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Pumped hydro storage plants with improved operational flexibility using constant speed Francis runners ☆

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HIGHLIGHTS

- Pumped hydro storage (PHS) would increase its effectiveness if it could provide variable capacities.
- Flexible energy storage and generation can be provided via variable speed drives and via turbine by-pass configurations.
- Variable speed equipment is suitable for small PHS capacities.
- For large capacities, a PHS innovative configuration featuring one small by-pass turbine is proposed.
- It is shown that the proposed configuration can provide a nearly continuous capacity range, with good efficiencies.

Keywords:
Pumped hydro storage
Regulation capacity
Francis impellers/runners

ABSTRACT

Pumped hydro storage (PHS) is a crucial technology for balancing large steam power plants, and may become increasingly important for storing renewable energies. Hence, capacity ranges of PHS, as well as its dynamic response to renewable power variability, will become progressively relevant. In this paper, we focus on determining capacity ranges and efficiencies of PHS plants using conventional constant speed Francis runners, adopting unconventional runner sets, arranged in innovative fashion. In the pumping mode, it is assumed that the impellers run at a single speed, but that they can have, depending on the plant, either the same or different design capacities. In the turbine mode, it is assumed that the runners can access the well-established range from 60% to 100% of design capacity via wicket gate adjustment. In order to extend the capacity ranges with constant speed runners, bypass loops to balance the plant are considered. Because bypass operation implies losses, the possible efficiencies are studied. The results show that (a) bypass is an effective means of extending capacity ranges, but high by-pass ratios decrease efficiencies. (b) One of the impeller sets postulated in this work offers the possibility of almost continuous capacity at high efficiencies, with relatively small capacity variation within the set.

1. Introduction

Pumped hydro storage (PHS) is a well-established large-scale energy storage technology, providing important capacity for grid reliability and ancillary services. Currently, the US has more than 20 GW of installed PHS plants [1], whereas the world boasts over a 100 GW [2]. Accounts of the earliest installations vary, with some publications naming Schaffhausen in Switzerland (1909) [3], and others claiming technology dating form 1894 [4]. A general description of the PHS technology is available [4], and we offer here a simplified explanation. A PHS plant (Fig. 1) is composed of two reservoirs, separated by an elevation H and a hydro turbine (or a set) of the Francis type in the present study. The turbine is connected to a generator, and when water flows from the upper reservoir to the lower one, the generator produces power which is delivered to the grid. Variable capacity can be obtained by varying the turbine inlet flow via movable gates, called wicket gates. When it is desired to store energy, the generator is activated by power from the grid to work as a motor and its rotational sense is inverted. The runner now works as a pump, and water is moved from the lower to the upper reservoir, where it can be stored to produce electrical energy when opportune. In arbitrage operation, inexpensive energy is purchased (typically at night when there is low demand) and stored by pumping water from the lower

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Nomenclature

BEP	best efficiency capacity point, %
BTC	by-pass turbine relative power as percentage of peak power, %
CR	capacity ratio ,–
E	specific mechanical energy, J/kg
f	fraction of total pumping capacity
MAXT	maximum plant capacity, 100%
N	total number of PTs
np	no. of PTs in pump mode
nt	no. of PTs in turbine mode
OVL	overlap factor
PC	relative runner pumping capacity, %
PT	pump-turbine
RHS	right hand side
RNG	by-pass turbine capacity range, %
TCM	maximum turbine relative power as percentage of peak station power, %
TP	turbine output power as percentage of peak station power, %
W	pump-turbine

Greek symbols

β	by-pass ratio, pumping mode
γ	by-pass ratio, turbine mode
ξ	francis turbine turn-down ratio
η	efficiency

Subscripts and superscripts

el	electric
g	generating operation
i	unit in pumping mode
in	input to system or to PT
j	unit in turbine mode
min	minimum
out	output to system or to PT
p	pumping operation
pu	pump
st	stored
tu	turbine

Abbreviations

PHS	pump hydro storage
BPT	by-pass turbine unit

reservoir to the upper one. The stored energy is released during peak demand hours (typically in the afternoon, when the selling price warrants such delivery). Optimization strategies for arbitrage operation are devised by Connolly [5], among others. Even if optimized, PHS profits could vary considerably and a recommendation is made to incorporate ancillary services such as frequency regulation in future analyses. Whereas arbitrage is typically implemented at constant pumping and generating capacities, ancillary services require some sort of capacity regulation.

The purpose of regulation is to allow the power delivered by the electrical grid to closely follow the consumer demand for electricity on a short time scale, which ranges from seconds for reactive power adjustments to minutes for load regulation. Hydro power is particularly suited to such an application due to the steep ramp rates that hydroturbines are capable of attaining. Generally, hydroturbines are much faster than conventional steam turbine coal plants that exhibit typical ramp rates of 1% of rated power in MW/min. In fact, hydroturbines have comparable response to heavy duty and aeroderivative gas turbines, providing respectively up to 20 and 30 MW/min per unit [6].

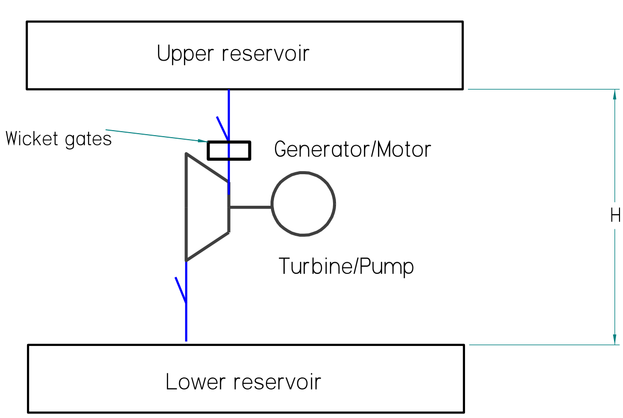

Fig. 1. Schematic of a PHS plant.

