Novel concepts of increasing energy storage capacity at Pumped Storage Power plants

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ABSTRACT. – The paper presents two novel concepts for increasing energy storage capacity at Pumped Hydro Storage (PHS) plants that are planned, being constructed or already exist. Both concepts make use of compressed air, but unlike other storage technologies that utilize compressed air, the air is not intended as the energy storage itself, it is a working fluid for moving water. By using compressed air, it is possible to utilize storage volumes that are positioned below the original upper reservoir in PHS plants. The two concepts presented here uses this principle, one by inflatable air bags positioned below the lower reservoir level, and the other by excavation of underground reservoirs that serve as the increased storage volume. The necessary operation comes at an efficiency penalty, but the energy storage reservoir will have an increase in size, without any new dam being built or existing water levels rise. This makes it ideal for retrofitting at existing PHS plants, which would increase the energy storage capacity as well as making it possible to install additional power generating capacity.

Key-words: PSP, Norway, capacity, enhancing

Nouveaux concepts pour augmenter la capacité de stockage des installations de pompage-turbinage

RÉSUMÉ. – Cet article présente deux nouveaux concepts pour augmenter la capacité de stockage des installations de pompage-turbinage (PHS) pour des installations en phase de conception, de construction ou déjà en fonctionnement. Les deux concepts font usage d'air comprimé, mais, contrairement aux autres technologies de stockage basées sur l'air comprimé, l'air ne stocke pas directement l'énergie, il opère plutôt comme un fluide moteur pour déplacer l'eau. En utilisant l'air comprimé, il est possible d'utiliser des volumes de stockage positionnés en dessous du réservoir supérieur de l'installation PHS. Les deux concepts présentés dans cet article utilisent ce principe : le premier en utilisant un ballon gonflable situé en dessous du niveau inférieur du réservoir, le deuxième en excavant des réservoirs souterrains qui vont servir de volumes de stockage supplémentaires. La mise en place de tels systèmes est réalisée au prix d'une perte d'efficacité, mais le stockage d'énergie est accru sans qu'un nouveau barrage (ou une augmentation du niveau d'eau) ne doivent être réalisés. Ce concept apparaît donc idéal pour la rénovation des d'installations de stockage-turbinage existantes, en augmentant leur capacité de stockage d'énergie ainsi qu'en permettant d'augmenter la puissance de production électrique.

Mots-clés : Stockage d'énergie par pompage, Norvège, amélioration de la capacité

I. INTRODUCTION

The recent COP21 meeting in Paris resulted in the Paris Agreement, a consensus agreement for the 196 parties attending COP21. The agreement will become legally binding first when at least 55 countries representing at least 55% of the world greenhouse gas emissions sign it, as well as adopt the agreement into their own legal systems (European Commission, 2016). A significant step in the process of accelerating the development towards The Green Transition.

The Green Transition has big implications for the energy sector. The energy sector must shift its source of energy from carbon based fossil fuels to renewable sources of energy. Intermittent energies are necessary for this shift. In order to achieve this, the intermittent energy needs to be balanced. Intensive efforts are being made to find new ways of balancing energy production and consumption. According to DOE Global Energy Storage Database, 394 energy storage projects are currently either announced, contracted or under construction, adding all types of technology. Adding all the rated power, the figure is close to 39 GW (Strategen Consulting LLC, 2016). The technology that is most mature, represents smallest capital risk and at the highest Technological Readiness Level (TRL) is Pumped Hydro Storage plant (PHS), which can be seen in Figure 1. 48 of the above mentioned projects are PHS projects. The sum of rated power is close to 34,5 GW, a staggering 88% of all rated power for all technologies. The number of PHS plants currently in operation is close to 300, and the sum of rated power is 142 GW. There are some uncertainties in the numbers above, but the US Energy Information Administration (EIA) database has a figure of 138 GW (when some obvious missing table entries have been added, like India) of summed installed rated power (US Energy Information Administration, 2016). The actual number is likely to be close to 140 GW. Figure 2 is showing the installed energy storage capacity by technology worldwide in 2010 (International Energy Agency, 2012).

