Supplementary Notes on Big Picture Resilience via Ocean Forests

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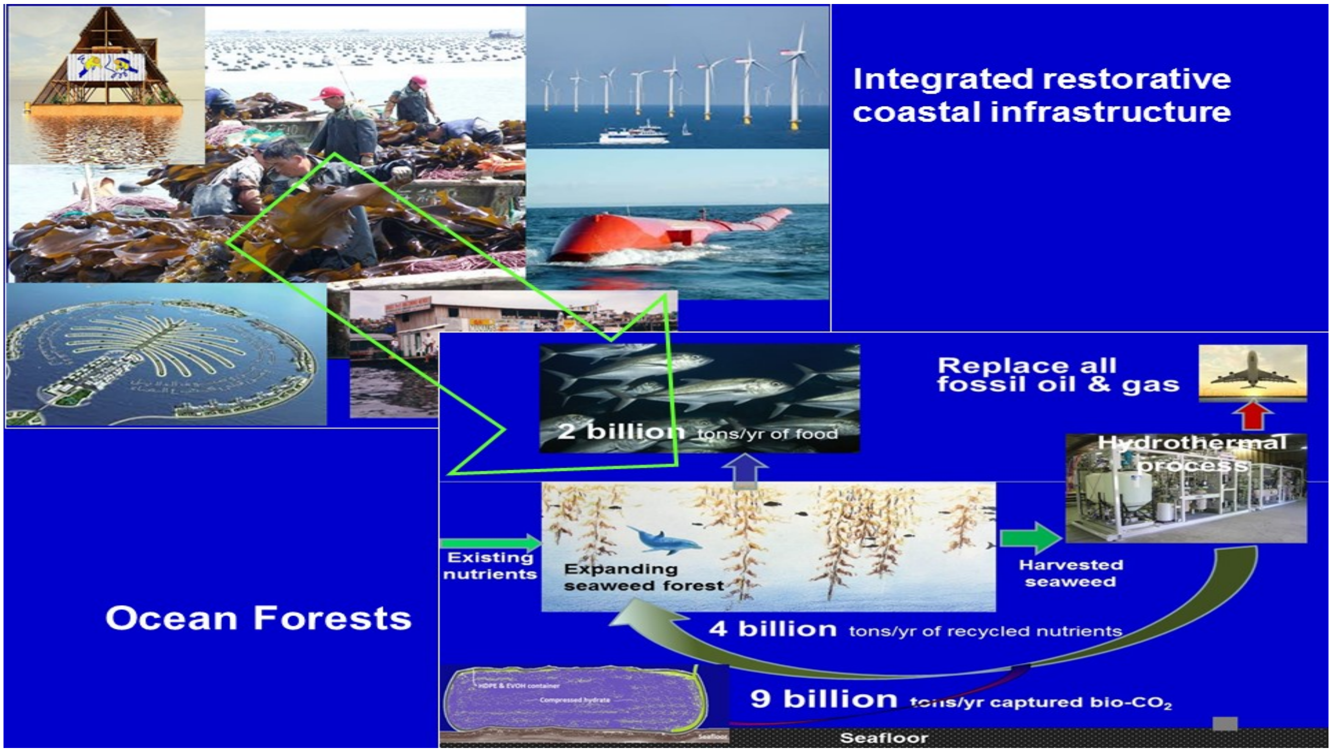


Reversing local ocean acidification and asphyxiation requires growing and harvesting seaweed. Growing and harvesting seaweed to produce food and energy requires integrated coastal infrastructure. Both seaweed operations and infrastructure construction generate jobs such that the new coastal infrastructure must accommodate humanity's migration to existing coasts and islands even as sea level rises. Building coastal systems will support eventually expanding Ocean Forests to about 5% of the world's ocean surface to completely replace fossil fuels and return atmospheric CO_2 concentrations to 1960 levels. See **Big Picture Resilience via Ocean Forests**,[1] "Best New Concept" in the American Society of Civil Engineers' Grand Challenge innovation contest.

