Gone with the Wind: Upgrading North Africa's Trade Wind-induced Phosphate footprints into carbon-free fertilizers.

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Host of COP22, Morocco, is amongst a group of 48 countries that have committed to meeting 100 per cent domestic renewable energy production. United within the Climate Vulnerable Forum (CVF), the country is committed to strive to meet 100% domestic renewable energy production as rapidly as possible while working to end energy poverty, protect water and food security, taking into consideration national circumstances. In the case of Morocco which closed in 2016 the world's most competitive 850 MW wind tender at 27€/MWh, these commitments bear a rather global dimension aimed at de-carbonizing an entire span of its economy. At its origins are the planetary trade winds. Generated by the earth's equator-to-poles temperature differences combined with the earth's rotational Coriolis force, they stir clockwise circular air movements over the North Atlantic. Ever since their apparition some 70 Million years ago, their friction over the Ocean surface generates a large current referred today as the Gulf Stream. Simulation from paleontological maps during the Eocene and Paleocene period identified a narrow bottleneck where these currents met with the wider, yet forming Indian and Pacific Ocean bodies of water. Ensuing current upwelling contained between the emerging Iberian and North African land masses led to an accumulation of plankton which attracted a very rich biotope. Composed in majority of the remains of large sea predators such as sharks and rays collected over a period ranging from 70 to 40 Million years, Morocco's phosphates plateaus concentrate about 72% of the world's known sedimentary deposits. In addition to their paleontological fossil footprints, today's prevailing trade winds achieve record-high capacity factors at the 50MW Foum el Oued wind farm located on the Sahara coastline. As it supplies 95% of the energy consumed by OCP's Phosboucraâ facility, a unique opportunity arises to dissociate phosphates in upgraded fertilizers from fossil fuels. Besides thermal processes, similar electro-intensive Hydrochloric-acid wet base phosphoric acid production plants co-generate hydrogen, the main feedstock in Ammonia synthesis. Local de-carbonized upgrades of phosphates into fertilizers generate higher added-value and consistently improve resource transformation efficiencies. Critical for its operational balancing, these processes can sustain the phased deployment of the Sahara Wind project's 5 GW High Voltage Direct Current transmission line. Needed to supply remote North African load centers at record-low wind-electricity costs, this interconnecting infrastructure will also enable green electricity surpluses to be exchanged with regional markets in Europe and sub-Saharan Africa.

Keywords: Sahara, Trade, Winds, Phosphates, Electrolysis, Hydrogen, Fertilizer, HVDC

I- The origin of the world's largest Phosphate deposits

Through intense solar radiation effects over the equator, heated air masses rise into the upper layers of the atmosphere. A natural convection effect draws this air towards the earths' pole's colder temperatures. The planet's rotation and its resulting Coriolis force turn these air masses clockwise in the northern hemisphere. This happens at around 30° of latitude over the Atlantic Ocean. Upon cooling and sinking down, a high pressure area (called Anticyclone) centered over the Azores Islands is created.

Driven by temperature differences on a planetary level and deviated by its rotation the perpetual clockwise circular winds over the North Atlantic are referred as the "trade winds". The name comes from their moving trading vessel fleets across the Atlantic Ocean during the age of sail. Unlike local winds influenced by the earth's topography, trade winds are global, planetary winds.

Ever since their apparition some 70 Million years ago, their friction over the Atlantic Ocean's surface consistently generate large currents which follow a similar path. Referred today as the Gulf Stream, these are responsible for northern Europe's milder climate.

As they are moved by planetary winds, Gulf Stream currents are independent from climate cycles. Their effects can therefore be consistently tracked through geological sedimentary deposits resulting from their occurrence some 70 to 40 million years ago. During this paleontological time-scale referred mostly as the Eocene epoch, trade wind induced currents pushed large quantities of planktons towards the forming North African coast.