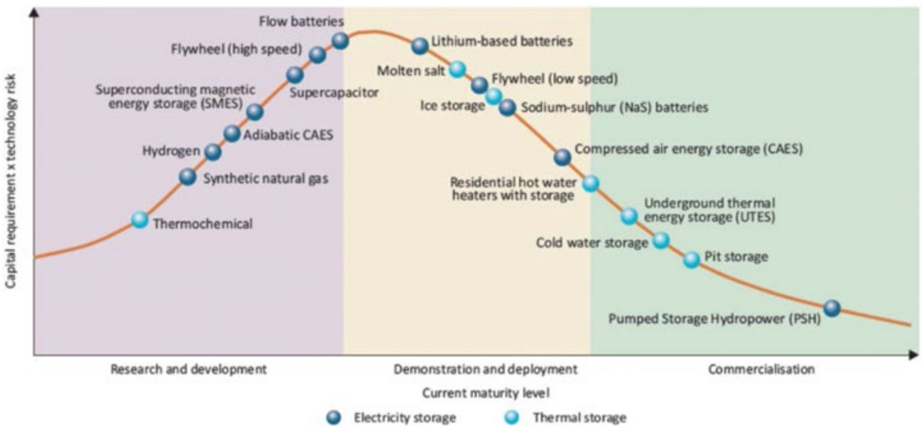

Figure 1 : *Capital risk and maturity of energy storage technologies, (International Energy Agency, 2012).*

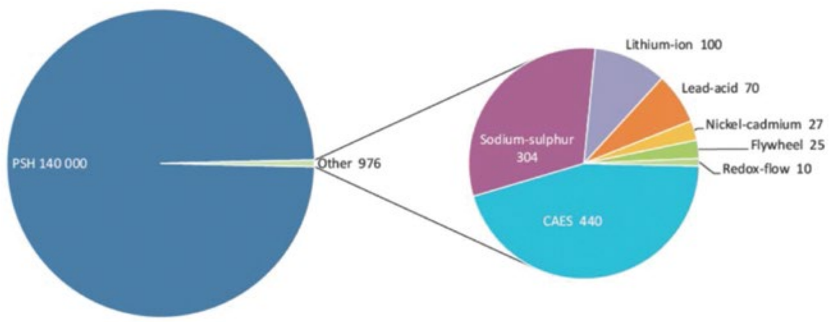

Figure 3 : *Global installed grid-connected electricity storage capacity by technology in 2010 (International Energy Agency, 2012).*

PHS technology is the technology with the highest energy storage capacities and time scales so small that it can serve many purposes in a future electrical energy grid (International Energy Agency, 2012), as well as having a high Round Trip Efficiency (RTE). As shown, several PHS projects are being developed throughout the world, however the best sites have already been developed. This paper presents two novel concepts of increasing the energy storage capacity of PHSs which can be implemented at PHSs that are planned, under construction as well as existing PHSs. The concepts are so novel that there is not much evidence of its potential other than the arguments presented in this paper. Feasibility studies and economic considerations have to be performed for each PHS project; existing, announced or under construction.

The reader might have the impression that these concepts are very far from anything remotely ready for commercialization. The reader is completely correct; there is a lot of work that has to be performed before these concepts reach TRL 3, which is "proof-of-concept". The reason for presenting the concepts at this stage is just to get the concepts disclosed. The engineers, technicians, and operators of the PHS plants around the world possess the detailed knowledge of those PHS plants. Getting the concepts out to those people will be the best test for a theoretical proof-of-concept there is. I hope that the concepts will pass the test, and can rapidly become a part of the Green transition. If not, hopefully, it can induce out-of-the-box thinking within the hydropower community.

2. PUMPED STORAGE POWER PLANTS

PHS is a mechanical energy storage technology that uses water as the energy carrier and energy storage medium. Lifting a mass of water using a pump to a higher elevation stores potential energy that can be utilized at a later time when needed.