Additional Information on Ocean Forests Components

1. Coastal Infrastructure Integration

Expand Envision[2] to strive for restoration – Build infrastructure to restore land and sea for the next few hundred years. Growing and harvesting seaweed for food and energy can reduce stress on fresh water supplies. Fresh water floods can be captured on the ocean. Floating and flexible breakwaters can tune waves in real time for sand deposition or erosion as needed.[3] Naturally additive structures – islands, reefs, and breakwaters – can rise with the sea level, using coral, mangroves, or oysters[4].

[1] See IMPLEMENTATION at http://oceanforesters.org/

[2] Institute for Sustainable Infrastructure, http://sustainableinfrastructure.org/

[3] More discussion in Public-Private Coastal Resilience on http://oceanforesters.org.

[4] Tottenville, New York is building a breakwater which will employ oysters to increase breakwater height over time. Also see Paul Kench, et al. who have documented how coral helps islands grow as sea level rises.

Collaborate and coordinate – Potential organizations collaborating with ASCE include the U.S. Departments of Energy, Agriculture, and Commerce, the Environmental Protection Agency, states, cities, and the insurance and plastics industries. For example: coastal structures can be components of systems built to win the $10 million Barley Water Prize for recovering phosphates from water.

Healthy coral reefs keep up with sea level – When coral bleaches and dies, it won't keep pace as the first line of wave defense at many locations. The Haven Atolls[5] combination of reducing heat stress with deep ocean water and raising pH and oxygen content with seaweed might keep coral growing and healthy for a thousand years.

2. Seaweed Grow-Harvest Systems and High Value Products

Currently, millions of tons of seaweed are being harvested profitably across the globe, mainly for food products and pharmaceuticals. The systems vary from hand harvesting from ropes and rafts to "mowers" on the front of ships to collect the top meter of kelp forests. Current grow-harvest operations are too energy intensive, too labor intensive, and lack the scale to meet current prices and demand for fossil fuel energy.

Necessary technologies include:

A. **Develop autonomous equipment** for working and managing seaweed (and coral) ecosystems. Consider the crown-of-thorns starfish killing robot (COTSbot) which gives the starfish a lethal injection.[6] Very similar systems could selectively harvest sea food (sea cucumbers, abalone, sea urchins, red dulse, etc.) from within Ocean Forests. Coastal systems may have permanent automated winches, hydraulic conveyances for harvested seaweed, and the like. More open waters might employ rotary sail-powered autonomous workboats to deploy nutrients to grow seaweed and self-shrinking encircling nets to harvest it. Artificial jellyfish might harness wave energy to tow long lines of kelp with nutrient release sacs.

B. **Improve space-based sensing** and communications for seaweed ecosystems – NASA-USAID have been using satellite observations of algae blooms (via chlorophyll resonance) to warn fishermen away from possible Red Tide areas off Central America for several years. Extend this to guiding robotic seaweed and plastic debris wranglers in tightly constrained coasts and open ocean gyres.

C. **Develop bulk food products from seaweed** – No one currently sells seaweed for energy because food pays better. Yet the demand for seaweed is not large enough to support the volume of seaweed growing needed to sustain/restore coastal pH and dissolved oxygen. We need bulk food products such as: seaweed feed (for livestock and fish); seaweed flour; KelpButter (a take-off from Plumpy'Nut); and healthy snacks of 3D printed seaweed jerky (fried dulse tastes like bacon).

D. **Find more bulk chemical products** – The primary bulk product from seaweed is alginate, a food additive. Seaweeds could be converted to chemicals, pharmaceuticals, refined fuels, and superior lubricants. The CO_2 from Ocean Foresters resource recovery processes (see below) is more concentrated CO_2 than is available from air breathing fossil fuel power plants. Many techniques for converting CO_2 into other products are becoming available. Some, such as artificial photosynthesis, employ bacteria needing pure CO_2 (without competing bacteria) at room temperature.

E. **Improve integrated aquaculture** – Many Ocean Foresters[7] are also associated with the Marine Agronomy Group (think ocean farming for food).

