OMA Process Concepts: Materials & Energy
Supplementary Information for "Negative Carbon via Ocean Afforestation"
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Background

Ocean Macroalgal Afforestation (OMA, aka Ocean Afforestation) is a branch of marine agronomy. Compared to terrestrial agronomy, humans have relatively little experience with marine agronomy. Efforts so far have involved growing and harvesting macroalgae using methods more resembling the mono-cultures of terrestrial agriculture than the species diversifying promise of ocean "forest" management.

Ocean Afforestation requires humans to rethink ecosystem management. Certainly, performing terrestrial style work in the ocean is more difficult and costly than performing the same work on land. Certainly, economical biofuels from macroalgae require lower per ton energy and labor costs than virtually all existing macroalgae grow-harvest techniques. But, Ocean Afforestation can be economically viable by foregoing terrestrial style approaches and weaving the properties of the ocean into the ecosystem management techniques.

Chynoweth offers this summary of his comprehensive review of the Gas Research Institute program on anaerobic digestion of marine and other plant biomass (Chynoweth, 2002), "In general, the cost of methane from marine biomass was quite expensive with the greatest uncertainties related to farm designs and performance. The conversion aspects are better developed."

The Gas Research Institute (GRI) efforts of the 1980s and 1990s (reported by Chynoweth, 2002) differ from Ocean Afforestation as follows:

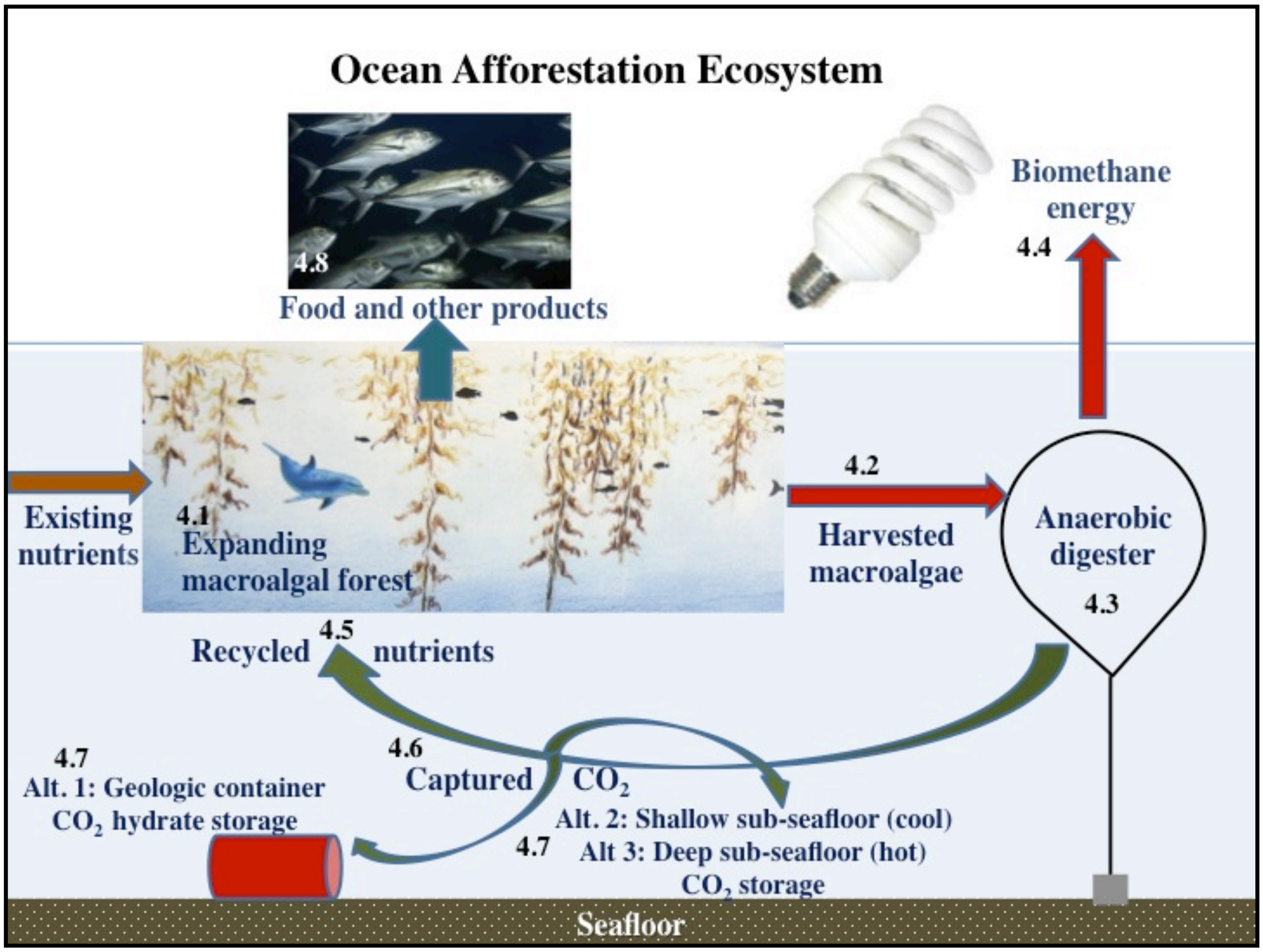
- GRI considered anaerobic digestion in the standard (relatively expensive) containers of the day. Expensive containers drive the growing and harvesting toward maximizing the biomass per area, dewatering the biomass, algae mono-cultures, energy consuming operations to speed the energy conversion, etc.
- GRI had a tiny fraction of the electronics capabilities of the 2020s: "smart dust" sensors; automated operations; autonomous vehicles; satellite sensors; etc.
- GRI did not have internet information sharing to quicken multi-disciplinary innovation.
- GRI focused on one product (biomethane), without complete consideration of food and health-related products to help cover the growing and harvesting costs. (OMA designs start as complete mass-balanced ecosystems with the same biomethane and food products plus carbon-from-air storage, species biodiversity, and perhaps nutrient remediation.)
- GRI did not consider recycling nutrients as a mechanism to sustain self-propagating macroalgae forests.

