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INTEGRATED WIND AND SOLAR QATTARA DEPRESSION PROJECT WITH PUMPED STORAGE AS PART OF DESERTEC

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ABSTRACT

A safe and economical approach is suggested to realize a wind and solar hydroelectric project at the Qattara Depression as part of the Desertec initiative. Instead of tunneling through the coastal hills as proposed in previous investigations, pipes can convey pumped water from the Mediterranean Sea to the upper Deir Kourayim reservoir and down to the depression. Wind turbines farms would provide the electricity to pump the water up into the reservoir. There, its potential energy is stored and then released to the Qattara Depression when electricity is in demand. While normal wind farms destabilize the frequency and voltage of the electrical grid due to the wind intermittency and sudden changes in wind speeds and thus varying power outputs, these wind turbines will not be connected to the grid but drive directly the pumps leading to the pumped energy storage reservoir. Not only can the intermittency of wind power be overcome and the produced electricity be constant for base-load application, but also an amount of energy corresponding to the difference in the ≥ 60 m elevation can be extracted.

An economical and technical analysis comparing the proposed approach to the previous tunneling one reveals the possibility of producing a larger amount of power of 1,120-1,550 MWe compared with 338 MWe. This is also associated with a more favorable capital cost of the electrical installed capacity at $3,560/kWe compared with 5,860 $/kWe.

INTRODUCTION

Over the last century, people have often considered the Qattara Depression in the north-western desert of Egypt as a site for hydroelectric power generation. Nuclear civil engineering excavation of a canal from the Mediterranean Sea to the depression across the coastal hills was once considered. It had been suggested to dig a tunnel from the Mediterranean Sea to the depression and use the difference in elevation between the ocean and lower laying depression for electric power generation. But due to the high capital costs associated with the excavation of a tunnel, the project has not been realized. In this work, a new design concept is presented. Instead of a tunnel, pipes would transport water from the Mediterranean Sea over the coastal hills into the depression. A natural reservoir on top of the hills is used as a water storage basin. Sea water is pumped with electricity generated from wind farms into the reservoir and then runs hydroelectric turbines when dropping into the depression. The flow rate has to be equal to the solar evaporation rate of the forming lake at 60 m below sea level. In that way, not only the wind's intermittency can be overcome, but there is also an additional energy gain from the effective head between the Mediterranean Sea and the formed lake in the Qattara Depression.

JUSTIFICATION

The world is facing serious ecological and economical challenges. A fast growing world population at about 8 billion people in 2050 and higher standards of living lead to an increasing demand in energy supply, especially in the developing countries. Today, most power is generated by burning fossil fuels like coal, natural gas or petroleum, which causes greenhouse CO_2 gas emissions into the atmosphere. According to the USA Energy Information Administration (EIA), the global CO_2 concentration increased from about 280 ppm (parts per million) in 1800 to a current value of 390 ppm.

A consensus has formed that the enlarged amount of CO_2 in the atmosphere is causing climatic change. The increase of the global average temperature leads to widespread melting of snow and ice as well as a thermal expansion of the world oceans' water, and thus to a rising sea level. Also extreme weather and climate events such as heat waves, heavy precipitation and droughts may result from the higher heat fluxes into the troposphere. To reduce CO_2 emissions and to gain independence from rising petroleum prices and peak oil production during this century, people are concerned to find alternatives in power generation. Renewable energy systems such as solar (concentrating solar thermal power and photovoltaic), wind or hydroelectric energy are becoming more and more relevant. However, the idea of completely substituting fossil power generation with wind or solar energy bares the hurdle of intermittency. While burning coal or natural gas can deliver electricity 24 hours a day at a high capacity factor, wind and solar power are strongly dependent on the environmental conditions. If the wind is not blowing or the sun is not shining, there is no power generation.

Currently, these technologies without the implementation of energy storage alternatives are mainly helpful to cover peak power production. In some situations, energy is produced but is not used by the grid. For a base-load usage of the renewables options for power supply, energy storage systems must be conceived and implemented. Pumped storage lakes whenever the geography allows it are one possibility to store energy on a large scale with only little impact on the eco-systems and climate.

THE DESERTEC INITIATIVE

The non-profit Desertec Foundation was established in January 2009 after six years of developing the Desertec Concept. In the same year, the Desertec Industrial Initiative (DII) GmbH was founded in order to accelerate the implementation of the Desertec project in the focus region EU-MENA (Europe, Middle East and North Africa). The estimated cost is 400 billion Euros (540 billion USA dollars). Important European Companies that are involved in energy issues such as Siemens, SCHOTT Solar and Abengoa Solar are participating in the project as shareholders. The main objectives of the initiative are:

1. Development of a technical, economical, political and regulatory framework for feasible investments into renewable energy and interconnected grids,
2. Origination of reference projects to prove the feasibility,
3. Development of a long term roll-out plan for the period up to 2050 providing investment and financing guidance,
4. Conduction of specific in-depth studies

A long term goal is not only to provide a large percentage of Middle East and North African (MENA) and about 15 percent of Europe's total electricity consumption, but also to create tens of thousands of new jobs that are needed in the MENA region.

Figure 1 shows Europe and the Mediterranean Sea with the bordering countries. It displays the different types of renewable energy production. As wind blows stronger and more permanently offshore and on sea shores than inland, this would the main energy source along the coasts. While the energy systems in Europe are very diverse – hydro, biomass, geothermal and photovoltaics – in North Africa and the Middle East the focus lies on Concentrating Solar Power (CSP). The retired Physicist and president of the Desertec Foundation Dr. Gerhard Knies is quoted as saying:

> "Within 6 hours deserts receive more energy from the sun than humankind consumes within a year."

