The Emerald Lakes: large offshore storage basins for renewable energy

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Maintaining the present world rate of economic rate progress over the next 50 years will require five times more energy than is available at present. Meanwhile, the use of fossil fuels, which at present supply about 80 per cent of needs, should be reduced to about 10 per cent. The shortfall could theoretically be made up by using just 20 per cent of wind potential and a small amount of solar photovoltaic potential (these sources could supply much more than 50 000 TWh/year, compared with the present total of 15 000 TWh/year). But they are intermittent and would require a vast storage capability. Large offshore basins, based on proven technologies, could store 5000 × 10⁹ m³ of sea water, the same as currently stored in hydro reservoirs. They could be used several times a week, according to the shortfall in wind or solar energy supply. Such valuable 'green' offshore structures, which could last for centuries, deserve the name 'Emerald Lakes'.

World economic progress has been based on low cost energy, essentially using fossil fuels. Present energy use is roughly equivalent to 10×10^9 tons/year of petrol, a large proportion of it being used through 15 000 TWh/year of electric power. Most is for one billion people living in industrialized countries.

The world population is likely to increase from 6 billion to 10 billion (by 2050). If, by the end of the century, this population were to be using 70 per cent of the energy per capita as is currently used in industrialized countries (for the same result, but with better energy utilization) the present energy would need to be increased by a factor of more than five, and electric power requirements could reach 100 000 TWh/year. But the use of fossil fuel for electric power should then be reduced to 5 or 10 000 TWh/year to limit global warming. By 2010, the contribution of renewable (and possibly nuclear) energy should have increased to 90 000 TWh/year from the present 5000 TWh/ year.

This target appears to be ambitious, but two points should be emphasized:

- Electricity is often trasnmitted for hundreds of kilometres, and this could possibly be extended to thousands of kilometres still at an acceptable cost. Virtually all the power would be used within large national or international grids, allowing for an optimized combination of the various available energy options, and the possibility to choose the best places for wind or solar production and for storage of energy.
- A few years ago the average world cost per kWh was less than US¢5 based on oil-fired plants. (All costs in this paper are expressed in US$). The only main ways to secure the necessary vast amounts of energy in the future at a rate of about US¢5/kWh appear to be major use of coal (unacceptable for controlling climate change) or of nuclear (unacceptable in many countries).

It therefore seems useful to analyse the various possibilities for obtaining renewable electric power at costs of between US¢5 and 15/kWh. (The present cost per kWh from oil powerplants is at present US¢20, and this is paid by many countries).

Beyond fossil fuel and nuclear, the three possible sources of very large quantities of electricity at these rates seem to be hydropower, wind, and solar photovoltaic. Relevant data about potential, costs, facilities and drawbacks are summarized below.

Hydroelectric power

Hydropower is now supplying 3000 TWh/year with 800 GW of capacity (including more than 100) GW of pumped storage). A remaining realistic potential of 3000 TWh was evaluated some years ago for a rate of about US¢5/ kWh. The figure could be increased if a cost of US¢10 to 15/kWh were to be considered acceptable. More than 1000 TWh of tidal energy at US¢10/kWh is also feasible and likely to be developed; however the overall hydropower supply seems limited to about 10 000 TWh/year even for a rate of US¢10 to 15/kWh. Most could be implemented by 2040. The greatest remaining potential is in the developing countries, and huge investments are at present being made in Asia and Latin America; there is also a great future in Africa.

Part of the annual hydropower generation is stored during the rainy season, when direct supply is also more important. This annual storage may exceed 500 TWh and is used mainly during weekly peaks throughout the year.

Wind power

World wind potential is very high; it could be as much as 20 to 30 GWh/km², particularly offshore or close to shore, using units of up to 5 MW. The investment per kWh is at present less than $1/kWh/year in the industrialized countries. A number of factors, such as the possible large scale development, lower costs in Asia, and cost savings in foundations offshore, will probably reduce the investment costs within 5 or 10 years; the cost may be less than US¢5 /kWh. Wind could in theory supply most of the necessary electric power in many countries (particularly in Europe, part of North America and China) but two-thirds of the continents (mainly in low latitudes) do not have sufficient wind.

