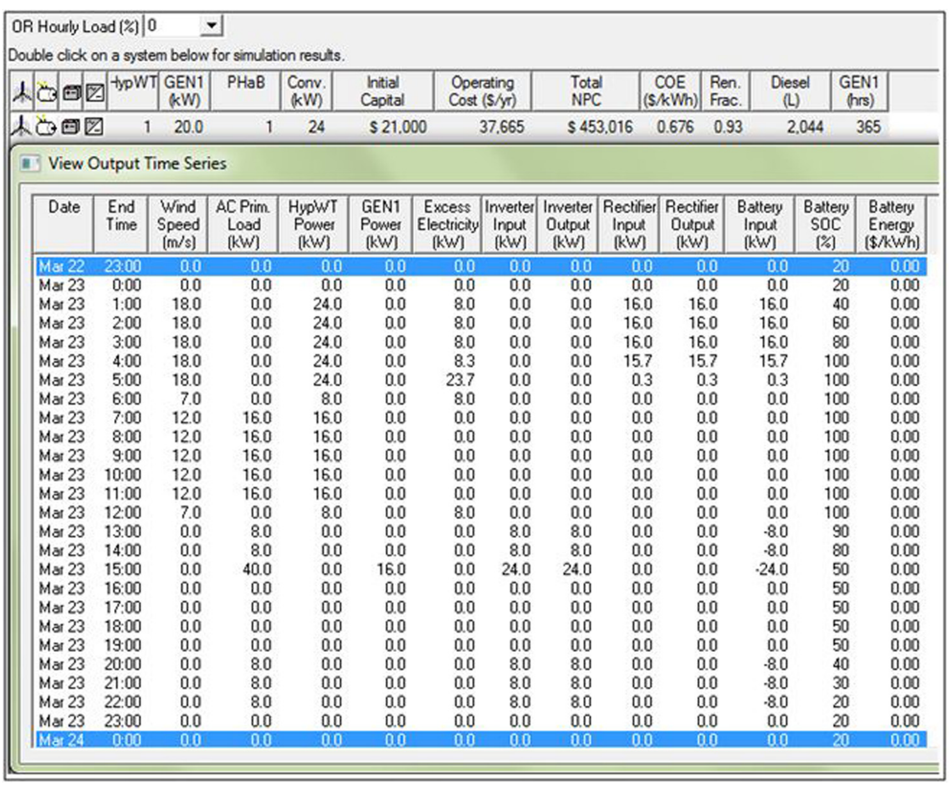


FIG. 8. Load profile and equipment to consider for system configuration for Scenario 2.

The stages for this scenario are similar to the previous one; the difference is that for the period from 12:00 to 22:00 there is a peak load of 40 kW (14:00–15:00) to serve. As seen in Figure 8, the maximum size to consider for the converter is 24 kW, as a way to describe the installed capacity of the pumped hydropower plant, which should not be able to deliver more power than this. The daily total load remains the same as in Scenario 1 (160 kW h/d = 58.4 MW h/yr).

After running the simulations in HOMER, with all the parameters and inputs described for this scenario, the results show the effect caused by the assumption taken for the converter. For a 24 h period in Scenario 2, a screen capture of the output time series is given in Figure 9.

Based on the information shown in Figure 9, the following observations can be made for Scenario 2:



OR Hourly Load (%) 0

Double click on a system below for simulation results.

HypWT	GEN1 (kW)	PHaB	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	GEN1 (hrs)
1	20.0	1	24	$ 21,000	37,665	$ 453,016	0.676	0.93	2,044	365