II.1. Mathematical foundation

The basic formula for hydraulic power P_h is (Cengel, Cimbala 2014):

$$P_h = \rho g Q H \tag{1}$$

where ρ is the fluid density [kg/m³], g is the gravitational constant [m/s²], Q is the discharge [m³/s] receiving the

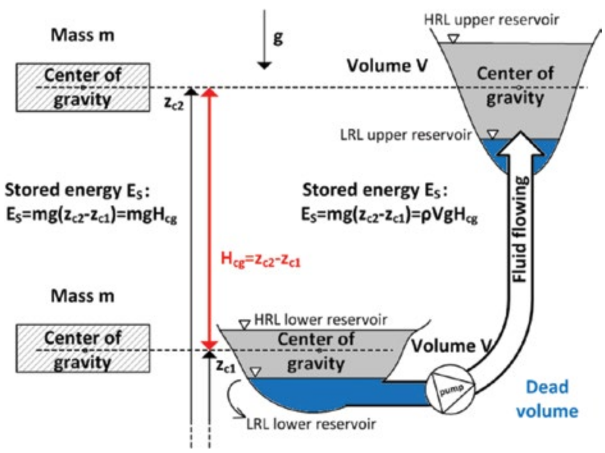

Figure 3 : *Working principles of PHS, HRL=Higher Reservoir Level, LRL= Lower RL*

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power leading to an increase in total energy height H [m] in the fluid. Much detail can be provided to this formula, but we are going to omit details. We are now going to assume that this power P_h is put into the fluid by a pump and rather integrate the power over some pumping time duration dt to find an expression for the energy E_h put into the fluid flow (Cengel, Cimbala 2014):

$$E_h = \int P_h dt = \rho g \int QH dt \quad (2)$$

It is not straight forward finding out how to perform this integration. Due to changing reservoir levels (means increasing H) from moving water between reservoir as well as the discharge Q changing when H increases due to the characteristics of the pump, more detail must be known. However, we would like to omit detail, and realize that the energy stored in the reservoir, E_s, must be equal to the energy put into the flow minus all the losses experienced by the water going from the lower to the upper reservoir. The formula for energy stored can be seen in Figure 3, which also includes a solid body energy storage analogy. Thus,

$$E_s = E_h - E_{losses} = \rho V g H_{cg} \quad (3)$$

V is the volume [m³] and H_{cg} [m] is the difference in elevation of the center of gravity of the volume, before and after being lifted. It can be seen in equation (3) that the energy stored is directly proportional to the volume available for storage at the upper reservoir, as well as the change in elevation for the center of gravity for the pumped volume. Increasing the storage means that either one or both of the parameters H_{cg} or V must be increased. Increasing H_{cg} without increasing V at an existing PHS would be a strange operation; the upper reservoir would have to be widened at upper levels, and the excavated material dumped at lower levels without the mass ending up in the dead volume. Dumping it in the dead volume would increase the storage volume as well, obviously preferable, but still this widening of the reservoirs is not something that seem feasible. Expanding the energy storage is therefore traditionally performed by increasing the volume in other ways.

II.2. Conventional expansion of existing PHS plants

In conventional expansion of energy storage capacity, the height of the dam must be increased for the storage volume to increase. Additional water can be stored “on top of” the existing reservoir. This imply that the Higher Reservoir Level (HRL) becomes higher than the original HRL, and any infrastructure on the shore of the upper reservoir will be flooded. Depending on the dam, there are different conventional methods of expanding a storage volume.

In case of a rock filled dam, the entire dam has to be expanded from its base, and that is in the ideal condition that the substrate inside the dam will maintain its water tight properties, given the increased pressure due to the increased water levels in the dam. Given that these dams are huge to begin with, the amount of rock needed to expand the height of the dam will be huge. The author has not heard of any such expansion projects being performed.

In case of a concrete dam, the only way of expanding the storage volume is to build a new dam which is higher than the original dam. In some cases, the existing dam can be used as a foundation for the new dam, but this is far from often. This is executed at Vianden PHS in Luxemburg, where the height of the upper reservoir has been increased with 1 m (RWE 2016). The reservoir at Vianden is constructed as a closed dam, and the height is not very high. This means that the existing structure is intrinsically so strong that is can easily withstand the additional forces due to the increase in pressure from an additional 1 m water column. This might very well *not* be the case for, say, an arch dam. This is the case for Nåvatn dam (Nilsen, 2016), where a multiple arc dam in need of refurbishment will be replaced with a new one, which also will increase the storage volume. The motivation for this work was, however, not increased energy storage, but new safety regulations. The refurbishment of the existing dams was considered very expensive, and it was decided to construct a new dam, as well as increasing the dam height for increased energy storage.