In fact, the solar radiation in the Sahara Desert is more than twice as high as in Central Europe. Also, the space is theoretically almost unlimited.

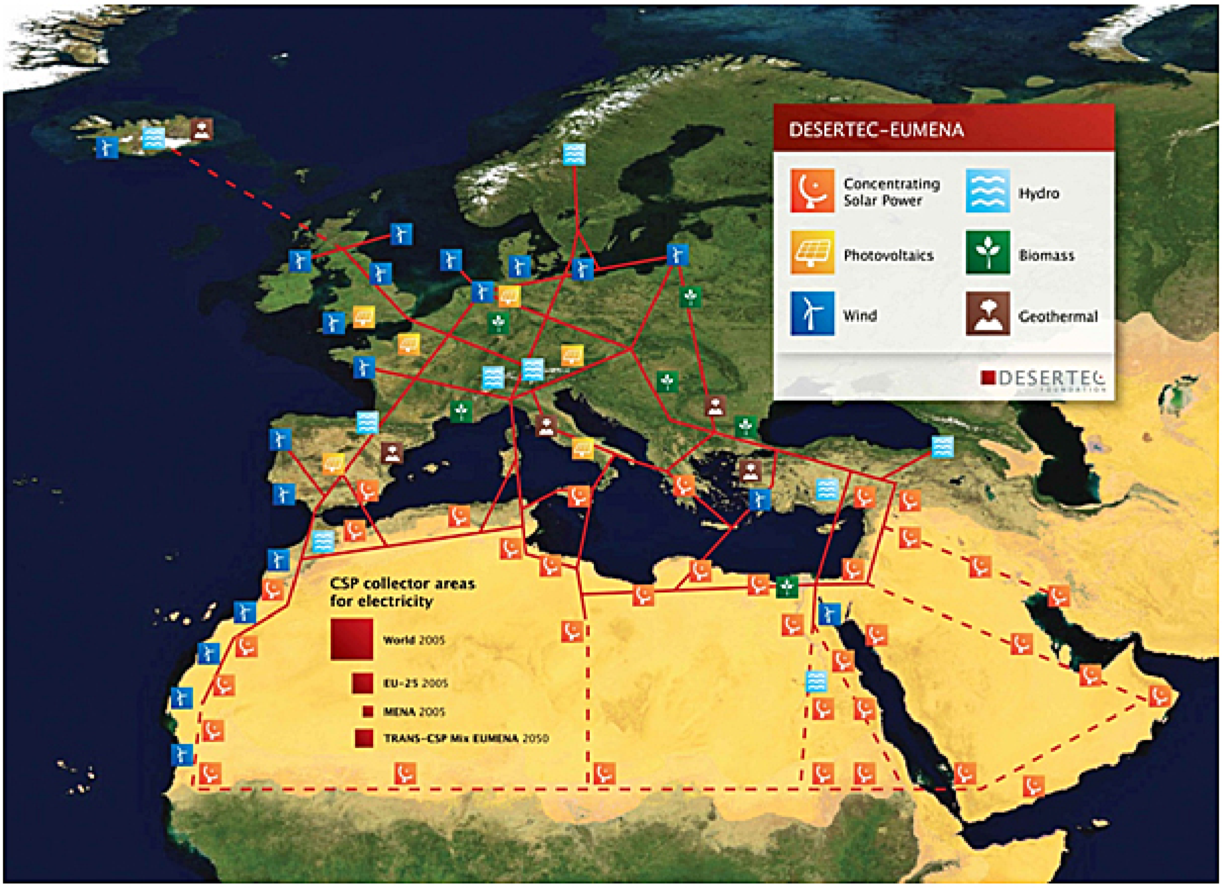

Figure 1. Map of the Desertec Project and the Grid in the European Union and Middle East and North Africa (EU-MENA) region. Source: Desertec.org.

The red squares in Fig. 1 in order of size represent the area of solar collectors which would be necessary to cover the energy consumption worldwide (largest square), Europe (excluding eastern Europe and Russia), MENA and EU-MENA. As the energy (especially solar thermal and wind) will be produced hundreds to thousands of miles away from where it is needed, new transmission lines will be needed. The most promising technology with the lowest losses over long distances is High-Voltage Direct-Current (HVDC) transmission lines.

These are marked as red lines in Fig. 1. Today, most grids use Alternating Current (AC), as it is more reliable and the components are cheaper. Due to cable capacitances which are steadily charged and discharged, AC transmission lines are limited in length. AC transmission lines have power losses up to 6 percent per 100 km (60 miles). The German company Siemens evaluates the power losses in HVDC at about 3 percent per 1,000 km (600 miles). Energy is lost due to the resistance of the wires. As the power loss is proportional to the square of the current ($P = I^2 \cdot R$), higher voltages (V) and thus lower current (I) ($P = V \cdot I = \text{const.}$, $V = R \cdot I$) minimize the transmission losses. In order to obtain direct current, large power conditioning units must be built which increase the cost of the installations for HVDC. However, significantly reduced power transmission losses make this technology advantageous for long-distance as well as for underground and underwater power transmission.

LOCATION AND TOPOGRAPHY OF THE QATTARA DEPRESSION

The Qattara Depression is located in North-West Egypt in the Libyan Desert (Fig. 2). With a maximum depth of 134 m below sea level, it contains the second lowest point in Africa after Lake Assal in Djibouti and is the fifth deepest natural depression worldwide. It has a length of about 300 km and a width of 135 km.