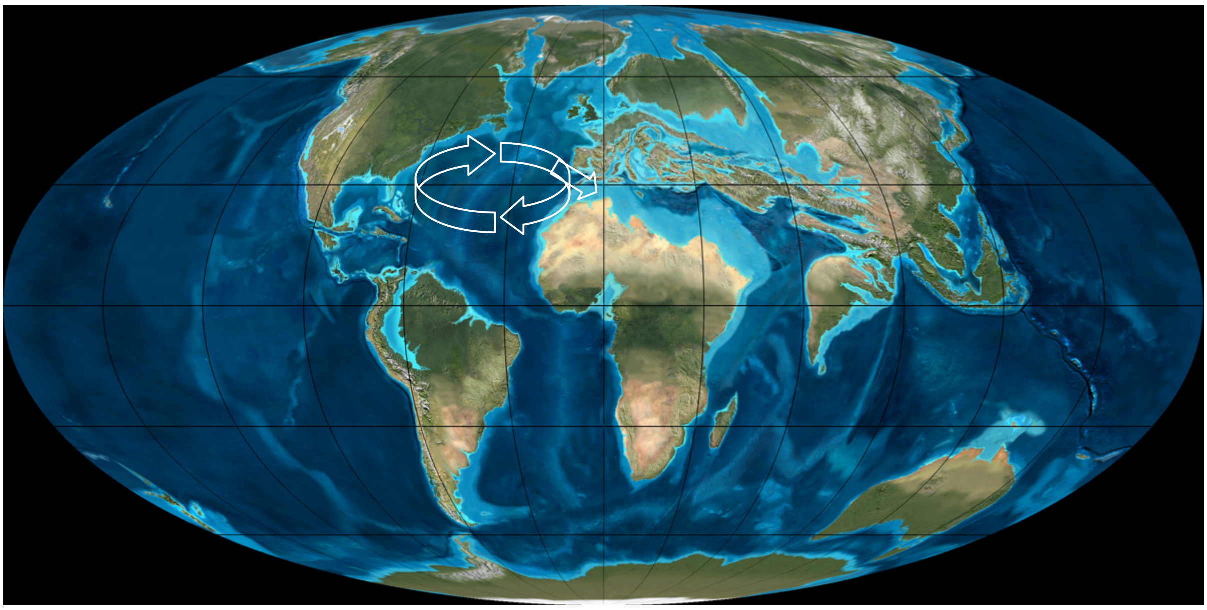

Figure 1: Trade Wind-induced currents over Earth's Map 50 Million years ago (Eocene Ypresian epoch) [1]

Simulation from paleontological maps (Figure 1 & 2) during the Ypresian & Priabonian Eocene epoch period identified a narrow bottleneck where these currents slowed and split upon meeting the wider, yet forming Indian and Pacific Ocean bodies of water. Ensuing upwellings contained between the emerging Iberian and North African land masses led to a substantial concentration of plankton which attracted a very rich biotope. The accumulation of mostly of Chondrichthyes remains (large sea predators such as sharks and rays that were active in this area), collected over a period spanning from 70 to 40 Million years benefited from good conditions for their subsequent phosphatisation. Today, they represent about 72% of the world's known phosphates sedimentary deposits [2]

