Calculations Supplement for “Negative carbon via Ocean Afforestation”

See the "Algal yields" tab for the macroalgae production and density data.

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OMA Calculations for Table 2, for Year:		2035	2050	2070	Reference and Comment
Ocean afforested area in scenario year	% of ocean surface	4%	6%	9%	Ocean surface area is about 36 billion hectares.
Ocean forest area	hectares	1.4E+09	2.2E+09	3.2E+09	
Microalgae production rate	AFDW tons/ha/yr	18	18	18	Ash-free dry weight (AFDW). Marine biologists report annual productivity in dry tons AFDW/ha/yr, which includes nutrients not consumed in digestion. Each species of microalgae has a different annual productivity and ash free dry weight. Researchers in energy (particularly anaerobic digestion) report input feedstock as volatile suspended solids (VSS), which is essentially the same as AFDW. Refer to Algal yields tab and discussion document for more explanation of this number.
Microalgae harvest fraction	%	75%	75%	75%	To ensure sustainability, not all productivity is harvested. Storms wash away some seaweed. Forest dwelling fish and crustaceans eat some and some is dedicated to increasing biodiversity. 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. The range could be from 40% to 90%, we have chosen a likely value as 75%.
CH_4 yield during anaerobic digestion	std m^3/kg	0.4	0.4	0.4	Many factors go into total biogas production and the CH_4:CO_2 ratio: species, feedstock properties, time at digestion temperature, hydraulic detention time, microbe and feedstock retention time and more. A review of Chynoweth and Isaacson (1987) suggests CH_4 numbers between 0.2 - 0.44 std m^3/kg of VSS for sea kelp at 35°C digesting for 5 - 60 days. The present authors' model projects 0.4 m^3/kg will be produced over an average of 135 days, at ocean temperatures (which vary from about 15 - 30°C for likely locations and depths), and employing local natural seafloor or fish intestine microbes, which are adapted to the conditions of higher dissolved gas contents and ocean ambient temperatures. This number will vary with different species and digestion processes.
Total Ocean Afforestation (OMA) energy output	GWh/year	8.1E+07	1.2E+08	1.8E+08	Energy available from CH_4 before conversion to electricity expressed in three different kinds of units. Many different units (generally within the natural gas industry) are used to express the energy or quantity of CH4. Billions of metric tons are not typical units for CH_4 but provide a mental reference for the billions of tons of combustion-CO_2 produced by OMA combined with OMA.
	std m^3/kg	7.9E+12	1.2E+13	1.8E+13	
	billions of metric tons of methane	6	8	12	

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Ocean Afforestation (OMA) Calculations by N'Yeurt, Chynoweth, Capron, Stewart and Hasan (September 2012)

Year		2035	2050	2070	Reference and Comment
EIA (2011) prediction of energy needed from fossil fuels in 2035 (600 quads = 176 million GWh)	quadrillion Btu/year	600	600	600	U.S. Energy Information Administration's 2011 projection of energy needed from fossil fuels in 2035. We assume any increased energy needs beyond 2035 are met by other renewables, such as wind and solar.
Total OMA renewable energy output, expressed as CH_4 before electricity conversion in 2035		280	420	620	This the same total OMA energy output in three rows above, but expressed in quads.
Remaining fossil fuel energy in 2035		320	180	0	by subtraction
Fraction of fossil CO_2 emissions sequestered	%	33%	67%	no emissions	The three sources of CO_2 involved have different fractions captured and sequestered. All of the bio-CO_2 is sequestered. We assume 50% of the CO_2 from the bio-methane combustion is captured by 2035 and that fraction continues. The fossil CO2 capture fraction begins at a third in 2035. We assume the non-capturing plants are shut down by 2050. The result is that 67% is captured in 2050. All fossil fuel use is gone by 2070.
Fraction of bio-CO_2 from OMA permanently stored		100%	100%	100%	
Fraction of combustion CO_2 from OMA sequestered		50%	50%	50%	
Prediction of fossil CO_2 emissions	billion metric tons of CO_2/year	43	43	43	Assuming U.S. Energy Information Administration's 2011 projection of combusted CO2 emissions in 2035 remains constant, as explained four rows above.
Fossil CO_2 emissions replaced by combustion of bio-CO_2 from OMA		-20	-30	-43	See the Supplemental Information "OMA Process Concepts" for an explanation of calculations used to estimate the CH_4 production per area of ocean.
Remaining fossil CO_2 emissions		23	13	0	Forcasted fossil emissions for scenario year times fraction sequestered.
Less fossil fuel emissions neutralized by CCS		-8	-9	0	The remaining CO_2 emissions times the sequestered fraction.
Less permanently stored bio-CO_2 from OMA		-8	-12	-19	This is the mass of microbially produced OMA CO_2 times the fraction sequestered.
Less permanent storage of half the OMA combustion-CO_2, BECCS process		-8	-11	-17	This is the mass of CO_2 from the combustion of CH_4 produced by OMA anaerobic digestion times the fraction sequestered.
Net CO_2 removal		0	-20	-36	by subtraction
Mass of earth's atmosphere	billion metric tons	5.2.E+06			An average value from Scripps site at $5.1x10^{15}$, and NASA site at $5.3x10^{15}$ metric tons.
Mass of 200 ppm of CO_2 in atm		1,040			About a thousand metric tons of CO_2 changes atmospheric concentration by 200 ppm.
Time to reduce atmospheric CO_2 by 100 ppm	Years	-	50	30	This assumes that half of the CO_2 removed will come from the atmosphere and half from the oceans.
Annual nitrogen flux for the global ocean afforested area	million metric tons N/yr	1,600	2,400	3,500	Atkinson (1983) indicates about 6% of microalgae's dry weight is nitrogen. We assume that the nitrogen fraction is the same for both dry weight and ash-free dry weight (i.e. the nitrogen is represented in equal fractions in the volatile solids and in the ash).
Global synthetic nitrogen production in 2010 for terrestrial agriculture, mostly ammonia	million metric tons N/yr	100			Supply of and access to key nutrients (nitrogen, phosphorus, potassium) for fertilizers for feeding the world in 2050 (Blanco 2011). (shown only for comparison)

