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Egypt's Wind-Generated Hydrogen-Fuel Prospects

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Abstract

This paper presents a future energy plan for Egypt that would adopt a Hydrogen economy in which Hydrogen is generated by electrolysis employing electricity generated from Wind energy. In addition to exploiting the full, economically viable wind energy resources of the Red Sea coast, this energy form would replace the depleting and polluting fossil fuel sources by an effectively renewable and zero harmful emissions source of energy. An analysis is conducted which reveals that the Red Sea coastline alone is capable of producing at least 3.81×10^{10} m^3/yr of hydrogen .

Introduction

Most of the present energy needs of Egypt , whether in the industrial, domestic or transportation field , are met from the burning of oil and natural gas and are expected to continue that way in the near future . This mode of extracting energy injects into the atmosphere a constant flow of pollutants, in particular SO_x , NO_x , CO, and CO_2. The industries are located either close to the main cities or within the city itself; the roads are busy with cars, and there is little greenery in the cities to dilute their pollution. The measured pollutant levels in down town Cairo are among the highest recorded in the world. A clean burning fuel for both the industry and transportation is urgently needed. The appearance of smog and "black clouds" in recent years is just a warning of worse environmental problems in the future , unless resort is made to more environmentally friendly options.

Moreover, Egypt's reserves of fossil fuels are quickly being depleted. Hydro-power which now accounts to about 10% of our energy sources, has been exploited to near it's maximum , and yet the energy demands are constantly rising due to both an improvement in living standards and a growth in population. Similar problems face many of the industrial and developing nations alike, but to varying degrees.

Clearly the future of Egypt is same as most of the world and lies in the development of an environmentally clean , abundant sustainable source of energy . This immediately points towards renewable sources of energy; indeed a recent Shell report[1] predicted that the market share of renewable energy sources will grow, and that by the year 2060 it is expected to be the largest source by a wide margin. The economic viability of renewable energy sources is highly site specific, Egypt is fortunate to have an abundance of both Solar and Wind Energy. However, both forms suffer from an intermittence of supply; moreover , they are neither directly storable nor mobile and hence may not be widely employed in the transportation sector to run cars and busses. This is a challenge which is addressed in this paper.

This paper proposes the use of a non fossil ; environmentally friendly fuel which may replace fossil fuels in both the transportation and industrial sectors. It is proposed here to exploit the available wind energy resources in Egypt to generate this fuel, thus creating a sustainable, renewable fuel source to replace the depleting fossil fuels, and to save the country from the perils of atmospheric pollution and global warming.

The Fuel for the Future

In a very recent review[2] it was stated that : "Scientists, environmentalists, industrialists and engineers are slowly beginning to agree that energy for the 21^{rst} century is going to come from hydrogen". There are many justifications behind this prediction; first the depletion of fossil fuels , and secondly the global warming and environmental issues involved with the burning fossil fuels.

Hydrogen fuel may produce electricity directly employing fuel cells. For automotive use, bottled hydrogen could be fed to onboard fuel cells producing an electrical current which drives an electrical motor replacing the internal combustion engine. Internal combustion engines could also be converted to employ hydrogen gas as a fuel, similar to the natural gas conversion; however, due to thermodynamic cycle efficiency limitations, this method of employing hydrogen fuel is much less efficient than when employing it in a fuel cell to generate electricity. According to the same review[2], "fuel cell cars are looming on the horizon; Daimler-Chrysler, to cite but one example, has promised production fuel cell vehicles by 2004" .

Hydrogen fuel potential is much more than a fuel for vehicles, which avoids the pollution of the atmosphere. A Hydrogen economy can be based on the generation of electrical energy at energy centers, subsequent generation of hydrogen by electrolysis, delivery of hydrogen to consumption sites employing pipe networks(existing natural gas pipe lines may often be employed) then conversion to electricity at the site employing fuel cells . It is envisaged that households in the future could obtain both their energy needs and fresh water needs this way[3].

Hydrogen could also provide a clean alternative to present metallurgical processes; for example , iron ore could be reduced directly as follows:

$$Fe_2O_3 + 3\ H_2 \rightarrow 2Fe + 3\ H_2O$$

with no CO or CO_2 rejected from blast furnaces, as at present.

