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Perspectives on the Relationship Between Water and Carbon

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Abstract. The global switch to energy sources that are more sustainable and less polluting than fossil fuels (particularly with respect to carbon dioxide emissions) seems to be inevitable given the current world situation. This switch is dependent upon local water resources and may also impact the global water cycle. Similarly, the effort to sequester carbon in the environment has both energy costs and potential long-term ramifications related to freshwater and marine resources and associated ecosystems. In an effort to increase the efficiency and reduce the negative impacts of new technologies, inventors and scientists are learning to mimic or emulate water in its natural settings.

Keywords: water, alternative, energy, carbon, sequestration, hydromimicry.

INTRODUCTION

The relationship between water and carbon is one that will impact many of today's critical issues. Anthropologist Peter Warshall noted that obtaining more water always requires more energy (usually supplied by fossil fuels) and that obtaining more energy always requires more water [1]. Recent attempts to exploit alternative energy sources, to sequester the carbon dioxide associated with conventional energy sources, and to increase our supplies of fresh water have been criticized on the basis of their sustainability, efficiency, environmental impacts, and long-term effectiveness. This presentation focuses on the tradeoffs between water quality/quantity and carbon reduction, as well as the implications of our attempting to control, rather than to emulate, natural processes in dealing with both water and carbon. Nature seems to prefer design and information, rather than materials and energy, in solving its challenges—perhaps we can learn to better mimic nature in addressing our water and carbon challenges.

Emerging energy technologies such as salinity batteries and wave or tidal power appear more sustainable and less water consumptive than are biofuels or conventionally produced hydrogen. Attempts to reduce concentrations of atmospheric carbon dioxide by pumping it into deep ocean basins, storing it in saline aquifers, or offsetting it with monoculture tree plantations pose risks and tradeoffs that are often dismissed. Methods of obtaining additional freshwater that require minimal energy inputs include rainwater harvesting, condensate collection, and even solar-powered desalination; however, interbasin water transfers, wastewater reclamation (treated to drinking water standards), and aquifer over-pumping are energy intensive. Emulating water in the design of everything from stormwater networks and wastewater treatment systems to fluid impellers and glacier grafts could save energy and reduce water demands. In attempting to address the global challenges associated with energy, water, and climate change, we should carefully evaluate the expanding array of short-term and admittedly desperate measures in terms of their potential to exacerbate, rather than to ameliorate, these challenges over the long term.

WATER AND ENERGY

Whereas converting the unusable byproducts of conventional agriculture into cellulose-based ethanol constitutes a green technology, its fuel yield is relatively low compared to that derived from using food crops such as corn, beets, and sugarcane [2]. Conventional production of bioethanol has the same irrigation (i.e., water) demands as growing food crops and the same potential to pollute both surface and ground waters with pesticides, herbicides, and fertilizers. Utilizing bioethanol as a fuel source requires either a conversion of the existing food crops (diminishing global supplies) or an expansion of the cultivated land under corporate agriculture (escalating water demand and pollution). Also, the considerable volume of water utilized for milling, hydrolyzing, fermenting, and distilling ethanol from either sugar-rich foods or fiber-rich plant material must be treated as an aqueous waste stream before it reenters the environment.

Besides the issue water pollution, there is an ongoing debate as to whether the total energy required to produce and transport bioethanol, as well as to clean-up its pollution, exceeds that gained from burning it in automobiles. Ethanol is a less efficient fuel than is gasoline (on a volumetric basis) and produces as much CO_2 when burned. On the positive side, combusting ethanol generates fewer air pollutants than does gasoline, and the carbon present in ethanol is derived from existing atmospheric CO_2, rather than from ancient petroleum reservoirs that contribute "new" CO_2 to the atmosphere.

Some analysts have posited that bioethanol may be better used as a feedstock for chemical processes, such as producing hydrogen gas, than as a motor fuel. In addition, growing crops specifically for biofuels in soils contaminated with radioactive elements (such as those around Chernobyl) has been proposed as a method to remediate contamination, because the distillation process separates radioactive elements from the bioethanol. This production of biofuels does not affect food supplies because the crops grown in contaminated soils are inedible; however, it does require the disposal of a radioactive residue.