Ocean Afforestation has developed the process concepts described in this paper to overcome the issues raised by Chynoweth and GRI. But this description of possible techniques is just a beginning. The primary objective of this supplementary paper is to provide more details regarding the Life Cycle Analysis (LCA) summarized in Table 1 of the main paper "Negative

Carbon via Ocean Afforestation." The desire is to indicate the main material and energy transfers included and give more people a chance to innovate new techniques with more knowledge of the issues. Consider this proposed design as an invitation to brainstorming, rather than a scientific paper. Therefore, questions, discussion and comments are most welcome to the author's email.

Process details

The numbers (4.x) match the process explanation numbers from the "Negative Carbon via Ocean Afforestation" published paper and Figure 1 below. It is best to read that section of the published paper before reading the details below.



4.1 Grow aquatic plants

OMA's relatively inexpensive geosynthetic water-supported anaerobic digestion containers change the economics of growing and harvesting. Anaerobic digestion is already indiscriminate of biomass species. Rather than designing growing systems around getting the biomass into the containers, OMA is based on finding locations where macroalgae (seaweed) grows when nutrients are supplied in the correct dose.

Benthic seaweed (kelp, *Gracilaria,* etc.) grow on the seafloor in shallow water. Free-floating seaweed (sargassum, etc.) grow in deeper water. The seaweed self-propagates because the harvests are relatively small, on the order of 1/300th to 1/100th of forest biomass volume during any one harvesting day. Sustainable harvest amounts and frequencies vary by species and locations, as discussed below.

Since seaweed forests are normally self-propagating, Ocean Afforestation needs research and development integrating the growing with the other ecosystem operations, particularly low-energy harvesting and plant nutrient recycling. For example, additional research is needed for each species and location to determine optimal nutrient distribution methods and recycling concentrations to favor macroalgae over microalgae.

The Life Cycle Analysis (LCA) mentioned in the main paper "Negative Carbon via Ocean Afforestation" is based on 5 metric tons AFDW/ha/yr of seaweed at an average density of 1 kg/m^2 of sea surface or seafloor at the time of harvesting. (See details in the "Algal yields" tab of the supplemental "OMA Calculations Spreadsheet.") Most of the harvested mass is growing in a layer about 1-2 meters thick either on the surface or the seafloor. We accounted for occasional storms and propagation needs by harvesting only 75% of the annual growth of seaweed. For further information and references on growth rate factors, see the online supplementary information file: "OMA Discussion of Macroalgae Production and Density," by Jim R. Stewart.