Hydrogen Generation

Hydrogen may be generated by electrolysis of water, or by several other methods such as production from fossil fuels(e.g. methane reformers) and closed cycle chemical decomposition of water; however, electrolysis has been proposed here because its avoidance of dependence on any fossil energy resource(such as coal or methane) and because it is well suited for integration with wind energy generation, regardless of the size of the plant; water electrolytic plants operate with few moving parts, require less space, can be maintained with semi-skilled labor and are non-polluting. The later feature is particularly desirable, since for a fuel cell application(e.g. vehicle) to be truly emissions free , the hydrogen for the fuel cell must itself be derived by a source that produces no emissions, which is the case when electrolysis employs wind generated electrical power.

A fuel cell, is a reverse electrolyzer in which a continuous stream of hydrogen and oxygen combine to produce electricity and water through electrochemical conversion; the basic reaction is the catalytic oxidation of hydrogen rather than combustion; the end product is water and some heat. The electrolyte may be either a strong alkali or a strong acid. Many cells are connected in series to attain the required voltage; each cell gives about one volt. The electrochemistry in electrolyzers and in fuel cells is essentially identical; in principle it is possible to build a single device that can function both as an electrolyzer or a fuel cell depending on whether it was operated in the "forward" or "backward" mode.

Ideally, the process is endothermic, i.e. heat should be added to the electrolysis cells, and a perfectly efficient cell would require 2.926 kWh of electrical energy in addition to 0.556 kWh of heat energy to produce 1 m^3 of hydrogen at N.T.P. However in practice , there is a surplus of heat generated due to resistance losses in cell and all the energy supplied is electrical[4].

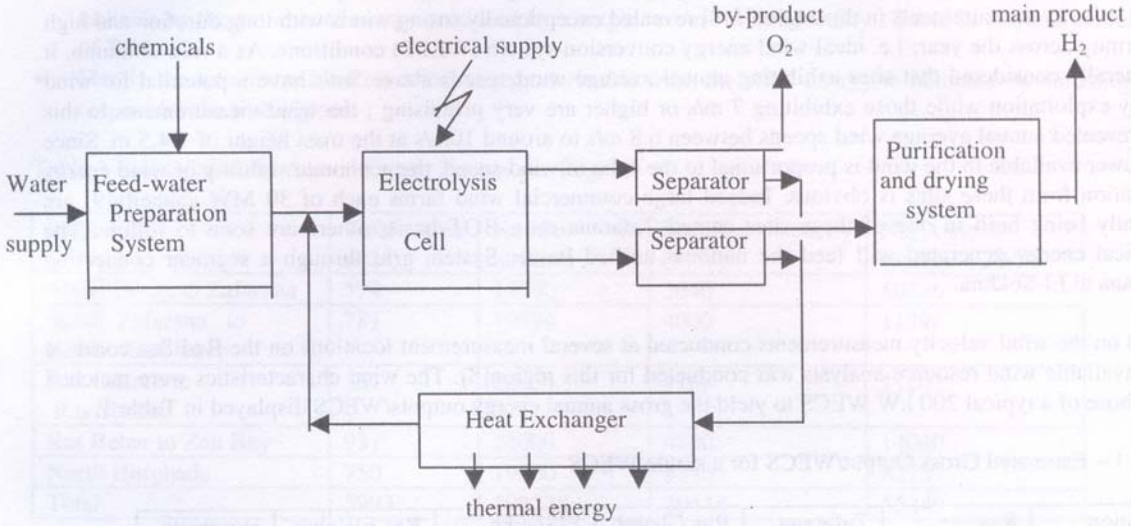

Fig. 1 Block diagram of a water electrolysis plant

Large scale electrolytic plants are not new to Egypt; the water electrolyzers in Aswan Dam produced 40,000 cubic meters of hydrogen per hour[4] many decades ago. In addition to the production of hydrogen, pure oxygen is also produced as a byproduct, as sketched in Fig. 1

Defining the electrolysis efficiency as :

$$\eta = \frac{heating \quad value \quad of \quad hydrogen \quad fuel}{energy \quad of \quad electrical \quad input} \qquad (1)$$

Commercially available electrolysis cells operate with an efficiency of the order of 83%; the rest of the energy is dissipated in driving the electric current through the cell and appears as heat. Improved electrolyzer efficiencies can be obtained by the operation at higher temperatures and higher pressures. Higher pressure operation would also reduce the work involved in bottling the hydrogen for mobile applications, or for pumping it through long pipelines.

