****

Correspondence to: Mark E. Capron, PODenergy, 2436 E. Thompson Blvd., Ventura, CA 93003, United States (MarkCapron@PODenergy.net), 805-760-1967, Fax: 805-639-0307

**Abstract**

Ocean Afforestation, more precisely Ocean Macroalgal Afforestation (OMA), has the potential to reduce atmospheric carbon dioxide concentrations through expanding natural populations of macroalgae, which absorb carbon dioxide, then are harvested to produce biomethane and biocarbon dioxide via anaerobic digestion. The plant nutrients remaining after digestion are recycled to expand the algal forest and increase fish populations. A mass balance has been calculated from known data and applied to produce a life cycle assessment and economic analysis. This analysis shows the potential of Ocean Afforestation to produce 12 billion tons per year of biomethane while storing 19 billion tons of CO2 per year directly from biogas production, plus up to 34 billion tons per year from carbon capture of the biomethane combustion exhaust. These rates are based on macro-algae forests covering 9% of the world’s ocean surface, which could produce sufficient biomethane to replace all of today’s needs in fossil fuel energy, while removing 53 billion tons of CO2 per year from the atmosphere, restoring pre-industrial levels. This amount of biomass could also increase sustainable fish production to potentially provide 200 kg/yr/person for 10 billion people. Additional benefits are reduction in ocean acidification and increased ocean primary productivity and biodiversity.

**1.0 Introduction**

Removing the major atmospheric greenhouse gas carbon dioxide is a priority in order to reduce global warming, ocean acidification and sea level rise, which threaten human civilization as well as animal and plant life on our planet. Given the need for such negative carbon technology on a scale at least equal to current anthropomorphic carbon emissions, the proposed capture technologies must be sustainable at scale in every sense of the word.

1. Environmental sustainability at scale implies addressing issues beyond carbon air capture such as: species biodiversity, food, and energy.
2. Climate sustainability with increased greenhouse gas concentrations implies a robust and distributed process that is neither affected by nor a cause of droughts, floods, heat, cold, changing wind patterns, and ocean acidification.
3. Political sustainability requires improving the quality of life and opportunities globally, and particularly in developing countries.
4. Social sustainability means countering the water, food, jobs, and natural disaster stresses of climate change, with no negative side effects.
5. Energy sustainability implies much more carbon is permanently stored than is required to generate the energy to pull the carbon from the air and store it.
6. Economic sustainability with current low carbon prices requires multiple products from the process so the overall system makes a profit.

All of the above are possible by operating a novel technologically accelerated natural ocean ecosystem, which we have termed “Ocean Afforestation” or more technically “Ocean Macroalgal Afforestation” (OMA) because it is based on forests of macroalgae (kelp and other seaweeds).[[1]](#footnote-1) In OMA, the energy inputs and outputs use the same pathways as in nature (photosynthesis, digestion, decomposition). What differs in OMA is that that digestion products are captured and separated, with the energy (carbon and hydrogen) set apart from the plant nutrients (nitrogen, phosphorus, potassium, sulfur, iron, etc.). Hence, an OMA ecosystem is almost a typical natural macro-algae ecosystem. The main difference is that the plant nutrients are captured and recycled at the surface to grow more plants, instead of dropping below the light level for millennia on the seafloor or traveling thousands of kilometers in subsurface ocean currents before surfacing.

**2.0 Historic discussions of macroalgae energy**

Thousands of researchers and businesses have unknowingly been developing technologies related to Ocean Afforestation for decades. OMA is a combination of concepts and technologies from marine agronomy, integrated multi-trophic aquaculture, ocean thermal energy conversion, the offshore oil industry, marine sanctuaries, municipal wastewater treatment, seaweed farming, and more. Even so, thousands of researchers, engineers, and multiple businesses will be necessary for decades integrating those existing technologies and refining new technologies for Ocean Afforestation ecosystems.

Recently, the large ocean area available and the high photo-efficiency of marine vegetation have prompted discussions of algae and other plankton as a sink for anthropogenic carbon emissions or as feedstock for biofuels. In “Blue Carbon” Nellemann et al. (2009) point out that marine primary producers contribute at least 50% of the world’s carbon fixation and may account for as much as 71% of all carbon storage in oceanic sediments. Potential annual yields per hectare of many of the highly productive macroalgal species are considerably higher than those of the terrestrial plants considered useful candidates for biofuel production (Chung, et al., 2010). Many researchers are looking seriously at macroalgae for energy production, such as Stanley and colleagues at BioMara (Day, et al., 2011), Oilgae (2011), Roesijadi, et al. (2008, 2010), Bruton, et al. (2009), Lenstra, et al. (2011) and references therein.

Chynoweth’s review article (2002) indicates that the productivity and digestibility of macroalgae to produce large quantities of biomethane have been well established by many researchers over many decades. He also reports that Hanisak (1981) has shown the feasibility of nutrient recycling for sustainability. He recommends generating income from co-products and by-products to reduce the cost of the biomethane to be competitive with U.S. natural gas prices. OMA proposes two additional co-products, fish and carbon sequestration, which make OMA currently economic for many developing nations, especially those using high-priced diesel fuel to make electricity. Other by-products, such as liquid fuels, agar, carrageenans, algin, etc., have not been analyzed for this paper.

