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Sharing Water: Multi-Purpose of Reservoirs and Innovations

The huge potential of new dams is based upon pumping

Le grand potentiel de nouveaux barrages est basé sur le pompage

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Abstract. Existing dams are mainly used for creating along river reservoirs filled by gravity. The potential of new dams for such uses is limited in most countries by the lack of sites, the competitive cost of wind or solar energy supply and the criticism of environmental impacts. But there is a huge potential of large new reservoirs filled by pumping. Such use will probably be very important after 2030 for storage of wind and solar energy which will become the main sources of electricity. Very large off rivers reservoirs have a huge future as well for seasonal water storage as for floods mitigation. Environmental impacts of such uses are usually better than for traditional ones. Yearly investments for new dams may be in 2040 much more important than ever in the past. Dams' designs may be traditional or innovative.

Résumé. Les barrages existants sont principalement utilisés pour créer le long des rivières, des réservoirs remplis par gravité. Le potentiel de nouveaux barrages basés sur cette utilisation est limité par l'absence de sites favorables, le coût compétitif des énergies éolienne et solaire, et les critiques de leurs impacts sur l'environnement. Mais il y a un potentiel très important de nouveaux grands réservoirs remplis par pompage. Cette utilisation sera probablement très importante après 2030 pour le stockage des énergies intermittentes vent et solaire qui deviendront les sources principales d'énergie électrique. De très importants réservoirs hors rivière ont un très grand futur pour le stockage d'eau et le contrôle des crues. Les impacts de ces usages sur l'environnement sont plus favorables que ceux des usages traditionnels. Les investissements annuels pour de nouveaux barrages peuvent être dans vingt ans beaucoup plus importants que par le passé. Les projets de barrages peuvent être traditionnels ou innovateurs.

Most dams have been used along rivers for creating reservoirs filled by gravity mainly for hydroelectricity supply, seasonal water storage or floods mitigation. The additional potential of new dams for this traditional use is low in many countries because best relevant sites are already used, the direct cost per kWh of wind or solar energy becomes lower than hydropower cost and criticism of the environmental impact of such reservoirs is preventing many useful implementations.

The realistic potential of reservoirs filled by pumping is much more important for the various needs and conditions and applies also to rather flat countries. Relevant dams designs may be specific and innovative. Environmental impacts may raise less criticism than traditional uses. Examples are presented below for electricity, water storage and floods mitigation.

1 The main future of hydropower is the energy storage

The hydropower supply is now 4 500 TWh/year by a 1 300 GW plants capacity. It is thus 17% of the world electricity of 26 000 TWh. Relevant reservoirs occupy 400 000 km^2, i.e., 100 km^2 per TWh.

The realistic potential of extra hydropower supply is about 2 000 TWh/year by a 500 GW capacity, for a future total of 6 000 or 7 000 TWh, about 10% of the likely future total use of electricity which may increase from 26 000 to 60 or 80 000 TWh. In the second part of the century fossil fuels will be avoided and most world electricity will be probably supplied by solar photovoltaic (P.V.) and wind because it is possible and cost effective for such needs. But a key point will be the storage of these intermittent wind or PV energies. It may be studied separately for sunny countries and windy countries.