The chemical modification of vegetable oils to biodiesel fuels requires a catalyst and heating, which transform the large, highly-branched molecules of the oils into smaller, straight-chain molecules that are optimal for diesel engines. While biodiesel is generally considered more environmentally friendly than is bioethanol (in terms of production processes and contributions to global climate change), it is a less efficient fuel than petroleum diesel and requires the cultivation of crops (not necessarily major food staples) such as soybeans, palms, or sunflowers from which the oils are separated. Oil separation and other preparatory processes for biodiesel require water, although not as much as those identified for bioethanol. Alternatively, certain species of freshwater microalgae produce oils appropriate for biodiesel, and the water in which they grow is suitable for multiple uses without any treatment.

Another suggested solution to the energy crisis is the use of methane gas trapped in frozen chunks of water known as clathrates. Methane clathrates are present on the seafloor along continental shelves and beneath the permafrost in polar regions. Methane produces less CO_2 than does either crude oil or coal when burned, and methane hydrates also yield freshwater from the ocean. Over the long term, methane hydrates would simply prolong a reliance on carbon-based fuels, but in the short term they could assist in our transitioning to renewable energy sources. Some proponents maintain that capturing this methane may be preferable to permitting the rising temperatures in oceans and permafrost regions to destabilize the clathrates and, thus, release methane (a more potent greenhouse gas than carbon dioxide) into the atmosphere. The latest method for extracting the methane from clathrates involves injecting them with carbon dioxide, which is sequestered on the seafloor as a result of exchanging CO_2 for CH_4.

Hydrogen gas is perhaps the most highly-touted of the alternative energy sources because it is a very efficient fuel and produces only water vapor when burned. Most hydrogen is produced from methane by reacting steam with natural gas. This process is not only energy intensive and dependent on water and fossil fuels; it produces carbon dioxide as a byproduct. Alternatively, hydrogen can be produced by green algae and by the combined efforts of two different types of bacteria that generate some of the nutrients and precursors required for their continued hydrogen production—an example of sustainability in the production of a renewable fuel. Photosynthetic green algae produce hydrogen gas using the visible portion of the solar spectrum, while certain photosynthetic bacteria simultaneously produce hydrogen gas using the near infrared portion of the spectrum. Discovered by Berkeley researchers, the process is not as simple as it first appears because the microbes must be switched between light and dark phases and the depletion or accumulation of certain gases and ions in the water can influence the entire process [3].

Besides hydrogen power, solar power is probably the most frequently suggested energy source for the upcoming decades. But how might a burgeoning solar economy affect local water demands? The answer appears to be that, for small-scale solar power generation, the greatest use of water is in manufacturing the hardware components. Large-scale solar power generating facilities require considerably more water. Some solar technologies, such as passive hot water heaters, depend on the direct heating of water and thus eliminate the requirement for water in generating power.

A challenge to the universal application solar power relates to differences in the amount of sunlight (particularly seasonally) that reaches various parts of the globe. One solution to the unequal distribution of solar radiation on Earth (both spatially and temporally) is to utilize wind, wave, and tidal energies that are ultimately derived from the interaction of the entire planet with the moon and/or sun. While all three of the aforementioned energy sources are dependent on global water dynamics, their demands on water in the conventional sense are relatively minimal.

Wind farms produce clean and renewable energy (meeting about 1% of the world's power needs), but the issues of aesthetics (particularly noise) and of bird and bat mortality remain a concern. Ultimately, solving these wind power issues may prove to be simpler than solving issues related to other alternative energy sources. Wave energy seems to be a viable alternative for coastal regions and remote islands; however, the structures, equipment, and instruments must be designed to withstand the battering of large storms. Concerns about construction costs and conversion efficiencies have been raised, but there is vast potential in ocean waves that, along with wind, represent energy alternative requiring very modest amounts of fresh water.