Egypt's Wind Energy Resources

Egypt is blessed by very attractive wind energy resources. In a 250 km long North-Westerly stretch of land extending from locations approximately 100 km South of Suez and Southward towards Hurghada, lies some of the best sites in the world for wind energy exploitation. This region is characterized by northerly winds aloft and sinking air masses; the ground topography exhibits a fairly narrow channel of water lined by coastal mountains typically reaching a height of 1-2 km which introduce a funneling effect responsible for the high wind speeds.

Wind velocity measurements in this region[5-8] revealed exceptionally strong winds with long duration and high uniformity across the year; i.e. ideal wind energy conversion system (WECS) conditions. As a rule of thumb, it is generally considered that sites exhibiting annual average wind speeds above 5m/s have a potential for wind energy exploitation while those exhibiting 7 m/s or higher are very promising ; the wind measurements in this area revealed annual average wind speeds between 6.8 m/s to around 10m/s at the mast height of 24.5 m. Since the power available in the wind is proportional to the cube of wind speed, the economic viability of wind energy generation from these sites is obvious. Indeed large commercial wind farms each of 30 MW capacity[9] are currently being built in one of these sites named Zafarana on a BOT basis; others are soon to follow. The electrical energy generated will feed the national unified Power System grid through a segment connecting Zafarana to El-Sokhna.

Based on the wind velocity measurements conducted at several measurement locations on the Red Sea coast , a total available wind resource analysis was conducted for this region[8]. The wind characteristics were matched with those of a typical 200 kW WECS to yield the gross annual energy outputs/WECS displayed in Table 1.

Table 1 – Estimated Gross Output/WECS for a single WECS

Location	Ras AbuDarag	Zafarana	Ras Ghareb	ElSheikh Fadel	Ras ElBehar	Hurghada
Energy in MWh/yr	1008	987	673	706	858	632

The net annual electrical energy produced per WECS in a wind farm should be considerably less due to line losses, blade soiling, turbulence and control losses, down time losses and interference(array) losses. Table 2 displays the estimated net output energy for wind farms/single WECS after introducing the effect of the previously listed losses.

Table 2 – Estimated Net Output/WECS for Wind Farm Sites

Location	Ras AbuDarag	Zafarana	Ras Ghareb	ElSheikh Fadel	Ras ElBehar	Hurghada
Energy in MWh/yr	687	673	459	482	585	431

A conservative estimate was then made of the maximum annual electrical energy that could be provided by wind farms located in the stretch of the sea coast lying between Hurghada South and Ras Abo ElDarag North, approximately 20 km wide. Based on detailed area maps, the estimate was made as follows:

- The favorable areas of land for erecting possible wind farms are marked on the map, employing the contour lines to indicate the slope of the terrain and location of bordering mountains. Five discrete regions were identified. Only 80% of this area is then assumed to be available for wind farm usage.
- In each region , the total number of turbines is assumed to be 32 /km^2. This is based on the adoption of 200 kW wind turbines of 25 m diameter, and employing 10 diameters spacing between rows and five diameter spacing between turbines in the same row. This arrangement is optimum since the wind direction is almost constant in this region as can be seen from the wind rose at Abou-Darag7], Fig. 2.
- The maximum annual output energy per region is derived from the product of the maximum number of wind turbines by the net annual energy produced by a single turbine in this locality , Table 2, to yield the results of Table 3.
- Finally the maximum total electrical energy derivable from the wind energy is obtained by summing the outputs for the five regions.

Table 3 Estimated Total Annual Output Energy per Region

Region	Total Area (km^2)	Number of turbines	Installed capacity (MW)	Net Annual Energy (GWh)
AboElDarag to Zafarana	594	15200	3040	10336
South Zafarana to North .RasGhareb	781	19994	4000	11396
Ras Ghareb to Ras Shokeir	931	23834	4768	11202
Ras Behar to Zeit Bay	937	24000	4800	14040
North Hurghada	750	19200	3840	8275
Total	3993	102228	20448	55249