During generation, each runner in a PHS plant can vary its capacity from about 60% to 110% [7] of design, thus providing some regulation, via the wicket gates. At capacity levels below 60%, runners and draft tubes may be subject to vibration and cavitation, reducing efficiency and service life. During pumping, the situation is much worse: the runners, driven at single speed, attain essentially one capacity even if small variations due to head changes do occur. Providing regulation during energy storage is then a technical impossibility, since only the runner discrete capacity can be accessed. Hence, variable capacity storage systems are needed particularly during pumping in the case of PHS [8]. When large power sizes are considered, electric batteries become less convenient than PHS and compressed air storage (CAES) systems [9].

Benefits of PHS have been highlighted in a recent study [10], which has shown the way to economic optimization of energy storage from wind. An interesting suggestion of [11] is that the power lines within some regions can be decongested via PHS. For an isolated grid, such as found in an island, the case is convincingly made in [11] that PHS can help increase the use of wind energy while improving the steady-state and disturbance-riding capabilities. In yet another island case [12] it is concluded that suitable PHS could lead to wind energy use of up to 50% on a yearly basis. Similar conclusions are arrived at in [13], where hydrogen storage is compared to PHS in another island. A careful analysis of the technology and economics of wind energy balancing via variable speed PHS is presented in [14]. An optimum PHS plan capacity is arrived at via insightful economics. In isolated regions, solar energy can also be effectively balanced with PHS hydro, and advanced optimization techniques can be used to determine the size of components [15]. Variable speed pumping is assumed in [15], with a much larger pumping than turbine capacity (90–28 kW). Even though the literature does not always incorporate capacity limitations, these are present in the dispatching of constant-speed Francis runners.

Financial incentives for the value that PHS offers in terms of regulation have been introduced in the USA [16], and PHS capacity will increase in Europe by 10 GW over the upcoming nine years. These studies reveal that both in isolated cases and over wide regions, PHS can contribute to the quality of energy provided to the public. Yet, an item of major concern for PHS is the relatively low number of daily hours the assets tend to operate [17], which reduces the profitability of the investment.

To extend operational ranges, one solution is to employ variable speed drives in the pumping mode, [18]. Currently, only about 8 GW out of 120 GW of PHS boast variable speed drives. Cost and capacity limitations seem to be the primary deterrent to widespread adoption of this technology. Variable speed equipment in small capacities can reach from 60% to 100% of design in pumping and from 20% to 100% in generating [19], and such limits should be abided by in studies invoking variable speed. For capacities above 50 MW, power electronics is too costly or not available, requiring the use of Doubly Fed Asynchronous Generators [20].

Assessment of more conventional technology to widen capacity ratios with good efficiencies is in order. Pelton turbines, in conjunction with centrifugal pumps, can provide wide capacity ranges and steep ramp rates when used in bypass configurations [21]. Kaplan runner/impellers are of sufficient flexibility [22] and the low heads for which they are optimal may require large water reservoirs to achieve reasonable storage capacities. Francis runners have high efficiencies and can operate within a wide range of heads and flows. However, these runners are designed to operate at constant speed in pumping and their turndown ratio during generation is limited by cavitation considerations, as already explained. Due to single machine efficiency limits in part-load operation, focusing on multiple machine sets could show the way to increased flexibility [9].

The objective of this paper is to determine how sets of multiple Francis PHS runners could be configured for a plant to vary capacity from hour to hour (or within a one hour bidding period), as identified in Richards' work [23]. The motivation and innovation of the study is to define runner sets that will increase the PHS flexibility. Efficiency is adopted as the figure of merit whereby the viability of each configuration can be determined. Hence, the nature of storage/generating efficiencies and losses is considered first in this report, in a simplified fashion to facilitate understanding and generality. For a more detailed evaluation of capacity ranges and accompanying efficiencies, a parabolic curve of efficiency vs. power is subsequently adopted. In total, three possible plant configurations are analyzed, and one is found to hold the promise of wide capacity ranges with acceptable efficiencies.

2. Efficiency and bypass

In bypass configurations, turbines or pumps are employed to control the net generating or pumping capacity. For instance, in Fig. 2, the flow directed towards the upper reservoir is decreased to activate a turbine (or set of turbines), reducing the effective pumping capacity. The energy produced by the turbine can be thought of as being routed back to the motor activating the pump. Whereas bypass arrangements broaden capacity ranges, they cause increased losses; hence it is important to characterize their potential efficiency. Regarding individual machine efficiencies, the smaller the machine, the smaller the efficiencies tend to be, (and this applies to both runners and motor/generators). The assumed component values are within the range of those obtained by the combination pump/motor or turbine/generator. A more complete treatment could discriminate between the turbo machine and the electrical machine efficiencies, but such decoupling is not undertaken here.

We focus first on efficiencies during pumping operation. To arrive at a valid definition of efficiency, we need to provide additional qualifications to the flows of Fig. 2. An incompressible fluid at an elevation H of the upper reservoir has potential energy per unit mass equal to (g · H). We use this simple concept to reduce

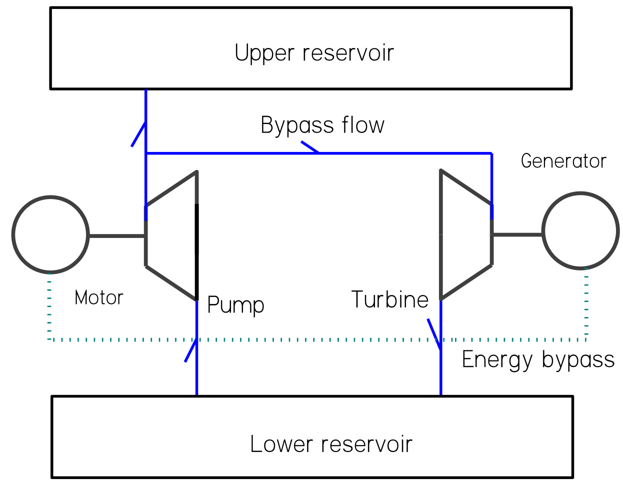

Fig. 2. Bypass in PHS plant.