WATER AND CARBON

The most often cited carbon sequestration technique includes pumping liquid CO_2 into the deep oceanic depths, where it is predicted to remain as a slowing-dissolving, dense, liquid waste [4]. This practice has considerable energy demands for capturing the carbon dioxide from point sources (e.g., the stacks of power plants), cooling and pressurizing it into a liquid, loading the liquid CO_2 onto tankers, shipping it to the ocean disposal sites, and pumping it through long hoses to prescribed depths. Even if it were possible to perform all of these tasks without utilizing the very same fossil fuels that generate CO_2, the act of disposing this liquid waste represents a major stress on the local marine environment, where many biological species are instantly killed and changes in seawater's pH (exacerbating oceanic acidification) and redox chemistry rapidly ensue.

It is not known if chemical and biological changes will remain localized to the designated disposal sites or if basin-wide conditions will remain constant in the face of a rapidly changing global climate. Should deep water conditions change slightly (as has already been observed in some locations), the stability of carbon dioxide pools and of gas hydrates that encase CO_2 could be compromised, permitting the CO_2 to mix into shallower waters and, with time, to enter the atmosphere. The behavior of these dense, CO_2-saturated, seawater masses is uncertain due to their susceptibility to gravitational forces and to episodic currents affecting the seafloor. Even if the CO_2 were pumped into geologic formations beneath the seafloor, seismic and related activity is not unusual. Whether or not the sequestered CO_2 ever finds its way back to the atmosphere, its inevitable mixing into oceanic waters is likely to affect conditions in ways that simply cannot be predicted at present.

The disposal of CO_2 in underground waters is more complex than pumping it into the ocean depths as a result of the physical and chemical characteristics of the *media* (i.e., sands or rocks) surrounding the pore spaces where CO_2 actually resides [5]. Carbon dioxide not only reacts with and changes the properties of groundwater (as it does with seawater), it also reacts with the rocks in ways that may permit it to be trapped as a solid mineral complex, to block the soil pore spaces, or to alter the chemistry of the reservoir. While these may not sound like monumental incidents, they could result in the blowout of injection wells, the leakage of CO_2 and other greenhouse gases (e.g., methane) into the air or shallow soil gas, the subsiding or uplifting of the ground surface, the initiation of shallow seismic activity, or the pollution of adjacent (and perhaps potable) aquifers.

Another water-related activity listed under the heading of carbon offsets, as opposed to sequestration, is the planting of trees in tropical and subtropical regions—many of which have lost their biomass to either logging or slash-and-burn activities during the last century [6]. These high biomass tree plantations have been shown to be a poor substitute for virgin forests in a number of ways. The monoculture plantations can disrupt local hydrologic regimes (reducing surface water flows and increasing the salinity and/or acidity of soils), can potentially increase the susceptibility of native trees to disease, and essentially constitute a swap of carbon credits for water losses. Virgin forests are far more efficient than plantations in stabilizing the global climate and preserving biodiversity.

The oceanic counterpart of tree plantations includes fertilizing surface waters with soluble iron (a limiting nutrient for the ubiquitous phytoplankton) to stimulate photosynthesis and convert near surface CO_2 into plant biomass that theoretically sinks into the abyssal depths. This practice not only alters the most fundamental level of a highly complex marine ecosystem, it affects a number of physical and chemical properties at the ocean surface, where crucial oceanic and atmospheric phenomena occur. Moreover, the extent to which the biomass is sequestered, rather than metabolized by marine bacteria near the ocean surface and converted back into CO_2, depends on a vast array of ocean properties that can vary substantially. While marine ecologists have cautioned against such manipulations, a number of entities are engaging in this practice for the purpose of making money in the lucrative carbon credit market, which has been cited as flawed in a number of ways [7].

The global water cycle and the planetary carbon balance are interwoven so tightly that a shift in one necessarily affects the other. In fact, water vapor is the only greenhouse gas that can reverse atmospheric warming trends on a short-term basis. Similarly, a subsurface combination of groundwater and biogenic and/or petrogenic gases is critical in maintaining the integrity of some geologic formations and in determining the kinds of microbial and geochemical processes that prevail. As we begin relocating substantial volumes of CO_2 into intricately-balanced natural systems (according to a 2007 international law that allows the oceanic burial of carbon dioxide), it may be worth reflecting on our rudimentary understanding of how nature maintains these systems and our record for burying other kinds of wastes in the oceans or beneath the ground.