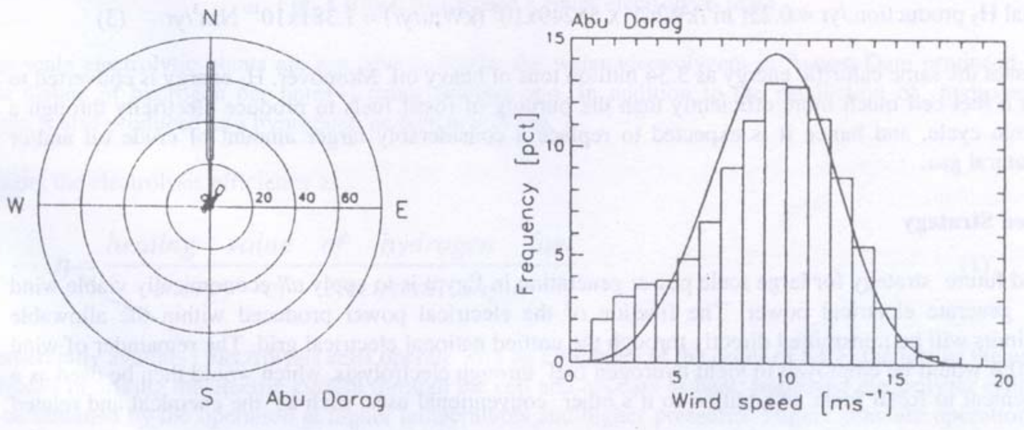

Fig. 2 Wind rose and frequency distribution at Abu-Darag [7]

It is seen that a net annual electrical energy output of 55,000 GWh/yr may be produced by wind energy in this region alone; this represents 70% of the total energy requirements of Egypt in the year 2000. As stated earlier, these estimates are very conservative and are based on the characteristics of a particular 200 kW WECS which is not optimum for the selected sites. Use of more suitable 500 MW WECS would allow higher installed capacity/km^2 and be more efficient in wind energy conversion.

However, a serious limitation to the exploitation of these available wind energy resources is the difficulty of controlling the utility network frequency and voltage when the proportion of Wind energy source exceeds a certain proportion of the total generating capacity in the network. This is due to the unreliability of the Wind energy and it's intermittence; the limit is known as the "penetration limit" and although it depends on the characteristics of the network and the experience of the utility, it is seldom allowed to exceed 20 %.

Another limitation to the use of wind resources is the immobility of the source and hence it's unsuitability to mobile applications. Both limitations are removed when the output of the WECS is employed to produce hydrogen fuel.

Estimate of Hydrogen Generation Potential

Large commercial electrolyzers can produce hydrogen at a rate of approximately 0.24 Nm^3/kWhr; since much research is going on to improve efficiency of electrolyzers it is possible that this figure would reach 0.287 m^3/kWhr in the future[5], which corresponds to an adiabatic process.

Thus the annual volume of Hydrogen at N.T.P. that can be produced by the Wind resources of the Red Sea coast may be estimated as follows:

$$H_2 \text{ production./yr} = \text{rate of } H_2 \text{ production(m}^3\text{/kWhr)} \times \text{Electrical energy (kWhr/yr)} \quad (2)$$

Employing a hydrogen generation rate of 0.25 Nm^3/kWhr as a conservative estimate for the near future electrolyzers, and directing all WECS output towards H_2 production would yield :

$$\text{Total } H_2 \text{ production./yr} = 0.25\text{(m}^3\text{/kWhr)} \times 55249\text{x}10^6 \text{ (kWhr/yr)} = 1.381\text{x}10^{10} \text{ Nm}^3\text{/yr} \quad (3)$$

which possesses the same calorific energy as 3.34 million tons of heavy oil. Moreover, H_2 energy is converted to electricity in a fuel cell much more efficiently than the burning of fossil fuels to produce electricity through a thermodynamic cycle, and hence it is expected to replace a considerably larger amount of crude oil and/or equivalent natural gas.

The Proposed Strategy

The proposed future strategy for large scale power generation in Egypt is to apply *all* economically viable wind resources to generate electrical power. The fraction of the electrical power produced within the allowable penetration limits will be transmitted directly through the unified national electrical grid. The remainder of wind power, say 80% would be employed to yield hydrogen fuel through electrolysis, which would then be used as a direct replacement to fossil fuels, in addition to it's other conventional uses, such as the chemical and related industries.

The electrolysis could either be performed at the wind farm site or elsewhere making use of the available electrical grid to conduct the electrical energy from the WECS to the remote electrolyzers. If produced on the wind farm sites , hydrogen could either be stored locally and called upon to fuel cells to supplement WECS output at low winds, or it could be carried through a network of pipes to the consumption centers where it would be employed to fuel cells to generate electricity, or used for other applications.

