Scrubbing the ocean of CO2, nature's way

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Abstract

Earth is facing an existential crises like none we have ever witnessed. This is not simply a matter of global warming which is a dramatic understatement of the seriousness of our problems. Potable water and food are as serious a problem as the implications of global warming. Here we propose a multi-tasking plan to solve all of these problems. As shown in Fig. 1 the proposal looks at the thermodynamic alternatives to separating ocean water into its 96.7% potable water and 3.5% salts. Figure 2 outlines the five processing steps proposed to convert the sea water into potable water with the sun as the sole source of thermal energy. One of the side components of this proposal is to bring together university faculty and students.

1 Introduction

Our basic concept is to cheap desalination of ocean water to generate large quantities of potable water, solving today's the water crises. The water will be used to grow plants (trees, grass, food, etc.) on a massive scale. The long term goal is to replace our many arid deserts with jungles, returning them to an earlier (e.g., 200,000 years ago) state. Given sufficient plant life, the CO2 will be absorbed naturally. Given enough water, this is a feasible long term plan, but will take at least several decades before this can be functional.

In the mean time we need to directly deal with reducing CO2 in the ocean, where it is doing the greatest damage. This is a distinct second step, to separate the dissolved CO2 in the water and reduce the carbon to an inert form, such as limestone or even pure graphite.
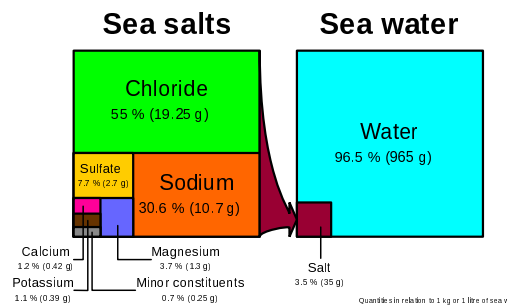
Much of the trapped heat and CO2 is due to our increased burning of fossil fuel over recent centuries, has been absorbed by the oceans and reflecting surface heat as the most important greenhouse gas. This has obscured our awareness of the severity of the problem, but at the same time lowered the PH of the ocean. Presently the PH is 8.1.[1] While the ocean is base, acid rains and absorbed CO2 have severely lowered the PH, causing the destruction of the coral, which is critical to life and diversity in the ocean. Life on earth is critically dependent on a healthy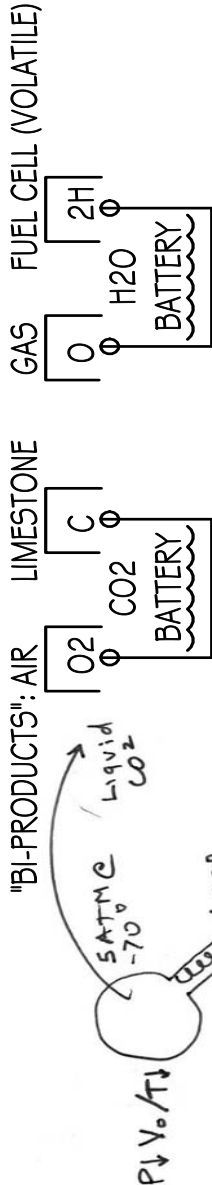 ocean. Thus besides desalinating ocean water, we need to concentrate the CO2 so that it may be reduced and converted into one of several possible inert compound substances, such as graphite and oxygen, or perhaps better, limestone. If we removed all the potable water from ocean water, only salts of various kinds would remain. This is what happens in existing salt ponds.

Figure 1: *Sea water is 96.5% H20 with NaCl being the largest contaminant.*

The driving principle for doing this is energy efficiency. Is it possible to do this using only solar and wind as sources of energy with close to 100% utilization and efficiency? This is the goal of our proposal.

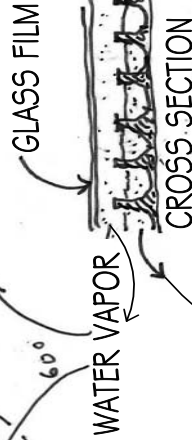[1]I'm told that somewhere between 8.2 and 8.3 is ideal. Neutral is 7.