**3.0 Objectives for Ocean Afforestation**

The sustainable nature of Ocean Afforestation makes the following primary objective theoretically possible: completely offset anthropomorphic CO2 emissions by 2035 and then restore the climate by reducing atmospheric CO2 concentrations below 350 ppm by about 2085. These ambitious but achievable timelines are discussed later.

There are three “steps” within the OMA ecosystem to accomplish this objective:

1. The biologic portion (seaweed and seaweed-digesting microbes) of OMA, concentrates carbon from about 0.04% CO2 in air to 40% bio-CO2 and 60% bio-methane.
2. Any of several chemical and physical technologies, including differential dissolution, pressure swing absorption, gas membranes, chemical extraction, metal-organic frameworks, etc. are available to separate out (purify) the bio-CO2 directly from the anaerobic digestion and the combustion-CO2 from combustion exhaust gases; and
3. Any of several geophysical and geochemical technologies permanently store pure CO2. Some are being developed by others, in addition to the one proposed in this paper.

Sub-objectives for Ocean Afforestation include:

* Create sanctuaries with regionally higher ocean pH. Since the oceans have absorbed approximately half of human-caused CO2 emissions (Sabine, et al., 2004) the oceans are rapidly acidifying and, in a relatively short time (2050 by projections, such as the Monaco Declaration, 2008), it will be inhospitable to many ecologically essential forms of life that rely on calcification, such as corals, marine mollusks and coralline algae (for example, Barton, et al. (2012) discuss oyster hatchery mortality). Ocean Afforestation could reduce atmospheric and dissolved CO2 concentrations in the area of the macroalgal forest; in much the same way that atmospheric CO2 is reduced in terrestrial agricultural regions (Miles, et al., 2012).
* Increase ocean biodiversity and primary productivity starting within the OMA areas.
* Produce higher value pharmaceuticals, chemicals, food, and fish/animal feed from the macro-algae to satisfy human needs.
* Produce environmentally and economically sustainable on-going renewable energy, thus preserving fossil fuels to provide chemicals for future generations, while providing income for maintaining the stored CO2.

These objectives are designed to be ambitious to match the urgency of the situation. If humans do not remove CO2 with OMA or other carbon storage technologies, the excess CO2 will persist, lowering the oceanic pH and raising global temperatures for a millennium, even if the world shifts rapidly to non-fossil fuels, such as solar, wind and geothermal energy, or even nuclear power.

**4.0 The Ocean Afforestation Ecosystem**



The flow chart for the OMA ecosystem has the major components labeled to the numbered sections below. This manuscript was prepared primarily to explain the nutrient, energy, and carbon removal mass balance for Ocean Afforestation ecosystems. Work on economic feasibility is on-going with a discussion of preliminary results in this manuscript and in the supplemental data. See the online supplementary information file “OMA Process Concepts” for more details of the materials and energy demands within a conceptual ecosystem.

**4.1 Grow aquatic plants, absorbing CO2**: Sunlight powers aquatic plants (primarily macro-algae or seaweed) to grow anywhere in the top few meters of the world’s oceans, as long as there are sufficient nutrients. Where there are insufficient nutrients, there are fewer plants. That is, much of the ocean is a nutrient desert. Presently, seaweeds grow mainly where nutrients are available from upwelling ocean currents or terrestrial runoff. An extensive analysis of harvest production data for many macroalgae from around the world (Gao et al., 1991; Chung et al., 2010; Oilgae, 2011; Roesijadi et al., 2008, 2010; Bruton et al., 2009; Lenstra et al., 2011; and references therein) indicates a conservative harvestable projection of about 18 ash-free tons per hectare per year, providing sufficient nutrients are available. Note that Table 28 of Chynoweth (2002) reports yields of 11 – 50 ash-free t/ha/yr are reasonable. More examination of the validity of 18 ash-free t/ha/yr is included in the online supplementary information, “Discussion of Macroalgae Production and Density.”

**4.2 Harvest aquatic plants:** There are many current cultivation and harvesting techniques depending on the type of macro-algae and climate, as documented by Pereira and Yarish (2008). OMA can better achieve its objectives of sustainability by harvesting small portions of the overall forest throughout the year. This may involve “mowing” the top meter of seafloor-rooted kelp, or encircling clumps of free-floating *Sargassum* in an ocean gyre, or cutting strips of *Gracilaria* in a tropical island bay. The sustainable harvest fraction depends on local climate conditions, species rate of growth, added nutrition from shore runoff, storms, etc. It could vary from year to year. Since the harvest fraction in any one year could range from 40% to 90%, we have projected a reasonable average as 75%. The harvesting techniques will be optimized for low energy consumption. For example, the harvested biomass would be moved distances up to about 6 kilometers at speeds less than 0.3 kilometers/hour to the energy conversion/nutrient separation digestion location.

