The key role of PSPs in the future of sunny countries

Le rôle clé des PSPs dans le futur des pays ensoleillés

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Abstract. The revenue per capita of various countries is quite proportional to their use of energy which in the future will be essentially through electricity from renewable sources. The rich countries of OECD are far from equator and use 10 000 TWh/year for 1.3 billion people, 8 000 kWh per capita. Their revenue per capita is five-fold the revenue of 5 billion people of sunny countries closer to equator which use 8 000 Twh, i.e., 1 600 kWh per capita. The economic progress of sunny countries is based upon a use close to 6 000 or 8 000 kWh for 7 or 8 billion mid-century, i.e., 50 000 TWh/year. All sources beyond solar will be limited in most sunny countries and the future seems based upon photovoltaic energy (PV) available 8 to 10 hours per day at low direct cost along year, possibly for 40 000 TWh. A key problem will be the storage from day to night of up to 15 000 TWh/year. The best solution may be pump storage plants (PSPs) storing some 10 hours/day for 10 000 TWh/year i.e., 30 TWh/day by a capacity of 3 000 or 4 000 GW. Beyond traditional solutions in mountains there are many opportunities of cost-effective PSPs based upon twin dams along large rivers or upon PSPs at sea along cliffs. Various examples are presented.

Résumé. Le revenu par habitant des différents pays est à peu près proportionnel à leur utilisation d'énergie qui sera essentiellement dans le futur l'électricité à base d'énergies renouvelables. Les pays riches de l'OCDE sont éloignés de l'équateur ; ils utilisent 10 000 TWh/an pour 1.3 milliard d'habitants, soit 8 000 kWh par habitant. Leur revenu par habitant est 5 fois celui de 5 milliards d'habitants des pays ensoleillés plus proches de l'équateur qui utilisent 8 000 TWh, soit 1 600 kWh par habitant. Le progrès économique de ces pays ensoleillés est basé sur l'utilisation de 6 000 à 8 000 kWh pour 7 à 8 milliards d'habitants au milieu du siècle, c'est-à-dire 50 000 TWh. Toutes les sources d'énergie en dehors du solaire seront limitées dans la plupart des pays ensoleillés, dont l'avenir paraît basé sur l'emploi d'énergie photovoltaïque, économique et disponible 8 à 10 heures

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par jour tout au long de l'année. Un problème clef est donc le stockage du jour à la nuit d'environ 15 000 TWh/an. La meilleure solution paraît l'usage des stations de pompage (STEPs) pouvant stocker 7 à 10 heures par jour pour 10 000 TWh/an, c'est-à-dire 3 TWh/jour par 3 000 ou 4 000 GW de STEPs. Les solutions traditionnelles peuvent être utilisées dans les zones montagneuses et il y a beaucoup de sites pour des STEPs économiques basées sur des barrages jumeaux (twin dams) ou sur des réservoirs à la mer sur des falaises ou le long des falaises. Divers exemples sont présentés.

The world countries may be classified according to their distance from Equator:

- **1.3 billion** people of OECD, i.e of the richest countries live 3 000 to 6 000 km from Equator, **5 000 km** as average. Their number is not increasing.
- 1.4 billion people in China live 2 000 to 5 000 km from Equator. Their number is not increasing.
- 5 billion people live in sunny countries within 3 000 km from Equator, **1 500 km** as average. Their number will probably reach **7 or 8 billion** within 30 to 50 years.

The revenue per capita is much increasing with the distance from Equator. This revenue is quite proportional to the use of energy per capita; and, within some decades, most energy will be used through electricity. A key problem is thus the use of electricity in sunny countries in 2080 i.e., for 7 or 8 billion people. It is the key to their economic progress; the target may be to reach the present revenue per capita of OECD which is fivefold the revenue from sunny countries; their use of energy is also fivefold as in sunny countries.

OECD is presently using 10 000 TWh for 1.3 billion people, about 8 000 kWh of electricity per capita. Their use of total energy is not much increasing but the share through electricity will increase and may be in the range of 10 000 kWh per capita within some decades.

5 billion people in sunny countries use presently 8 billion TWh/year i.e., 1 600 kWh per capita. A target of 6 000 or 8 000 kWh as average in 2080, for 7 or 8 billion appears advisable, i.e., **50 000 TWh/year** instead of 8 000 now.