The surface area at zero level is approximately 19,500 km², covering almost 1/15th of Egypt's total land area. About 5,800 km² of the depression's bottom are covered with *Sabkhas*, also known as Salt Flats or Dry Lakes. These *Sabkhas* contain salt saturated with water and covered with a thin layer of desert sand. The remaining surface area consists of sand, gravel, mud and limestone. As the depression lies far north of the main aquifers routes that go through the northern part of the Sahara Desert, small amounts of groundwater seep into the depression. But due to the high evaporation rate in the arid climate, no permanent lake is formed. Although there are no permanent settlements, Bedouin nomads use parts of the area for animal grazing and rare desert animals live in the region.

Figure 2: Location of the Qattara Depression. Source: inwent.org.

Even though the shortest distance between the Mediterranean Sea and the Qattara Depression is only 56 km, the north-western edge of the depression is formed by hills with heights up to 230 m above sea level. Figure 3 shows the topography of North Egypt and the Qattara Depression. While the northern and western parts of the depression are bordered by steep, high slopes, the southern and eastern borders are smooth and slowly rising to the level of the surrounding desert. The depression itself has different elevations with the deepest point in the south-western part. It is generally deeper in the west than in the east. It is thought to be a remnant of the ancient Tethys Sea.

One kilometer off the north rim and at a level of 215 m above sea level is another small depression: the *Deir Kourayim* depression. Its lowest point is at an elevation of 175 m above sea level, a maximum surface area of 3 km² and a total capacity of 50 million cubic meters (0.05 km³).

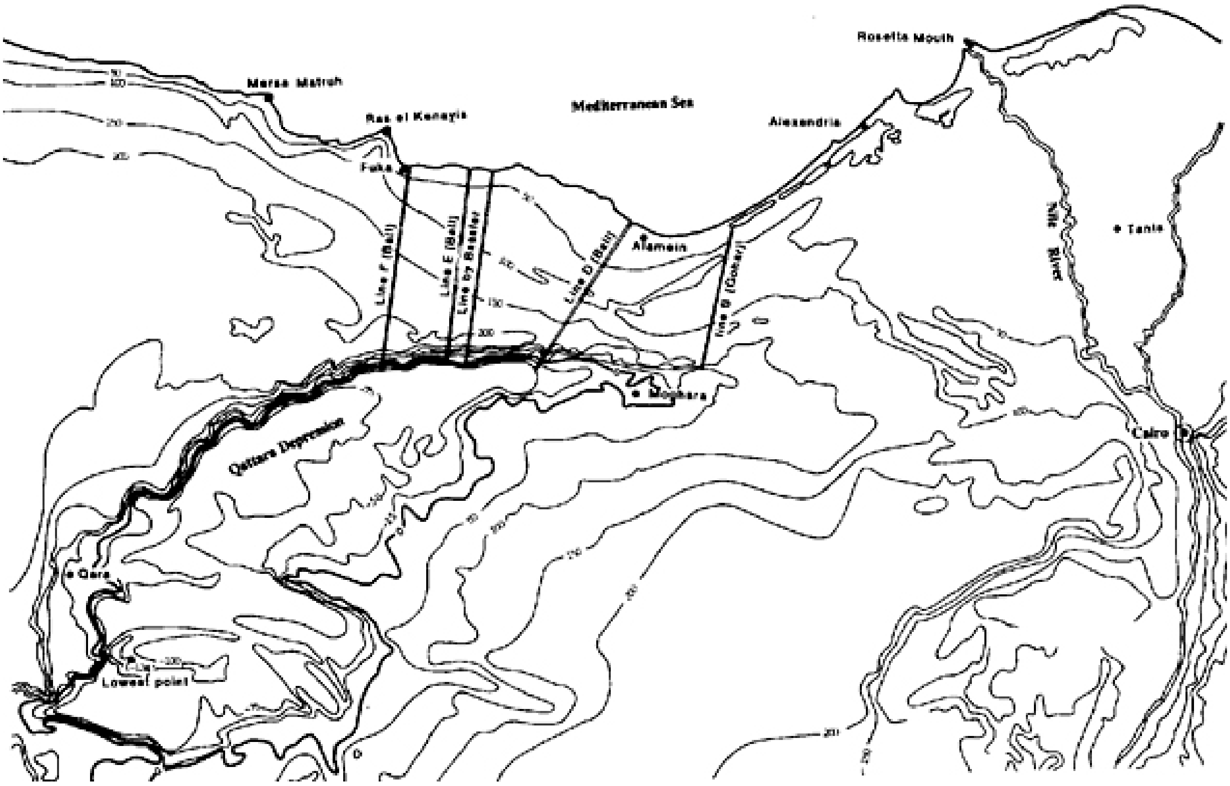

Figure 3. Topography of the Qattara Depression. Source: greenstone.org.