all energy flows to their mechanical equivalent, and we show them in green in Fig. 2. The water streams with no potential energy value are shown in blue. Potential, mechanical and electrical energy are considered of equivalent Second Law value, namely as shaft power. So, whether we refer to a water or to an electricity flow, they are both reduced to shaft energy per unit mass of an appropriate water flow. With this understanding and the nomenclature of Fig. 3, the pumping efficiency is defined (for the unit mass stored and the system enclosed by a dotted line) as,

$$\eta_p = \frac{E_{st,in}}{E_{el,in}} \tag{1}$$

The energy input to the pump is then

$$E_{pu,in} = E_{el,in} + E_{tu,out} \tag{2}$$

The energy stored is in turn given by

$$E_{st,in} = E_{pu,out} - E_{tu,in} \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1), we get:

$$\eta_p = \frac{E_{pu,out} - E_{tu,in}}{E_{pu,in} - E_{tu,out}} \tag{4}$$

We now note that the RHS of Eq. (4) can be modified by applying efficiencies reflecting conversion and circulation losses. For instance, for the pump we adopt a combined efficiency η_{pu}, reflecting the conversion from electrical energy into potential energy. This efficiency could include not only the pump efficiency, but also the motor and the penstock efficiency. The same idea (this time for

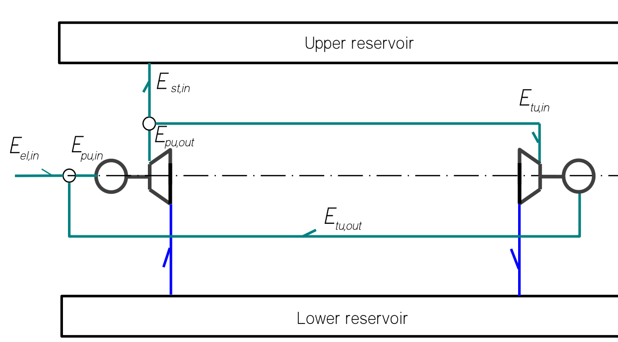

Fig. 3. Bypass nomenclature on a common energy basis.

conversion from fluid potential energy to electrical energy) can be applied to the turbine. Then, Eq. (4) becomes,

$$\eta_p = \frac{E_{pu,in} \cdot \eta_{pu} - E_{tu,out}/\eta_{tu}}{E_{pu,in} - E_{tu,out}} = \frac{\eta_{pu} \cdot \eta_{tu} - E_{tu,out}/E_{pu,in}}{\eta_{tu} \cdot (1 - E_{tu,out}/E_{pu,in})} \tag{5}$$

The ratio of energy flow out of the turbine to the energy flow into the pump (per unit mass of water stored) is given the symbol β, whereby Eq. (5). simply becomes,

$$\eta_p = \frac{\eta_{pu} \cdot \eta_{tu} - \beta}{\eta_{tu} \cdot (1 - \beta)} \tag{6}$$

With

$$\beta = \frac{E_{tu,out}}{E_{pu,in}} \tag{7}$$

Note that β is a ratio of energy returned to the pump to its total energy input. When β equals zero (i.e. no bypass) then η_p and η_{pu} are equal. A plot of the pumping efficiency vs. β (Fig. 4, for constant η_{pu} and η_{tu} , equal to 0.92 and 0.93 respectively), shows that when β exceeds 0.5 the efficiency begins to drop quickly, and can become negative. A negative storage efficiency, obviously of no practical interest whatsoever, indicates that the turbine is receiving the pump output as well as water from the upper reservoir.

Similar considerations apply to generating operation. In addition to wicket gate action, the capacity of Francis runners could be modulated via feeding some generated energy to motors activating pumps, with the outcome of removing less energy from storage. With the nomenclature of Fig. 5, the generating efficiency is defined as

$$\eta_g = \frac{E_{el,out}}{E_{st,out}} \tag{8}$$

Using the same method which led to Eq. (6), and applying the following equalities:

$$E_{tu,in} = E_{st,out} + E_{pu,out} \tag{9}$$

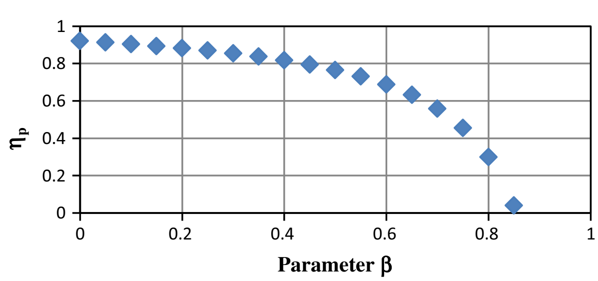

Fig. 4. Pumping efficiency vs by-pass parameter.

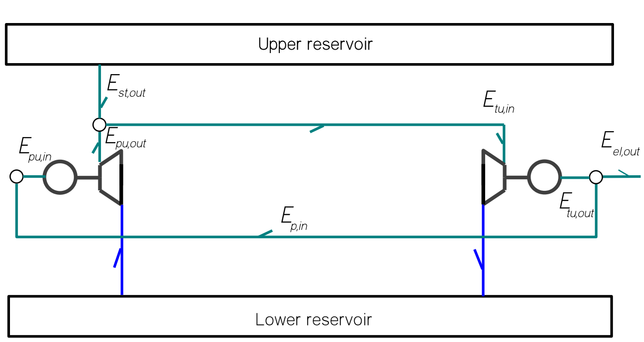

Fig. 5. Energy bypass to regulate turbine capacity.

$$E_{tu,out} = E_{el,out} + E_{pu,in} \tag{10}$$

$$\gamma = \frac{E_{pu,in}}{E_{tu,out}} \tag{11}$$

We obtain for the generating efficiency:

$$\eta_g = \frac{\eta_{tu} \cdot (1 - \gamma)}{\left(1 - \eta_{tu} \cdot \eta_{pu} \cdot \gamma\right)} \tag{12}$$

Note that η_g and η_{tu} become equal when there is no by-pass. A plot of generating efficiency vs the ratio γ (Fig. 6) shows that, as more energy is sent back to the pump, the generating efficiency decreases. Similar to the plot for η_p vs. β (Fig. 4), beyond γ values of 50%, the efficiencies experience a considerable decrease.