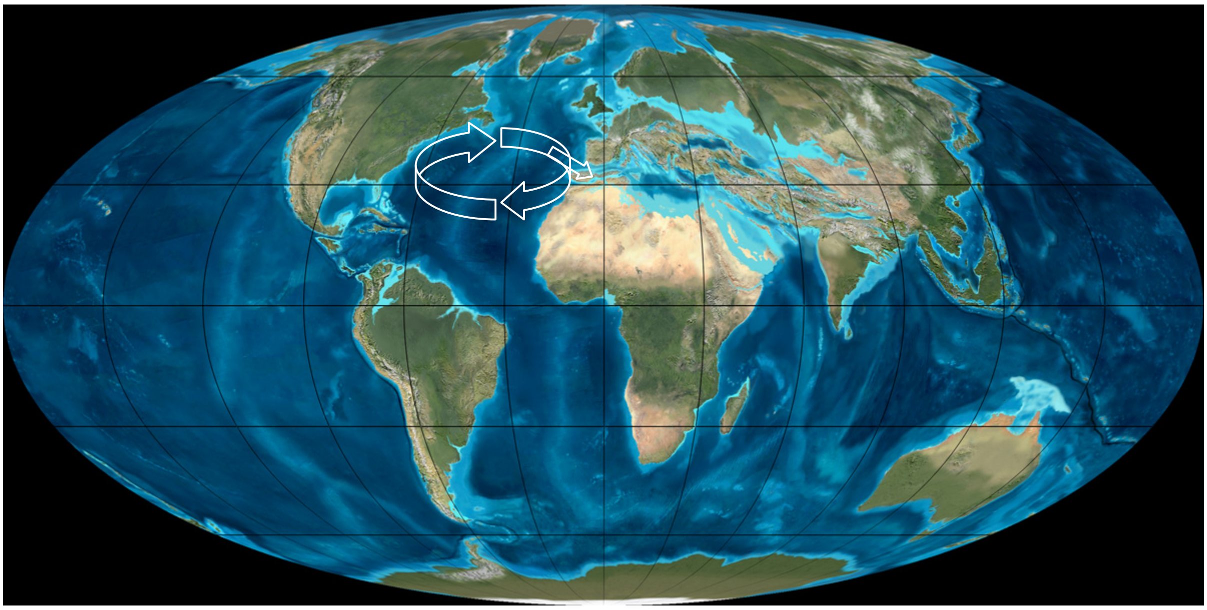

Figure 2: Trade Wind currents & Plate Tectonic Map 35 Million years ago (Eocene Priabonian epoch) [3]

Submerged during most of the Paleocene & Eocene Epoch, as illustrated by yellow triangles on the map over the mining sites of Khouribga, Benguérir, Youssoufia and Boucrâa, Chondrichthyes remains kept accumulating on a shallow sea floor. The deposition of these phosphate-rich remains in marine environments led to their sedimentation and subsequent transformation into Phosphorites.

Located inland today, the sites identified by triangles on Figure 3 below, represent the largest commercially mined phosphate-rock deposits available worldwide.

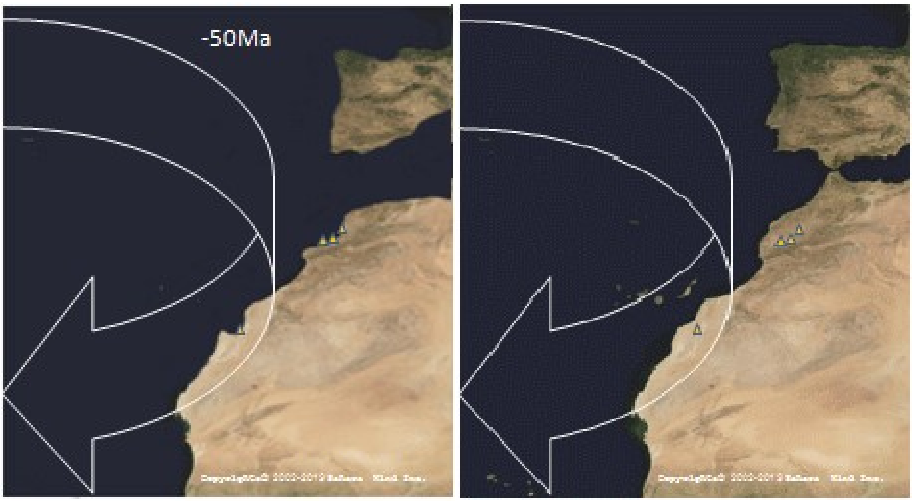

Figure 3: Trade Wind currents & phosphate-rock deposits 50 Million years ago (left) vs actual sites (right)

Used essentially in the production of fertilizers, their processing into higher value-added derivatives requires the transformation of Phosphate rock into Phosphoric acid. As Ammonia, synthesized through energy-intensive processes is also needed in the formulation of fertilizers, an unprecedented opportunity arises to take advantage of the trade winds.

II- Processing the planet's largest phosphate reserves

II.1. Renewable ammonia from phosphates fertilizer upgrades to substitute imports

Morocco holds the largest export market shares of global phosphates rock and phosphoric acid. Producing the latter via common wet-base sulfuric acid processes relies on Sulfur which needs to be imported. Besides these, Morocco's state-owned Phosphate conglomerate –Office Chérifien des Phosphates (OCP Group) - which supplies 20% of world fertilizers, needs to import significant amounts of Ammonia.