WIND AND SOLAR POTENTIAL IN EGYPT

Wind power is considered as second order solar energy. Solar radiation heats the equatorial and polar regions differently due to the atmospheric layering and the orientation towards the sun. The temperature difference in the air causes variations in the atmospheric pressures which turn into movement of air masses as wind. The same phenomenon happens on land and sea. As land mass and water have different heat capacities, they warm up differently. The thermal and pressure gradients cause the wind to blow. While local wind varies a lot in time, winds caused by thermal updraft blow almost steadily – day and night, as the ocean stores the solar energy better than the land mass. Wind turbines convert as much of the wind's kinetic into rotational energy and at the end with a generator to electricity. The power content of a wind stream is:

$$P = \frac{1}{2}\rho S V^3 = \frac{1}{2}\rho \frac{\pi D^2}{4} V^3 \qquad (1)$$

where: P the rated turbine power in Watts [W]
ρ the air density in [kg/m³]
S the swept area of the turbine in [m²]
D the turbine diameter in [m]
V the wind speed in [m/s]

Wind turbines could cover a substantial part of our energy demands. In addition, they are economical and do not need much land area. The high initial capital cost for their installation is compensated by a zero cost for the fuel and low maintenance costs. Their manufacture, construction, operation and maintenance is man-power intensive which would provide jobs and establish local industries in high population areas.

Wind turbines can be installed right next to fields and pastureland. The impediment to widespread wind power use is the intermittency issue. As energy is not storable at a large scale yet, utility companies fear to install too many wind turbines in case that there is no wind blowing. Wind, and thus power generation, can change dramatically within seconds. Wind turbines have an intermittency or capacity factor of only 20 – 40 percent. In comparison: fossil fuel and nuclear power plants operate at larger than 90 percent capacity factors. This means that only 20 – 40 percent of the time wind turbines operate at their rated power. Despite the fact that wind energy has zero emissions, needs no fuel and has a high potential, it is not yet being implemented on a large scale. Without appropriate energy storage possibilities, wind will not be able to serve as a base load energy supplier like nuclear, hydroelectric and fossil fuel based power plants. Similar to solar energy, the fluctuation in the power output due to intermittencies is a strong impediment that needs to be surmounted by judicious engineering design.

In 2005, the New and Renewable Energy Authority (NREA) in cooperation with Risö National Laboratory published a Wind Atlas for Egypt based on observations and numerical simulations of the wind conditions in Egypt. The goal was "*to provide reliable and accurate wind atlas data sets for evaluating the potential wind power output from [...] wind turbine installations*." The result of this eight years lasting program can be observed in Figs. 4 and 5, which demonstrate the mean wind speeds on land and sea, respectively, at a height of 50 m above ground level (a.g.l.). The reddish colors represent higher wind speeds up to 10 m/s as average.

Especially in the Gulf of Suez and the region around Ras Ghareb or Ras Zaafarana the winds blow very strongly and quite continuously with a capacity factor of almost 70 percent. It is not surprising that a wind farm was built at Ras Zaafarana with a total rated power of 430 MW (planned: 600 MW total) at an average wind speed of 9 m/s and an average capacity factor of 55 percent. Yet, the capacity factor has been significantly lower in the winter months and higher the rest of the year.

A promising location for offshore wind farms is – apart from the Gulf of Suez – the Gulf of Aqaba off the Saudi Arabian Coast. In these areas with high wind speeds and relatively high capacity factors, the annual energy output could lie between 3 – 5 GWhr per installed MW, enough to power 1,000 European households with four people each for a whole year. Assuming an area of 180 km in length from Ras Zaafarana to the Gulf of El Zayt and 50 km in width, the potential of wind energy in Egypt is as high as 200 TWhr/yr, twice the current energy consumption of Egypt. Although the mentioned region has a high capacity factor of ~50 percent, wind energy always has the risk of intermittency. An electricity generation of only wind energy would be unrealistic, rather a mix of many sources like wind, nuclear, natural gas, hydro, and solar is needed, unless energy storage options are developed.

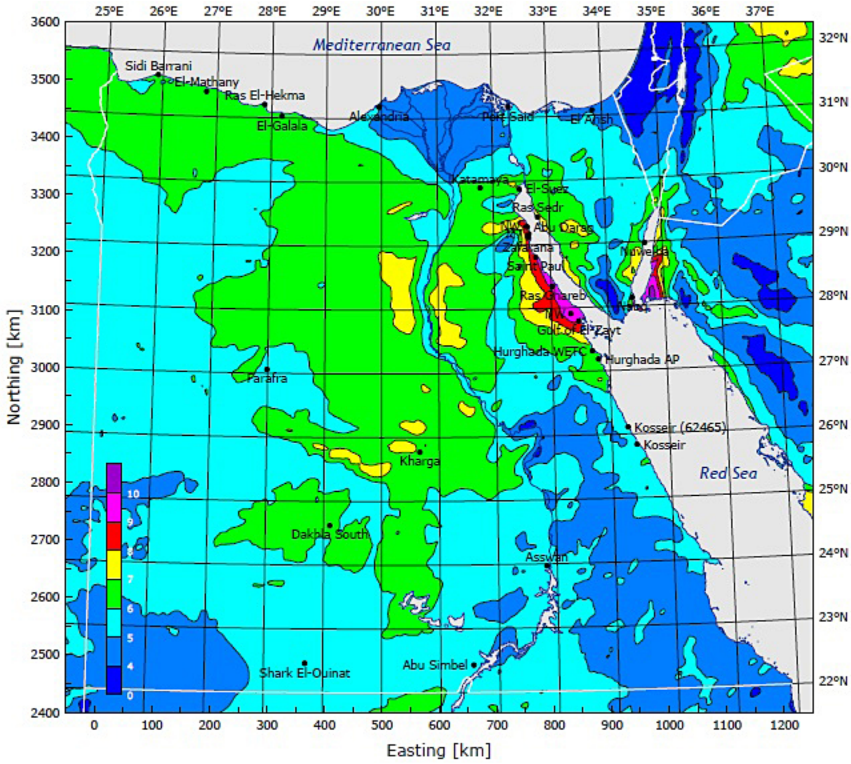

Figure 4. Wind resource map: mean wind speed at 50 m agl (above ground level). Source: Wind Atlas of Egypt.