Figure 2: *Process diagram showing the five different proposals for converting sea water into pure water and liquid CO2, to prepare it for electrolysis to split it into O2 and graphite, or alternatively limestone. Also shown is the electrolysis of H2O to split it into 2H and O2. This figure outlines the 5 PROCESS SYSTEMS (PS) required to convert the ocean water into potable water and various salts. After most of the water has been removed the remaining 3.5% of ocean salts are extracted from the water as a solid and broken down into their various components, by one several possible PSs, as outlined in the proposal. The extraction of the CO2 is the most expensive step because Ca is a highly reactive element, thus the most difficult to purify. It is also only present in trace amounts (300-400 [ppm]). There are biological systems that naturally extract Ca from water, such as clams.*

2 A specific proposal:

Our proposal is presented in Fig. 2. On the far right ocean water is piped in and fed to an aqueduct, which we call an *aquipure*, denoting a conduit used to extract pure water and then concentrate and reduce the dissolved CO2. This aquipure is slightly angled, so as to gravity–feed the water inland. Wind farms could provide the electricity to run the pumps. Once available systems are prototyped, it would be replicated on a massive scale, creating thousands of fresh water lakes and jungles.

There are numbered *process systems* (PS) indicated in the diagram labeled as `PROCESS SYSTEM #N` with $N = 1, 2, \cdots, 5$. Process System #1 (PS-1) delivers the ocean water to the aquipure, shown in PS-2 is the heart of the desal system, where the ocean water is heated by the sun's radiant energy (solar heat), raising the water temperature causing it to evaporate. PS #4 shows a cross-section of the aquipure operation, with corrugated channels to transport the ocean water and the saturated air above it. PS-4 further describes the inner workings of the system, for extracting the desalinated water, leaving behind the sea salts and CO2. A few centimeters above the water surface is a film (e.g., a transparent layer) to contain the evaporated water vapor.

On the right and slightly above the aquipure is the sun, which is the energy source to heat and thus evaporate the sea water. The ideal strategy is to raise the humidity to 100% within the air space between the water surface and the cover sheet. As shown in Fig. 3, 100% humidity at 94 [°F] corresponds to 5% [kg/kg] water vapor. By dropping the temperature to 59° the humidity drops to 1.5%, yielding 3.5% desalinated water. If the humid air is reduced to 39 [°F] the humidity would drop to 0.5%.
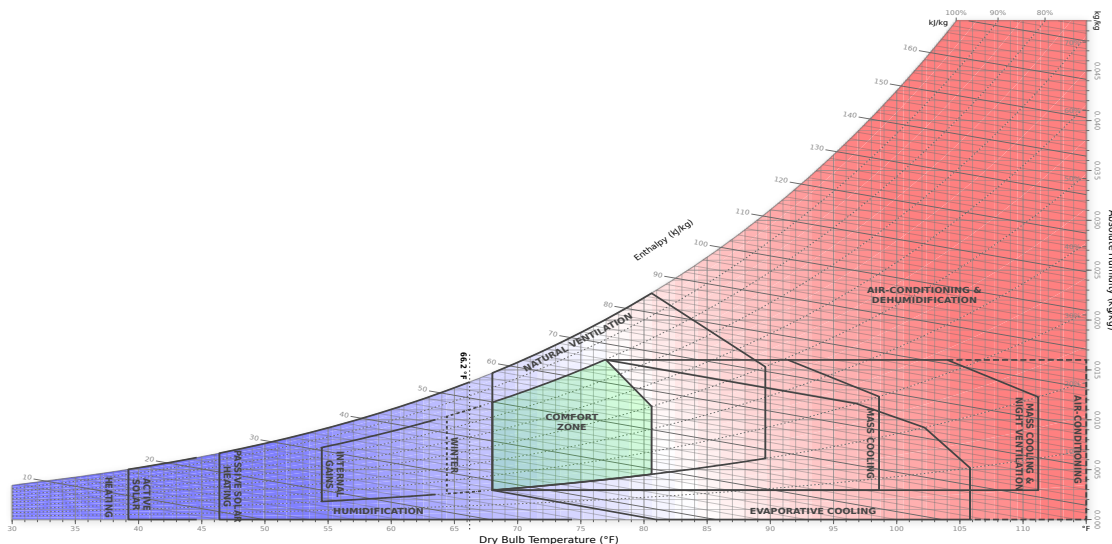