China has increased in 40 years its use of electricity per capita from quite nothing to 6 000 kWh/year and keeps increasing to the level of OECD. Together OECD and China could use **25 000 TWh** in 2080, half of sunny countries.

1 Which sources of electricity in sunny countries?

Presently most electricity is supplied by fossil fuels, roughly 6 000 TWh from 8 000 TWh; hydropower is supplying 1 500. Nuclear energy is very reduced. Wind energy is developed in some sunny countries but as average for few per cent. Solar energy is much developing but is yet a minor share.

When needs will reach 50 000 TWh, possibly before 2080, fossil fuels will be much reduced, possibly to 1 000 or 2 000 TWh. Nuclear is quite nil presently and seems to have little future in these countries, electricity should be supplied essentially by renewable: Hydro, wind and solar.

Hydro will be very useful, but the realistic potential is limited to 3 000 or 4 000 TWh.

Wind is well available in some countries but reduced in most of them.

Solar energy will thus probably be the essential source of electricity, possibly for **40 000 Twh/year**.

The direct cost of photovoltaic energy will probably be 20 to 30 $ per MWh according to countries, much less than the present cost of electricity using often imported fossil fuels. A key problem in sunny countries will thus be a huge storage from day to night of PV electricity.

Concentrated solar energy may be an alternative in some countries but probably more expensive in most of them.

2 Which storage of electric energy in sunny countries?

There is presently quite no need of storage as the main present use of fossil fuels is very flexible. But the need will much increase after 2030 as PV energy will be available about 10 hours per day for supplying directly 50 or 60% of needs; 20 000 may be needed when there is no PV direct supply.

Hydropower may then supply 2 000 or 3 000 TWh and wind, limited to some countries, some thousands.

The need of storage may be between 10 000 and 15 000 TWh/year for sunny countries. The needed capacity, mainly after sunset, will be higher than the average yearly use of 50 000 TWh/8640 hours # 6 000 GW, possibly 7 000 of which 1 000 may be supplied by hydro and miscellaneous.

The future need of storage seems thus to be 10 000 to 15 000 TWh/year by a capacity of about 6 000 GW. Batteries seem the best solutions for a part of daily peaks at sunset, as example for 1 000 or 2 000 GW partly or totally used 3 or 4 hours per day and thus for 2 000 TWh/year.

Hydrogen or fossil fuels may be used for weeks of low average sunshine, as example for 10% or 20% of needs along 20% of weeks, i.e., for some 1 000 TWh or 2 000 TWh.

And PSPs may be the best solution for pumping daily along 10 hours. A capacity of 3 000 or 4 000 GW pumping 3 000 hours/year may be the best solution for 10 000 TWh/year of storage. **Is it possible to find in sunny countries for 8 billion people 4 000 GW of PSP storage along 10 hours for an acceptable cost?**

As example an investment of 1,5 billion $ per GW and thus a yearly cost of 100 million $ per GW for 4 000 GW would mean 400 billion for 50 000 TWh, i.e., 8 $ per MWh. This could be reduced to 5 or 6 $ per MWh for an investment per GW of 1 billion $.

3 Which technical solutions?

Presently there are worldwide about 200 GW of PSPs (few in sunny countries) they associate two reservoirs linked by rather long tunnels; the level of reservoirs may differ by 100 or 1 000 m. There are many possibilities in mountainous areas but a large part of sunny countries has no high mountain.

There are two other solutions: “Twin dams” along large rivers and PSPs at sea along cliffs.