2 The need of energy storage in sunny countries could be the main opportunity of future dams

The countries within 3 000 km from equator total 5 billion people and use 8 000 TWh, i.e., 1 600 kWh as average per capita; many people use few hundreds kWh or nil. The revenue per capita of these sunny countries is 20% of the revenue per capita of OECD windy countries where 1,3 billion people use each 8 000 kWh i.e., 10 000 TWh and live far from equator. Worldwide the revenue per capita is quite proportional to the use of energy and the advisable economical progress of the sunny countries will require within some decades at least 5 000 kWh for 8 billion people, i.e. 40 or 50 000 TWh: fossil fuels should be quite avoided, Hydropower may supply 10%, wind is available in rather few countries but the huge technical and economical progress of photovoltaic (PV) may be a miracle for these countries if it is possible to store from day to night a large part of the PV production; it is available 8 to 10 hours per day as average according to countries. A large part of needs is during the sun hours and may be supplied directly but possibly half cannot be direct PV use. Some will be supplied by hydropower or by wind in few countries but possibly one third i.e., 15 000 TWh should be stored. Batteries may be the solution for the peaks in the evening and hydrogen or fossil fuel for extreme monthly needs but Pump Storage Plants (P.S.P) appear the best solution for most of it such as 10 000 TWh/year i.e., 30 TWh/day in 8 or 10 hours, i.e., 3 000 or **4 000 GW** with a storage capacity of 10 hours. For a possible investment of 1 billion $ per GW, and thus a yearly cost of about 80 million $ x 4 000 GW = 320 million for 45 000 TWh, i.e., 7 $ per MWh plus the loss of power through pumping of 15 000 TWh x 0.20 x 40 $ i.e., about 3 $ for a total of 10 $ which is very acceptable.

An investment of 4 000 GW in 40 years, i.e., 100 GW/year will be five-fold the investment for power supply of 1 300 GW in 70 years.

3 The energy storage in windy countries

OECD and China use 17 000 TWh/year. Their total population of 2,5 billion people is not increasing: their overall use of energy may not increase much but the share through electricity will probably increase up to 20 or 25 000 TWh, half of the likely future use in sunny countries. Most will be supplied by onshore or offshore wind and possibly 30% by solar PV hardly available along 4 months. The evaluation of storage need is more difficult than for sunny countries; but the large part of offshore wind energy, the association of various solutions and sites and a higher use of hydrogen will reduce the share of energy to be stored and the need of P.S.P may be limited probably to about **1 000 GW**.

4 Which solutions for P.S.P.?

The need of electricity storage is low presently but will much increase with the increased share of intermittent energies, most investments being probably between 2030 and 2070. The overall need may be 5 000 GW along 10 hours. An investment of 100 $/kWh, i.e. 1 billion $ per GW along 10 hours seems a reasonable target; it is about the same investment per kWh as for batteries, but PSPs have the huge advantage to operate along centuries when batteries life is one decade.

An existing PSP is usually the association of two reservoirs linked by some km of tunnels. The difference of level between reservoirs may be 100 to 1 000 m. The total reservoirs area is usually under 10 km^2 per GW, i.e., few per cent of the area per GW for hydroelectricity supply.

These PSPs are mainly used for peaks of electricity utilization; the length of tunnels prevent a quick adjustment of these PSPs to variations in wind or solar energy generation.

The total investment for existing PSP has been some hundreds billion of $ of which the share of dams investments has been under 100 billion $, 2 billion/year. The cost per GW of electromechanical equipment has been rather high because it refers to few units specific to each site.

The potential of this solution is high in mountain areas but is low in many rather flat countries where needs of energy storage will be high. Two other solutions for energy storage may be in the future as important as this traditional one: « Twin Dams » along large rivers and PSPs at sea along cliffs; dams will be an important part of relevant investments.

5 « Twin dams » may optimize the use of rivers

Linking along a river two close reservoirs of about the same capacity and exchanging daily through pumping and power supply the upper part of these reservoirs may provide a huge capacity of energy storage (fig. 1)

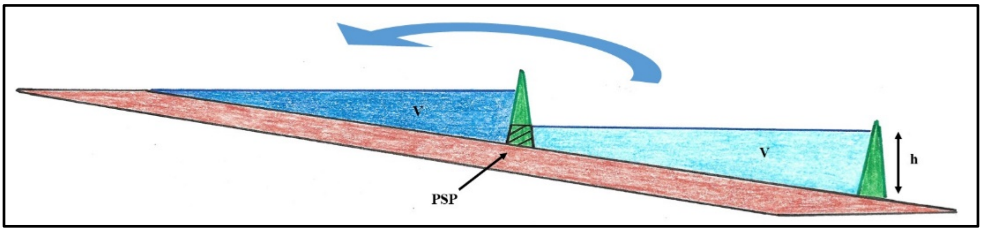

Fig. 1. Twin Dams.