The expansion in energy storage can be utilized in two principal ways; increase the duration of the operation of the existing units or installing additional units, increasing the installed capacity at the PHS plant. Most often the latter is preferred, since the duration of the pumping and generating cycles are already filling most of the hours of the day. In addition, the amount of ancillary services that can be sold is dependent on the installed power. It has been stated that the participation in ancillary service markets is emerging as the main source of revenues for PHS plants, and traditional price arbitrage and/or peak shaving operations appears to be no longer economically feasible (Pérez-Díaz, Cavazzini et. al 2014).

II.3. Operating limitations for PHS plants

Operating limitations can be numerous, and based on consideration from many different field of science and engineering. I will not discuss the diversity in all limitations in this paper; I will merely point to one strict limitation. This limitation is related to the rate at which the water level at the upper reservoir is decreasing when the PHS is operating in generating mode. The limit is not a general and set limit; it will differ from reservoir to reservoir due to the shoreline conditions. If the water level decreases too fast, the remaining water pressure inside the shoreline substrate can push the substrate out into the reservoir causing landslides, jeopardizing the integrity of the upper reservoir (Sassa, Canuti et. al 2014).

This limit is an implicit limitation on the power that can be produced from the reservoir. The rate of decrease in water level is proportional to the discharge from the reservoir, which produces power in the turbines. Installing and generating additional power at PHS plants already operating on this limit is not something that the author encourages anyone to try.

III. THE NOVEL CONCEPTS

The novel concepts are both making use of compressed air. In relation to energy storage compressed air is traditionally connected to the concept Compressed Air Energy Storage (CAES). The CAES concept uses the compressed air as the energy storage. The compressibility of the air mimics the properties of a mechanical spring, where compressing either the spring or air stores energy for later. In these two new concepts presented here, compressed air is just a medium; a working fluid for moving water between where we want it to be. Actually, when the purpose is to generate electrical energy at a PHS (retro) fitted with either of the two novel concepts, electrical energy needs to be used