The main drawback of wind energy is to be available only 2000 to 3000 hours per year, with a total lack of energy for hours or days, or even weeks in some cases. Fossil fuel is then generally used, that means, for most of the time, and at present wind energy may represent only about one-third of the fossil fuel energy, which needs to be reduced as far as possible in the future. Wind energy is now being developed at a rapid rate in Europe, even in places without very significant wind availability, to reduce the use of expensive oil at existing plants. However, its overall future appears very limited, because of the present lack of storage.

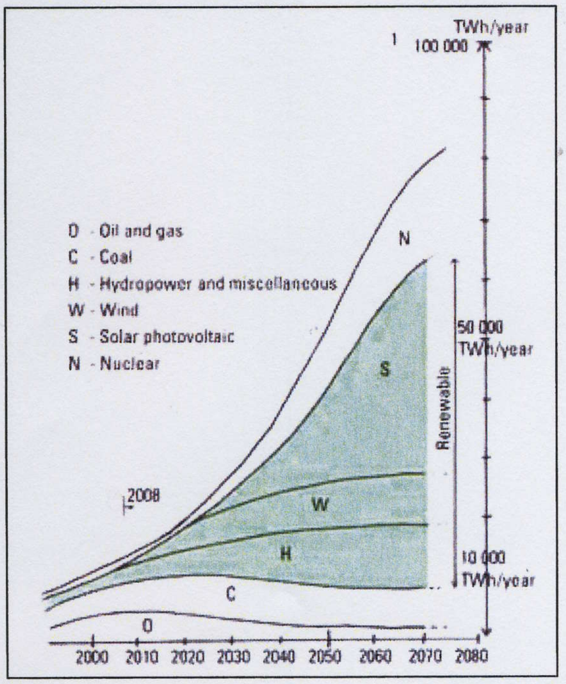
Solar photovoltaic energy

Solar PV has a much higher theoretical potential than all world future needs. It can be used locally in individual houses in addition to thermal solar for heating; but it can also be used in very large plants.

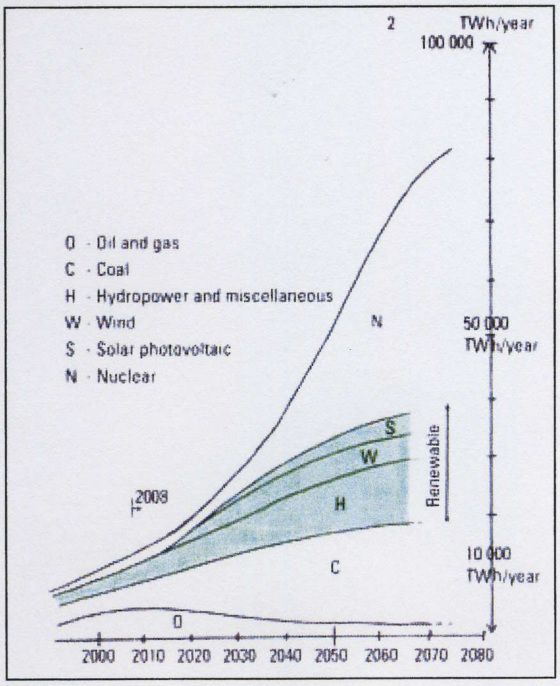
A first drawback is its present cost, in the range of US¢20 to 40/kWh. However this cost is decreasing, and it is likely that it will be about US¢10/kWh by 2020 in countries where there is a lot of sun and where the costs of engineering and labour are low, which means, most developing countries, and especially places where there is not much wind energy. The solar energy potential is generally reduced for about four months during the rainy season, but at this time hydropower becomes much more significant.

But the key drawback of solar photovoltaic, as with wind, is that availability is limited to about one third of the time;so this would also require temporary storage.

Future world electric energy with wind and solar energy storage.



Future world electric energy without energy storage.



Therefore it can be concluded that wind and solar power would, in the future, be able to supply sufficient power at an acceptable cost, if it would be possible to store the energy for a few days (even if this storage cost is several cents per kWh).