Steam reforming of hydrocarbons to extract Hydrogen in order to combine it with Nitrogen picked from ambient air which is made of 78% dinitrogen (N_2), is the most frequently used path to generate Ammonia (NH_3). In terms of global figures, over 95% of the Hydrogen needed as feedstock in the 140 million tons of Ammonia produced each year comes from fossil-fuels (coal and natural gas). This Ammonia synthesis absorbs over 2% of the world's global energy demand. As fertilizer industries - essential to world food security- represent the main end-uses for Ammonia, developing cleaner more sustainable ways to generate Hydrogen is critical. As chemical feedstock in ammonia synthesis, hydrogen can also be used as an energy carrier to stabilize and store intermittent renewable energies (such as wind) in a power grid. Indeed fuel cell technologies enable hydrogen to be converted into electricity in stationary as well as mobile applications. The latter can be hybridized to extend electro-mobility applications or be used exclusively as a carbon-free ground transportation fuel using existing fuel cell vehicles currently in the market. Coupled to Morocco's phosphate-based fertilizer industry where it is used as feedstock, wind-electrolysis generated Hydrogen can therefore play a constructive role, in today's broader energy transition.

A recent paper from the Renewable Energy Division of the International Energy Agency [4] has assessed the production of ammonia and fertilizers from new renewable energy technologies such as solar & wind. Their recent cost reductions, makes large-scale ammonia production plants based on water electrolysis competitive in areas with world-best combined solar and wind resources. Morocco represents one of these cases.

According to the paper's simulation, a 500 000 t/y Ammonia plant fed by 785 MW of Wind Capacity at 4000 Full Load hours backed by Solar PV cells to ensure continuous operations for a 735 MW electrolysers array generates Hydrogen at costs below 2$/kg. This is competitive w fossil fuels.

II.2. Phosphoric acid and Ammonia: a Hydrochloric acid wet-base process

As hydrochloric acid (Hcl) can substitute sulfuric acid in the wet process preparation of phosphoric acid, new synergetic changes are also possible. The production of hydrochloric acid -a mix of Chlorine and water- requires no other feedstock but earth's most basic elements; namely water and salt (NaCl) mixed in brine where electrical currents are applied. With the availability of cheap wind-electricity, Chlorine can be co-generated with hydrogen in addition to caustic soda as by-products in the Chlor-alkali electrolysis process. Whereas Chlorine can substitute Sulfur and sulfuric acid in the production of phosphoric acid, co-generated electrolytic hydrogen -used as feedstock- can be transformed into ammonia. This endogenous process replaces fossil-fuel based sulfur and ammonia imports in the production of fertilizers. Considering the extraordinary scale of the region's phosphate and trade wind resources, other synergetic processes can be derived as well. Prices for phosphate rock, sulfur and ammonia, the primary inputs for the production of phosphate fertilizers, fluctuate significantly. When rock prices more than tripled from 2005-2010, this resulted in higher production costs for approximately 30 percent of global producers that relied on purchased rock. Since phosphates rock prices historically follow costs of non-integrated producers, higher costs provide good margin opportunities for producers with their own supply of rock [5].

II.3. China's sustainability considerations in Morocco's fertilizer industry

Sulfur price increases created conditions for the resurgence of other phosphoric acid production alternatives such as the electro-thermal processes. A few decades ago, the nature of energy production in China largely based on hydroelectric generation at a local level, supplied inexpensive power to phosphoric acid plants. Since thermal acid production is very energy intensive, this advantage has been decisive in China's large thermal phosphorus production capacity. Today, the country's significant wind capacity additions of over 20 GW/year since 2010 (37 GW in 2015) comes with non-negligible grid stability issues. Coupled to Solar PV additions, the intermittency of new renewable energy generation can indeed be balanced by the scale of China's energy-intensive industries. Intermittent wind energy generation is favorably predisposed in powering China's fertilizer industries, the worlds largest. Relying on coal feedstock, they are also the most polluting.