4 Twin dams in sunny countries

“Twin dams” associate along a river two close reservoirs of about same capacity and exchange daily their upper part (fig.1). For a usual reservoir of maximal depth H, the upper storage of a 0.2 H depth is about 50% of the total reservoir storage. If exchanging as average 80% of it along 365 days under a head of H, with an output of 0.8 and a reservoir volume V, the yearly storage, in kWh is

$$0.8 \times 0.5 \times V \times H \times 0.8 \times 365 \times \frac{g}{3\,600} \neq \frac{HV}{3} \quad (1)$$

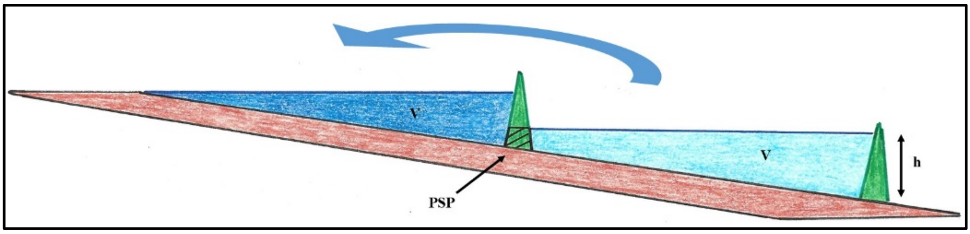

Fig. 1. Twin dams.

As there are 2 reservoirs of volume V, the yearly storage per m^3 of reservoirs capacity is H/6 i.e., 5 to 15 kWh for H between 30 and 100 m. It is about 10-fold the efficiency of present reservoirs for hydropower supply which supply 4 500 TWh for a reservoir's capacity of 6 000 km^3, i.e., 0.7kWh/m^3 and the inundated area per stored kWh by twin dams is a small part of the average area inundated for hydropower supply.

This solution may apply to undammed rivers, to optimization of large existing reservoirs, to addition of a new reservoir close to an existing one, to association of a reservoir on a main river with a reservoir in a tributary.

Various examples are presented below:

- **The Cunene river in Africa** which is the border between Angola and Namibia is undammed and has a potential of traditional hydropower supply of 5 TWh/year with a total head of 600 m. It is possible to produce locally during day 200 TWh of low-cost PV power per year and to store 100 TWh by three dams and two PSPs totalling 30 GW. The total cost per MWh would be half of the cost of traditional hydropower supply. Part of power could be used for exporting hydrogen.
- The head of Cunene PSPs may reach 200 m which is exceptional but the existing reservoir of Bagre in Burkina Faso which supplies 50 GWh/year could be adapted as twin dams operating under lowhead and storing 1 TWh/year.
- **One of the largest world reservoirs**, Kariba has a capacity of water storage of 150 km^3 with an area of 5 000 km^2 by a 100 m dam: it is supplying 7 TWh/year. The reservoir is operated between levels 475 and 490. There are many solutions for optimizing the use of the site as Super Kariba: As example a 100 m high dam may separate the downstream part of the present reservoir for 4 000 km^2 from a new reservoir of 1 500 km^2 extending 100 km upstream in a deep desert gorge (fig. 2).

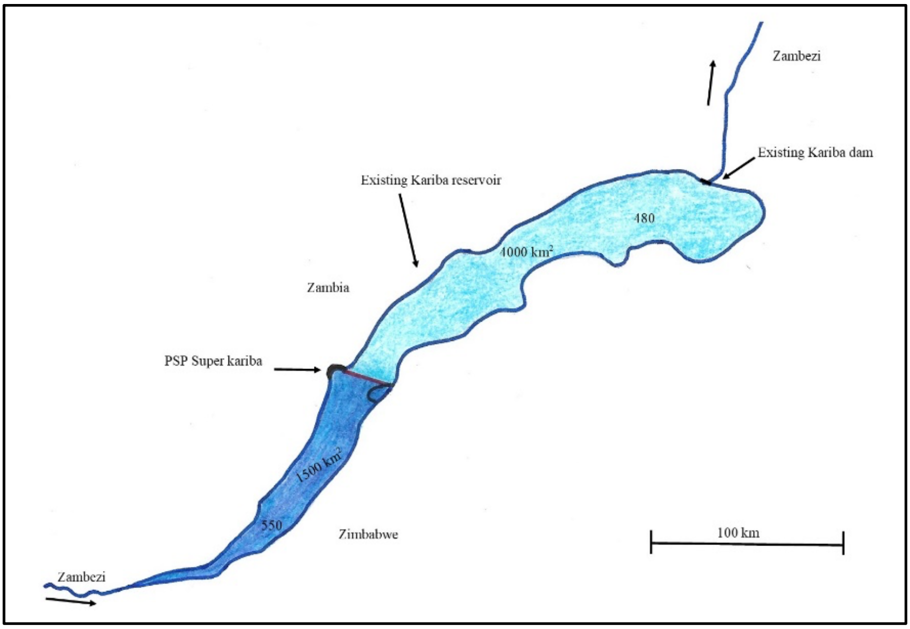

Fig. 2. PSP 100 GW – Superkariba.