The optimum storage capacity would vary with local climatic conditions, and could be more significant for wind power than for solar. The storage could be insufficient at several times of the year, typically for a total of up to 30 days; the energy shortfall would then be supplied from fossil fuel (coal or gas). But this fossil fuel would only be necessary for 5 or 10 per cent of the annual energy supply. Some biomass could also be used instead of fossil fuel.

If wind and solar power would be able to supply half of the electric power requirements by 2040 (0.5 × 35 000 TWh) and require an average storage time of two days, this would require storage of about 100 TWh. This storage could be increased to 200 TWh by 2070, and 300 TWh by the end of the century.

Storage of this energy in very large basins at sea, as proposed below, would be possible based on well proven technologies and at acceptable costs. This could be the key to full time availibility of the energy required for worldwide development, with limited global warming.

Energy storage

Innovative new storage solutions could, in the future, favour these renewable energies, but hydraulic storage of energy appears, at present, to be the only realistic solution for such vast quantities of energy. Storing 1 kWh requires a volume of about 1 m^3 of water used with a 400 m head, or a volume of 10 m^3 used with a 40m head.

Storing 100 TWh would thus require for instance 1000×10^9 m^3 under an average head of 40 m. Such storage would need to be used every day (for solar power) or about twice a week (for wind).

Existing hydropower lakes store much more than 100 TWh, but the water is used only once a year. Existing pumped storage reservoirs have a total capacity of 100 GW, but they generally store power for around 20 hours, that is, a total of about 2 TWh. It will be possible to increase the number of these, but the total stored energy would probably be limited to 10 or 20 TWh, because it is difficult to find two very large basins of the same capacity within the same area, onshore.

Using the sea as one basin is the basis of many possible solutions for obtaining the necessary storage volume.

One solution is based on dams built along the shore; structures around 50 m high and operated between 30 and 50 m above the sea level, for example, could store about 1.5 GWh/km^2 with a full basin, corresponding to a water volume of about 15×10^6 m^3/km^2, under a 40 m head. The cost of dams per m^3 of storage, or per kWh can vary enormously. Storing about 5000×10^9 m^3 of water in existing hydropower lakes has already cost about US$1500 billion, which is equivalent to $0.3/$m^3$. Using this figure as a reference would mean an investment per stored kWh of:

$$\frac{0.3 \times 15 \text{ million}}{1.5 \text{ million}} = \$3/\text{kWh}$$

Many cliff areas could favour another solution, the upper part of the cliffs usually being relatively flat. Building a basin of some tens of km^2 surrounded by dykes 50 m high on average above a cliff 100 m high could provide a storage of:

$$\frac{50 \times 120 \times 10^6 \times g}{3600}$$

that is, 15 GWh/km^2.

A basin of 20 km^2 would require 15 km of dykes totalling 100 × 10^6 m^3 of earth- or rockfill for 20 × 15 = 300 GWh, that means, about 0.3 m^3/kWh, or about $5/kWh.

A basin which is totally offshore, with an area of 100 km^2, would require 35 km of dykes. There are many large flat areas with an average depth of 10 or 20 m, where the sea bed is sand or possibly gravel or rock. The best solution could be to build a breakwater all around the area first: this breakwater (like some existing ones) could be made of prefabricated reinforced concrete caissons (using up to 100 m^3/m). Dykes could then be built in the calm waters, using sand dredged in optimal conditions by very large sea dredgers. In cases where there is insufficient sand and gravel above the rock foundations, large quantities of rockfill could be brought from island quarries and transported by conveyor belts.

The cost per m^3 of the dykes could thus be, for very large quantities, in the same range as for traditional dams, or probably even lower. The dykes could typically be 100 m behind the breakwater, but much more locally to create harbour facilities for construction or operation. Dykes 50 m above the sea level would store 2 GWh/km^2, that is, 200 GWh for 35 km of dykes and the breakwater.

The corresponding cost, which would vary depending on local physical and economic conditions, should include around 2 × 10^6 m^3 of reinforced concrete, and 400 × 10^6 m^3 of sand and gravel, for a total of about $4 billion/ 200 GWh. The investment ($20/kWh) would be reduced for larger basins or for basins along the shore, either close to a cliff, or extending partly onshore. An investment of $4 billion may seem high, but in fact it is equivalent to the cost of a nuclear plant.