Regardless of whether sequestering CO_2 in saline aquifers or abandoned oil fields results catastrophic events, we have learned that there are no isolated environmental compartments into which we can dump our wastes without affecting other systems. Whereas researching methods of sequestering carbon is useful, our implementing these kinds of drastic measures should be very carefully considered. Global climate change may have already elicited a planetary response that incorporates a higher level of complexity than we readily recognize. Planetary-scale responses are often implemented in very gradual or subtle ways; hence, we could unintentionally override them in our zeal to attain a quick fix.

WATER AND TECHNOLOGY

The rapid and widespread destruction of wetlands throughout the world has prompted the design and installation of artificial wetlands to replace the lost ones. The process of wetland mitigation strives to create conditions that are ecologically “equivalent” to the original ones; however, the replacements are never identical to the original because nature’s intricacies are too numerous and complex to be fully understood or recreated. Nonetheless, the extent to which the artificial wetlands mimic both the structure and function of the lost wetland (in terms of hydrologic regimes, vegetation types, and soil conditions) is the extent to which they serve as a viable mitigation measure.

In assessing the performance of artificial wetlands, landscape architects from Penn State compared their effectiveness to natural wetlands by evaluating functions in selected areas (e.g., depressions, slopes, floodplains) [8]. Some of the most important parameters included the degree and duration of flooding, which had to be recreated in the artificial wetland by situating water inlets, outlets, weirs, and other engineered control structures in a manner that best emulated these parameters. The selection of geotextiles (as soil or sediment covers), brush, and rocks for habitat improvement were designed to recreate the measured rates of water infiltration and evaporation, and to achieve a balance among the mineral, aqueous, and organic phases of the soil.

If natural watersheds are extremely complex systems to model, then the oceans are impossibly complex. In order to use the oceans as either an energy source or CO_2 repository, scientists have to understand more about how their complex systems function. One of the best ways to learn about the oceans is to mimic the movement of water masses—particularly upwelling. A group of university scientists from Oregon and Hawaii have attempted to use wave energy to power a pump that lifts cold, nutrient-rich water from deep waters to the warmer sunlit waters of the surface, where these nutrients are utilized by the phytoplankton in consuming CO_2 and producing oxygen [9].

Whether or not we deliberately dump our CO_2 waste into the oceans, much of it ends up there. In fact, the oceans act as a CO_2 sink in keeping atmospheric CO_2 levels in check, or at least they did until precipitation patterns and evaporation rates changed as a result of global climate change. Not only do the oceans receive and store much of the excess CO_2 associated with the warming atmosphere, they also receive and store much of the excess heat. There is some concern that as much as one half of all coral reef species could face extinction if the acidity and temperature of the oceans continue to rise.

One suggestion for rescuing the ailing coral reefs involves a version of the wave-powered pump. The pump consists of a long plastic tube that is weighted at the bottom and buoyed at the top. As the buoy drops into the trough of a wave, water is pushed into the tube through a one-way valve at the bottom. Although the pump itself does not mimic any common form of water movement in nature, the process of raising colder and less acidic water from the ocean depths mimics upwelling. As observed in the previous example, this technique has both mechanical and ecological challenges, prompting researchers to propose backup strategies such as seeding the reefs with heat-tolerant coral species—as might occur naturally if an unusual ocean current delivered them. While the reef rescue techniques may indeed mimic ocean processes, their long-term ramifications are largely unknown.

As the most ubiquitous liquid on Earth's surface, seawater is now being considered as a source of clean, renewable energy in conjunction with a number of different technologies. The first is actually a revival of an old technology known as Ocean Thermal Energy Conversion (OTEC), whereby heat associated with shallow tropical and subtropical oceans is used to vaporize a liquid such as ammonia, creating enough vapor pressure within a closed system to drive a turbine and generate electricity. The ammonia vapor is then cooled and condensed by passing it through a chamber that is in contact with cold water pumped-up from the deep ocean, thus permitting the vaporization process to be repeated. The OTEC technology is generally considered to yield clean energy because its major pollutants are limited to slightly heated seawater and the chemicals that are used to treat algae or barnacle fouling in the intake and discharge pipes.