For two dams of height H storing each a volume V and exchanging 300 days per year the upper part of reservoirs under a depth of 0.2 H the exchanged volume will be usually about 0.5 V with an output of 0.8. The yearly energy storage will be in kWh.

$$0.8 \times 0.5 \times \mathrm{V} \times \mathrm{H} \times 300 \times \frac{\mathrm{g}}{3600} \neq \frac{\mathrm{HV}}{3} \quad (1)$$

As there are two dams of volume V, the yearly storage per m^3 of reservoirs will be in kWh: HV/6 i.e., 5 to 15 kWh/m^3 for height H between 30 and 100 m; it is as average about tenfold the number of kWh per m^3 of reservoirs supplied by traditional hydropower: (4 500 TWh/year for 6 000 km^3 i.e., 0.75 kWh/m^3).

- Twin dams should be studied as alternatives for rivers which are not yet used. As example the Cunene river between Angola and Namibia has a yearly potential of energy supply of **5 TWh** between levels 0 and 500 m for a cost close to 100 $/MWh. As the valley is deep and inhabited it is possible to build two dams 200 m high and to store 100 TWh/year of PV solar from day to night in addition to 100TWh of PV supplied directly during day. The total average cost of PV + storage will be 40 to 50 $/MWh for 200 TWh instead of 100 $/MWh for 5 TWh of traditional energy supply. A large part of it may be used for exporting hydrogen.

The Cunene conditions are very favourable to storage but Twin Dams may be also the best option for many rivers, even with a dam height of 20 m. The storage is an addition to the hydropower supply.

- It is also possible to divide an existing very large reservoir in two parts used as Twin dams. And adding a new reservoir upstream or downstream of an existing reservoir may be very efficient.

The most impressive example is the Kariba existing reservoir in Southern Africa: a 100 m high dam creates a reservoir of 150 km^3 for supplying **7** TWh/year. It is possible to add an upstream new reservoir of 50 km^3 and to store yearly well over **<u>500 TWh/year</u>** by a PSP capacity over 200 GW. The total supply may reach within 50 years over 500 TWh of direct solar energy during day and 500 TWh of stored energy for night. It may be implemented by steps of 10 or 20 GW, the needs of electricity of this century are lower but a part may be used for hydrogen.

Many existing reservoirs of some hundred hm^3 or some km^3 may be adapted for storing much more energy than their present supply. As example, the Bagre reservoir in Burkina Faso, presently 40 m deep and supplying 50 GWh/year may store 1 TWh.

It may be also very efficient to associate a reservoir in the main river with a close reservoir in a tributary. An example is the High Aswan dam in southern Egypt which stores over 150 km^3 and supplies 7 TWh/year. It is possible to use a dry tributary; the Ouadi El Allaqi for a higher reservoir of 50 km^3 and to use as low reservoir of« Twin dams » a part of the existing Aswan reservoir: the other part being devoted to water storage and flood mitigation which are essential for Egypt. The El Allaqi new reservoir will be used for energy storage and water storage. This solution may supply 1 000 TWh/year of PV electricity of which half stored from day to night. There are never clouds in this area and the direct cost of PV will be close to 20 $/MWh. Electric lines will be easy in the desert, thus a total cost of 40 $/MWh for Egypt use or export of power or hydrogen to Southern Europe. The implementation may be along 20 or 50 years through steps of 10 or 20 GW.

Kariba and El Allaqi may supply over 2 000 TWh of hydro solar energy, as much as the present world nuclear energy, for half the cost per kWh.

6 Pump Storage Plants along cliffs: (Emerald Lakes)

The potential of PSPs along cliffs seems much higher than the potential of PSPs in islands and the cost per kW lower.

There are close to worldwide populated areas dozens of thousands km of cliffs: their height is some dozens or some hundreds m. 1 or 2 % of this length could be used for a large part of future energy storage needs, as example for 1 000 or 2 000 GW. The availability of cliff rock will favour long rockfill embankments above or along cliffs. Open air or underground plants will be favoured by the cliff rock.