**4.3 Digest the aquatic plants anaerobically**: The harvested plants are taken through processes that separate their energy from their plant nutrients. Our calculations are based on microbial anaerobic digestion in submerged geosynthetic containers. No energy is wasted to lift the seaweeds out of the water or dry the algae for combustion or squeeze out oil. The calculations are based on an average 2% solids input to the digestion container although 1% solids may be economically feasible.

The analysis is based on energy saving features that are not typical for anaerobic digestion when volume and time are expensive, such as at a municipal wastewater treatment plant. Not lifting the seaweed out of the water is one such energy saver. Not removing all the excess water surrounding the seaweed is another. (Seaweed has about 10 – 15% total solids when the external water is drained from the plants (Chynoweth, 2002).) Not heating or mixing the digester also saves energy. The trade-off for using less energy is having more time and volume available. We are projecting nearly complete digestion over an average period of 135 days. The online supplementary information file “OMA Calculations Supplement” provides more detailed information.

Our calculations are based on direct anaerobic digestion which produces biogas that is about 60% CH4 and 40% CO2, by volume (Chynoweth, 2002). We term this bio-CO2 to distinguish it from the combustion-CO2 that is produced during CH4 combustion. The Ocean Afforestation ecosystem could work with first doing other renewable energy processes, such as: oil squeezing, ethanol fermentation, and other such energy extraction processes, or product extraction, such as carrageenans, to improve the economics. When the waste from these other processes is fed to anaerobic digestion, the production of bio-CO2 would be less, but the amount of key plant nutrients recovered for recycling can be similar.

**4.4 Recover the separated bio-CO2 and bio-CH4**: When employing a differential dissolution technique, the tops of the geosynthetic digestion containers are held below about 100 meters (10 bar pressure). Our calculations are based on 200 meters depth where most of the carbon dioxide remains dissolved with the nutrients in the water inside the container. But relatively little methane dissolves. We expect the gas collected will be about 90% CH4 and 10% CO2 at the 200 meter depth when interpolating from equilibrium dissolved gas concentrations identified by (Van der Meer, 2005; Duan and Mao, 2006) and adjusting for partial pressure effects. Small amounts of H2S and N2O will remain dissolved. Deeper containers would return higher purity of CH4, perhaps better than 90%, but limited by partial pressure effects.

Even CH4:CO2 ratios as low as 1:1 may be combusted as-is to produce electricity. Higher than about 95% CH4 purity gases may be shipped as natural gas (depending on local requirements). Bio-CH4 can be converted into many products: synthetic diesel, methanol, jet fuel, plastics to make more OA facilities, etc.

The differential dissolution separation of bio-CO2 and bio-CH4 is but one of several options for concentrating the bio-CO2. Other technologies are typically employed at natural gas wellheads: membrane separation and pressure swing adsorption, for example.

More details of the arrangements preventing inadvertent CH4 release are included in the online supplementary information file “OMA Process Concepts.” An analysis showing the likely effect of potential N2O emissions is a small fraction of the CO2e captured is in the online supplementary information “OMA N2O Discussion.”

**4.5 Recycle the plant nutrients**: Microbial anaerobic digestion converts the biomass to biogas, plant nutrients, and water. The plant nutrients are mostly dissolved with some trapped in undigested solids. (The term “solids” is applied to what remains after anaerobic digestion even though the material may be 98% water. These “solids” include water, the ash component of the biomass, some undigested volatile “solids,” and the digesting microbes.) The nitrogen nutrients are mostly in the form of dissolved ammonia. The water with both liquid and solid nutrients is pumped to the ocean surface for distribution back to the algal forest. The nutrient distribution must be carefully managed to prevent ammonia toxicity and maximize macroalgal forest sustainability without microalgae “blooms.”

Our model includes the materials and energy to use all three of the following mechanisms to ensure maximum local recycling of the plant nutrients:

1. The dissolved nutrients are distributed evenly through a grid of floating hose. Because this is mostly ammonia at perhaps 800 mg/L of nitrogen, it may have to be distributed only during daylight hours when the algae are providing high dissolved oxygen concentrations so that aerobic microbes can quickly convert the ammonia to nitrate.
2. The undigested solids from digestion float in “tea-bags” through the forest providing a slow-release fertilizer. When the aerobic bacteria of the ocean surface have extracted most of the remaining plant nutrients, the remaining solids would be released to sink.
3. The nutrients from dying plants that are not harvested are pumped back up from the water or seafloor beneath the forest.

Table 1 indicates nutrient recycling is the most energy intensive process of the ecosystem. OMA covering 4% of the world’s ocean could be cycling about sixteen times the world’s 2010 synthetic nitrogen production. Hanisak (1981) indicates that recycling nutrients from anaerobic digestion will work well to sustain and perhaps increase macroalgae growth when combined with existing nutrients in the seawater. Recycled digester residues were shown to provide 62-83% (recycling efficiency) of the required nutrients for seaweed cultivation (Hanisak, 1981). Given ambient levels of inorganic nitrogen in Florida coastal waters, a recycling efficiency of only 45% would be required to support maximum *Gracilaria* productivity of 66 ash-free dry t/ha/yr (Chynoweth, 2002). (Note our energy calculations are based on conservative average projections of only 18 ash-free dry t/ha/yr.)