Figure 3: *This psychometric chart provides the quantitative relationship between the temperature, humidity, the vapor pressure and dew-point (Ambaum, 2010). For example (see upper right corner of chart) given a dry–bulb temperature of 105 [°F] (40 [°C]) and a relative humidity of 100%, the absolute humidity is 50 g/kg (5.0%). If the temperature were to drop to 38 [°F] (3 [°C]), the humidity would drop to 5 [g/kg] (0.5%). This would release 50-5=45 [g] of water per [kg] of air, or 4.5% of the air mass in water. The real question is, how fast can this reaction take? The answer depends on the power input from the sun required to keep the air temperature at 105 [°F], as the humid air is removed from the vessel, to be replaced from the liquid water surface. Namely, how fast can the humidity return to 92% as it is passed to the chill–plate at 38 [°F] and replaced by less humid air? Based on this chart, it is a table-lookup to find the ratio of input energy [Joules] to water recover ratio [g/kJ] via the enthalpy, which at 92 [°F] is 41 [kJ/kg]. Ref:* `https://drajmarsh.bitbucket.io/psychro-chart2d.html`.

This water vapor is then sucked down through small holes in the ducts, where it meets a cold plate, having a high heat capacity and thermal conductivity. When the water vapor comes in contact with the cold plate, the dew point is met and the water vapor turns into liquid water, where it is collected, and by gravity, transported to the fresh water lake (PS #3). As it is cooled the heat is used to pre-head the cold seawater feeding the aquipure. Thus in theory no heat is lost in this process.

This low temperature for condensation could, in theory, be obtained from 1) cold ocean water that has not been heated by the sun, via 2) heat pump buried deep in the earth, or by 3) electrically driven air conditioning. These various methods have different efficiency limitations, thus are not equivalent. In the case of the air conditioner, the heat expelled from the AC unit could be used to further heat the water, somewhat raising the net efficiency.

For this system to convert sufficient water/hr, the humidity needs to be close to 100% and be a continuous

process. Misting the water above the aquipure can increase the rate of evaporation which is mainly a power-driven process. Work needs to be done to determine the efficiency of the water-vapor creation rate. Of course sun-based evaporation is how rain is naturally made. Natural atmospheric pressure and temperature variations (i.e., a cold front) trigger the release of the vapor to liquid water. This is all well know, and is the main source of our fresh water. However this process is not under our control, and happens somewhat randomly, leading to long periods of drought. Figure 2 is envisioned to give us precise control of this natural process.

All public desalination systems use reverse-osmosis, which requires large amounts of electricity. There is research on using evaporation, but I do not know the status of such proposals.

In the case that supplementary electricity (e.g., for night) is needed, we may need a type of nuclear reactor technology, presently under development called *small modular reactors* (SMR). The claim is that this new technology solves many of the problems of older technology. For example SMR is claimed to be 100% free from melt-down incidents due to the use of molten salt rather than water, as a coolant.

2.1 Water vapor evaporation rate

Here we discuss the theory of water evaporation based on radiant energy from the son as the soul source of input energy. The theory behind this is outlined in most books on atmospheric science (Ambaum, 2010). The best source I have found is Sommerfeld (1954). Two relations are needed, 1) the water temperature when heated by the sun and 2) the mass of water evaporated as a function of the water temperature. The radiation from the sun must first heat the water to temperature T [°C], which results in the creation of water vapor above the water. The amount of water vapor is determined by the vapor pressure, which depends of course on the pressure. Assuming the air pressure is one atmosphere, one formula for the vapor pressure is given by *Tetens' formula*, which is an empirical approximation to the vapor pressure

$$e_s = ae^{bT/(T+c)} \qquad [\text{Pa}]$$

where the constants are $a = 611.2, b = 17.67$ and $c = 243.5$ where T in in °Celsius (Ambaum, 2010, p. 98), and the value for the latent heat L is

$$L = L_o - (c_{pl} - c_{pv})(T - To)$$

with $L_o = 2.4$ [MJ/kg] and the heat capacity at constant pressure as $c_{pl} = 4.18$ [kJ/kg-K] at $T_0 = 25$ [°C].