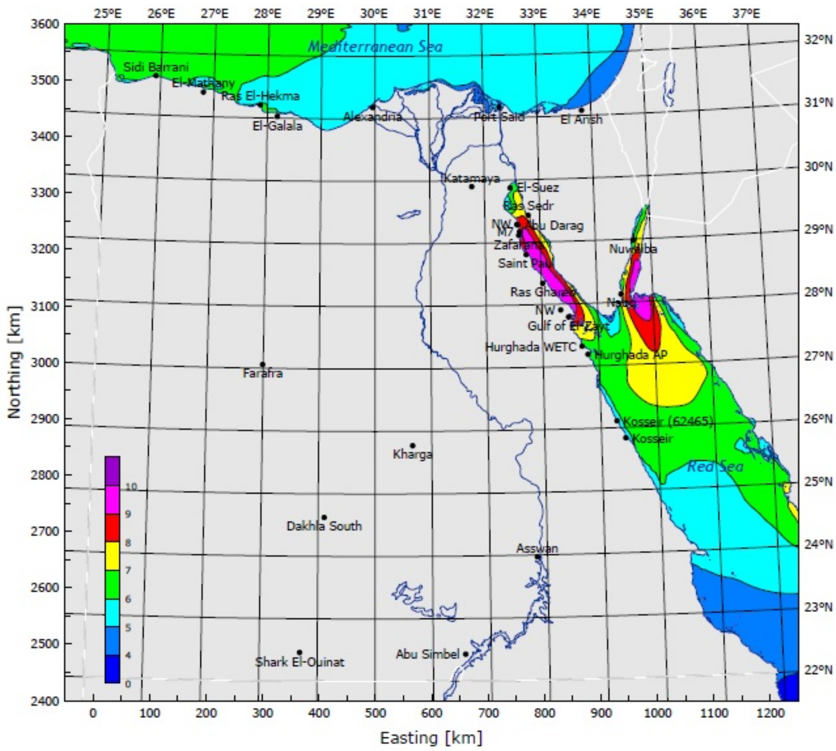

Figure 5. Offshore wind resource map: mean wind speed at 50 m above ground level, agl. Source: Wind Atlas of Egypt.

A growing population and the Qattara Depression project in mind, wind power generation along the Mediterranean coast is suggested. Although the average wind speeds of about 7 m/s at 50 m a.g.l. are slightly lower than those at the Red Sea, the omission of long terrestrial power transmission lines to the consumption population centers in the Nile Delta region compensates for the lower power output. The estimated annual energy output at a hub height of 80 m and an overall efficiency of 25 percent is 2 – 2.5 GWhr/y per installed rated MW. This takes into account that the wind speed changes with height above ground level according to:

$$V(H) = V_0 \left(\frac{H}{H_0} \right)^{\alpha} \tag{2}$$

with: V_0, $V(H)$ the wind speed at the measured height and the new height respectively in [m/s]
H_0, H the measured height and the new height respectively in [m]
α power coefficient dependent on ground surface roughness; for water $\alpha \approx 0.1$

Figure 6 shows a map of the direct normal solar radiation in the EU-MENA region. It is clearly noticeable that the Sahara Desert offers optimal conditions for solar power usage. The solar irradiation [W/m²] is not only extremely high, but also very constant throughout the year with only minor fluctuations due to weather changes (clouds, etc.). Worldwide, only parts of Australia, South Africa and Namibia and South-West USA can compete with this amount of solar irradiation.

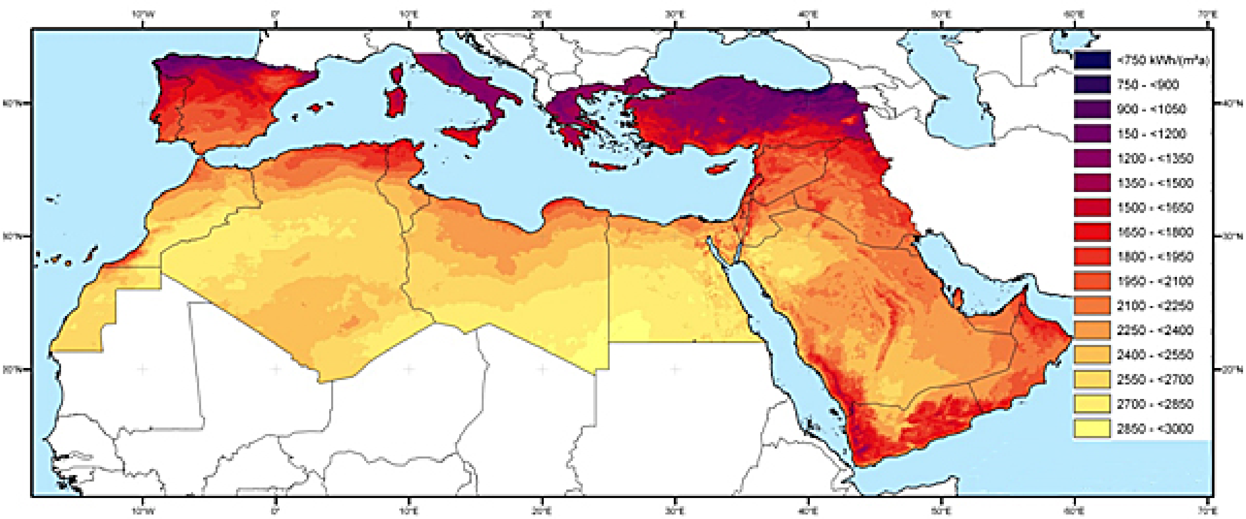

Figure 6. Annual Integrated Direct Normal Irradiation [kWh / (m².yr)] for the year 2002. Source: desertec.org.

