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Flat-land large-scale electricity storage (FLES)
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Abstract Growth of renewable sources requires a smarter electricity grid, integrating multiple solutions for large scale storage. Pumped storage still is the most valid option. The capacity of existing facilities is not sufficient to accommodate future renewable resources. New locations for additional pumped storage capacity are scarce. Mountainous areas mostly are remote and do not allow construction of large facilities for ecological reasons. In the Netherlands underground solutions were studied for many years. The use of (former) coal mines was rejected after scientific research. Further research showed that solid rock formations below the (unstable) coal layers can be harnessed to excavate the lower water reservoir for pumped storage, making an innovative underground solution possible. A complete plan was developed, with a capacity of 1400 MW (8 GWh daily output) and a head of 1400 m. It is technically and economically feasible. Compared to conventional pumped storage it has significantly less impact on the environment. Less vulnerable locations are eligible. The reservoir on the surface (only one instead of two) is relatively small. It offers also a solution for other European countries. The Dutch studies provide a valuable basis for new locations.

Introduction

This paper introduces a new, innovative, large-scale electricity storage system, which is based on proven technology.
First the characteristics of conventional pumped storage plants (PSP) are briefly explained. Thereafter an underground solution will be introduced for electricity storage in flat lands, which is also applicable in areas where natural differences in height cannot be used. It refers to an underground pumped storage plant or U-PSP. Finally the chances for U-PSP in Europe are discussed.

As a result of the expected growth of wind and solar energy, it will become increasingly difficult to match electricity supply and demand. On top of that, most northwest European countries have the same strategy to solve this problem a.o. by cross border trading (virtual storage).
Present and future connections between countries open new possibilities to store renewable electricity virtually. Yet virtual storage can only offer part of the solution, it is certainly not enough to safely absorb all wind capacity expected in the North Sea area (Germany, Netherlands, UK, Belgium and Denmark) without jeopardizing security of supply. It is indeed so that the wind blows in that whole area approximately at the same times. This means that surpluses and shortages in the system due to the production profile of those wind parks will occur quasi-simultaneously

The produced wind energy will often exceed demand and lots of renewable energy can get lost. The European Commission and leading countries such as Germany are convinced that the growth of renewable energy sources requires smart grids in which large-scale storage systems are integrated.

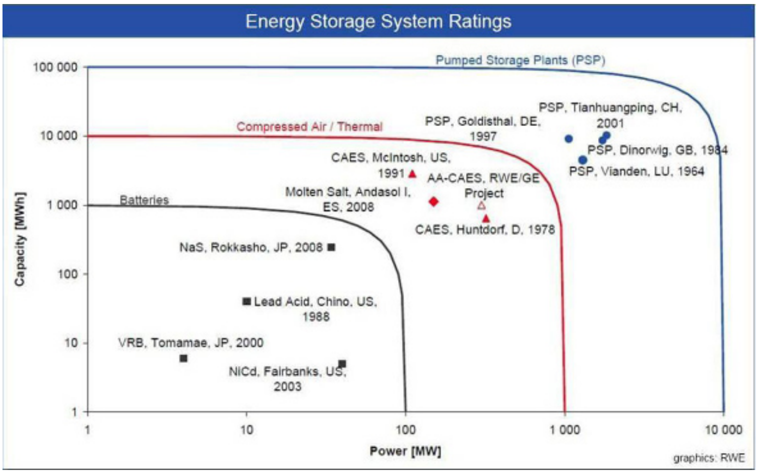
The current available storage capacity is more than 100 GW worldwide; in 2030 the market potential is expected to grow 400% to ca. 430 GW. For example, the Boston Consulting Group has calculated that Germany alone will need 28 GW storage capacity in 2025. The problem is too large scale for a singular solution. More technologies are needed to meet future requirements.

Conventional Pumped Storage Plants (PSP)

The selection of a storage system generally depends on the required capacity on the one hand, and the realizable capacity together with the load and unload characteristics on the other. Large-scale storage till now mainly exists in the form of pumped storage.