3. Pump-turbine capacity scenarios

In what follows, we seek to establish the capacity ranges accessible with four Francis pump-turbine (PT) in PHS, with individual turbine capacities given in percentage of station capacity. Typically, hydro-power stations have from 2 to 10 (or more) runners. The chosen number of 4 could be easily varied, and it is chosen as a mid-range value for the analysis. Key assumptions are:

- PTs operating in turbine mode have an efficiency curve as function of the percent of rated power TCM given by:

$$\eta_{tu} = 0.928 - 8 \cdot 10^{-5} \cdot \left(\frac{(TP/TCM - 0.92)}{0.0104}\right)^2, \tag{13}$$

  which results in a peak efficiency of ~0.93 at 92% of maximum power (best efficiency point, BEP), and a minimum of 0.85 at 60% power level. The quadratic dependence of efficiency on capacity given by Eq. (13) reflects an approximation of the convex efficiency typical of Francis runners. Each runner is assumed to be capable of operating from 60% to 100% of maximum power.
- In the pump mode, the pump efficiency η_{pu} is assumed to be 0.90, at one single speed and rated capacity. (The efficiency will vary with head, but such small variation is neglected for our purpose.)

Each PT is assumed capable of delivering approximately the same design capacity in turbine mode as is absorbed in pumping mode, namely

$$CR = \frac{TCM}{PC} \approx 1 \tag{14}$$

Figs. 2 and 3 were already used to illustrate the possibility of regulating pumping capacity through use of a bypass. This regulation arrangement, present in Vorarlberger Illwerke AG [24], is called for when the pump has a fixed capacity, as is the case when the motor/generator is synchronous with a fixed number of poles.

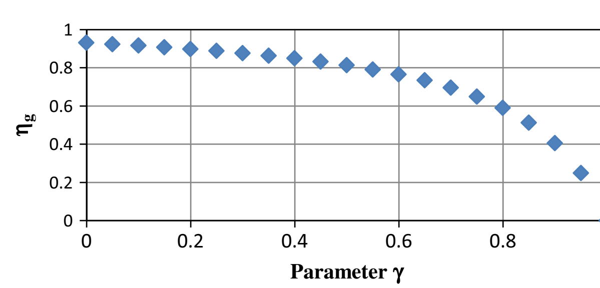

Fig. 6. Generation efficiency vs. by-pass parameter.

Consider a plant with N pump/turbine units. The following Eq. (15) establishes a basic relation between the net energy stored, the energy output of the pump(s) and the energy input to the turbine(s) in bypass mode.

$$\sum_{np} E_{st,in} = \sum_{np} E_{pu,out} - \sum_{nt} E_{tu,in} \tag{15}$$

To keep track of individual PTs and of their operating mode, we now switch to percent capacities, as opposed to capacities per unit mass stored, to get from Eq. (15),

$$TP \cdot f = \sum_{i=1}^{np} PC_i - \sum_{j=1}^{nt} TCM_j \cdot \xi_j \tag{16}$$

with the constraints:

$$nt + np \quad \leq N \;\&\; 1 \geq \xi \geq 0.6 \tag{17}$$

which reflect that the total number of units in pumping or generating mode, in a selected time interval, can be lower than the total number of units of the system because some PTs can be shut down. Concerning the capacity of each PT, three cases are considered:

3.1. Equal capacity

Four pump/turbines with the same generating capacity each, and the possibility of bypass. (TCM equal for each unit):

$$TCM_j = \frac{MAXT}{N} \tag{18}$$

The runners (Fig. 7) all have the same capacity, and they can receive flow from the upper reservoir, or from the discharge of other runners working as pumps, in red in the figure.

3.2. Constant factor

Four turbines with geometrically increasing generation capacity:

In this configuration, (Fig. 8), each runner is specified in order of decreasing turbine capacities, with its maximum capacity equal to the minimum capacity of the larger runner immediately above in the series. For Francis runners, we assume a lower capacity limit of 0.6 (i.e. 60% of design) of design, as explained in the introduction. Hence, we have:

$$TCM_4 = MAXT, TCM_{j-1} = TCM_j \cdot 0.6 \tag{19}$$

3.3. Constant overlap

This case comprises four runner/impellers of increasing capacity, and a small dedicated bypass turbine (Fig. 9). As given by Eq. (20), the capacity of each runner partially overlaps that of the next one, by a constant factor $RNG \cdot OVL$. Hence this case is labelled constant overlap. Regarding then the runners, their peak capacities are given by:

$$TCM_{j+1} = TCM_j + RNG \cdot (1 - OVL) \tag{20}$$

In Eq. (20), RNG denotes the capacity range of the bypass turbine (namely, 9.1% of the total generating capacity in this case). The smallest PT in the series, TCM_1, has a peak capacity of:

$$TCM_1 = BTC \cdot 1.2 \cdot (1 - OVL) \tag{21}$$

where BTC is the relative peak design capacity of the dedicated bypass turbine. In the case considered, OVL is 16.7% and BTC is 22.7% of the peak plant capacity, so that TCM_1 is equal to BTC, namely the smallest runner and the by-pass turbine are of equal design capacity. The series of impellers is constructed starting with Eq. (21). For the given values of OVL and BTC, the capacity of the smallest runner is 22.7% of the plant capacity. The next runner

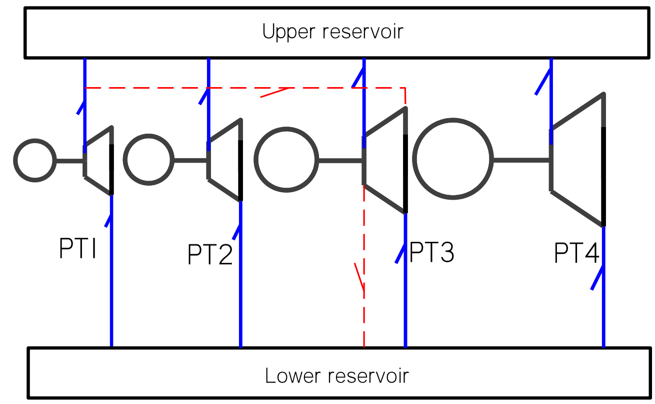

Fig. 8. Four PTs of constant capacity ratio, Case 3.2.