THE QATTARA DEPRESSION AS A SITE FOR HYDRO-SOLAR ELECTRICAL POWER GENERATION

Hydroelectric power generation is considered as the best developed renewable energy production source. It has existed for more than a century with only minor changes in the design. As pumped storage dams can store the water at a higher elevation, hydroelectricity can be used both for base and for peak load. Additionally, water turbines are relatively fast and easy to control. The power output is determined by:

$$\begin{aligned} P_e &= \rho \mathrm{v} \mathrm{A} g h.\eta \\ &= \rho \dot{\mathrm{v}} g h.\eta \\ &= \dot{m} g h.\eta \end{aligned} \tag{3}$$

where: P_e the power output in Watts [W]
v the flow speed in [m/s]
$\dot{\mathrm{v}}$ the volumetric flow rate of the water in [m³/s]
A the cross sectional flow area [m^2]
$\dot{m}$ is the mass flow rate in [kg/s]
ρ the density of water in [kg/m³]
h the hydraulic head in [m]
g is the gravity acceleration constant (9.81 m/s²) [m/s²]
η the overall conversion efficiency

The conversion efficiency can reach a value of 67 - 93 percent, which is a remarkable value compared to thermodynamic processes. The main losses are due to frictional drag and turbulence. A turbine and a generator convert the kinetic energy (conversion from potential energy) of the water directly into electricity. Typical power outputs range from a few MWs to hundreds of Megawatts per turbine.

At various occasions over the past 100 years the Qattara Depression has been discussed as a site for hydroelectric power generation in addition to the Aswan High Dam and Low Dams across the Nile River. The general idea is to run large turbines by filling the depression with water from the Mediterranean Sea and forming a large artificial lake. The project can be divided into two stages. During the initial stage, the depression would be filled with water to a stable water level below sea level. In the second stage, the water flow from the Mediterranean would be equal to the amount of solar evaporated water. Previous discussions, including a study by a Commission of the Egyptian Ministry of Electricity and Energy in the 1970s, had proposed to build canals or tunnels from the Mediterranean Sea to the Qattara Depression. This should have been realized either through nuclear civil engineering excavation or conventional excavation of the sand- and limestone with conventional boring machines. The black lines in Fig. 3 show possible locations for the tunnel lines. The final location suggested lead to a total distance of approximately 80 km between the depression and the Mediterranean Sea. The project has never been actually implemented. While the latter excavation possibility is not economical, the idea of tunneling by nuclear civil engineering has been abandoned due to political and safety concerns.

In this work, both a safe and economical way is suggested to realize a wind and solar hydroelectric project at the Qattara Depression. Instead of tunnels through the hills, pipes can lead from the Mediterranean Sea to the upper Deir Kourayim reservoir and down to the depression. Of course, the volume of the Deir Kourayim reservoir would have to be increased to allow a temporary storage in the reservoir. But compared to the excavation of tunnels, this can be easily achieved by small chemical explosions that are both safe and economical. Figure 7 shows a schematic of the suggested realization of the project. Large wind farms provide the electricity to pump water up into the reservoir. There, it is stored as potential energy and released to the Qattara Depression when electricity is needed. Not only can the intermittency of wind be overcome and the produced electricity be constant, also energy equal to the difference in elevations can be gained (here: ≥ 60 m).

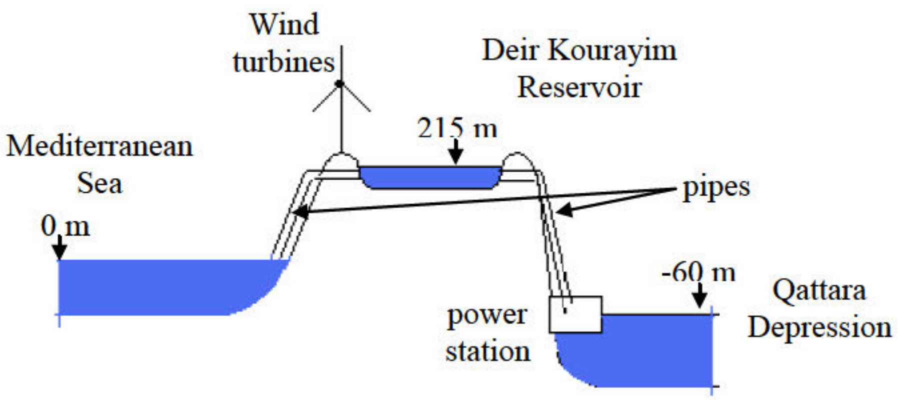

Figure 7. Proposed approach with wind turbines and pipes at the Qattara Depression.