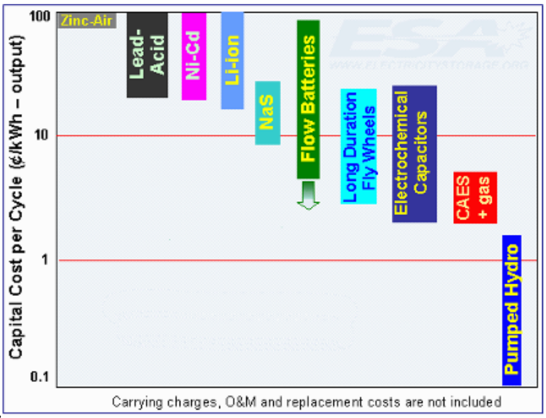
Surpluses of electricity are stored by means of pumping up water from a lower reservoir to a higher situated basin. During peak hours, the water flow is reversed via turbines to gain back the electricity. Pumped storage power plants can deliver full load immediately.
It is already applied for several decades to balance the electricity network, to match supply and demand and to spare conventional production capacity.
The existing pumped storage power plants are built in an environment with large natural differences in altitude.

This diagram shows that only pumped storage is able to deliver high capacity storage, for instance 1000 MW or more, during several hours.



So, for large-scale application, pumped storage is a major solution.

When we look at the capital cost per cycle, it becomes clear that pumped hydro is the number one in storage options (source: Electricity Storage Association).



Life span and efficiency are taken into account. The life expectancy of pumped storage plants is several decades and possibly a century. The cycle efficiency is more than 80%.
Also in terms of sustainability pumped storage plants score better than other systems.

When we finally consider that pumped storage plants are operating reliable for several decades, not based on using fossil fuel, the solution for future storage demand seems to be obvious. Unfortunately reality is far more complicated.

The growth potential of conventional pumped storage plants is marginal, because of topographical constraints and hence environmental, political and public opposition. The mountainous areas in which pumped storage plants can be realized, are often ecologically vulnerable.
Such environment does not allow to build water basins measuring many square kilometres and containing millions cubic metres water.

However, the qualities of pumped storage are so favourable, that it is worthwhile to look for an alternative solution.
In the Netherlands this was considered for many years, since there are no significant natural differences in altitude. When we can conquer land from the sea, we may also be able to create differences in height.
The solution must be sought underground: a water reservoir at large depth.

Underground Pumped Storage Plant (U-PSP)

It speaks for itself that the use of abandoned coals mines, with many millions cubic metres underground space, is considered.

In the Netherlands mining professors examined by government's order, whether the Dutch coal mines are suitable to use as lower reservoir of a pumped storage plant. Unfortunately this was not the case.
Although we did not study other mining areas in Europe, we have good grounds to assume the same finding: too scattered, unstable and unfavourable hydrodynamics.

Subsequently other rock layers were studied in order to obtain the required stability.
We found out that beneath the Dutch coal a homogeneous, dense and stable rock layer is located, with a thickness of approximately 700 metres.

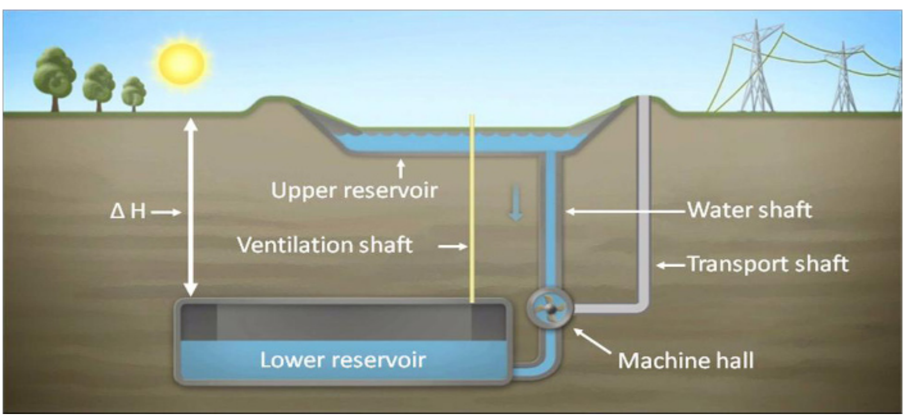
Here you see a sample of a core drilling of lime stone from the geological age Dinantien.