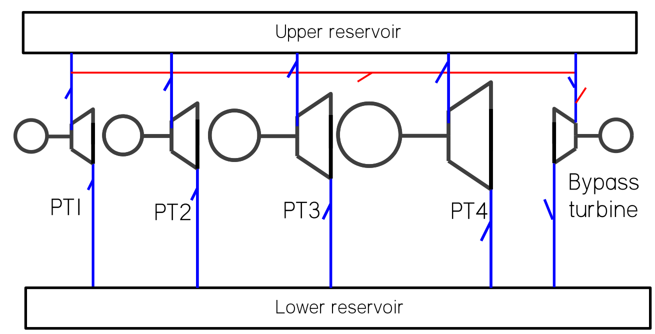

Fig. 9. Gradually increasing capacity ratios with dedicated bypass turbine, Case 3.3.

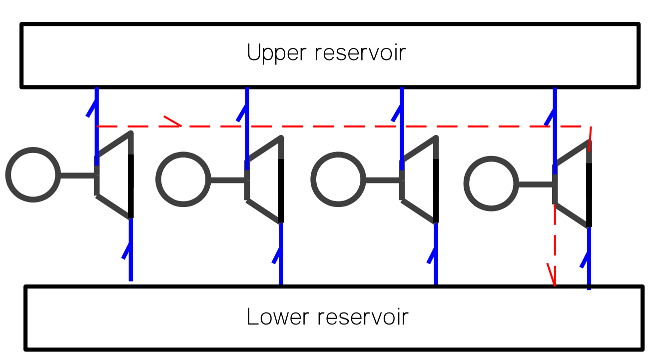

Fig. 7. Four PTs of equal capacity, Case 3.1.

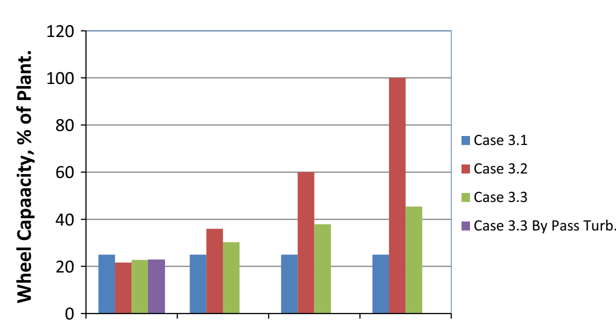

Fig. 10. Comparison of relative capacities of impeller/runners for the three cases considered.

capacity is determined with Eq. (20). For a Francis runner, *RNG* is (as already stated) 9.1% (namely 0.4 of 22.7%, reflecting the range possible via wicket gate adjustment). Hence, TCM_2 is 30.3% of the plant capacity. Using the recursive relationship of Eq. (20), the other capacities are arrived at. The given values of *OVL* and *BTC* were chosen to result in a continuous capacity sequence, as it will be shown under results.

Individual runner capacity selection has important consequences with regards to the accessibility of plant capacity ranges. We study in what follows the three cases outlined in this section in terms of the generating and pumping ranges that can be obtained in single speed configurations. The PT capacities were chosen for each of the three cases as per Eqs. (18)–(20). The relative capacities for each case are compared in Fig. 10. For Case 3.1, all PTs have the same capacity, equal to ¼ of the target plant capacity. For Case 3.2, one of the PTs has capacity equal to the target capacity of the plant, and the three remaining have sharply decreasing capacities. In Case 3.3, a dedicated by-pass turbine is added, with striking results, namely the capacities of the runners vary from 23% to 45% of the plant capacity, and hence the distribution is much narrower than in Case 3.2, as can be ascertained from Fig. 10.

The accessible capacities and the corresponding efficiencies, both in pumping and generating were all calculated using the same programming logic briefly described below with reference to Table 1. This was accomplished by first forming all the possible combinations of pumping/generating groups. For instance, Table 1 shows for Case 3.1 only two PTs for clarity, and three possible groups. When only PT1 is active as a turbine (index 1 in the first column), it can generate between 15% and 25% of the plant capacity (first row), being one of four PTs of equal capacity. Next, a systematic query is automated, regarding whether the row under consideration could meet any plant capacity range from −100 (i.e. pumping) to 100% (i.e. generating). In the case under consideration, PT1 as turbine could meet from a minimum of 15% to maximum of 25% capacity. The efficiency from Eq. (12) then would range from 0.852 to 0.923 (last column of the first row). When PT1 and PT2 are simultaneously active (second row), the capacity range doubles, since both PTs operate at the same turbine capacity. When PT1 is a regulating turbine and PT2 is pumping (−1 in column 2, third row), the accessible capacity range is from −10% of plant capacity to zero, when both PTs are operating at equal capacity. The efficiencies are obtained from Eq. (6). for pumping and from Eq. (12) for generation. It is noteworthy that, as defined here, the pumping efficiency (Eq. (6)) for null capacity is negative.

The same principles summarized with the help of Table 1 were extended to four PTs, and to one dedicated by-pass turbine in Case 3.3. The spreadsheets were programmed to pick the possible capacity ranges, and where overlap existed, to select the maximum calculated pumping or generating efficiency. When several turbines were active, their percent of BEP power was set to be the same.

The results of the analysis are summarized in the next section.

4. Results

We present simultaneously the efficiency and accessible capacity ratios for each case. The efficiencies are shown in the vertical axis and the capacity ratios in the horizontal axis. Pumping capacities are negative, generating capacities are positive in all cases.