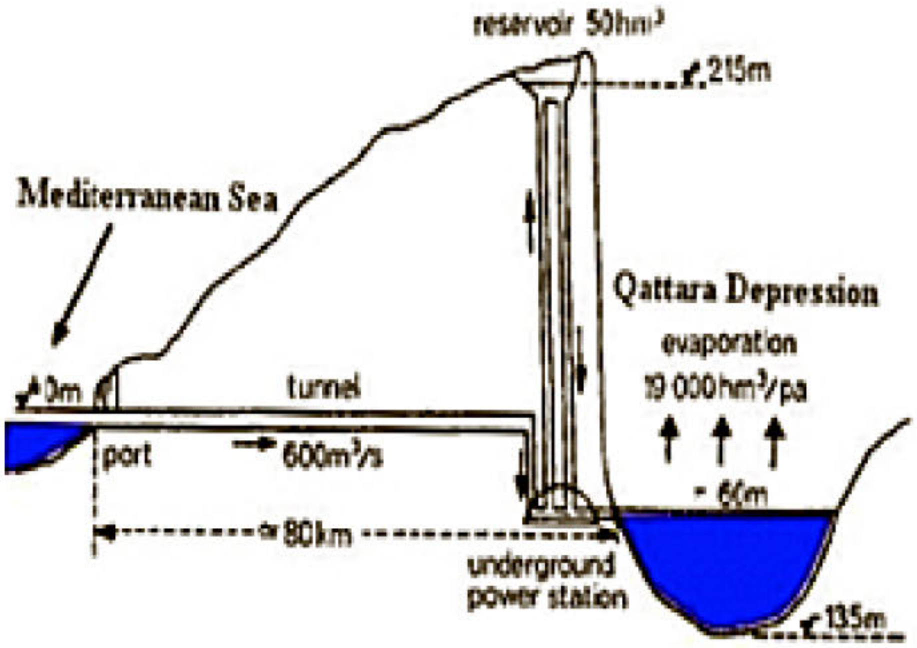

Figure 8. Previously suggested design with a tunnel and pipes for pumped storage [3].

One obvious concern with the solar evaporation rate might be the long term salinization of the produced lake. After decades of evaporation and saltwater feeding, the lake is expected to become more and more saline. Then, either the lake can be mined for crystallized salt and other minerals such as the Dead Sea potash fertilizer plants on the Jordanian and Israeli sides, or a Reverse Osmosis power generation plant could be built in addition to the hydroelectric turbines to take advantage of the saline gradient in the depression and the open Mediterranean Sea.

Table 1. Surface area and water volume at different filling levels in the Qattara Depression [6].

Filling level [m]	Surface area [km²]	Filled water volume [km³]
-40	15,400	508
-60	12,500	227
-80	4,650	39.3
-100	526	6.3

In order to maintain a specified head for the power gain, it has been suggested to stabilize the lake filling height at 60 m below sea level. Table 1 shows the relation between filling levels, corresponding surface areas and the volume of the formed lake.

The pipes going from the reservoir to the depression must be designed in such way that at the designated filling level the flow rate forms an equilibrium state to the solar evaporation from the formed lake. Assuming a filling level of 60 m below sea level, the evaporation rate is about 19 km³/year.

Thus the required flow rate from the reservoir to the depression is about 600 m³/s (51.84 million m³/day). With a minimum head of 275 m (|-60| m + 215 m) and an overall efficiency of 93 percent, using Eqn. 3, the maximum power output (depending on the filling level of the lake) of the power station is:

$$P_{\max} = 1,030\frac{kg}{m^3}\times 600\frac{m^3}{s}\times 9.81\frac{m}{s^2}\times 275m\times 0.93 = 1.55\times 10^6 We = 1,550\,MWe$$

At a lower value of the conversion efficiency of 67 percent, the rated capacity of the plant would be:

$$P_{\min} = 1,030\frac{kg}{m^3}\times 600\frac{m^3}{s}\times 9.81\frac{m}{s^2}\times 275m\times 0.67 = 1.12\times 10^9 We = 1,120\,MWe$$

In contrast to wind power generation alone, this electricity can easily be used to cover base loads. Compared with wind energy only, this is a power gain of at least 338 MWe due to the additional head. With a flow rate of 600 m³/s it would take approximately 35 years for filling the lake up to a level of 60 m below sea level. During this period, the power output is higher than mentioned above due to a larger head and more than 495 TWh of electricity could be produced. After the filling process, the maximum annual electricity generation is 13.5 TWh. From the energy equilibrium between potential energy (mgh) and kinetic energy (1/2 mv^2, without losses), the water flow speed in the pipes can be determined from:

$$v = \sqrt{2gh} \tag{4}$$

where: v the speed in [m/s]
h the head (difference in height) in [m]
g the gravity acceleration constant 9.81 [m/s²]

Knowing the flow rate and the speed in the pipes, the needed pipe diameter can be calculated from:

$$\dot{\mathrm{v}} = \mathrm{v}.A = \mathrm{v}\frac{\pi D^2}{4} \tag{5}$$

where: $\dot{\mathrm{V}}$ the volumetric flow rate in [m³/s]
v the speed in [m/s]
A the area cross-section of the pipe in [m²]
D the diameter of the pipe in [m]

Using Francis turbines with a rated capacity of 760 MW each, two pipes are needed. For a total flow rate of 600 m³/s and a head of 275 m, the ideal diameter of each pipe leading from the reservoir to the depression is D = 2.3 m.

The suggested option, however, is to add two additional pipes from the reservoir to the depression. During the filling process the power output could be increased (not doubled, as the wind farms needed for the pumping have a limited capacity) and the filling time shortened. Once the lake has formed and is stabilized at 60 m below sea level, the flow rate has to be equal to the evaporation rate. The idea is to run the plant at lower base load capacity of P = 465 MWe or Q = 180 m³/s during night and times of low electricity demand. Assuming high power demands for 10 hours a day, the resulting electricity output during this time could be as high as 3.10 GWe (or Q = 2 x 600 m³/s).