The storage capacity of Super Kariba is amazing if using daily the low reservoir between levels 480 and 490 for over 30 000 km^3 under an 80 m head, i.e., for a storage of

$$0.8 \times 30 \times 10^9 \times 80 \times \frac{g}{3\,600} \tag{2}$$

about 5 TWh/day by a 500 GW capacity. It is much more than future needs.

Within 1 500 km from Kariba will live in 2080 about 200 million people using up to 1 000 or 1 500 TWh/year. Using half from Super Kariba could be 500 TWh, half of it being stored by a PSP capacity of 100 GW. An example of PSP for 100 GW is suggested in fig. 2: The low reservoir is most of the area (4 000 km^2) of the existing reservoir at a level close to 480. The high reservoir at a level close to 550 may have an area close to 1 500 km^2; 1 TWh could be stored daily in 10 hours, exchanging 7 or 8 billion m^3, few m of each reservoir.

The length of the pumping plant will be about 10 km.

This capacity could be implemented in phases of 10 or 20 GW between 2030 and 2080.

- **The 100 m high Aswan dam** in southern Egypt creates at level 180 a lake of 6 000 km^2 storing 150 km^3; 80 to 100 km^3 are used for seasonal or interannual storage. It supplies 7 TWh/year. It is difficult to create, as in Kariba, an higher upstream reservoir but it is easy by a 1 km dam to divide the existing lake in two quite equal parts and to create a reservoir up to level 250 in the dry old tributary Al Allaqi (fig.3).

The upstream part of the Aswan reservoir will be used as now for a water storage of 50 to 60 km^3. The downstream part may be used between levels 150 and 160 as low reservoir of a "Twin Dam". The Al Allaqi reservoir will be used as high reservoir of a twin dam for the Al Allaqi PSP and as water storage for 30 to 50 km^3. A daily exchange of water up to 15 billion m^3 will store 2 TWh/day by a 200 GW PSP, i.e., over 500 TWh/year of PV energy; its direct cost will be close to 20 \$/MWh because there are never clouds there. And over 500

TWh of PV may be supplied directly during day. Part of PV panels may be on the lakes thus reducing evaporation.

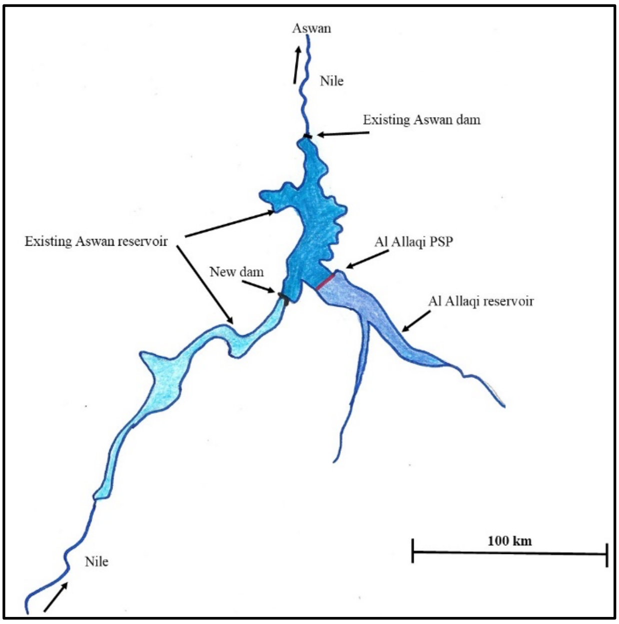

Fig.3. Al Allaqi PSP: 200 GW.

A part of power may be exported as electricity or hydrogen to Middle East and Southern Europe but most will be used by Egypt.

The PSP will have a total length of about 20 km and may be built in phases between 2030 and 2060. An example is as per fig.4.