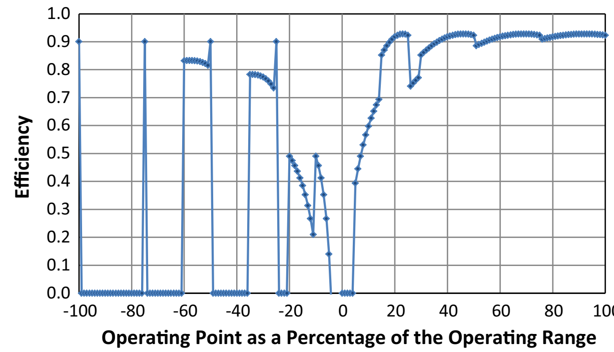

Fig. 11. Accessible ranges and efficiencies for Case 3.1.

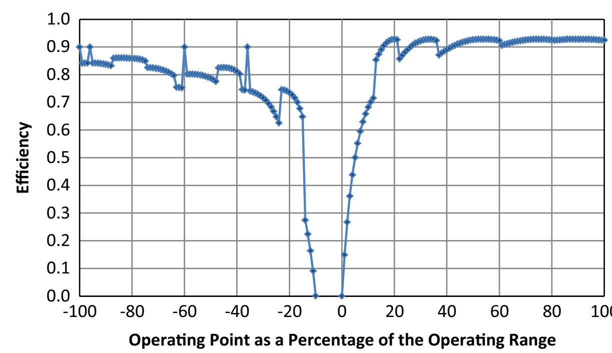

Fig. 12. Accessible ranges and efficiencies for Case 3.2.

The results for Case 3.1 (four equal capacity PTs), are shown in Fig. 11. The available pumping ranges, (values from −100% to 0%), are in this case rather limited. Other than single operating points at −100, −75, −50 and −25%, two small continuous pumping ranges (−60 to −50% and −35 to −25%) are possible. The efficiencies drop below 75% in some cases of the latter range. Other pumping ranges have either negative efficiencies or drop below 50% efficiency, and are probably of no interest. The available generating ranges, due to the wicket gate regulation and the use of bypass, attain a continuous range from 15% to 100% at efficiencies above (except for one single point) 75%, and above 85% except for four other points. There is also an accessible range below 15%, though it has low efficiencies.

A similar chart for Case 3.2 (Fig. 12) reveals a vastly improved picture. Whereas the PTs are in this case much larger than in the former case, the accessible ranges show more continuity and larger efficiencies. For pumping, a continuous range from −100% to −36% at efficiencies above 75% is available. For efficiencies above 60%, the range extends to include −36% to −15%. Efficient generation (>85%) is possible in the range of 13–100% of plant capacity. The lower range of generation (0–13% of plant capacity) is accessible, but with reduced generating efficiencies. A PHS plant configured

Table 1
A sample of programming for capacity and efficiency determination.

PT1 Status	PT2 Status	Pumping capacity[a]	Minimum generating capacity (%)[a]	Maximum generating capacity (%)[a]	Plant capacity range (%)[a]	Efficiency range
1			15	25	15–25	0.852–0.923
1	1		30	50	30–50	0.852–0.923
1	−1	−25%	15	25	−10 to 0	0.490–0.000

[a] Capacities are expressed as percentages of total plant capacity.

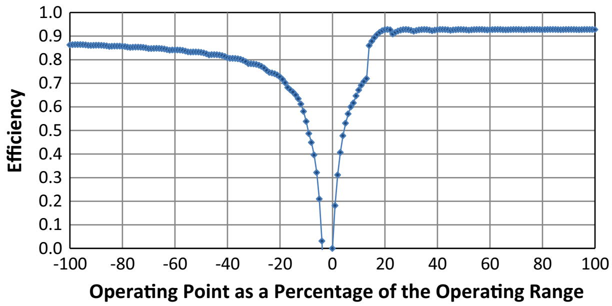

Fig. 13. Accessible ranges and efficiencies for Case 3.3.

Table 2
Summary of findings.

CASE	Pumping ranges, % of plant capacity	Generating ranges, % of plant capacity	Comment
1	−100, −75, −60 to −50, −35 to −25	15–100	Discontinuities in efficiencies vs. capacity
2	−100 to −28	11–100	Smaller discontinuities in efficiency than in Case 3.1
3	−100 to −18	13–100	Continuous efficiencies

as in this case could offer part-load power at good efficiencies, except at low capacity ranges.

Case 3.3 shows the most promising results, as shown in Fig. 13. The chart shows a continuous pumping range from −100% to −3% at efficiencies that are generally higher than possible with the other two arrangements. The chart is also much smoother in terms of efficiencies when compared to the results from Cases 3.1 or 3.2, in which several sharp discontinuities exist. At efficiencies higher than 75%, the pumping capacity range is from −100% to −25%. Concerning generation, the efficiencies exceed 85% for the capacity range from 14% to 100%. Generation could proceed at lower efficiencies for lower capacities. It is noteworthy that in Case 3.3, the runners are smaller than in Case 3.2, and that regulation takes place via the small by-pass turbine. Although an economic analysis is well beyond the purpose of this work, it is not adventurous to state that the runners of Case 3.3 could offer higher efficiencies at lower costs, as denoted by the relative sizes given in Fig. 9.