In effect hydrogen generated by electrolysis would behave as a cost effective storage medium for the fluctuating wind energy enabling the electrical power network to control it more reliably and thus increase its dependence on it, in addition to providing a mobile storage medium for mobile applications like vehicles.

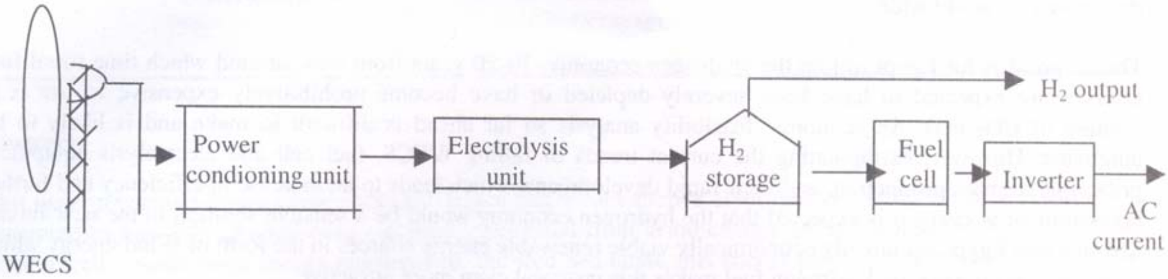

Fig. 3 WECS design with hydrogen storage

For remote areas not directly connected to the electrical grid and for which wind energy resources are attractive such as East Oweinat[10], a relatively small stand alone WECS may be employed to generate electrical power. When there is a surplus of power generation over demand , the surplus will be employed to generate hydrogen and store it locally; when power generated is less than demand, the stored hydrogen would be called upon to overcome the deficiency employing fuel cells. In addition, hydrogen stored in a portable medium may be employed to fuel tractors, vehicles and other equipment; such a system was examined in detail for farm and rural use[11], and is sketched in Fig. 3 .

Environmental Impact

Hydrogen generation by electrolysis whose energy is derived from a WECS is practically pollution free; so is it's reaction in a fuel cell to generate electricity. If, as the case is here, hydrogen fuel is used to replace fossil fuels it offsets various harmful emissions which harm the environment[12]; it also reduces the risk to marine life and contamination of the coasts due to the transport of crude oil in ship tankers. When displacing nuclear power stations, a future option for Egypt, hydrogen offsets 3.641 tons of nuclear wastes/GWh for which to date there is no totally safe way of disposal.

The only negative impact worth considering is the killing of birds due to the rotating Wind turbine blades; however, the numbers actually killed flying through the rotor blades are considerably less than those killed by the adverse effects of pollution introduced by the conventional sources of energy it replaces. If a full fledged hydrogen economy is operational, high voltage power lines, a notorious large bird killer, will be replaced by hydrogen pipelines which do not harm birds in anyway.

Summary and Conclusions

Egypt possesses excellent wind energy resources in the red sea area which are economically viable , however only a fraction of this energy may be introduced directly into the unified national grid due to the penetration limits set by the utility; this limit is due to the intermittence of the source. Thus, currently the majority of Egypt's energy needs are met by burning fossil fuels which increase the pollution levels of the major cities to above the permissible norms. Moreover, Egypt's natural reserves of fossil fuels are being depleted at an alarming rate. The solution to both the future energy demands and pollution prevention lies in the adoption of a

Hydrogen economy in which Hydrogen fuel is generated by WECS , exploiting the full wind energy potential of Egypt. An analysis of the potential of a 250m long and 20 km wide stretch of the Red sea coastline shows that with current WECS and electrolysis technology , WECS erected in this area could produce up to 1.381×10^{10} m^3/yr of hydrogen at N.T.P . This is an energy source with zero harmful emissions and has been predicted to be the future fuel world wide.

The proposal is for Egypt to join the Hydrogen economy 10-20 years from now, around which time fossil fuel reserves are expected to have been severely depleted or have become prohibitively expensive to use (e.g. because of CO_2 tax). An economic feasibility analysis so far ahead is difficult to make and is likely to be unreliable. However, extrapolating the current trends of falling WECS, fuel cell and electrolysis equipment prices due to mass production, and their rapid developments which leads to an increase in efficiency and further breakthrough in costs, it is expected that the hydrogen economy would be a sensible solution in the near future. The fact that Egypt has already economically viable renewable energy sources in the form of Wind energy which could be used to generate Hydrogen fuel makes this proposal even more attractive.

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