These numbers are approximate for current natural seaweed forests and could be increased after a decade of intense nutrient recycling (see 4.5) optimization research.

4.2 Harvest aquatic plants

The method below presents one possible low-energy harvesting technique, which is the technique used in the LCA for calculating the materials and energy demands of harvesting. It may be suitable for either an ocean gyre or sheltered water with minor currents. Future research on the open-ocean process will refine this harvest technique for better efficiency harvesting long rows of higher seaweed densities formed by Langmuir circulation.

a. Five sailboats (Each about 900 kg empty displacement made of fiberglass, nylon, stainless steel, aluminum, and coated steel) deploy curtain nets (each primarily 40 kg of polypropylene) in circles about 300 meters in diameter. They connect the circles with a tensioning/rolling device (T/R, each device about 400 kg of HDPE and stainless steel). Each sailboat may use an average of 6 kW of biomethane fueled power over a 10-hour harvesting day (300 kWh/day for five sailboats) for incidentals and when wind is inadequate.
b. The T/R automatically contracts the net over 5 days using a small average force combined with the alternating tension and relaxation of wave motions to reduce the net diameter to about 66 meters. (The estimated 2 kWh to "wind-up" each T/R is included in the incidentals of a. above.) The contracted net becomes a "tea bag" container of seaweed at about 2% ash-free biomass density.

c. Another sailboat attaches winch lines (2,200 kg of polypropylene winch lines per 10,000 ha forest) to the nearly contracted "tea bags." The attaching boats sail from contracting tea bag to tea bag while paying out winch line so they do not expend energy pulling the winch line.
d. One winch line attached to the digestion container would pull several tea bags toward it. The winch pulls slowly, perhaps 0.5 km/hr. (Hydrodynamic drag is about 0.6 kW to winch each tea bag at 1 km/hr. Each winch contains 50 kg of HDPE, steel, and copper.) As the tea bag approaches the digester, the T/R and "excess" net are removed so that they can be reused without the time delay of processing them through the digester.

The density at harvest is a function of the yield and the number of harvests per year. The density drives how much a circle of net must be contracted to achieve the desired algae density for towing and insertion into the digester. One picks the initial net diameter to be as large as the sailboats can handle. The height of the net is set for the vertical extent of dense algal growth for which harvest is determined to be sustainable. Note that less net height means less swept volume but less expensive nets. Floating algae concentrates on the surface. Kelp also grows along the surface. Benthic algae would be harvested with an analogous net on the seafloor, in which case the bottom of the net may have sharp wire to help cut the seaweed from its holdfasts.

The Life Cycle Analysis accounts for the mass and energy associated with everything mentioned above plus an offshore living and maintenance barge. The barge may be consuming an average of 150 kW for digester processes, occasional movement, repairs, HVAC, cooking, etc. The 100,000 kg empty displacement barge is mostly coated steel and supports ten 10,000 ha forests. On the open ocean, the barge and sailboats would move away from tropical storms. The seaweed would be moved, but not be harmed by storms, unless the benthic algae are swept from their holdfasts.

4.3 Digest plants anaerobically

Anaerobic digestion in relatively inexpensive geosynthetic floating or submerged containers is the key difference from other techniques for negative carbon via biomass, or biomass-to-energy, or biomass-to-food. Because there is no differential pressure difference between inside and outside water at the bottom of the container, the tea bags can be fed into the digester with very little energy expenditure. An actual mechanism was not designed but the materials and energy were approximated in mass and energy estimates for the harvesting and digestion systems.

This initial process model has 1.5 digesters of 650,000 m^3 capacity per 10,000 ha forest digesting batches of seaweed inserted as tea bags of 2% solids with 135 days combined detention and emptying time. Each digester is made from 37,000 kg of HDPE and 27 kg of EVOH. (See the online Supplemental Information "OMA Artificial Geologic Seafloor Storage" for a discussion and references on gas permeability of geosynthetics.) 150,000 kg of polypropylene cables and 220,000 kg of coated steel anchors restrain each digester beneath the ocean surface (counteract the buoyancy of the biogas stored in the digester.)