More details about a potential method for recovering ammonia to be recirculated to needy Ocean Afforestation ecosystems are presented in the online supplementary information file “OMA Gas membrane ammonia concentration.”

**4.6 Capture and compress the bio-CO2**: As the water with dissolved gas and nutrients is pumped to the ocean surface, the gases are captured at one atomosphere pressure as they come out of solution, comprising about 90% bio-CO2 and 10% bio-CH4. Our LCA presented below presumes energy is consumed moving the nutrient-laden water to the surface. In practice, gas bubbles coming out of solution could pump the nutrient return water above the ocean surface without the assumed parasitic energy loss.

To reduce greenhouse gas effects, our calculations include the materials and energy for a biologic removal process for any remaining bio-CH4 even though very little remains dissolved after the CO2 capture. The removal process is based on CH4 digesting microbes, as was found in the BP Gulf of Mexico oil spill (Kessler, et al., 2011). This ensures no CH4 or H2S is emitted to the atmosphere. Also, during the CH4 separation process, some of the ammonia will be converted to nitrate and be recycled with the rest of the nutrients.

All the remaining previously dissolved CO2, CH4, H2S, N2O, etc. is compressed to 50-bar and cooled as it is moved to the 500-meter depth in a pipe. (When in shallower water the CO2 is either chilled or compressed until it liquefies.) The compressed bio-CO2 condenses to a liquid. Other gases will either be recovered with most of the bio-CH4 or will remain dissolved in the liquid CO2. The (mostly) bio-CH4 will still be gaseous and will be used to produce more energy.

**4.7 Store the bio-CO2**: Ocean Afforestation concentrates CO2 from air that can be then be stored as pure gas or liquid CO2 with a variety of carbon storage technologies:

1. Deep geologic storage where the CO2 is either a gas, a supercritical fluid, or dissolved in saline aquifers several kilometers below the surface of the earth or the seafloor;
2. Shallow sub-seafloor storage, proposed by House, et al. (2006) where the CO2 is either a liquid or a hydrate perhaps 100 meters below the seafloor for a combined depth in excess of 3 kilometers;
3. Solid snow, proposed by Agee, et al. (2012) where the CO2 is a frozen solid “landfill” in Antarctica;
4. Artificial geologic seafloor storage where the CO2 is hydrate or denser-than-seawater liquid embedded in geosynthetic and other artificial geologic layers; or
5. Other future technology.

The International Maritime Organization (2011) indicates that sub-seabed CO2 storage is legal under recent amendments to the London Protocol. While dumping unconfined CO2 in the ocean is prohibited, both the London Protocol and the OSPAR Commission are silent on storing CO2 in containers on or in the seafloor. Research indicates that appropriate undisturbed geosynthetics will prevent contact with seawater for millennia (Rowe and Islam, 2009) and that, should the geosynthetic be damaged, insignificant CO2 hydrate dissolves before the damage could be detected and repaired. See the online supplementary information file “OMA Artificial Geologic Seafloor Storage” for a more detailed description of the technology and legal issues.

Our economics calculations for storing the OMA-derived pure CO2 are based on the geosynthetic containers because the locations ideal for OMA may lack the geology for the above options a, b, or c. In addition, the hydrate is more secure than gas or liquid CO2 as it is denser than seawater below 500 meters and could slowly dissolve only if water with less than the equilibrium dissolved CO2 is in direct contact and heat is available.

**4.8 Harvest fish and other products**: Additional potential sources of income include sustainable harvests of fish, sea vegetables, and other macroalgal products. Replacing fossil fuels will require so many macroalgal forests that the production of fish sufficient to provide 0.5 kg of fish and sea vegetables per person per day for 10 billion people could be almost an “incidental” by-product. In actuality, seafood production is likely to be a higher fraction of OMA products initially because food is generally a higher unit value than renewable energy. However, food uses can remove nutrients from an OMA ecosystem. We project that this would mean less than 2% of the annual forest nutrient requirement, in the 2050 scenario (OMA over 6% of world oceans) actually leaving the forests in the form of fish and other edible food stocks (based on data from Ramseyer, 2002). We have not included fish and other food products in our calculated energy balance. Potential other products include liquid fuels, agar, carrageenans, algin, etc.

Quast (1968) and Limbaugh (1955) report that the long-used southern California practice of harvesting kelp by “mowing” the top 1.3 meters three or four times a year had no effect on the sportfish populations or kelp productivity even though the harvesting operation was exporting plant nutrients from the ecosystem.