Of importance is the large ratio of the latent heat and the specific heat capacity

$$\frac{L}{c_p \Delta T} = \frac{2.4 \times 10^6}{4.2 \times 10^3 \Delta T} = \frac{600}{\Delta T} \approx 24,$$

because this shows that most of the sun's solar radiation goes into the conversion of water to vapor, once it has been heated to the maximum temperature (i.e., 90°) to the evaporation process. The above numbers a approximate and depend on the two working temperatures temperatues. Thus to recover the desalinated water it is essential to use the cold sea water to cool the vapor, so the design of the heat exchanger is critical Wang et al. (2019).

During this process it is critical to use the heat stored in the vapor to pre-heat the cold sea water. If this is not done efficiently then most of the solar energy would be lost, making the entire process extremely inefficient. Thus of key important is how this pre-heating must be implemented to assure an efficient process. To the extent that there are no parasitic heat leaks to the environment, all of the vapor's latent heat may be recovered during the cooling process. This pre-heating of the cold sea water will greatly boost the temperature of the cold sea water because most of the energy is in the vapor's latent heat. The final increase from the pre-heating to the final temperature before the cooling of the vapor, will take the water from the pre-heated to final working temperature. This temperature determines the percentage of water vapor per kgm of sea water according to the Clausius-Clapeyron equation as described next.

At the surface of the earth the solar constant is $P_{\text{sun}} = 1.3$ [kW/m^2]. The specific heat of water $L_e = 4.186$ [J/gm °C] is defined as the energy required in Joules to heat 1 [gm] of water by 1 degree [C]. Namely the temperature increases by 1 degree at a rate of P_{sun}/L_e [kJ/s m^2][kgm °C/kJ] =1.3/4.186 [kgm °C/s m^2], or about 31 [gm] (1/3 of a kgm) per second per square meter of maximum (overhead) sunlight.

To heat the water by Δ_C [°C/s], we must divide by that amount to determine the output water mass Δ_w:

$$\Delta_w = P_{\text{sun}}/(L_e \, \Delta_C) \; [\text{s/C°}][\text{kgm °C /s m}^2] = 1/(3.49 \, \Delta_C) \; [\text{kgm/m}^2]. \tag{1}$$

As the change in temperature Δ_C increases, the water production output (rate) decreases. In other words for every square meter of sunlight the temperature rise will be 1/3.22 [°C/s]. To raise 1 kgm to 95 [°C] starting from 70°would take $\Delta C P_c/L_e = (95 - 70)/3.49 = 8.16$ [s].

Several classic laws are evoked such as the phase rule of Gibbs, Dalton's law and the Clausius-Clapeyron equation. A combination of these results gives the partial pressure of water vapor in air $e_s(C)$ as a function of the temperature of the water C°

$$e_s(C) = 6.112 \exp\left(\frac{17.67C}{273.5 + C}\right) \quad \text{[hPa]} \tag{2}$$

C is degrees Celsius (Ambaum, 2010, p. 98), and $P_o = 1$ [atm] $= 10^5$ [Pa] $= 1000$ [hPa].