1.350 m *1.450 m* *1.680 m*

O-PAC samples Limburg (NL)

This type of rock is suitable for building large underground water reservoirs, by means of both tunnels as larger caverns, and also for the voluminous machine halls containing the hydroelectric installations. The risk that tectonic disturbances hamper the building process is judged to be minor. By means of the known and proven underground constructing techniques the necessary spaces can be realized. The stability and the permeability of the stone is excellent, so that walls only need locally a limited concrete coating or reinforcement.

An underground pumped storage plant (U-PSP) looks as follows:



A complete engineered plan is custom-made for a specific location here in Limburg and is named O-PAC. I will show the specs of this project as an example how an underground pumped storage plant could be designed elsewhere in Europe.

This U-PSP (O-PAC) consists of a small pond at surface measuring ca. 400 x 400 metres, which is connected to a underground reservoir at 1400 metres depth. The complete machine hall is situated at approximately the same depth. Three shafts are connected to the underground spaces.
The large difference in height allows to generate so much pressure that the kinetic energy of the water can generate a maximum capacity of 1400 MW. This requires seven turbines of 200 MW. Any capacity between 10 and 1400 MW can be provided. The volume of the water reservoirs is 2.5 million cubic metres each. With this amount of water an output of 1400 MW can be delivered for 6 hours. This implies that the storage capacity is more than 8 GWh per cycle and more than 2 TWh per year.

The capacity of such systems depends on the fall difference and the amount of water.
The bigger the difference in fall, the larger the capacity of the installation and hence the less water is needed.

Pumped storage has been employed successfully for decades here in Europe and all over the world. Similar to underground pumped storage, a number of conventional pumped storage plants have built water shafts and hydroelectric installations in a mountain.
Here you see an example in Dinorwig in Wales (Great Britain).




These impressive water shafts and enormous machine halls are operational since 1984.

Recently updated calculations of the construction costs revealed that it will take ca. 1,8 billion € to build this underground pumped storage plant.
Here you see how these construction costs are composed:

· Infrastructure at surface	1,9 %
· Hydroelectric installations	25,1 %
· Lower reservoir, dry shafts, shaft installations, rock transport and geology	47,2 %
· Water shaft, machine hall, high- and low-pressure water tunnels	17,1 %
· Grid connection	4,5 %
· Preparation and development	4,1 %
· Total 1,8 billion €	100,0 %

Almost half of the costs consist of underground works for the lower reservoir and shafts. Therefore one could presume that an underground pumped storage plant is much more expensive than a conventional system. However, this is not the case.

In actual practice it has been revealed that it involves considerable expenses to adapt a conventional pumped storage plant in order to create acceptance for the natural environment and ecology. In case of underground pumped storage plants this problem does not occur and as a result the construction costs are practically the same as for its conventional counterpart.


Existing pumped storage plants generally have a fall of a few hundreds metres, sometimes five to six hundred metres. In comparison an underground pumped storage with more than 1000 metres depth can provide a greater amount of energy with significantly less water, up to four times less.

Because of the enormous size of the two water reservoirs, the construction of a conventional pumped storage plant on a mountain or in a hilly environment is very costly. This explains why the construction costs of both the conventional and the underground pumped storage do not deviate significantly.