It is suggested to power the motors that pump the water from the Mediterranean Sea to the upper reservoir with wind-generated electricity. Unlike the turbines on the depression side, the pumps do not need to run continuously. They can follow the intermittency of the wind and fill the reservoir whenever the wind power is available. The average flow rate, however, has to be equal to and from the reservoir (Q = 600 m^3/s). With an efficiency of 86 percent and a head of h = 215 m, the yearly electricity generation from the wind turbines must be 13.3 TWhr. Assuming an intermittence factor of the wind turbines of c_F = 40 percent, which is a reasonable factor at shores and offshore, the installed rated power must be:

$$P_R = \frac{E}{c_F.8760} = \frac{13.3\,TWh}{0.4 \times 8760\,h} = 3{,}800\,MW \tag{6}$$

While normal wind farms destabilize the grid due to wind intermittency and sudden changes in wind speeds and thus strongly varying power outputs, these wind turbines will not be connected to the grid but drive directly the pumps leading to the reservoir. Of course, the pumps and pipes must have a rated capacity of 3,800 MW or 2,050 m³/s. Five pipes with a diameter of D = 2.4 m each could be enough to satisfy this requirement.

ECONOMICAL ANALYSIS

In this section, the initial costs of the original project idea with a tunnel from the Mediterranean Sea to the Qattara Depression and the suggested alternative in this work with pipes between the Mediterranean, the upper reservoir and the depression shall be compared. It must be taken into account that the pipes from the Qattara Depression to the reservoir for pumped storage exist in both scenarios and would not be taken into account. Also, no big dam has to be built as the upper reservoir is given by a natural formation and is part of both designs.

Costs for excavation tunneling vary strongly with the hardness of the rock formations. The hills on the northern edge of the Qattara Depression consist mainly of sand- and limestone formations which can be considered as soft rocks. Thus, the cost would lie in the lower region of the price range. From a comparison of different realized projects, the tunneling costs range between 9,000 $/m and 28,000 $/m for train or street tunnels. The diameter for the Qattara Depression project and thus the cost would have been smaller. A tunneling project in the size (cross section area) of the Qattara tunnel has been established at the Fermilab, Illinois, funded by the USA Department of Energy. Here, the cost for a tunnel with 4.88 m diameter and soft stone with areas of difficult excavation has been calculated to be about 24,750 $/m. If the excavation cost of the Qattara tunnel is estimated to be the same, then the 80 km long tunnel would cost about $1.98 billion. Although nuclear excavation would be a cheaper way of building the tunnel, this is not a current option due to political and safety concerns.

This estimated value has to be compared to the cost of five additional pipes with a diameter of 2.4 m each that replace the tunnel in the suggested design. The advantage of pipes is that they are produced in mass production for different purposes like for the oil and gas pipelines or urban and suburban water supplies. Five pipes with 80 km each sum up to a total pipe length of 400 km that are needed instead of the 80 km long tunnel.

The Canadian Energy Pipeline Association reports an average cost for pipelines of $1,000 per millimeter diameter per kilometer. A diameter of 2.4 m or 2,400 mm would lead to a cost of $2.4 million per pipe per kilometer. The total cost for the five pipes from the Mediterranean Sea to the reservoir would be $960 million. Compared to this value, the cost of the pipes from the reservoir to the depression with a length of 300 m each can be almost neglected.

In this design, also the cost for the additional wind farms has to be taken into account. A typical cost is $1.2 million per installed rated MW of power. With an installed rated power of 3,800 MW, the wind farms would cost approximately $4.56 billion. By adding the costs of the five pipes and of the wind turbines, this results in a total cost of $5.52 billion.

In order to compare the economics of the two options, the cost per unit power generated has to be compared. The power output of the tunnel version with a head of 60 m and an efficiency of 93 percent would be 338 MW. The power output of the design with the pipes is 1.55 GW. As Table 2 shows, the proposed approach with pipes and wind farms is more economical than the one with a tunnel.

Table 2. Economical comparison between the two considered approaches.

	Tunnelling Approach	Proposed Pipes + Wind farms
Capital cost (excluding the power block and the pipes between reservoir and depression)	$1.98 billion	$5.52 billion
Average power output	338 MWe	1,550 MWe
Initial cost per unit of installed capacity	5,860 $/MWe	3,560 $/MWe

DISCUSSION

The energy mix of the future has to come from many different renewable energy sources. Due to the natural abundance of wind and solar energy, large scale storage units have to be built. Pumped hydro storage is one of the best possibilities. At the Qattara Depression

Project, the three main sources of renewable energy – wind, solar and hydro – can be combined to overcome the wind's and solar intermittencies and to supply Egypt with renewable base and peak power electricity. This work proposes a both safe and economical way of using the topography of the Qattara Depression. The electricity from large wind farms drive motors that pump sea water from the Mediterranean Sea to the higher Deir Kourayim reservoir avoiding the negative effect of the wind intermittency. The stored water is then released into the Qattara Depression and forms a lake at 60 m below sea level. The resulting power output can be either used for base load supply only, or for both base and peak loads. In addition to the electricity generation and water desalination, the region with the lake can become a new tourist destination comparable to that at the Red Sea. Due to the high solar evaporation rate, salt and other minerals such as potash as a fertilizer can be eventually be mined from the depression and thousands of new jobs can be created.

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