The actual quantities of increased fish production need to be studied for each region and species. As Graham et al. (2008) and Graham (2004) report, “One property clearly common to southern and central Californian kelp forests is the fundamental importance of kelp (primarily *Macrocystis pyrifera*) as an overwhelming source of primary production and detritus that fuels both the grazer-dependent and the detritus-dependent trophic pathways in these systems. The actual diversity of forest-dwelling species involved in either or both of these pathways has never been quantified, but clearly constitutes a major portion of the great diversity characteristic of these communities.” (2008, p. 7)

Another “product” of the Ocean Afforestation process can be concentrating fertilizer from ocean dead zones for application on terrestrial farms. Normally, the digestate with its seawater salt concentrations and 500-1000 mg/L ammonia concentrations would be too salty for land application and too dilute for transporting. However, gas membrane technology for concentrating the salty digestate ammonia into a concentrated freshwater fertilizer is presented in the online supplementary information file“OMA Ammonia Concentrating Process.”

**5.0 Potential scenarios to accomplish the objectives and economics**

Ocean Afforestation’s bio-CH4 is an appropriate fuel for bio-energy with carbon capture and storage (BECCS). We leave the discussion of BECCS technology to BECCS researchers. However, our scenarios include the expectation of a significant amount of BECCS and carbon capture and storage from fossil fuel exhaust in the future.

Table 1 combines the materials and energy input for the processes 4.1 – 4.7. (The costs and benefits of Process 4.8, fish and other products, are not related to negative carbon emissions.) The materials have been converted to their energy equivalent in kWh. These calculations are detailed in a not-yet-published paper with supporting documentation by Colosi (2012). The online supplementary information file “OMA Process Concepts” presents a conceptual outline of the process designs and many of the numbers used in the LCA, which are summarized in Table 1.

|  |
| --- |
| Table 1 - LCA calculations including materials and energy for OMA component processes |
| Process # | Process Description | kWh/ Mg of bio-CO2 stored |
| 4.4 | Energy produced from recovered CH4 | 4,400 |
| 4.1, 4.2 | Growing and harvesting macroalgae | -60 |
| 4.3, 4.4 | Digesting macroalgae and recovering CH4 | -150 |
| 4.5 | Recycling plant nutrients | -340 |
| 4.6 | Converting atmospheric CO2 to liquid CO2 at 500 meters depth | -430 |
| 4.7 | Converting liquid CO2 to permanently stored hydrate in artificial geologic seafloor containers | -80 |
| Total parasitic energy to operate above processes | -1,060 |
| **Net energy production** (rounded) | **3,300** |

Table 2 presents a scenario to attain a 2035 objective of net zero carbon emissions. The U.S. Energy Information Administration (EIA) (2011) presents current projections as 600 quadrillion Btu/yr (176 million GWh/yr) global fossil fuel use by 2035, producing 43 metric tons of CO2. The 2035 OMA scenario would have OMA displace nearly half of the fossil fuels, while half of OMA combustion-CO2 exhaust and a third of remaining fossil CO2 emissions would be captured from power plant exhaust and stored. In addition, all 8 billion tons from the OMA bio-CO2 would be stored, producing a carbon neutral world. Varying the proportions of fossil fuel use, other renewable energy, OMA energy, and OMA sequestration would yield other scenarios.

|  |
| --- |
| Table 2 - Scenarios for OMA to remove anthropomorphic CO2 |
| Scenario parameter during scenario year | Units | 2035 | 2050 | 2070 |
| Global energy quantity: EIA (2011) prediction of energy needed from fossil fuels in 2035 (600 Quads = 176 million GWh) | Quadrillion Btu/year | 600 | 600 | 600 |
| Total OMA renewable energy output, from CH4 (before efficiency losses electricity conversion) | 280 | 420 | 620 |
| Remaining fossil fuel energy in scenario year | 320 | 180 | 0 |
| Prediction of fossil CO2 emissions  | Billion metric tons of CO2/year | 43 | 43 | 43 |
| Fossil CO2 emissions replaced by combustion of bio-CH4 from OMA | -20 | -30 | -43 |
| Remaining fossil CO2 emissions | 23 | 13 | 0 |
| Less fossil fuel emissions neutralized by CCS | -8 | -9 | 0 |
| Less permanently stored bio-CO2 | -8 | -12 | -19 |
| Less permanent storage of half the combustion-CO2 from the bio- CH4, BECCS process | -8 | -11 | -17 |
| Net CO2 removal | 0 | -20 | -36 |
| Algal forest area during scenario year | % of ocean surface | 4% | 6% | 9% |
| Time to reduce atmospheric CO2 by 100 ppm, with oceans off-gassing half the removed CO2 | Years | - | 50 | 30 |

But even with net zero emissions, ocean acidification, climate changes, glacier melting, and methane hydrate dissociation will continue to cause human misery and mass extinctions, because atmospheric concentrations have run above 350 ppm. The 2050 scenario involves storing all the OMA bio-CO2, half of OMA combustion-CO2 exhaust, and two-thirds of fossil fuel emissions while producing 420 quads/yr (123 million GWh/yr) of energy. This removes a net 20 billion metric tons per year from the atmosphere. Unfortunately, atmospheric CO2 concentrations would drop at only half that rate as the oceans start giving up their dissolved CO2.