A comparison of the three cases studied here is offered in Table 2. We only consider efficiencies above 70% for the purposes of evaluation. The capacity and efficiency ranges for Case 3.1 are certainly discontinuous. A plant configured along the guidelines for this case would not be flexible in pumping, although it could offer some flexibility in generation, depending on how the turbine start-up procedure would allow transitioning of capacities. Case 3.2 offers much more continuity in pumping or generating

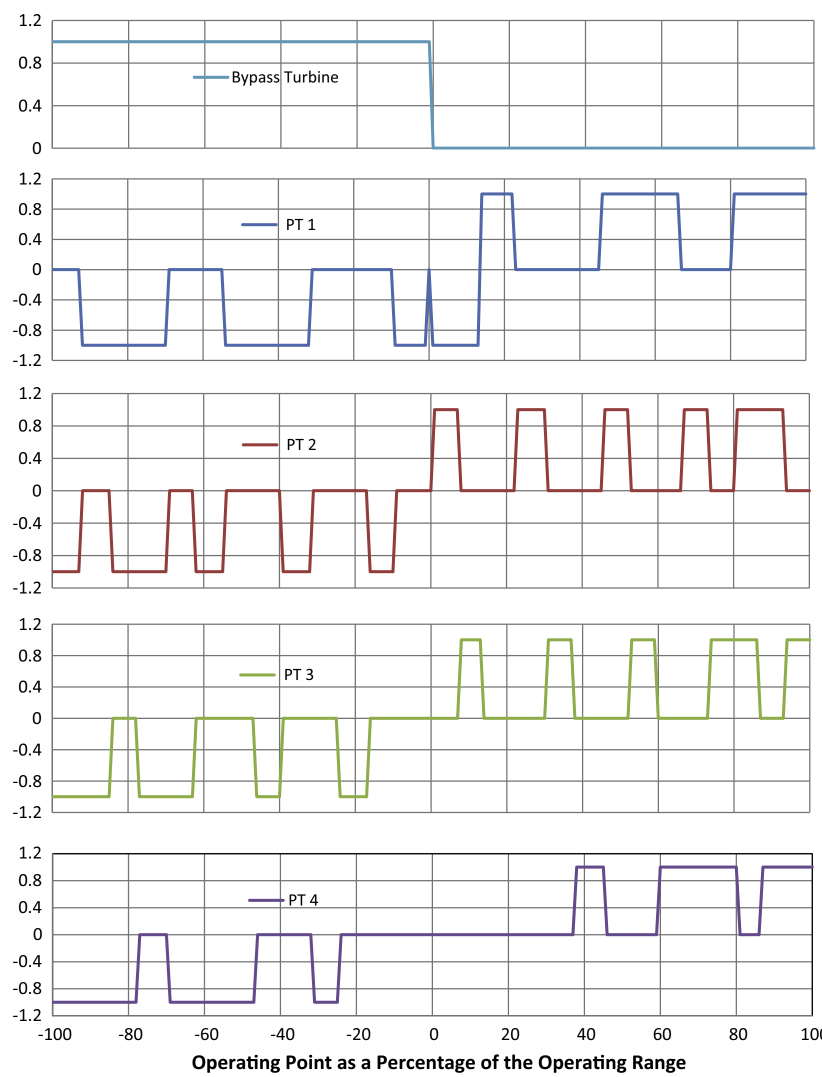

Fig. 14. Groups active for each capacity. PTs 1 to 4 (top to bottom, smallest to largest) are shown when active by a −1 or a 1 for each capacity.

capacities, and the efficiency discontinuities are smaller than for Case 3.1. Finally, Case 3.3 offers a wider capacity range in pumping, and slightly smaller in generation than Case 3.2. Efficiency discontinuities are non-existent. Perhaps more significantly, the use of the by-pass turbine is an innovative aspect that does not require inversion of rotational direction of Francis runners, as discussed next.

The groups for best efficiency in Case 3.3 are shown in Fig. 14. In this figure, from top to bottom, we show in the horizontal axis the percentage capacity of the plant and in the vertical axis a 1 when the PT is active as a turbine, a −1 if the PT is active as a pump, and a 0 if the PT is inactive. The figure shows on top the status of the by-pass turbine, and immediately below the status of each PT from the smallest one (top) to the largest one (bottom). Whereas the bypass turbine is always active during pumping (and hence could provide regulation), it is never active as a generating unit.

Francis runners are reversible (i.e. they can function as pumps or as turbines), but their reversal requires switching the direction of rotation. Hence, if a runner is operating as a turbine and must change to the pump role, it first must be isolated from the penstock, slowed down by brakes, and subsequently its rotational direction must be inverted. The reversal operation is far from instantaneous. Hence, the significance of Fig. 14 relies in that, as long as the by-pass turbine is in operation, none of the activated PTs needs to reverse rotational direction. Hence, bidding different capacities during pump or turbine operation for different temporal intervals is a real possibility with Case 3.3. For Cases 3.1 and 3.2, a similar plot would show that some PTs would have to reverse rotation for reaching the estimated capacity ranges noted, which would pose serious challenges in terms of dynamic response. In the generating mode, flexibility would exist for all cases, due to the accessible part-load operation via wicket gate regulation of turbines. However, reversal of operation for pumping would pose serious challenges in Cases 3.1 and 3.2.

As noted in the introduction, variable speed PTs can reach wide operating ranges, namely between 60% and 100% for pumping, and between 20% to 100% for generating. Variable speed equipment has good dynamic response, and could be used to balance the grid if needed [14]. For capacities above 50 MW, power electronics are too costly or not available, requiring the use of Doubly Fed Asynchronous Generators [15]. The technology proposed in Case 3.3 could employ conventional Francis runners and drives, but would be limited in its dynamics in responding to variable pumping loads to the adjustments provided by the dedicated by-pass turbine.

5. Conclusion

PHS is one of the few large scale technologies capable of storing renewable energy for use at an opportune time, without excessive consumption of fossil fuels. As determined in this work, PHS plants equipped with runners of different capacities and a by-pass arrangement, could reach high efficiencies even at part-load operation. Operation reversal may be required in some instances for Cases 3.1 and 3.2.

Our main contribution towards flexibility is the technology outlined in Case 3.3. In this case, a smooth efficiency vs. capacity profile is projected, which means that the plant could bid any of many pumping capacities for intervals of one hour or so, with some regulation emanating from the by-pass turbine. The same conclusion applies to the generation regime, and regulation could be provided according to the capacity of the PT or PTs operating at the time bracket of interest. The key significance of Case 3.3 is that no rotational reversal is anticipated during the pumping or generating regime.