View Output Time Series

Date	End Time	Wind Speed (m/s)	AC Prim. Load (kW)	HypWT Power (kW)	GEN1 Power (kW)	Excess Electricity (kW)	Inverter Input (kW)	Inverter Output (kW)	Rectifier Input (kW)	Rectifier Output (kW)	Battery Input (kW)	Battery SOC (%)	Battery Energy ($/kWh)
Mar 22	23:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20	0.00
Mar 23	0:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20	0.00
Mar 23	1:00	18.0	0.0	24.0	0.0	8.0	0.0	0.0	16.0	16.0	16.0	40	0.00
Mar 23	2:00	18.0	0.0	24.0	0.0	8.0	0.0	0.0	16.0	16.0	16.0	60	0.00
Mar 23	3:00	18.0	0.0	24.0	0.0	8.0	0.0	0.0	16.0	16.0	16.0	80	0.00
Mar 23	4:00	18.0	0.0	24.0	0.0	8.3	0.0	0.0	15.7	15.7	15.7	100	0.00
Mar 23	5:00	18.0	0.0	24.0	0.0	23.7	0.0	0.0	0.3	0.3	0.3	100	0.00
Mar 23	6:00	7.0	0.0	8.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	100	0.00
Mar 23	7:00	12.0	16.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100	0.00
Mar 23	8:00	12.0	16.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100	0.00
Mar 23	9:00	12.0	16.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100	0.00
Mar 23	10:00	12.0	16.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100	0.00
Mar 23	11:00	12.0	16.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100	0.00
Mar 23	12:00	7.0	0.0	8.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	100	0.00
Mar 23	13:00	0.0	8.0	0.0	0.0	0.0	8.0	8.0	0.0	0.0	-8.0	90	0.00
Mar 23	14:00	0.0	8.0	0.0	0.0	0.0	8.0	8.0	0.0	0.0	-8.0	80	0.00
Mar 23	15:00	0.0	40.0	0.0	16.0	0.0	24.0	24.0	0.0	0.0	-24.0	50	0.00
Mar 23	16:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50	0.00
Mar 23	17:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50	0.00
Mar 23	18:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50	0.00
Mar 23	19:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50	0.00
Mar 23	20:00	0.0	8.0	0.0	0.0	0.0	8.0	8.0	0.0	0.0	-8.0	40	0.00
Mar 23	21:00	0.0	8.0	0.0	0.0	0.0	8.0	8.0	0.0	0.0	-8.0	30	0.00
Mar 23	22:00	0.0	8.0	0.0	0.0	0.0	8.0	8.0	0.0	0.0	-8.0	20	0.00
Mar 23	23:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20	0.00
Mar 24	0:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20	0.00

FIG. 9. Output time series for a 24 h period in Scenario 2.

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- At the peak load of 40 kW the maximum output of the equivalent battery is 24 kW, suggesting that setting a maximum size limit on the converter is an adequate way to represent the installed capacity of the pumped hydropower plant. The remaining part of the peak load that has to be served is supplied by the AC generator, and the effects of the fuel cost assumptions on the results of the simulation are easily observed in the Total NPC value, when compared to Scenario 1.
- As in Scenario 1, the state of charge of the equivalent battery follows the behavior expected from observing the information displayed in Table II. For example, if the pumped hydro supplies 8 kW during 1 h it represents a 10% depletion of its total reservoir volume, based on an average flow $Q = 0.1\,m^3/s$. Respectively, if the hydro delivers 24 kW during 1 h it corresponds to 30% depletion, caused by $Q = 0.3\,m^3/s$ needed to produce this power.
- For this scenario the renewable fraction is 93%, the excess electricity 31% (the battery never empties completely), the unmet electric load 0%. The equivalent battery is able to serve up to 40% of the total primary load (58.4 MW h/yr).

IV. CONCLUSIONS

Most renewable energy technologies suffer from an intermittent characteristic due to the own diurnal and seasonal patterns of the natural resources needed for power generation, therefore, a complementary energy storage system must be considered. The capability to store great amounts of energy, along with the maturity of the technologies involved in hydropower generation, turns the pumped hydropower plant in a suitable alternative to consider as an energy storage device for hybrid systems. The HOMER optimization model is widely used around the globe for designing, comparing or evaluating the performance of hybrid power systems, but it does not include an explicit component to model a pumped hydropower facility.

This paper described a method for representing a pumped hydropower plant by creating an equivalent battery in HOMER, and the procedure was accompanied by a detailed example. The reservoir volume can be related to the equivalent battery capacity in a straightforward way by adopting a constant nominal voltage. It is also possible to establish a relationship between the equivalent battery current (charge or discharge) and the flow rates (Q or Q_P).

Additionally, an example of a wind-hydro hybrid power system with controlled parameters to validate the method was presented. The results support that the procedure explained in this paper adequately represents, by means of an equivalent battery and converter, the following traits of a hydropower plant: depletion and refill of the reservoir, energy storage, power output as a function of the flow rate, and installed capacity of the turbines.

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