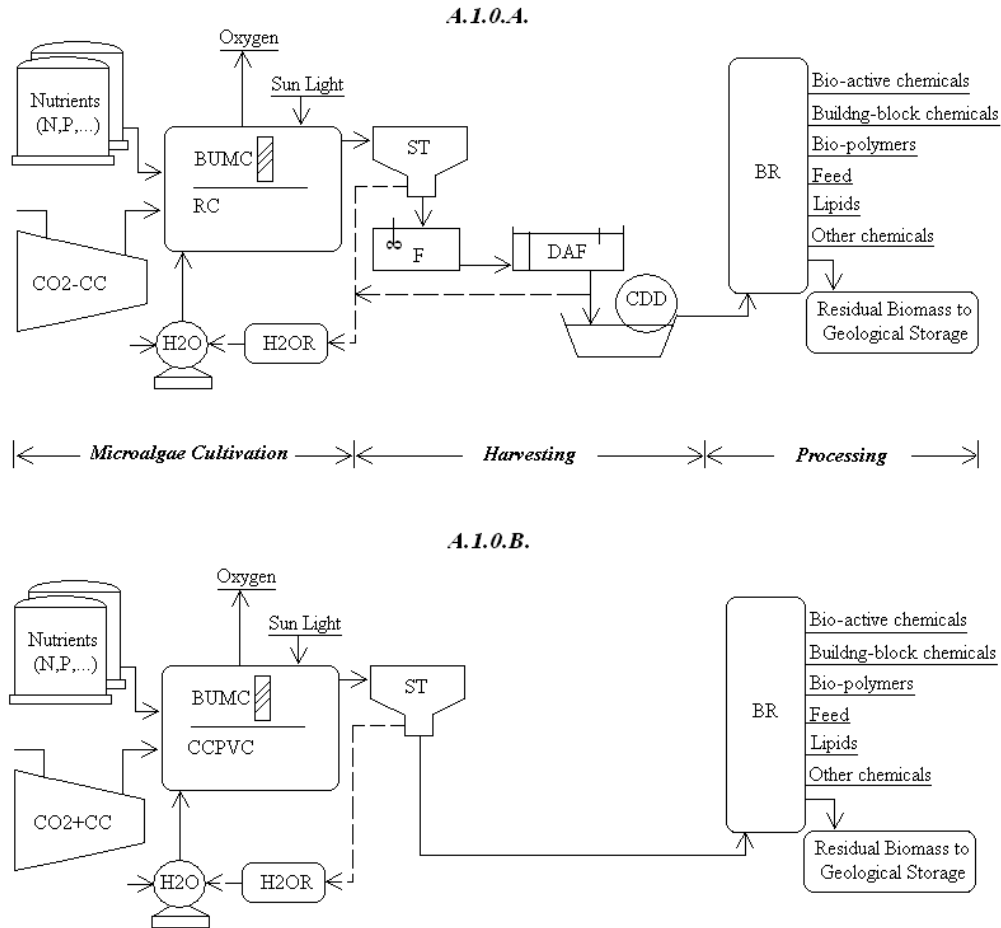# Appendix A. - Supplementary Data

Bilanovic D., Holland M., R. Armon

Microalgal CO_2 sequestering – Modeling microalgae production costs.

A.1.0. Process Flow Diagram

Figure A.1.0 Flow diagram of process for production and harvesting of microalgal biomass. A.1.0.A. Production and harvesting process schematics used in assessment of maximal total crude production costs of microalgae. A.1.0.B. Production and harvesting process schematics used in assessment of minimal total crude production costs of microalgae.

Legend: BUMC = Basic Unit for Microalgae Cultivation, RC = reinforced concrete, CCPCV = compacted clay and PVC lining, CO2+CC = CO2 costs with carbon credit,

CO2-CC = CO2 costs without carbon credit, H2OR = water recycling, ST = settling tank, F = flocculation, DAF = dissolved air flotation, CDD = centrifugation and/or drum drying. BF = bio-refinery. Modified after Berend et al. [23], and Shelef et al. [41].