The storage of 1 kWh would thus cost on average about US$10; the storage capacity, representing about two days of power supply, should thus be about 1/200 of the annual supply and the investment per kWh/year supplied should thus be about 10/200, that is US¢5, and the cost per kWh would be in the range of US¢0.5. For a storage facility of 100 TWh, which will probably be necessary by 2040, the investment would be: 100 × 10^9 × $10, which is $1000 billion over 30 years, about the same annual investment as for existing dams. This amount does not include the cost of the power units for pumping and turbines.

The cost of the power units used as pumps and turbines is usually, for existing onshore schemes, around $1000/kW. The very large quantities of standardized units and the possibility of supply from low cost countries involving sea transport of heavy elements could probably keep the average cost between $500 and $750 per kW. The capacity of such plants within a large grid would be about half the capacity of wind or solar plants operating on average for 2500 hours a year. The capacity of pumping plants would thus probably be about 0.2 GW per TWh/year of wind or solar energy, which means an investment per kWh/year of US¢10 to 15

Some investment for transmission lines must be added to the above figures, and the total investment for storage (basins, plants and the associated transmission lines) would thus be in the range of US¢20 to 30 per kWh/year of wind or solar power, well adapted to needs, and a cost of about US¢2/kWh.

Wind power, with the investment for wind farms currently being around US¢50 per kWh/year (and probably less in the future) therefore appears to be very attractive, even taking into account the extra cost of the storage facilities. Furthermore, wind energy combined with storage could be developed extensively in many countries over the next 20 years. Optimization of foundations offshore could be very favourable to make this feasible. The total cost may be close to that of coal-fired plants. Even energy storage of one or two weeks could be justified.

The direct cost of solar PV is currently much higher. But its future is mainly in the developing countries, which have 8 to 10 hours of sun each day and low engineering and labour costs. It is therefore likely that, for large standardized quantities in sunny places, the total investment per kWh/year (including the necessary storage facilities) would be between US$1 and 1.5, or a total cost per kWh of about US¢10; that is much less than the cost paid at present for power from oil-fired plants. However, this cost will probably be higher (at least before 2020 or 2030) than power from coal plants and possibly from nuclear plants.

Another advantage of very large storage and pumping plants will be the possibility to match the power supplied to needs within just a minute. Possible outages of large grid systems can thus be avoided. Problems of daily or weekly peaks will also easily be solved.

The area of the required offshore basins in the world could reach 100 000 km^2 within 50 years (2020-2070). This could be compared with 300 000 km^2 of onshore lakes created between 1950 and 2000 for 3000 TWh/year of hydropower.

Possible future sources of energy

As long as it is possible to use renewable energies at an acceptable cost, there will be no reason to prevent world economic progress. But it is useful to evaluate the necessary extra investments or costs for such energies compared with the use of fossil fuel.

The evaluation set out next is done based on a global perspective; there will obviously be large differences between different countries, but most large grids will probably use various sources, with quite similar proportions as described below.

The world population will probably reach 9 billion by 2040, with subsequent increases gradually reducing. World economic production is now close to $50 000 billion per year, and could be more than $100 000 billion by 2040, reaching more than $200 000 billion by 2070 ($20000 per capita compared with the present $30 000 in the industrialized countries).

Even with reasonable energy savings, world energy needs will probably have doubled by 2040, and will have increased fourfold by 2070. The share of energy use conributed by electric power will probably have increased further because most road transport will probably be based on electric or hybrid cars or hydrogen for trucks.

Present annual energy electricity consumption may thus have increased from 15 000 TWh at present to 35000 TWh/year by 2040, and to 70 000 TWh/year by 2070. But the fossil fuel used at present for 10 000 TWh/year should be limited to 5000 TWh/year (or less) by 2040 and 2070 (domestic consumption of fossil fuel should also have reduced considerably by then, thanks to biomass and solar thermal, as well as transport based on electricity and hydrogen).

It is likely that hydropower will be developed to the maximum possible extent, but even using tidal and other miscellaneous types, it will be limited to around10 000 TWh/year.