If atmospheric CO2 concentration (currently 400 ppm) continues to grow at its current business-as-usual exponential pace, it will be about 480 ppm in 2035 (Climate Interactive, 2011). However, perhaps rapid implementation of renewables, efficiency, OMA, and other carbon capture technologies will keep it below 450 ppm. Presuming 100 ppm of atmospheric concentration equates to 500 billion tons of CO2 and half of CO2 removed will re-emerge from the oceans, it would take the removal about 1,000 billion tons of CO2 to drop the atmospheric concentration from 450 ppm to 350 ppm. This could be done in 50 years using the 2040 scenario with OMA over about 6% of ocean surface. Or it would only take 30 years (and save much human misery) in the 2070 scenario with OMA over about 9% of ocean surface.

Note that the OMA renewable energy output of 176 million GWh/year (600 quadrillion Btu/year) is equivalent to all the energy projected to be needed from fossil fuels in 2035. We assume additional energy needed in future years would come from other renewables, such as wind, solar power, geothermal, and other ocean energy technologies. The timeline could be faster with more rapid implementation of other renewables and efficiency measures than currently assumed by EIA (2011).

The efficiency of CO2 removal is important and may be expressed by a life cycle assessment as two or more output/input ratios. Table 1 suggests the overall ecosystem ratio of energy output/input (including all materials properly amortized and expressed as energy and the losses from conversion to electricity at 45% efficiency) for the CO2 stored is 4. (This analysis is based on the method described by a private communication (Colosi, 2012) and including the analytical methods presented by Clarens, et al. (2011)). Another important ratio is about 20 tons of CO2 are stored for each ton of CO2 emitted from the energy required for capture and storage (processes 4.6 and 4.7).

Converting the above LCA numbers to costs using a forecasted cost for on-site generated electricity of $50/MWh and appropriate material costs would yield:

Process 4.6 – $9/ton of CO2 to capture, compress, and condense the CO2.

Process 4.7 – $7/ton of CO2 to manufacture, monitor, and maintain in perpetuity CO2 hydrate stored inside a geosynthetic container on the seafloor.

Total: $16/ton of CO2 from air to permanent storage.

**6.0 A path to deploying Ocean Afforestation**

Since Ocean Afforestation is an entire ecosystem and not a single product, it is difficult to do the entire process including storing carbon economically at a small scale. On the other hand, it is not necessary to wait for governments to impose a price on CO2 emissions, because OMA produces energy. Fiji and many other locations have looked at producing local biofuels (for example, Krishna, et al., 2009) but the potential of land-based feedstocks is small. However, recently, one of the authors (N'Yeurt) and other researchers at the University of the South Pacific have begun to see how Ocean Afforestation could expand to accomplish Fiji’s goal of replacing 100% of their expensive diesel-fueled electricity with bio-CH4 using about 20,000 hectares of their sheltered bays.

Our analysis indicates that sheltered water OMA can compete with Fiji’s diesel-powered electricity while providing many eco-benefits, such as cleaning up excess nutrient runoff. The report of a demonstration beginning in Fiji will be published in a couple years. (This would initially be without carbon storage.)

Beyond sheltered bays, OMA requires research and demonstrations of marine agronomy in the open ocean by recycling nutrients to grow macroalgae without producing excessive microalgae. New low-energy and low-materials techniques should be developed for growing and harvesting macroalgae. Marine microbiologists may find methanogens capable of faster digestion at higher dissolved gas concentrations than the present authors interpolated from previous studies using terrestrial methanogens. Techniques may be needed to address the potential loss of macroalgae during storms. (The submerged digesters and most other process equipment would be below the depth influenced by storms. The harvesting equipment may relocate to avoid storms.)

Trials should include liquid biofuel production and other systems for separating CO2 from CH4. OMA use of geosynthetics, other CH4 purifying techniques, and nutrient recycling may help other terrestrial bio-waste-to-energy and sequestration operations. There are potential feedbacks to investigate as large algal forests may change ocean albedo and thereby alter local temperatures. Increasing ocean temperatures and acidity from climate change could have an effect not only on macroalgal distribution and biodiversity, but also on their physiology and photosynthetic performance.

We project it could take up to five years (2013-2018) to get an initial demonstration 10,000 hectare forest operating economically in a near-shore sheltered water environment (involving an investment of about $20 million). This forest may be located where there are sufficient existing nutrients that nutrient recycling needs would be minimal and inexpensive.

It could take another ten years (2018-2028) to get many sheltered water 10,000-hectare forests operating. Initial forests may be located where there are sufficient existing nutrients that nutrient recycling needs would be minimal and inexpensive. The sheltered water approach could involve as much as 0.3% of the ocean’s surface (1 million km2). In this case, ‘sheltered water’ may be the entire Mediterranean Sea, the Gulf of California, and other such bodies of water where tropical storms are rare or enclosed, perhaps 4 million km2. Sheltered water can be any depth. Occupying a quarter of the available sheltered water may be a challenge, but all the sheltered water operations will put only a small dent in humanity’s CO2 debts. Open ocean operations are needed.