A rapid (adiabatic) cooling of the water vapor causes a condensation of the water vapor, releasing the vapor as water in the amount $L_e dq$ where dq is the amount of water vapor condensed (Peixoto and Oort, 1992, pp. 52-54).
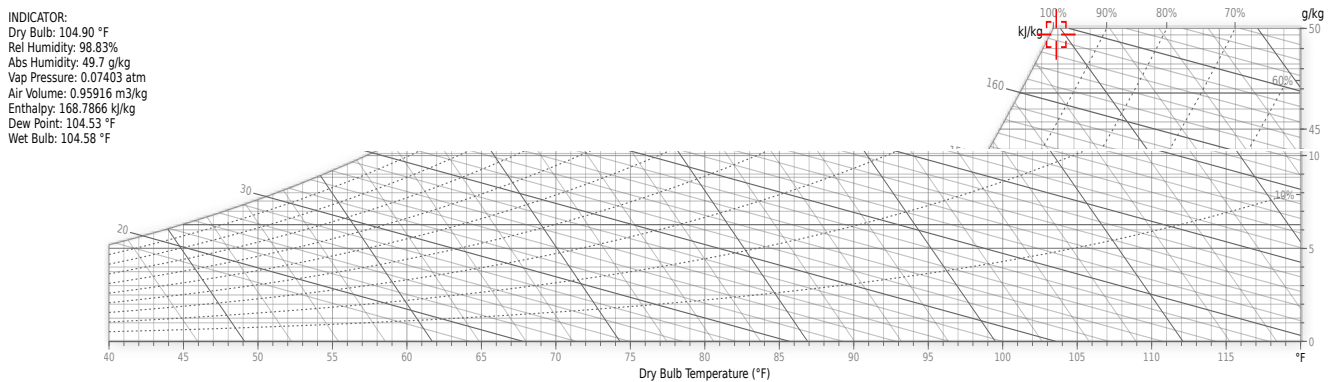

Figure 4: *This version of the chart from Fig. 3 expands the top and bottom portions, for improved readability. The axes for the two figures are the same, only the middle portion of the chart has been removed. The bottom axis is the dry-bulb temperature, from 40 to 120 [°F]. On the right most ordinate is the absolute humidity in [gms] of water vapor per [kgm] of water. The top-left axis is the relative humidity, from 100% on the left to 60% on the right. The the cross-hair values are given the text in the upper left corner of the chart which marks 50 [g/kgm] (5% of water vapor water mass).*
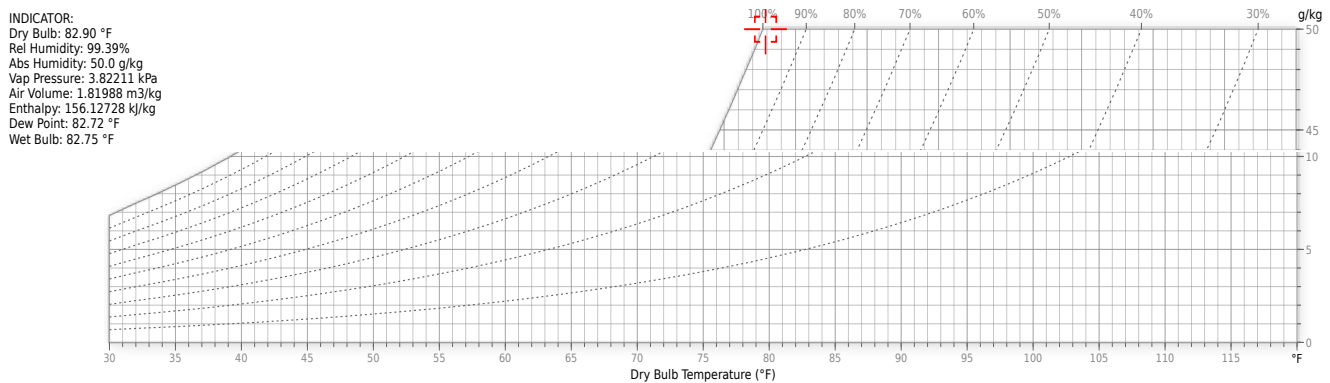

Figure 5: *Note the same saturated water vapor production rate of 50 [gm/kgm], but at the much lower temperature of 80 [°F]. The difference is the much greater vapor pressure (3.8 [atm]), vs. Fig. 4 where it is 0.074 [atm].*

2.2 CO2 scrubbing:

The last step (PS-4) in this process is scrubbing the CO2 from the brine. Note that if we are successful in creating many jungles from arid regions, this step is not necessary, once the jungles have matured. There are some considerations prior to purging the CO2:

1. The ocean is 96.5% pure water and 3.5% salts. If a large percentage of this wather has been removed as potable water, for sake of argument, say 75%, the remaining volume would be 25% and the concentration would increase by four times, to 15%. The exact percentage of residual CO2 is presently unknown, and needs to be determined experimentally. We assume it increases by four fold as well, from 0.400 to 1.5 [ppk] (0.15%). If it were possible to remove remove 7/8 water and 1/8 brine, the concentration would increase by 8 to 0.3%.