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Key Parameters	units	quantity		Reference and Comment
Ratio of energy (as electricity) output/input including bio-CO_2 storage	ratio	4		This is the energy after the CH_4 has been converted to electricity, based on the LCA calculation by Becker and Colosi (Colosi, 2012). The ratio is a probable number based on a Monte Carlo analysis which varies several inputs over ranges suggested by research mentioned above.
Ratio of GHG stored/emitted during the bio-CO_2 storage	ratio	20		The ratio is a probable number based on the LCA calculation by Becker and Colosi (2012). The favorable result partly stems from the carbon storage being a relatively small part of the ecosystem. For example, nutrient recirculation energy is part of the OMA energy production and thus is provided at low cost to the carbon storage.
Bio-CO_2 fraction of biogas before differential dissolution	ratio	40%		The CO_2 fraction varies for many of the same reasons as the CH_4 yield, explained in the text. Less CO_2 would mean more CH_4.
Bio-CO_2 fraction of biogas after differential dissolution	ratio	15%		The 85% CH_4 is possible when operating with the digester gas pressure of 20 bar (200 meters depth). Differential dissolution within anaerobic digestion has not been researched for the likely conditions. The authors expect partial pressure effects to limit the purity of the CH_4. The bio-CO_2 sequestration amounts would be higher with other CO_2-CH_4 separation processes.
Dissolved CO_2 equilibrium concentration at 200 meters depth	g/kg	25		B. van der Meer (2005) lists CO_2 solubility for temperature pressure conditions similar to those in the anaerobic digestion container. Z. Duan and S. Mao (2006) discuss CH_4 solubility. Digesters would operate at CH_4 dissolution equilibrium. They may or may not operate at CO_2 dissolution equilibrium.
Dissolved CH_4 equilibrium concentration at 200 meters depth	g/kg	0.5		
Cost to capture CO_2 from air and compress it to a liquid	\$/t of CO_2	\$7		These costs are converted from the masses and energy consumption in the Becker and Colosi LCA (Colosi, 2012). The cost of electricity for the compression and other energy uses is assumed to be \$50/MWh which is projected for on-site produced OMA electricity.
Cost for storage and monitoring of CO_2 as a hydrate in geosynthetic containers	\$/t of CO_2	\$9		
Total cost for capture from air and permanent sequestration	\$/t of CO_2	\$16		
Number of people on Earth	each	9.E+09		This is an example quantity for the actual number of people living on Earth in 2050.
Fish per day	kg/day	0.5		This is an example quantity, not that people would want or need to eat that much fish.
Nitrogen fraction in fish	g/kg of fish	28		Ramseyer (2002) explains a method for calculating the nitrogen (N) and protein content of fish. The quantity indicated is within a range which varies with species and the mass of individual fish.
Nitrogen in the fish people would consume in a year	Mg of -N/yr	5.E+07		Multiply number of people by kg of fish per day by nitrogen fraction.
Annual OMA nitrogen flux when OMA covers 6% of the world's ocean surface (2050 scenario)	Mg of -N/yr	2.4E+09		Previously calculated above.
Fraction of OMA nutrient flux exported as fish	ratio	2%		The fish and other foods from OMA are likely to move hundreds or thousands of kilometers from where they were grown. But if OMA is covering 4 to 9% of the oceans those nutrients will be returning to some other OMA operation shortly.

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References in addition to those included in the main article:

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