Another source is nuclear energy: there will probably be major possibilities after 2040, but the proportion of nuclear electricity (2000 of 15 000 TWh/year now) will probably not be much higher in 2040 (5000 of 35 000 TWh/year). Of the 35 000 TWh/year required by 2040, 15 000 TWh/year may therefore come from hydropower and nuclear, and 20 000 TWh/year will probably be supplied by fossil fuel, wind, or solar photovoltaic.

If there is no energy storage, wind and photovoltaic would only be able to supply about one third of the fossil fuel quantity, that is, 5000 TWh/year; but if storage is provided, as proposed above, these sources could supply 15 000 TWh/year, reducing the fossil fuel share to 5000 TWh/year. This solution will require an extra investment, which is evaluated below.

The investment in thermal plants should not be greatly reduced, so as to guarantee power if there is neither sun nor wind for some weeks; but these thermal plants should only be used for about 10 to 20 per cent of the time. The investment for storage corresponds to:

$$15\ 000 \text{ TWh/year} \times \text{US\$}0.3 = \text{US\$}4500 \text{ billion.}$$

The extra investment for 10 000 TWh more to be contributed by wind farms and solar photovoltaic will be around $1 per kWh/year (lower for wind and higher for photovoltaic); that means, $10 000 billion. The total extra investment would then be:

$$\$10\ 000 + \$4500 = \$14\ 500 \text{ billion.}$$

This investment will reduce the cost of fossil fuel by 0.5 × 25 years × 10 000 TWh, or 125 000 TWh × US¢5 cents on average. That means, by $6000 billion, and the final extra cost over 30 years will be:

$$\$14\ 500 - \$6000 = \$8500 \text{ billion}$$

or close to $300 billion/year, which is about 0.5 per cent of the world production over these years.

It is thus possible, at an acceptable cost, to obtain the necessary energy for world economical progress and to control the global warming.

However, this extra investment may prove difficult for the less developed countries, which may prefer to use coal-fired plants; loans from the richest countries could provide a solution which would be prudent for all in the interest of reducing global warming.

After 2040, extra power demand will be mainly in sunny countries, and the extra requirements will be able to be met, without any limit, by solar PV and wind power, with some energy storage, and also possibly by the next generation of nuclear plants, if their cost will by then be lower. The extra investments after 2040 will be balanced by the savings in fossil fuels based on earlier investments.

Supplying 100 000 TWh/year by renewable energies by the end of the century thus appears to be a reasonable target.

Figs. 1 and 2 show the likely shares of energy supply, with and without energy storage.

Conclusion

The vast economic development which is necessary for 80 per cent of the world population will need a lot more energy, but global warming will require a large reduction in the use of fossil fuels. Part of the solution may be the use of nuclear energy (which may be cost effective in many places), but it will be essential to exploit renewable energy sources to the maximum possible extent.

All countries have some potential for the development of biomass or hydropower; virtually all have a very large solar or wind potential, which in fact represents considerably more than their future needs. Technical solutions for the development of this potential are available; the cost of wind energy is close to that of energy from coal, and the extra cost associated with photovoltaic electricity will probably be quite acceptable within 10 years in sunny areas (which in fact are most of the places where future development is necessary).

The main disadvantage of these energies is that their availability is limited to only a few hours per day, or a few days per week. Storage of this energy for several days is the solution: this is possible at an acceptable cost, by the use of large hydraulic storage basins offshore, using proven technologies.

The share of fossil fuels in global electric power production could thus be reduced from 70 per cent at present to 10 or 20 per cent after 2040. This would reduce the risk of conflicts for their control. The availibility of renewable electricity will favour its use for road transport by electric cars or by trucks using hydrogen. Using such electricity for domestic heating (in addition to biomass and solar thermal) would also reduce the need for fossil fuels.

A few days storage of wind and solar power, using large offshore structures, is an attractive and realistic solution, important for exploitinig the potential of these renewable energies. The expertise which exists in the fields of dam engineering and offshore technologies will be extremely valuable in optimizing the required structures.

It thus seems possible, with a moderate additional investment over the next 30 years, to combine full worldwide development with the control of climate change. ◊

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