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Negative carbon via Ocean Afforestation

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A B S T R A C T

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.

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1. 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.

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- 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 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. Historic discussions of macroalgal 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., 2011). 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. 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:

- 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.
- 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
- 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.

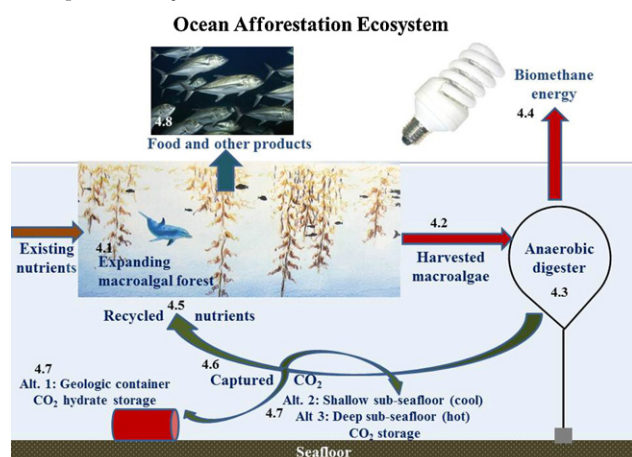
Produce environmentally and economically sustainable on-going renewable energy, thus preserving fossil fuels to provide chemicals for future generations, while providing income for maintaining the stored CO₂.

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.

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.

4. 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 "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., 2011; 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, "OMA 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 1 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 km at speeds less than 0.3 km/h 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 "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 m (10 bar pressure). Our calculations are based on 200 m 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 m 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 well-heads: membrane separation and pressure swing adsorption, for example.

More details of the arrangements preventing inadvertent CH₄ release are included in the [online supplementary information “OMA Process Concepts.”](#) An analysis showing the likely effect of potential N₂O emissions is a small fraction of the CO_{2e} 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:

- a. 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.
- b. 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.
- c. 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 “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 atmosphere 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-m 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:

- a. 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;
- b. Shallow sub-seafloor storage, proposed by House et al. (2006) where the CO₂ is either a liquid or a hydrate perhaps 100 m below the seafloor for a combined depth in excess of 3 km;
- c. Solid snow, proposed by Agee et al. (2012) where the CO₂ is a frozen solid “landfill” in Antarctica;
- d. Artificial geologic seafloor storage where the CO₂ is hydrate or denser-than-seawater liquid embedded in geosynthetic and other artificial geologic layers; or
- e. 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 “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

Table 1 – LCA calculations including materials and energy for OMA component processes.

Process #	Process description	kWh/Mg of bio-CO ₂ stored
4.4	Energy produced from recovered CH ₄	4400
4.1, 4.2	Growing and harvesting macroalgae	–60
4.3, 4.4	Digesting macroalgae and recovering CH ₄	–150
4.5	Recycling plant nutrients	–340
4.6	Converting atmospheric CO ₂ to liquid CO ₂ at 500 m depth	–430
4.7	Converting liquid CO ₂ to permanently stored hydrate in artificial geologic seafloor containers	–80
Total parasitic energy to operate above processes		–1060
Net energy production (rounded)		3300

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 m 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, alginate, etc.

Quast (1968) and Limbaugh (1955) report that the long-used southern California practice of harvesting kelp by “mowing” the top 1.3 m three or four times a year had no effect on the sport fish 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 “OMA Ammonia Concentrating Process.”](#)

5. 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 “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 2 presents a scenario to attain a 2035 objective of net zero carbon emissions. The [U.S. Energy Information Administration](#) 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.

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.

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/yr	600	600	600
Total OMA renewable energy output, from CH ₄ (before efficiency losses electricity conversion)		280	420	620
Remaining fossil fuel energy in scenario year		320	180	0
Prediction of fossil CO ₂ emissions	Billion metric tons of CO ₂ /year	43	43	43
Fossil CO ₂ emissions replaced by combustion of bio-CH ₄ from OMA		–20	–30	–43
Remaining fossil CO ₂ emissions		23	13	0
Less fossil fuel emissions neutralized by CCS		–8	–9	0
Less permanently stored bio-CO ₂		–8	–12	–19
Less permanent storage of half the combustion-CO ₂ , BECCS process		–8	–11	–17
Net CO ₂ removal		0	–20	–36
Algal forest area during scenario year	% of ocean surface	4%	6%	9%
Time to reduce atmospheric CO ₂ by 100 ppm, with oceans off-gassing half the removed CO ₂	Years	–	50	30

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 1000 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/yr) 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/t of CO₂ to capture, compress, and condense the CO₂.

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

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

6. 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 bio-fuels (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 ha 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 5 years (2013–2018) to get an initial demonstration 10,000 ha 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 10 years (2018–2028) to get many sheltered water 10,000-ha 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 overabundance of anthropomorphic nutrients.

During these 10 years (2018–2028) the first open-ocean 10,000-ha forest could be developed with an investment of perhaps \$100 million. But it could take another 7 years (2028–2035) to get many open-ocean 10,000-ha 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.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.psep.2012.10.008>.

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