A low cost per GW will be obtained where it is possible to create an upper reservoir above a rather flat cliff with a low need of resettlement. The cost will be mainly the cost of electromechanical equipment. The upper reservoir will require long dams 20 to 40 m high founded on rock using cliff rock.

Creating the high reservoir at sea along the cliff is more expensive but the cost may be very acceptable for schemes of some GW using a reservoir of some km^2 closed by a 100 m high dam using cliff rock. Such dam may be built in calm water within a breakwater built in a first phasis and used later as downstream toe of the dam (fig. 2). Within few hundreds m from the cliff toe there is usually a flat area of rock favourable to the plant itself.

Such schemes are too large for present needs but may be a large part of PSPs investments in 2040. The potential is well beyond needs in many countries.

The above solutions at sea may also apply along very large natural lakes used as low reservoirs.

As the Twin Dams, PSPs above or along cliffs without tunnels have the huge advantage of a quick adaptation to variations in PV or wind production.

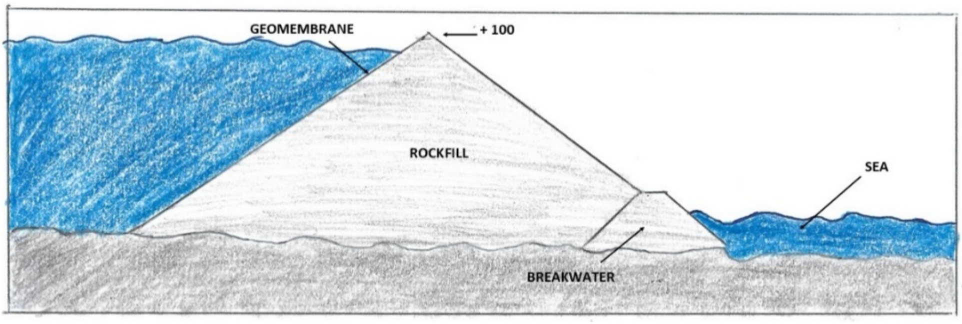

Fig. 2. Rockfill.

7 Off river reservoirs

Where a river slope is lower than 1 m per km, traditional dams use is not usually cost efficient for seasonal water storage or for floods mitigation although the relevant needs may be high. Off river water storage by pumping is much used but mainly for volumes of dozens or thousands m^3 of water. There is a much higher cost-effective potential in flat areas for reservoirs storing millions or dozens hm^3 with an average depth of 5 or 10 m and a few km long dyke of height between 0 and 20 m. the key part of the cost is the dyke cost requiring about 1m^3 for 10 m^3 of water storage and the target a cost per m^3 of dyke under 10 $ for a dyke volume in the range of 1 hm^3 using local available materials.

Construction methods and relevant designs of such Long Low Off Rivers Dams (LLORDS) could be very different from traditional dam's construction methods and designs and closer to highways construction methods.

Such reservoirs may not be very close to the river and possibly few dozen m above it. The risk of loss of storage by leakage should not be overestimated because there is the huge experience of hundreds of thousands traditional small dams and reservoirs storing 0.1 or 1 hm^3 on same soils with about the same storage per m of closure: some thousands m^3 per m.

The main use of such reservoirs may be the seasonal water storage in countries where there is a long dry season. The cost of pumps and energy will be low. The needs will be very high with the increased population and the siltation of many existing reservoirs; a potential of 500 km^3 upon 50 000 km^2 for 500 billion $ in 50 years may be very useful for billion people in sunny countries.

Such reservoirs may also be used for storing a part of the floods peak. The pumping capacity may then reach hundred m^3/s but the relevant cost may be lower than the cost of a traditional dam which is more adapted to rather small catchment areas and short time floods. Storage of floods by pumping seems more adapted to catchments of thousands km^2.