2. An alternative is to remove all the water leaving the 3.5% salts. Then using SMR technology (EPA, 2019) we can heat the salts to the melting point. Once the salt is a liquid it might be possible to use either fractional distillation to seperate the various salts, or electrolysis. These alternatives need further research. It is likely the answer is well known.

There a number of proposals to address this process:

There are several possible ways to remove the carbon from the CO2 enriched brine.[2] This CO2 enrichment process requires much more energy than the desal process since we must heat the brine to either (1) a gases state (boiling temperature)[3] (Milow and Zarza, 1997b,a) or (2) by removing all the water and converting the salt to a molten mass followed by a fractional distillation process to seperate the various elements.[4]

Assuming scenario (1), the liquid brine will be hot due, to the solar heating. For sake of argument, assume it is between 60 and 80 [°C] and 0.2% brine. The exact values are key experimental variables. This process is shown as PS-4, just below the words "Energy Turbine" in Fig. 2.

Once the brine is in the gaseous state the steam is highly compressed, raising the temperature, for example, to 600 [°C] (eight-fold increase in temperature). This high-pressure supper heated brine-steam could be used to drive a steam turbine to generate electricity, raising the efficiency of the overall process. Once cooled to atmospheric temperatures, the pressure is released, causing an eight-fold decrease in temperature, from 75 to 600°[F]. It is then further cooled to -70[°C] at 3 [atm], which is near the triple point for CO2. In this way the CO2 is converted to a liquid. It is assumed (and confirmed) that if electricity is applied to the liquid CO2, graphite will attach to one electrode (moving to remove the graphite deposit) and O2, which is saved or released into the environment.

The method of disposing of the salt needs to be described. There are a number of alternatives, including converting it to molten salt, mining the salt for valuable minerals and precious metals, or returning it to the sea to assure the ocean balance is not modified. In the third case we do not want to return the CO2 to the sea, so it must first be removed.

Hydrogen generation: A second electrolysis could optionally be used on the remaining water to produce Hydrogen, which could be used as the alternative to fossil fuel. When Hydrogen burns the byproduct is of course water, releasing the energy used to create it. This is believed be a relative efficient store of the electrical energy. The alternative would be batteries, but that is believed to be a more expensive technology (and much greater weight). This is a trade-off that must be further explored as an alternative fuel source.

Management of the aquipure: The aquipure will need people to manage it. This is not a minor detail, and could be a way to manage the serious problem of displaced people. Since this is not a scientific problem, it will not be further explored here. But such a source of labor has certain positive benefits, especially for the displaced individuals. It could, in theory, solve much of the world's homeless problem, which is as serious as the fresh water, energy and food shortage problems mentioned in the introduction.

How to proceed

The question is where do we go from this proposal? First we must submit a proposal to one (or all) of many possible funding organizations. Second we must convene a campus based conference for experts in the faculty in the many areas that are required to evaluate the proposal, including but not limited to Physics, Engineering, Atmospheric Science, Chemical and Molecular engineering. Even the business and law school might be needed. Graduate students must also be invited, and culled for their specialize talents.

There are a great many open questions that need answers, and the U of I faculty likely know, or at least know how to answer, many of these questions. There are many alternatives to the explicit proposal of Fig. 2, which need to be evaluated.

The motto that has been suggested for this grandiose proposal is

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[2]This step assumes that most of the CO2 stays with the brine rather than with the condensed water vapor. CO2 that escapes with the purified water are harmless to the desal process.

[3]Think what happens in a pressure cooker.

[4]Using proposed *Small modular reactor* technology.
https://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors

To be, or not to be, that is the question.

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