The reason OMA expansion can be so rapid is that the basic technology involves low-tech components, such as harvesting nets, large geosynthetic (plastic) bags, and pipes, with the methane feeding into existing natural gas and diesel power plants. Also, many sheltered waters suffer from an over-abundance of anthropomorphic nutrients.

During these ten years (2018-2028) the first open-ocean 10,000-hectare forest could be developed with an investment of perhaps $100 million. But it could take another seven years (2028-2035) to get many open-ocean 10,000-hectare forests operating. Note the long-term goal of 9% ocean coverage (32 million km2) is daunting from an occupied space and necessary technology perspective. This surface area represents most of every ocean gyre. On the other hand, collecting and removing plastics from ocean gyres could be another OMA product.

Other issues that may slow deploying OMA and carbon storage include gathering start-up or expansion nutrients and energy infrastructure. In the steady state, Ocean Afforestation nutrients cycle in a tight circle. When increasing the size of the algal forest, nutrients must come from outside the tight circle. Where there are anthropomorphic nutrients, the nutrient diversion recreates a more pre-human environment. In either case, about 140 million metric tons of nitrogen are needed for each increase of Ocean Afforestation area by 0.35% of total ocean area. It appears necessary to increase Ocean Afforestation area at 0.35% per year for several decades in order to drop atmospheric CO2 below 350 ppm before the end of the century.

Whatever fuel is produced will require transportation and conversion. When the OMA energy product is pure bio-CH4, it is identical to natural gas. Currently inexpensive natural gas is displacing coal as the fuel of choice for electricity generation. The world is already building more power plants fueled by natural gas and the associated liquefied gas transportation systems. Those power plants fueled by bio-CH4 and outfitted with exhaust capture can continue generating energy, capturing, and storing bio-CO2. New infrastructure required for OMA produced energy is not likely to be a limiting factor to rapid expansion. New infrastructure for other products: fish and other macroalgal products may be important for economics but the volumes are so much less that building their demand and infrastructure is not likely to limit forest expansion.

Quickly implementing Ocean Afforestation would be an effort on the order of putting a man on the moon, but both less expensive and likely a much better return on investment. Research and development is needed in ocean ecosystems, marine biology, ocean chemistry and physics, ocean microbiology, geosynthetics, ocean engineering, economics, business, international law, and more.

**Supplementary Information Available**

The following supplementary files regarding OMA calculations and processes are available at <http://dx.doi.org/10.1016/597j.psep.2012.10.008>

- OMA Process Concepts

- OMA Discussion of Macroalgae Production and Density

- OMA Calculations Supplement

- OMA N2O Discussion

- OMA Artificial Geologic Seafloor Storage of CO2

- OMA Gas Membrane Ammonia Concentration

**References**

Agee, E., Orton, A., Rogers, J., 2012. CO2 Snow Deposition in Antarctica to Curtail Anthropogenic Global Warming. J. Clim. 2012 (in press). <http://dx.doi.org/10.1175/JAMC-D-12-0110.1>

Barton, A., Hales, B., Waldbusser, G.G., Langdon, C., and Feely, R.A., 2012. The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. Limnol. Oceanogr. 57, 698–710.

Bruton, T., Lyons, H., Lerat, Y., Stanley, M., and Rasmussen, M.B., 2009. A review of the potential of marine algae as a source of biofuel in Ireland. Sustainable Energy Ireland, Dublin, Ireland.

Chung, I. K., Beardall, J., Mehta, S., Sahoo, D., Stojkovic, S., 2011. Using marine macroalgae for carbon sequestration: a critical appraisal. J. Appl. Phycol. 23, 877-886.

Chynoweth, D.P. 2002. Review of Biomethane from Marine Biomass. Department of Agricultural and Biological Engineering, University of Florida. <http://abe.ufl.edu/chyn/Webpagecurrent/publications_dc.htm>

Clarens, A.F., Nassau, H., Resurreccion, E.P., White, M.A., and Colosi, L.M., (2011). Environmental Impacts of Algae-Derived Biodiesel and Bioelectricity for Transportation Environ. Sci. Technol. 45, 7554–7560.

Colosi, L., 2012. Private communication.

Day, J.G., Slocombe, S., Stanley, M.S., 2011. Algal Biofuels: Biological Bottlenecks. Eur. J. Phycol. 46 (Supplement 1), 60-61.

Duan, Z., Mao, S., 2006. A thermodynamic model for calculating methane solubility, density and gas phase composition of methane-bearing aqueous fluids from 273 to 523 K and from 1 to 2000 bar. Geochim. Cosmochim. Acta, 70, 3369–3386.

Gao, K., Aruga, Y., Asada, K., Ishihara, T., Akano, T., Kiyohara, M., 1991. Enhanced growth of the red alga Porphyra yezoensis Ueda in high CO2 concentrations. J. Appl. Phycol. 3, 355–362.

Graham, M.H., 2004. Effects of local deforestation of the diversity and structure of southern California giant kelp forest food webs. Ecosystems 7, 341-357.