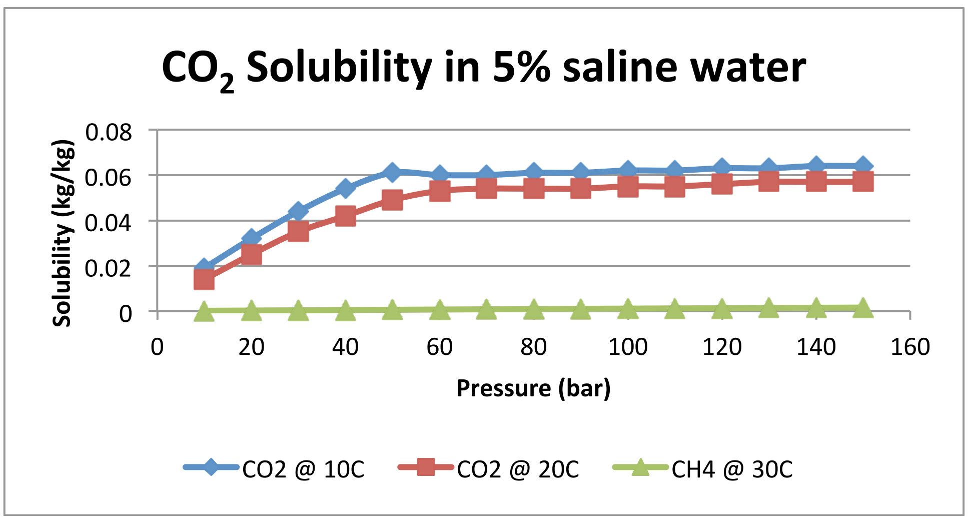
There are many process flow arrangements used for contained microbial anaerobic digestion: batch, plug flow, continuous mixed, staged, etc. Each of these will accommodate different means to insert seaweed and recycle the liquid left over after anaerobic digestion (digestate).

Even with no mixing and no heating, we accounted for some energy expended in loading and unloading. Plus, we may find a little mixing energy is economic, if it can shorten digesting time and provide steadier gas production rates.

The digester wall is likely to be an impervious liner supported by a structural fabric. Only the gas in the bubble at the top of the container could penetrate the liner, because that is the portion with pressure driving gas through the membrane. We estimate about 16 standard m^3/year/forest of CH_4 could escape through a 20-µm thick layer of ethylene vinyl alcohol copolymer (EVOH) coating, which is much less than the annual CH_4 production of 58 million standard m^3. The EVOH coats twice the area expected to be exposed to gas. See the online Supplementary file, "OMA Artificial Geologic Seafloor Storage" for a discussion of gas permeability for assorted geosynthetic materials.

4.4 Recover separated bio-CO_2 and bio-CH_4

While there are other processes for the initial separation of bio-CO_2 from bio-CH_4, the LCA is based on differential dissolution.



The data graphed above are from Van der Meer (2005). It shows the solubility of CO_2 is much greater than that of CH_4. (Each 10 bar of pressure is about 100 meters of depth.) Employing differential dissolution concentrates the biogases which at one atmosphere would be 60% CH_4 and 40% CO_2. When the top of the container is at some depth between about 100 – 500 meters, the biogas should be about 90% CH_4, 10% CO_2, and very small amounts of N_2, H_2S, and N_2O. Chynoweth's (2002) extensive documentation of anaerobic digestion of macroalgae at one atmosphere pressure informed our estimate of 0.4 standard m^3 (SCM) of CH_4 and 0.27 SCM (40% of the biogas) of CO_2 produced from each kg (ash free dry weight) of macroalgae.

The 90% bio-CH4 is sent directly to gas turbines. The turbines form a 300 MW base load power plant (400 MW nominal capacity) for a ten-forest OMA operation. The turbine materials are approximated as 370,000 kg of steel. The HDPE pipe to convey the biogas from digesters to the gas turbine power plant, compressed to 2.5 bar absolute pressure, weighs 1,700,000 kg. A highvoltage direct current power line 100 km long conveys the energy to shore with 0.3% transmission losses.

After digestion, the water removed from the digester is laden with nutrients, saturated with bio-CH_4, and nearly saturated with bio-CO_2, plus some dissolved N_2, H_2S, and N_2O. As it rises, gases bubble out of solution to be about 90% of the CO_2, 10% of the CH_4 and a little N_2, H_2S, and N_2O. Note the bubbles create an air-lift pump whose energy is not assumed in the LCA. The gas bubbles are captured under a "hat" (consisting of 84,000 kg of HDPE) at the ocean surface, where the methane can be separated from the CO_2. This LCA calculation was not adjusted for these partial pressure affects meaning the actual amounts of gases remaining dissolved, when the total pressure under the hat is one atmosphere, will be less than calculated.