8 An innovative use of pumping

A very large part of floods damages is in very flat areas where the slope of rivers is lower than 0.5 m per km and where are living billions of people. Floods reach thousands m^3/s; the water speed is about 2 m/s and the river depth 5 to 10 m. Increasing the speed by 10% or 15% would reduce the depth by 0.5 or 1 m and avoid most damages. The present speed is linked with the available gravity energy. Adding energy by pumping may be a cost-effective solution for reducing the water level and damages.

A solution associating a dam and a pumping plant allows pumping **from upstream to downstream** all the flood discharge under a 1 or 2 m head. There is no impact downstream but the upstream water level is reduced by 1 or 2 m close to the plant and very significantly along 10 or 20 km upstream; it may be very cost efficient. There is a shortage of electricity during operation, the dam will be designed for opening safely without human action.

As example most flood damages in Paris or close to Paris could be avoided by an investment of 1% of the probable damages along a century.

This solution applies in many world areas and especially close to sea for large cities as Bangkok and populated deltas as the Mekong. Relevant dam and plant designs will be specific. It may be also a key way for fighting the impact of oceans raising and increased floods due to climatic change.

The overall world investments will be limited to some dozens billion $ but will be extremely efficient for saving yearly dozens of billions $ of damages.

9 Environmental impacts of reservoirs filled by pumping

The traditional uses of dams are now much criticized in many countries. The uses of dams based upon pumping have usually much more acceptable impacts:

- The area needs for Twin Dams per GW is about one tenth of the area per GW needed for present hydropower. The impact on siltation along rivers is also lower per GW.
- The PSPs at sea will have capacities of several GW with a limited local impact.
- The off-river water storage has a much better impact on rivers than traditional dams and especially for siltation and downstream impact.

10 Specific dams designs and construction methods

Traditional dams designs and construction methods may be used for most dams linked with pumping but innovations may be used for specific problems such as dams at sea along cliffs or for cost optimization for off rivers water storage.

A solution for dams at sea may be as per fig.2; a breakwater built in first stage favours works in calm water. Geomembranes may be a cost-effective solution, a large part of the huge quantities of rockfill may be transported by conveyor belts at low cost per m^3.

Off river large reservoirs will require millions m^3 of earth fill dams 5 to 15 m high. Construction methods may be close to highways construction methods. Contractors specific proposals for optimizing construction methods and best use of local materials could favour low-cost alternative designs.

11 Dams safety

- The possible reasons of failure are about the same for Twin Dams as for traditional dams use but a same volume of reservoirs withstands 10-fold more GW.
- The impacts of a failure of a dam at sea are much lower than impacts of failures along rivers.
- The off river large reservoirs avoid the main risk of failure of traditional dams which is linked to floods. And the first filling of these reservoirs may be easily controlled, especially if using optic fibbers.

12 Investments for dams uses linked with pumping

Figures below are very rough evaluations:

- The main investment seems for Pump Storage Plants (PSP), possibly for 5 000 GW with an average cost of one billion per GW and possibly less as the cost per GW of pumps will be reduced by the large world number of similar units. Twin Dams and dams at sea do not require tunnels and the cost of dams may be a significant part of the investment such as 200 or 400 million $ per GW, i.e., 1 000 or 2 000 billion $ in 50 years, some dozens billion $/year.

The investment for 500 billion m^3 of water storage. Off rivers may be up to 1$ per m^3, of water i.e., 500 billion in 50 years, essentially for the dams, i.e., close to 10 billion/year.

The investments for floods mitigation of large cities may be very cost effective but the world investment will be billion/year and not dozens of billions.

A key point should be underlined: the cost efficiency of dams linked with pumping is much better for very large schemes of some GW or dozens of hm^3.

13 Conclusion

The potential of new reservoirs filled by gravity as traditionally is very limited in most countries but the potential of large cost-effective reservoirs filled by pumping is very high.

After 2030, energy storage may be a key use of dams, especially in sunny countries using photovoltaic energy. And using in flat areas very large off rivers reservoirs filled by pumping may be very cost effective for seasonal water storage and floods mitigation. The environmental impacts are much better than for traditional dams uses. And innovative pumping may avoid huge damages of large cities by floods.