While a comprehensive analysis will shed some light in an increasingly resource constrained world, the development of patents and technologies on processes to open these opportunities is of paramount importance. As highlighted during OCP Groups comprehensive R&D meetings with industry [6] and academia [7], China maintains the lead in the numbers of patents around phosphates processing. Outmatching several times Morocco's export processing capacities, and although lacking reserves, China is the world's largest player in phosphates industries. Aimed at sustaining high agricultural production through intensive fertilizers use, export tariffs are at times applied, to secure adequate supplies of its competitive domestic market. By consuming one-third of the world's ammonia China is also its largest producer. With a heavy reliance on coal, China's case-study may be indicative on how strategic renewable energy-intensive industrial processing combinations will be in the future. The country's wind energy leadership is unprecedented, as is its pledge to curb global emissions in meeting its ratified Paris agreement objectives.

III- Morocco's wind portfolio already linked to phosphate industry

On the Sahara coastline, the processing of phosphate rock for exports -namely its screening, conveying & washing- is mostly powered by wind-electricity. Over 554 MW of Morocco's current 891 MW of installed wind capacity operates on the Atlantic trade wind-blown Sahara coastline. Besides urban load centers such as Laayoune and Boujdour that are supplied by wind-electricity, the bulk of the region's electric loads consists in reverse-osmosis desalination plants.

Figure 4: Phosphate rock conveyor belt adjacent to a 125 kV power line near Phosboucraâ

As wind generating capacities exceed by far the region's loads, an opportunity for local electricity-intensive phosphate rock upgrades into fertilizer becomes economically viable. Morocco's Renewable Energy Law 13-09, enables wind-electricity to be wheeled directly to industrial end-users. The Phosboucraâ phosphate rock export terminal is for that matter already powered by several wind farms. One of which, the Foum El Oued 51 MW wind farm (Figure 5), is in fact event even adjacent to it.

Figure 5: Foum El Oued Wind farm Turbines over Phosboucraâ export terminal (in the background)

Provided that extensions of the 1.2 Billion USD fertilizer plant under construction at the Phosboucraâ terminal (Figure 4) can be powered by wind energy, an ideal setting arises for the carbon-free upgrade of phosphates into fertilizers. This investment includes an integrated chemical complex aimed at producing a broad range of fertilizer products with high flexibility to respond to changes in market pricing for raw phosphate rock [8].

By scaling-up wind generation capacities and facilitating their absorption in the region's weaker grids, flexible electro-chemical processes will be essential in the operational balancing of the Sahara Wind project's large HVDC line infrastructure.

Morocco imports 96% of its primary energy needs through fossil fuels. Upon hosting UNFCC COP22, and as part of its Nationally Determined Contribution, the country pledged that 52% of its power generating capacity will come from renewable by 2030. From projects under construction, its 2.5 GW wind portfolio already exceeds its 2GW listed 2020 target. This outmatches the country's significant 2 GW solar power objectives as well. With a local industrial integration that could reach up to 70% of total project value, achieved through one of the world's lowest wind energy tender at 27€/MWh, the region is set for a promising future. Indeed, Morocco's latest 850 MW integrated wind energy tender won by a consortium which includes Siemens wind energy [9] already encompasses a local integration of both wind turbine blades [10] and tower factories.

IV- Conclusion: towards 100% renewable energy

Pooled to Morocco's phosphates industries, the value-added processing of Mauritania's iron-ore deposits into steels referred to in Sahara Wind's previous publication [11] is likely to support a major deployment of renewable energies. As electricity demand grows from 6 to 8% per year in Morocco [11] and Mauritania the region's electricity consumption may be quadrupled within 20 years. Besides improving local access to wind-electricity, the Sahara Wind project High Voltage DC line will enable the transfer of substantial amounts of cost-competitive green electricity to North African load centers. Located over 1200 km away, this HVDC infrastructure will be indispensable to cover North Africa's growing electricity needs. Powered by cleaner, more competitive sources of electricity, the region will be able to transition into a low-carbon path and sustain its economic development.

As Morocco is separated from Europe by the 14 kilometer-wide strait of Gibraltar which includes several electrical interconnections, the Sahara Wind Project's HVDC transmission line will also enable excess intermittent wind power flows to be exchanged with the Iberian Peninsula. The export clause of Morocco's renewable energy law 13-09 and the European Union's Article 09 Directive for meeting the 2020 renewable energy targets, allow these exchanges. Within such context, Morocco's COP22 endorsed commitment to reach 100 % renewable energy in the nearest future seems achievable [13].

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