**Graham, M.H.**, Halpern, B.S., Carr, M.H., 2008. Diversity and dynamics of Californian subtidal kelp forests, in: McClanahan, T.R., Branch, G.R. (Eds.), Food Webs and the Dynamics of Marine Benthic Ecosystems, Oxford University Press, United Kingdom, pp. 103-134.

Hanisak, M.D., 1981. Recycling the residues from anaerobic digesters as a nutrient source for seaweed growth. Bot. Mar. 24, 57–62.

House, K.Z., Schrag, D.P., Harvey, C.F., Lackner, K.S. 2006. Permanent carbon dioxide storage in deep-sea sediments, Proc. Natl. Acad. Sci. USA 103, 12291–12295.

International Maritime Organization, 2011. Carbon Dioxide capture and storage in geological formations as clean development mechanism project activities. <http://unfccc.int/files/meetings/cop_16/application/pdf/cop16_cmp_ccs.pdf>

Kessler, J.D., Valentine, D.L., Redmond, M.C., Du, M., Chan, E.W., Mendes, S.D., Quiroz, E.W., Villanueva, C.J., Shusta, S.S., Werra, L.M., 2011, A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. Science 331, 312.

Krishna, I., Bukarau, L., Fairbairn, P., Mario, R., 2009. Potential for liquid biofuels in Fiji. SOPAC Miscellaneous Report 677. Suva, Fiji. <http://ict.sopac.org/VirLib/MR0677.pdf>

Lenstra, J., Reith, H., van Hal, J., 2011. From seaweed to chemicals and fuels: Current activities in the Netherlands on seaweed cultivation and biorefinery, Energy Research Centre of the Netherlands. <http://www.aquafuels.eu/attachments/076_11%20-%20H.Reith%20-%20From%20seaweed%20to%20fuel.pdf>

Limbaugh, C., 1955. Fish life in the kelp beds and the effects of kelp harvesting. University of California Institute of Marine Resources, IMR Reference 55-9. San Diego, California, USA.

Miles, N.L., Richardson, S.J., Davis, K.J., Lauvaux, T., Andrews, A.A., West, T.O., Bandaru, V., Crosson, E.R., 2012. Large amplitude spatial and temporal gradients in atmospheric boundary layer CO2 mole fractions detected with a tower-based network in the U.S. upper Midwest. J. Geophys. Res. 117, G01019.

Monaco Declaration 2008. Second International Symposium on the Ocean in a High-CO2 World, Monaco, October 2008.
http://www.ocean-acidification.net/Symposium2008/MonacoDeclaration.pdf

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G., 2009. Blue carbon. A rapid response assessment. United Nations Environment Programme.

Oilgae 2011. Oilgae guide to fuels from macroalgae. <http://www.oilgae.com/ref/report/report.html>

Pereira, R. and Yarish, C., 2008. Mass Production of Marine Macroalgae, in: Sven Erik Jørgensen, S.E., Fath, B.D. (Eds.), Ecological Engineering. Vol. 3 of Encyclopedia of Ecology. Elsevier, Oxford, pp. 2236-2247.

Quast, J.C., 1968. Effects of kelp harvesting on the fishes of the kelp beds, in: North, W.J., Hubbs, C.L. (Eds.). Utilization of kelp-bed resources in southern California. State of California Resources Agency and Fish and Game, Sacramento, California, USA.

Ramseyer, L.J., 2002. Predicting Whole-Fish Nitrogen Content from Fish Wet Weight Using Regression Analysis. North American Journal of Aquaculture, 64,195-204.

Roesijadi, G., Copping, A.E., Huesemann, M.H., Forster, J., Benemann, J.R., 2008. Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products, Battelle Pacific Northwest Division Report, Number PNWD-3931.

Roesijadi, G., Jones, S.B., Snowden-Swan, L.J., Zhu, Y., 2010. Macroalgae as a Biomass Feedstock: A Preliminary Analysis, PNNL-19944.

Rowe, R.K., Islam, M.Z., 2009. Impact of landfill liner time–temperature history on the service life of HDPE geomembranes. Waste Manag. 29, 2689-2699.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.H., Kozyr, A., Ono, T., Rios, A.F., 2004. The oceanic sink for anthropogenic CO2. Science 305, 367–371.

U.S. Energy Information Administration 2011. International Energy Outlook 2011. (data from: http://www.eia.gov/forecasts/ieo/world.cfm and http://www.eia.gov/forecasts/ieo/emissions.cfm)

Van der Meer, B., 2005. Carbon dioxide storage in natural gas reservoirs. Oil Gas Sci. Technol. 60, 527-536.

1. Abbreviations appearing later:

OMA is Ocean Macroalgal Afforestation, which is synonymous with “Ocean Afforestation” in this paper.

bio-CO2 is carbon dioxide when produced by anaerobic digestion; and

combustion-CO2 is carbon dioxide when produced by OA’s bio-CH4 (methane) combustion. [↑](#footnote-ref-1)