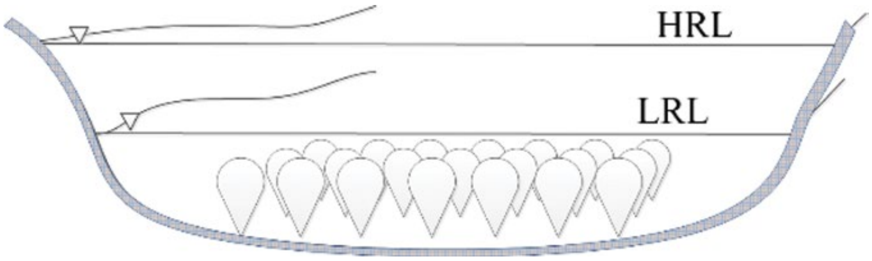

Figure 4 : *The inflatable air bag concept as envisioned in the reservoir*

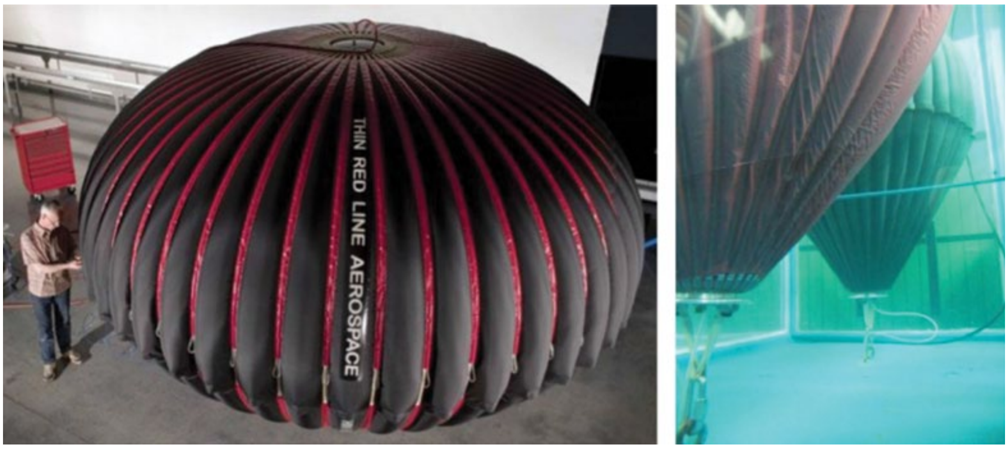

Figure 5 : *Energy bag originally intended to be used for sub-sea Compressed Air Energy Storage (10) Left: Thin Red Line Aerospace Chief Engineer and CEO Maxim de Jong inspects the CAES "Energy Bag" during initial test inflation (photo Keith Thomson/Thin Red Line Aerospace). Right: © University of Nottingham*

for compressing air. As we shall see, this energy consumption will be rather small compared to what is generated from the hydraulic turbines.

III.1. Using inflatable air bags below the lowest reservoir level

Below the Lowest Reservoir Level (LRL) there is most often a volume of water. This is not a volume that can be used for storage, since it is not allowed to produce power from this water, the water level should not drop lower than LRL. This volume is called the "dead volume", and is seen in Figure 3. However, by installing inflatable air bags on the bottom of the reservoir the water can be lifted to a higher elevation above the LRL by the displacement provided by inflating the air bags. In this way, the energy storage is increased with the volume of the fully inflated air bags. The concept is seen in Figure 4. Such air bags are being developed for ocean CAES (de Jong, 2014), and are likely to be easily installable at existing reservoirs. Still, the potential of increasing the energy storage is limited to parts of the volume of the existing reservoir that is below LRL.

III.2. Air Cushion Underground Reservoir (ACUR)

Whereas the limitation for the intended use of air bags was the volume beneath the LRL, the limitation for ACUR is how large volumes of rock can be excavated close to the upper reservoir. Obviously, for ACUR to be implementable the upper reservoir needs to have a surrounding terrain consisting of mountains where it is possible to excavate the ACUR, but also ensure long-term stability and structural integrity.

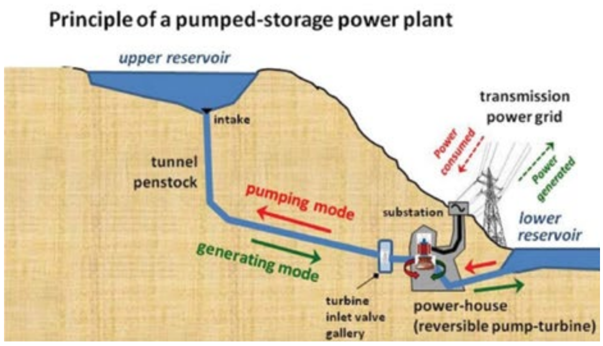

Figure 6 : *Principal PHS plant (www.eurelectric.org)*

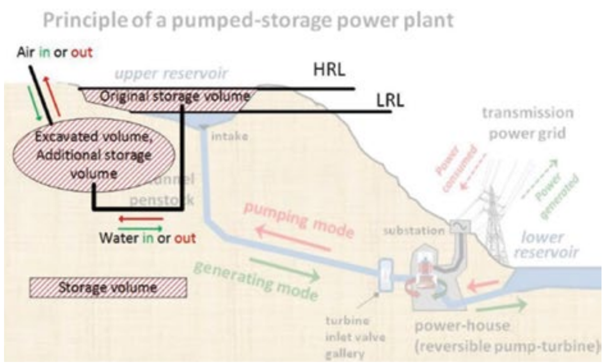

Figure 7 : *PHS plant retrofitted with ACUR*

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ACUR is a much bigger modification than the air bags, but one that potentially can allow for much more additional capacity. ACUR is based on excavating underground reservoirs close, and connected to, the upper reservoir. The intention is to excavate the underground reservoir so that the highest level in the ACUR will be below the LRL of the main reservoir. The reason for this is twofold; first, for safety reasons it is beneficial that the stored water volume can't drain into the main reservoir if something malfunctions. Second, the investment that the underground reservoir represents can be utilized independently of the water level in the reservoir. This is where the compressed air comes into play for the concept ACUR; the water needs to be pushed back into the reservoir and this is intended by compressed air.