Additionally, Case 3.3 has no pumping capacity gaps, and only one small, unavoidable gap in the generating mode. In all cases, when the bypass approaches large values (i.e. the plant capacity is low), the efficiencies decrease. The exact value at which bypass operation becomes uneconomical depends on the prices of energy and regulation and on the achieved efficiency.

Future work should focus on the dynamic response by-pass arrangements. Such studies could open the way for PHS assets to be deployed for a longer time that they currently are. Profitable use of the equipment during an increased number of hours will improve economic feasibility. In the ultimate analysis, whether to choose a by-pass arrangement over a variable-speed or constant speed depends on the price of flexible power, and economic analysis should be devoted to ascertaining which technology would be more promising.

Grid operators will compensate for supply and demand variability with a host of technologies. Some of the alternative technologies will undoubtedly consume primary energy. The present work shows that if planned properly, PHS could be capable of providing energy arbitrage at variable capacities to assist managing the storage and delivery of renewable energy. PHS designs using constant capacity overlap (Case 3.3) have the potential to provide adjustable hour to hour pumping capacities covering wide ranges without resorting to variable speed motors.

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References

[1] National Hydropower Association, 2014. <http://www.hydro.org/tech-and-policy/technology/pumped-storage/>.
[2] Energy Storage Association; 2014. <http://energystorage.org/energy-storage/technologies/pumped-hydroelectric-storage>.
[3] Whittingham S., 2012. History, Evolution, and Future Status of Energy Storage. In: Proceedings of the IEEE (vol. 100, Issue: Special Centennial Issue) p. 1518–34.
[4] Sulzer, 2014. <http://www.sulzer.com/en/-/media/Documents/Cross_Division/Industries/Power_Generation/Brochures/PumpedHydroStoragePower_E10125.pdf>.
[5] Connolly D, Lund H, Finn P, Mathiesen BV, Leahy M. Practical operation strategies for pumped hydroelectric energy storage (PHES) utilizing electricity price arbitrage. Energy Policy 2011;39(2011):4189–96.
[6] L. Branchini, M. Bianchi, N. Cavina, A. Cerofolini, A. De Pascale, F. Melino. Wind-Hydro-Gas Turbine Unit Commitment To Guarantee Firm Dispatchable Power, GT2014-25049, Proc. of ASME Turbo Expo 2014.
[7] Kjølle, Arne. *Hydropower in Norway*. Trondheim: Norwegian University of Science and Technology, 2001. <http://www.magnu.polymtl.ca/contenu/ressources/docDivers/doc/Turbines101.pdf>.
[8] Cutter E, Haley B, Hargreaves J, Williams J. Utility scale energy storage and the need for flexible capacity metrics. Appl Energy 2014;124:274–82.
[9] Bradbury K, Pratson L, Patiño-Echeverri D. Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. Appl Energy 2014;114:512–9.
[10] Dursun B, Alboyaci B, Gokcol C. Optimal wind-hydro solution for the Marmara region of Turkey to meet electricity demand. Energy 2011;36:864–72.
[11] Padrón S, Medina JF, Rodríguez A. Analysis of a pumped storage system to increase the penetration level of renewable energy in isolated power systems. Gran Canaria: a case study. Energy 2011;36(2011):6753–62. <http://www.hydroworld.com/articles/print/volume-21/issue-5/articles/pumped-storage/converting-to-variable-speed-at-a-pumped-storage-plant.html>.
[12] Papaefthymiou SV, Karamanou EG, Papathanassiou SA, Papadopoulos MP. A wind-hydro-pumped storage station leading to high res penetration in the autonomous island system of ikaria. IEEE Trans Sustain Energy 2010;1(3):163–72.
[13] Islam SM. Increasing wind energy penetration level using pumped hydro storage in island micro-grid system. Int J Energy Environ Eng 2012;3:9. http://www.journal-ijeee.com/content/3/1/9.
[14] Kapsali M, Kaldellis JK. Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms. Appl Energy

2010;87(11):3475–85. ISSN 0306-2619, <http://dx.doi.org/10.1016/j.apenergy.2010.05.026>. (http://www.sciencedirect.com/science/article/pii/S0306261910002126).

[15] Tao Ma, Hongxing Yang, Lin Lu, Jinqing Peng. Pumped storage-based standalone photovoltaic power generation system: modeling and techno-economic optimization. Appl Energy 2015;137:649–59. ISSN 0306-2619, <http://dx.doi.org/10.1016/j.apenergy.2014.06.005>.

[16] Ingram E. "Balancing the Grid with Pumped Storage" Hydro Review, August 10, 2011. <http://www.renewableenergyworld.com/rea/news/article/2011/08/balancing-the-grid-with-pumped-storage>.

[17] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems: a market operation based approach and understanding. Energy 2012;42:96–102.

[18] 2014. <http://energystorage.org/energy-storage/technologies/variable-speed-pumped-hydroelectric-storage>.

[19] Krenn J, Keck H, Sallaberger M. Small and mid-size pump-turbines with variable speed. Energy Power Eng 2013;5:48–54. <http://dx.doi.org/10.4236/epe.2013.52A007>.

[20] Henry J, Maurer F, Drommi J, Sautereau T. Converting to Variable Speed at a Pumped-Storage Plant. Hydro Review Worldwide, 2013.

[21] Francis Z. The Dynamics Of Pumped Hydro Storage With A Pelton Wheel And Bypass: Response And Revenue. Mechanical Engineering Honors Thesis, Penn State, 2013.

[22] Dixon S, Hall C. Fluid mechanics and thermodynamics of turbomachinery. Amsterdam: Elsevier; 2014. p. 386.

[23] Richards S. Technoeconomic Analysis of Pumped Hydroelectric Storage as a Means to Mitigate the Variability of Renewable Generation" Master Thesis, Mechanical and Nuclear Engineering Dept., Penn State, 2012.

[24] Vorarlberger Illwerke AG (Illwerke). 2011. <http://www.kopswerk2.at/downloads/Folder_061006_englisch.pdf>.