[5] See IMPLEMENTATION at http://oceanforesters.org/

[6] Quote from Australia's Matthew Dunbabin in *Scientific American*, January 2016.

[7] Partial list at http://www.oceanforesters.org/Contact.html

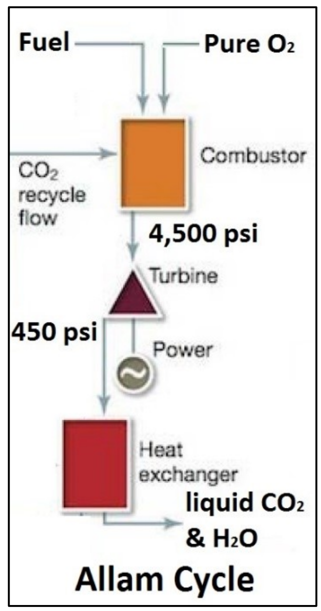
3. Complete Resource Recovery Technologies[8]

If Ocean Forest's energy process recovers and recycles only 90% of the nutrients, operating at the scale to replace all fossil fuels, we will need more than current total global artificial ammonia production to make up the 10%. That is why we address the energy production processes in this Complete Resource Recovery component. If energy production does a poor job of separating the energy from the macro and micro nutrients (including metals), the system will not be sustainable. On the other hand, if the energy process allows further concentration of molecules accumulated by the seaweed (CO_2, mercury, plastic debris, runoff, etc.), the Ocean Forest becomes restorative. Or hyper-accumulating plants can become energy feedstock while mining for metals or removing toxics from superfund sites.

A: **Hydrothermal processes** (HTP) operate at near supercritical conditions of 350°C and 200-bar. HTP output options include bio-oil and biogas (60% CH_4 with 40% CO_2), phosphate and sulfur precipitates, and all the other input minerals in clear water. The feedstock should be between 10% and 30% solids for several reasons. When operated for maximum bio-oil output, 30% of the input nitrogen (proteins, ammonia, nitrate) is caught in the bio-oil and 70% is dissolved in the clear water in the form of ammonia and ammonium. When producing only biogas, the clear water contains 100% of the input nitrogen as ammonia. The CO_2 in the biogas is easily separated and purified.

Ocean Foresters believe the nearest to market HTP has been licensed to Genifuel by the Pacific Northwest National Laboratory. Genifuel has built and sold two 1-wet ton/day units for microalgae feedstock. The Water Environment Research Foundation has completed a laboratory-scale demonstration with Genifuel and PNNL with assorted wastewater treatment plant sludge. Genifuel and WERF members are arranging a 10 to 20 wet ton/day demonstration as of May 2016.

B. Ocean Foresters would like to see a blend of **supercritical water oxidation** (SCWO) with the Allam Cycle. NET Power is building a 50 MW gross (25 MW net, 50% efficient) Allam Cycle power plant. The fuel will be natural gas and the produced liquid CO_2 will be sold for enhanced oil recovery. By using renewable fuel, Allam Cycle power plants will help reduce atmospheric CO_2 concentrations rapidly. Future developments of the Allam Cycle promise to replace landfills for carbon-containing "wastes" which are low in organic nitrogen. Its operation at 1,100°C ensures any N will become N_2.



SCFI appears to have the most market-ready SCWO. It combusts sewage sludge in supercritical water above 374°C and 321-bar. The sludge must be at least 5% solids for breakeven energy production. SCFI believes 15% solids is optimal for pumpability and other factors. SCWO produces heat when oxygen is injected into the supercritical mixture of biomass and water. The heat can be used to produce steam, which produces electricity through a steam turbine. SCWO outputs include heat, phosphate and sulfur precipitates, and all the other input minerals in clear water. When operated at temperatures above 430°C, almost 100% of the organic nitrogen will emerge as elemental nitrogen (N_2). Input nitrate will remain nitrate. When operated at lower temperatures, the organic nitrogen emerges as ammonia and ammonium. When pure oxygen is injected, the gas output is pure CO_2 with some water vapor. SCFI has been running a demonstration model in Ireland and Spain.