The so-called salinity powered battery illustrates an even more innovative conversion of seawater to power. Salinity power is driven by the osmotic gradient created between seawater and fresh water stored on either side of a synthetic membrane. As fresh water moves spontaneously through the membrane to dilute the dissolved salts on the other side, the seawater is pressurized and then piped through a turbine to generate electricity [10]. Technical challenges to salinity power include developing a membrane that is durable, highly efficient, and resistant to biofouling, as well as building a facility that can operate in deltas, estuaries, or other places where rivers meet oceans. Anticipated environmental impacts include the disposal of a brackish water (although far less salty than the brine solutions produced by desalination plants), the presence of platforms or pylons in potentially sensitive aquatic habitats, and the release of chemicals used to prevent biofouling of the pipes.

Not only can water's chemical and physical properties be exploited or emulated for designing technologies, so can the geometries created by its flow forms. Inventor Jay Harman has designed an impeller based on the geometry of flowing water that relies on the efficiency with which a whirlpool is able to mix large volumes of water using only a modest amount of input energy. The elegant geometry of a whirlpool actually represents the most efficient way to mix water, air, or any other fluid; however, this concept has not been universally applied because standard engineering designs are based on a different approach to fluid mechanics. His impeller is a small (10x15 cm) stainless steel apparatus that looks like the inside of a conch shell [11].

So, what is the application for such an impeller? The answer is large tanks that hold the drinking water supplied to a majority of people in the industrialized world. Regardless of the source of drinking water, its disinfection and storage normally takes place in large (i.e., greater than one million gallon capacity) tanks where the water tends to stratify. Stratification, or the layering of water possessing slightly different temperatures, causes problems with treating microbes and with maintaining the water's chemical quality. Using conventional pumps or aerators to solve this problem is energy intensive and creates a number of secondary problems. By contrast, Harman's tiny mixer employs nature's efficiency in entraining all of the water in the tank and mixing it with a fraction of the energy required by the pumps or stirrers it replaces.

A group of scientists at Cornell University have developed a *hydrogel*, which is the major component of a "synthetic tree" that mimics the processes of water transport and transpiration (i.e., the uptake of soil water from tree roots and the release of water vapor from tree leaves). To construct the synthetic tree, the special gel is etched with 80 tiny channels that run parallel to one another and simulate the tube-filled vascular system, or *xylem*, of a real tree trunk. Water wicks upward in the nanometer diameter pores under the driving force of capillary action [12].

The synthetic tree consists of a couple of circles (one representing a root network and the other a leaf network) in a thin gel and could never be mistaken for a real tree; however, the mechanisms for their transporting water are quite similar. It is actually a continuous water pump that requires no energy (other than that required to produce the synthetic tree itself) to move the water under negative or vacuum pressure against the force of gravity. The operating principle of the synthetic tree is one that employs design, rather than additional energy, to achieve the desired goal. Potential applications include heat transfer dynamics, soil hydrology, and fuel cell technology.

The previous examples have focused on emulating the physical, chemical, or dynamic properties of water in its liquid phase; however, researchers have also begun to mimic processes that involve water's solid (ice) and gaseous (vapor) phases. The practice of growing glaciers, which is also known as glacier *grafting*, has been practiced for centuries by mountain villagers in Asia to augment their water supply [13]. There are two types of glaciers—a slow growing type with an abundance of rocks/soil and fast growing type that contains more ice. Indigenous peoples recognize that both are required to successfully grow a glacier and, as such, ice or snow that is relocated to the foot of a glacier must also be seeded with rocks, sawdust, and charcoal that can trap and shield the frozen water during its growth. Once the mixture of rock and ice is sufficiently heavy (usually after three years), it begins to move downhill as a self-sustaining glacier. While the grafts could never be mistaken for a naturally formed glacier, they can grow to lengths exceeding 100 meters and provide a reliable source of water for local communities.

Researchers are now investigating the physical processes that contribute to growing grafts and the potential for expanding the practice on a larger scale. This is an example of people observing the natural dynamics of glaciers and then attempting to emulate the structures and patterns of those dynamics via the addition of readily available materials. While water-oriented technologies have traditionally been designed to either confine or coerce water, there seems to be a new trend toward mimicking water and its behavior in the natural world as a means of designing more energy efficient methods of utilizing and garnering water.

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