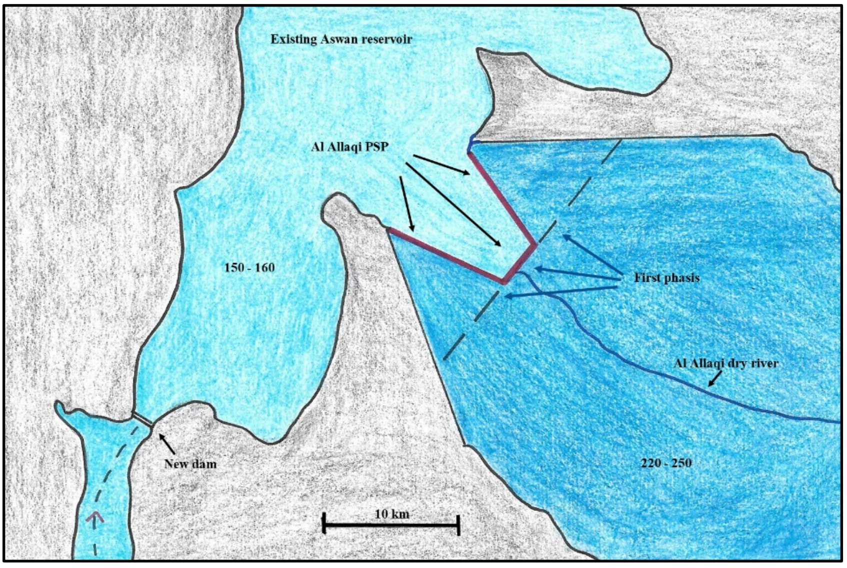

Fig. 4. Al Allaqi PSP: 200 GW.

5 Dams at sea along cliffs: (Emerald lakes)

There are many opportunities of large reservoirs for twin dams in Africa and America but there are less opportunities of large reservoirs in much populated Asia.

Another solution of PSP is to use the sea as low reservoir and to create a large high reservoir **above** a cliff. The cost of civil engineering is reduced and the cost per GW of such PSP may be under 1 billion $/GW. As example 10 GW are possible 100 km north of Paris. However, opportunities are limited in many countries by the resettlement of people living presently on top of the cliffs.

But there are worldwide and in many sunny countries many sites for creating the high reservoir **along** a cliff: this solution is more expensive but may be cost effective for PSPs of some GW. A typical example is suggested below (fig. 5).

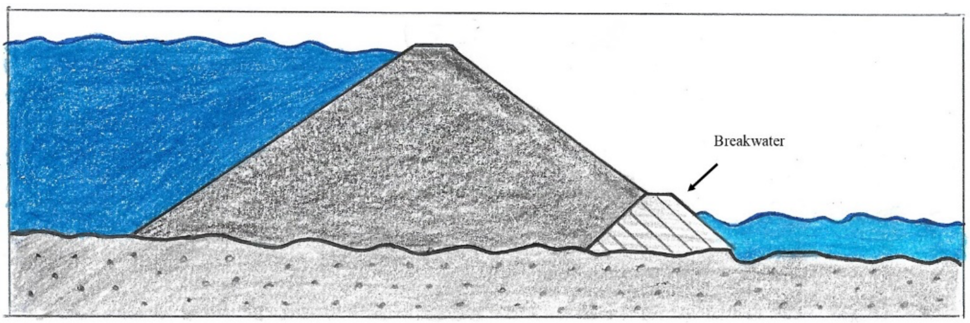

Fig. 5. Dam at sea.

Usually along cliffs there are some hundreds m of flat rock at sea level and thus opportunities of plants with reduced civil engineering. And the sea is not deep within 1 or 2 km from the cliff. It is thus possible to build a 100 m high dam using rockfill from the cliff and geomembrane. A breakwater built initially favours dam construction in calm water and is further used as downstream dam toe.

The huge quantities of rockfill may be transported by conveyor belts from the cliff to the dam along some km at rather low cost.

For a reservoir operated between level 60 and 100, the exchanged volume per km^2 is 40 million m^3 under an 80 m head, i.e., an energy in kWh:

$$0.8 \times 40 \times 10^9 \times 80 \times \frac{g}{3600} \neq 7GWh \tag{3}$$

through 8 or 10 hours of pumping as average i.e., about 1.3 km^2/ GW.