After off-gassing under the hat, the water still contains dissolved CO_2, CH_4, H_2S, and N_2O appropriate for the partial pressures beneath the hat. Normally, when the dissolved water exits the hat, it would carry about 40 kg of dissolved CH_4 and perhaps 0.4 kg of dissolved N_2O per forest per day into the ocean. However, the LCA includes a 50,000 kg HDPE mixing tube employing about 200,000 kWh/forest/year to mix. In the tube, gas-saturated water is mixed with ambient ocean water (which has considerable dissolved O_2). Some recirculation maintains a population of methane-metabolizing bacteria in the de-methane tube. This operation mimics the de-nitrifying step converting NH_4 to NO_3 at wastewater treatment plants and should also convert sulfides to sulfates. See the online Supplementary Information file "OMA N_2O Discussion" for more discussion of dissolved gases.

4.5 Recycle plant nutrients

Not losing nutrients means not needing to import nutrients in the steady state operation. Therefore the LCA includes the mass and energy for all three nutrient recycling operations conducted in parallel:

a. Nutrients dissolved and suspended in the liquid digestate;
b. Nutrients trapped in the otherwise sinking digested solids;
c. Nutrients dropping into water beneath (below the reach of the plants) the forest.

The calculations outlined below are rough estimates due to a dearth of research on optimal nutrient recycling factors. One unknown is if the liquid needs to be distributed only during daylight to ensure quick conversion of ammonia to nitrate.

The liquid digestate distribution (a) employs a radial arrangement of hoses totaling 1,500 kilometers long distributing nutrients over a 10,000 ha forest within 10 days. 0.7 kW moves the water in a single hose at 0.6 m/sec. Liquid distribution may be more efficient, less time constrained, and less in-the-way using a large slowly moving bladder, but the LCA model is simplified to involve many radial hoses. The energy to move the water is supplied by electricity generated from the biomethane.

The otherwise sinking digested solids (b) are contained in the same tea bag nets used to harvest. Those tea bags are attached to floats and allowed to drift through the forest, slowing releasing the nutrients.

The dropping nutrients (c) are recovered with upwelling tubes sized for a deep water plant nutrient concentration of 1 mg/L-N. Each tube is about 2 meters in diameter and 200 meters long. We estimate 175,000 kWh/forest/year to force the upwelling at about 0.1 m/sec. The upwelling tubes (c) empty into the radial tubes (a), when the radial tubes are not otherwise employed. In actual practice, any upwelling return would probably be wave, wind, or biogas bubble powered, which would improve the LCA.

4.6 Capture and compress bio-CO_2

The gases captured under the hat of Step 4.4 are compressed to about 50 bar (500 m depth) using the ~10°C ocean water to liquefy the CO_2. The commercially available compressors consist of 25,000 kg of steel and 1,300 kg of copper. They employ 5.4 million kWh/yr/forest of electricity pushing the gas into 40,000 kg of HDPE pipe. The high-pressure pipe thickness is one kilometer long while the low pressure pipe thickness is two kilometers long. About 760,000 SCM/forest/yr (3.4 million kWh @ 45% turbine efficiency) of CH_4 and any other gases that do not dissolve in liquid CO_2 are recovered as a gas when the CO_2 liquefies.

4.7 Store Bio-CO_2

As mentioned in the main manuscript, there are many ways to transport and store CO_2 once it is a liquid.

See the online supplemental information "OMA Artificial Geologic Seafloor Storage" for more information. The LCA includes 30,000 kg of HDPE mixing pipe to speed dissolution of the liquid CO_2 in seawater and start hydrate formation using 16,000 kWh of energy per forest per year. The geosynthetic storage system is estimated at 110,000 kg/forest/year. The estimates for monitoring and maintenance energy are 100,000 kWh/forest/year.

4.8 Harvest fish and other products

Fishing and harvesting seaweed for food is relatively ancient art and are not detailed for this manuscript. They are not included in the LCA, as they are assumed to have their own separate sustainable economic income and expenses.

References

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