Why not push this water by using a pump? you may ask. The reason for this is that a pump is a much more complicated installation, since a new hall with tunnels for access and so on must be constructed between the main reservoir and the excavated storage volume. Even with a pump installed, air vents must be made to let air back into the ACUR when the pump is pumping the water back into the main reservoir. So, the prime initiator of the desired dynamics might very well be the air itself, using compressed air.

4. CALCULATION EXAMPLE FOR ACUR

Let us consider a case; an existing PHS has H_{cg}=500m. The original energy storage volume is not important, as we will consider additional storage volume by ACUR and additional installed capacity. The additional installed pumping capacity is 50 MW, which gives an average flow rate of 10,2 m^3/s. Average flow rate is found when using H_{cg}, which is the average lifting height for the duration of pumping, in equation (1). Let us assume the intention is twelve hours of pumping, and let us for simplicity assume constant power pumping where the water end up storing energy represented by H_{cg}. This will then result in a volume of 440000 m^3 being moved to the upper reservoir. Using equation (3), the stored energy is 600 MWh. However, this volume is drained into an ACUR, and it ends up at H_{cg} equal to 480m. These 20 meters in head difference represent 24 MWh of lost energy. To get the water back into the main reservoir for energy production through the turbines will cost equally as much using a compressor to generate the air push needed. Therefore, 48 MWh is lost due to this cycle, if nothing is able to collect the initial 24 MWh lost. Without any energy harnessing from the draining of water from the main reservoir into the ACUR, we have stored a net energy of 552MWh. This introduces an energy conversion efficiency of 92%, which has to be multiplied with the existing Round Trip Efficiency of the PHS to obtain the new, overall RTE.

The energy could, however, be regenerated using CAES technology. The pressurized air used to push water back into the main reservoir has to be released when water needs to go back again for energy storage purposes. It is uncertain as to what extent current available CAES technology can be used for this purpose. Traditionally, CAES technologies are trying to store air at high pressures, because the volumetric energy content becomes higher. The pressures involved in ACUR will not be very high, however the volumes and air flow rates must be high. Avoiding too high pressures is actually beneficial to the efficiency, because large compression heat losses are avoided. Being conservative in the RTA of an applicable CAES technology used in combination with ACUR, an RTA of 50% is assumed. Using this figure, the loss of stored energy for the case above will be 36 MWh, and the net stored energy end up at 564 MWh. This introduces an energy conversion efficiency of 94%, which has to be multiplied with the existing RTE of the PHS to obtain the new, overall RTE. If the CAES technology resulting in 2% points higher efficiency will return the additional cost of investing in CAES technology instead of a conventional compressor must be investigated further.

V. GENERAL CONSIDERATIONS FOR BOTH CONCEPTS

The two concepts both move water between different levels, providing an increase in the energy storage volume available. It is easy to think that this will increase the possible duration of operation, but not the possibility of increasing the installed power at the site since this might be limited by how fast the water level decrease in the upper reservoir. However, the operation of the compressed air system can be made to mitigate the decrease in the water level in the main upper reservoir, allowing for more power to be installed. Say, that the upper reservoir has a limitation on the water level decrease on 10 cm/hour. This will then be a limitation for the amount of power that can be produced. But if the operation of the compressed air system could result in water corresponding to an increase in the water level in the main reservoir of, as an example, 3 cm/hour, power corresponding to 13 cm/hour could be produced while water level still decreasing by only 10 cm/hour in the main reservoir. This will make possible the installation of additional power from the reservoir retrofitted with this possible future technology.