C. **Anaerobic Digestion** (AD) is extremely well developed and used constantly in wastewater (sewage) treatment plants, landfills, and by nature. The bacterial ecosystem is available for fresh water biomass at a variety of temperatures. The bacteria can be evolved for seawater and ocean

[8] See **Complete Resource Recovery: C, N, P, K, & metals** in Implementation at http://oceanforesters.org.

temperatures. However, it is difficult to recover and concentrate the nutrients and metals in the dewatered digestate and the dewatered digestate is not easily or aesthetically distributed into Ocean Forests. AD cannot do anything with plastics and other contaminants.

The PRD Tech Ammonia$^+$ Recovery (A^+ R) works on the liquid exiting HTP or SCWO plus the liquid rejected during dewatering of AD digestate. It concentrates the ammonia to dry powder ammonium sulfate or other ammonia products. Ocean Foresters have an agreement with PRD Tech and an investor planning to recover metals from sewage sludge. Others are also developing processes to concentrate ammonia, phosphates, other nutrients, and metals from "wastes."

AD may be immediately economically viable in specific locations and situations. HTP and the supercritical processes appear to need a tipping fee and complete resource recovery while growing to mass production. In addition to the income from commercial products, potential customers would like to have the C, N, P, K, and metals removed from their water-cleaning facilities.

While there are many locations for demonstrating complete resource recovery, few can make a better case than Guam.[9] The U.S. military is relocating from Okinawa to Guam straining water, wastewater, solid waste, and energy utilities. The U.S. EPA wants Guam to improve wastewater treatment in ways which will increase the amount of sludge sent to the landfill with its $170/ton tipping fee. Guam is also a good location for deep water seaweed grow-harvest at the scale needed to fuel the U.S. Navy.

Including complete resource recovery with bio-energy has wider appeal than either resource recovery or energy production alone. Potentially interested agencies include the Environmental Protection Agency, the Departments of Agriculture, Defense, Energy, Homeland Security, Commerce (National Ocean and Atmospheric Administration); philanthropists; local governments; and businesses, plus their counterparts in other countries. These agencies are interested in recovering resources from, and reducing pathogen and toxic chemical hazards from, wastewater, municipal waste, and farm operations. Some are interested in using the processes as low-cost centerpieces of quality of life enhancing waste systems in refugee camps and developing country slums.

4. Carbon Dioxide Storage

The crises caused by nearly 2 trillion tons of excess CO_2 (trending toward 5 trillion tons) in the atmosphere and oceans require a crash removal program. The Ocean Foresters could use any of many carbon storage techniques suitable for the CO_2 produced by growing and harvesting seaweed. The most market-ready is geologic storage (injecting CO_2 into old oil and gas formations and saline aquifers). We could also react CO_2 with silicates to make rock, but that is currently either energy or time (decades, if not centuries) intensive. Although CO_2 can help make plastics, there is insufficient demand for trillions of tons of plastics.

In order to introduce competition to geologic storage, and for locations where the geology is inappropriate, Ocean Foresters recommends investigating "Secure Seafloor Container CO_2 Storage"[10]. The CO_2 would be stored as a stable contained hydrate, easy for anyone to view via webcam, with fill rates limited only by how fast we can make and deploy geosynthetic HDPE sandwiched with ethylene vinyl alcohol copolymer. Thin membranes would lose less than 0.1% of the stored CO_2 per thousand years, much less than projected losses for many geologic storage locations.

[9] Commercial Scale Demonstration of Hydrothermal Process (HTP) on Guam at http://oceanforesters.org

[10] Secure Seafloor Container CO_2 Storage Mark E. Capron, P.E., Jim R. Stewart, PhD, and R. Kerry Rowe, PhD, OCEANS'13 MTS/IEEE San Diego Technical Program #130503-115 (2013). Paper at http://oceanforesters.org/Ocean_Forests.html