The length of high dam per km^2 of high reservoir will be over 1 km; the length per GW about 1,5 km and the rockfill volume 30 million m^3 per GW.

An alternative may be based on PSP on Islands operating between the sea and a low reservoir within the island. It seems more expensive than PSPs along cliffs and there are less possible sites.

The solutions along cliffs or above cliffs may also use very large natural lakes as low reservoirs as the sea.

For PSPs along cliffs, as for twin dams PSPs, the two reservoirs are very close and the power supplied or pumped may be adapted very quickly to available solar energy or to changes of needs.

6 Cost of PSPs

The investment for PSPs includes two parts:

- The electro mechanical part: it's cost per GW may be lower than for traditional hydro electricity because most future PSPs could be standardized according to few typical heads and hundreds similar units needed every year; Presently equipment for traditional hydro power supply is by few units specific to each site and thus expensive.
- The investment for civil engineering varies with the sites and solutions and will usually be more important for PSPs at sea along cliffs than over cliffs and as "twin dam".

A total investment per GW storing 10 to 12 hours seems between 7 and 15 billion $, i.e., about 100 $/kWh, i.e., not much different from the likely investment for batteries. But the life of a batterie is some **years** and the life of a PSP is **centuries**. There is probably a future for both solutions, PSPs being mainly used for large schemes and daily storage, and batteries mainly for hourly peaks. Main investment of PSPs may be between 2030 and 2070. PSPs are not cost efficient for monthly or yearly storage. Few per cent of electricity shall be supplied by hydrogen or thermal energy. In sunny countries it may be realistic to keep along decades a significant capacity of thermal plants used under 1 000 hours/year for 1 000 or 2 000 TWh.

7 Construction methods and volumes

The PSPs suggested above may be built by traditional methods and more easily than many large dams built fifty years ago in very large rivers. The huge quantities of materials and technical progresses for 50 years may also favour unusual solutions such as conveyor belts, RCC, geomembranes.

A huge scheme of 100 or 200 GW as Super Kariba or Al Allaqi may appear much too important and thus unrealistic but it may be built in phases of 10 or 20 GW, by dams 50 or 100 m high with no more difficulties than for damming very large rivers 50 years ago.

8 Comparison between Europe and sunny countries

The revenue per capita of OECD and especially Europe is fivefold the revenue of sunny countries. A reason may be that OECD uses fivefold the energy per capita of sunny countries and had in the past more sources of energy easily used:

- Hydropower was much used in Europe from the year 1600 through dozens of thousands mills in permanent rivers when rivers are dry 6 months in sunny countries.
- Wind was a key solution onshore and for transport and war at sea and the wind expertise gave to Europe from 16^{th} to 19^{th} century the leadership in Asia and Africa.
- The energy of men could be better used in the climate of Europe than in hot sunny countries except where it was imposed as example by slavery.
- The horses' energy was essential in Europe up to 1940 and was not much used in most sunny countries for climatic reasons.
- The energy and the revenue per capita were thus already much higher in Europe than in sunny countries 150 years ago. The future situation will be different and energy will be probably essentially based on renewable energies.
- Hydropower may supply as average 10 % of sunny countries energy as in OECD.
- Most OECD countries may associate offshore and onshore energy available along the year with some PV energy much reduced during half year.

- Sunny countries will have PV energy along year. The direct cost of PV per MWh will be 20 or 30 $ in sunny countries, lower than the PV cost in OECD and probably than the cost of wind energy worldwide. The future cost of energy will thus be low in sunny countries if the additional cost for storage is low: this, seems possible mainly with PSP.

Climatic conditions and solutions are different for OECD and sunny countries. Targets and studies could be different:

- Many people in OECD advocate a reduction of energy use. A huge increase is necessary for sunny countries.
- The official target in many countries is a **totally** clean energy as soon as possible. It is hardly realistic and may not be the best target in sunny countries: keeping along decades a significant capacity of thermal plants used 500 hours per year may be economical and favour an earlier implementation of PV.

And the traditional studies of energy through "primary energy" and so called "final energy" appear **totally unadapted** to the analysis of the future energy of sunny countries.