Another aspect to take into consideration is the fact that for conventional energy storage expansion, the water level in the upper reservoir will increase. As hydraulic machines are constructed with pressure (ultimately the difference in water level between the upper and lower reservoir) as a design parameter, the already installed machines installed at the PHS plant have to operate at different conditions, the penalty being reduced efficiency, in both pump and turbine mode of operation. Using both the presented concepts, water levels after retrofitting will be the same as before retrofitting, and the hydraulic machines are not faced with new operation boundary conditions. Their efficiency will therefore be the same as before.

As the calculation example is showing, the potential increase in energy storage will be directly proportional to the elevation of the upper reservoir relative to the lower reservoir. The water in the energy storage end of the PHS is cycled between two separate storage volumes at different levels; the upper, original level, and the lower level represented by the additional storage volume, either by the inflated air bags, or the ACUR. As an example; consider the case where there is a dam in a river, and the river bed in the upper reservoir is the same as in the river downstream the dam. Installing inflatable air bags on the river bed of the upper reservoir would then not give an additional storage volume, because the energy is cycled between the same levels when the air bags are operated as the PHS is when operating. The additional volume needs to be above the lower reservoir for creating a net storage effect, and the higher above, the better. This imply that both new concepts will represent better investments the higher the elevation difference between the original PHS reservoir are. The energy cycled between the main reservoir and the air bags/ACUR and the accompanying losses, becomes smaller relative to the energy stored in the new volumes. In the above-mentioned case, the inflatable air bag should be positioned directly underneath LRL, and not at the bottom.

Both concepts could also be used to construct PHS plants where conventional PHS plants are not permitted because the water level oscillations can't be accepted. This might be where natural lakes or ponds are close to residential areas, where the oscillating water levels are considered to destroy the value of recreational areas, wildlife habitat, etc. The operation of the air bags/ACUR could be performed in a way that would keep the water level constant, while water would pass through a PHS in a normal way. The energy storage capacity of such PHS would then be the volume of ACUR, or the volume of the air bags.

Quite often there is a limitation to the available volume of the lower reservoir as well as the upper reservoir. Increasing the storage in the upper reservoir might not be possible because a new limitation presents itself at the lower reservoir. In this case, an additional ACUR or air bags at the lower reservoir would increase the storage there as well. Obviously, the cost of increasing the energy storage capacity at such PHS plants will be much higher, but the technical limitation is easily overcome. What is then needed in case of ACUR is the additional water, which can be a challenge for closed loop PHS plants. For the air bags the needed volume and water must already be available under LRL.

V.1. Additional considerations for the inflatable air bags

Some PHS plants are installed between reservoirs where settling of sediments contained within the naturally flowing water is a huge problem. These sediments are filling up the reservoir, first the dead volume, but potentially also the valuable storage volume. Getting rid of these sediments is not easy. However, an installation at the bottom of such reservoir could be used to whirl up sediments into large concentrations, and then the heavily sediment-laden water could be bypassed the hydraulic machines in a controlled way.

V.2. Additional considerations for ACUR

The Construction of the ACUR will obviously require the excavation of huge amount of rock masses. The question where to deposit these rock masses naturally comes to mind. In case of a new PHS being constructed, like for instance the proposed Coire Glas PHS (SSE, 2016) in Scotland, the excavated rock might be used in the construction of the dam. If ACUR is retrofitted at existing PHS plants the rock might be deposited in the dead volume. In case of combining ACUR with expansion of the original reservoir, some of the excavated material might be used as a construction material for the new dam. If none of the above is possible, the rock must be deposited somewhere else, with no indication here on what is the best case for each PHS.

VI. CONCLUSION

Two novel concepts for increased energy storage at PHS plants have been presented. The concepts have several benefits compared to conventional methods of increasing the energy storage at PHS plants. The author considers both concepts technically feasible. If they will return the investments is still an open question. However, completely new PHS plants are being constructed, clearly, because investors are certain that investments will be returned. The increased energy storage concepts presented here are likely to represent smaller specific investments, either specific to unit stored energy or to unit power installed. The concepts are at least disclosed, and it would please the author if they could prove to help the Green Transition.

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