PSP – Comparison	P/T Power	TIC	Costs/MW
Kopswerk II (A) *	525 MW	350 M€	667 k€
Vianden M 11 (L) *	200 MW	155 M€	775 k€
Atdorf (D) **	1400 MW	1200 M€	857 k€
Nant de Drance (CH)	600 MW	819 M€	1365 k€
Veytaux (CH)	240 MW	273 M€	1136 k€
Linthal 2015 (CH)	1000 MW	1750 M€	1750 k€
O-PAC (NL)	*1400 MW*	*1800 M€*	*1285 k€*

* *Expansion*
** *Costs of environmental protection not included*

The Swiss recent examples are far more expensive than O-PAC, except the installation in Veytaux which is incomparable due to its smaller size. The Atdorf data are biased since the costs of environmental protection measures are not included.
The other two systems in this benchmark, Kopswerk II and Vianden, are expansions of existing plants, which possibly explains the relatively low costs per MW.

This table from the Energy Risk Advisory Group shows the expected annual income (gross margin) from 2020 of O-PAC under different assumptions.

Estimated annual income O-PAC, € mln.					
		Volatility			
		0%	30%	40%	50%
Average price per year, €/MWh	50	119	135	149	163
	70	166	190	208	230
	90	214	243	267	291
	110	237	299	327	356
	130	309	354	389	425
	150	356	405	445	489

Source: Energy Risk Advisory (www.eriskgroup.com)

Volatility measures the degree to which prices vary daily or even from one hour to the next.
Volatilities over the past 4 years have been around 30% on average.
Higher prices and more volatility lead to a higher gross margin.
The blue area shows the annual income based on present volatility and prices:
150 to 200 million € per year.
Increased volatilities which are to be expected with the increase in the share of wind power in the overall energy mix would add additional revenues. The green area shows the outcome of this "sustainable" scenario, resulting in an annual income of more than 300 million € per year.

Assuming a total income of O-PAC of € 200 million (which is € 80 million more than the expected annual cost) we calculate an overall return on equity of almost 11.9%. On request of government of the Province of Limburg these data were reviewed and confirmed by Ernst & Young.

Summarizing the following advantages of pumped storage can be mentioned:

- it is a proven and stable technology for large-scale application
- independent of environmentally unfriendly and/or hard to obtain, expensive materials and fossil fuel
- high availability and reliability
- long life span.

Additionally underground pumped storage has a number of unique advantages:

- maximizing the difference of fall
- therefore less water is required; up to four times less
- only ONE relatively small reservoir needs to be fit in the landscape, instead of two large water basins
- does not depend ecologically on vulnerable natural landscape
- can be realized in the direct vicinity of renewable energy production as well as electricity consumers and industry.

What is needed to realize O-PAC? Besides the necessary technical and geological requirements, investors must be able to rely on the expected long term market development. It is only worthwhile to build O-PAC, when growth of renewable sources perseveres and the government refrains from market interference when volatility increases significantly

Does underground pumped storage offers chances for Europe?

The future demand for large-scale electricity storage is large. Several technologies must be applied to meet this demand. Pumped storage is not the only, but nevertheless a very important solution. I have illustrated that locations for conventional pumped storage are scarce.
There are elsewhere in Europe, as in the Netherlands, without any doubt locations which fulfil the geological requirements of underground pumped storage. For this purpose we closely collaborate with geological experts and engineers at RWTH Aachen University.

For each location the optimal dimensions have to be defined. This depends on (storage) demand and the depth, size, and extensiveness of the rock layers. Based on our studies we have the know-how and the methodology to examine the feasibility of potential locations within a short time frame. We also developed tools to determine the economic feasibility.
Underground pumped storage can be a valuable asset to the future storage mix. Continuation of a decisive policy regarding renewable energy will lead to a healthy business case.

Finally I would like to point out that the governments play a key role. The governments need to set up conditions to realize large storage with sufficient capacity to accommodate renewable sources as wind and solar.

Underground pumped storage plants are a feasible and sustainable solution.