A.1.1. Yield of Microalgal Biomass

In theory microalgae can use up to 9% of the incoming solar energy to produce 280 mt^{-1} of dry biomass ha^{-1} y^{-1} while fixing/sequestering roughly 513.0 ton of CO_2 [7]. Much higher rate of CO_2 fixation (i.e. 1.85 times higher), and biomass production were reported in literature [28,29]. Industrial MCO2SF are likely to be five to eight orders of magnitude larger than laboratory reactors and will operate 340 to 365 days a year. In preparing this study we decided not to use high yields obtained on the laboratory scale in experiments that were shorter than few weeks [28, 29].

A yield of 50 metric tons of microalgae (dry weight) per hectare per year is rather common today in high rate algal ponds and other, industrial algae production facilities. Microalgae production and harvesting technology is still rather primitive and has a long way to go before 75 - 85% of the theoretical biomass yield is achieved in industrial plants. Minimal algal yield of 50 and maximal of 100 metric ton dry biomass per hectare per year were used to calculate maximal and minimal production costs of microalgae (Table 1 and Appendix A.).

A.1.2. Construction Expenses - Basic Unit for Microalgae Cultivation (BUMC)

BUMC construction expenses include: A) construction of the basic unit for microalgae cultivation (see Figure A.1.0. and Section 2.1.), B) land acquisition, C) construction of roads and offices, D) capital expense.

A1) Maximal BUMC construction expenses (Figure A.1.0.A) The expensive way to construct BUMC of size of 22,333 m^2 is to make it out of reinforced concrete 0.1 m thick. Roughly 2,407 m^3 of cement are needed to construct such BUMC. Maximal BUMC construction expenses that include site preparation, masonry & reinforced concrete works, and other civil engineering works were estimated at $511,488.00 using a quote provided by a construction company located in Bemidji, USA.

A2) Minimal BUMC construction expenses (Figure A.1.0.B) The economic way to construct the BUMC includes: site leveling, spraying sea or brackish water over leveled soil to form salt crust upon drying (i.e. this method is used in Namibia to construct roads on desert sand), cover salt crust with PVC or similar lining, and construct BUMC walls from corrugated PVC, old tires, PVC lining, clay and a minimal amount of reinforced concrete. Total minimal BUMC building expenses were estimated at $179,375.00.

B1) Maximal land acquisition expenses were estimated at $250,000.00 assuming land price of $10.0/$m^2$.

B2) Minimal land acquisition expenses could be zero if land would be donated by local government or some other entity (i.e. power company that does not want to owe/operate MCO2SF could buy then donate land to MCO2SF to decrease its carbon tax).

C1) Maximal expenses of roads and offices construction were estimated at

$100,000.00 which represents 40% of the maximal land acquisition expenses (see B1).

C2) Minimal expenses of roads and offices construction were estimated at

$62,500.00 or 25% of the maximal land acquisition expenses (see B1).

D1) Maximal capital expenses for A1, B1, and C1 were estimated at $534,122.60

assuming interest rate of 3.5% and pay-back period of 30 years.

D2) Minimal capital expenses for expenses A2, B2, and C2 were estimated at

$58,050.00 assuming interest rate of 1.5% over 30 years period.

Maximal BUMC construction expenses (i.e. sum of A1, B1, C1, and D1) were

estimated at $1,395,611.56. The sum was divided by 3,345 to get $417.22 $ $t^{-1}ha^{-1}y^{-1}$ (US

dollars per metric ton algae biomass dry weight per hectare per year). The expense of

$417.22 $t^{-1}ha^{-1}y^{-1}$ was used to calculate maximal production cost of microalgae (see Table

1). Division factor (i.e. 3,345) is a product of microalgae yield (i.e. 50 metric tons dry

weight per hectare per year), BUMC size (i.e. 2.23 hectare), and pond "shelf life" of 30

years minimum.

Minimal BUMC construction expenses (i.e. sum of A2, B2, C2, and D2) were

estimated at $299,925.00, the sum was divided by 6,690 to get 44.83 $t^{-1}ha^{-1}y^{-1}$; the

expense was used to calculate minimal production cost of microalgae (see Table 1).

Division factor (i.e. 6,690) is a product of microalgae yield (i.e. 100 metric tons dry

weight per hectare per year), BUMC size (i.e. 2.23 hectare), and pond "shelf life" of 30

years minimum

A.1. 3. Expenses of CO_2, N and P Supply

Microalgal composition changes with availability of light, nutrients and other physic-chemical conditions [24,25]; for modeling purposes the C:N:P atomic ratio of 106:16:1 (i.e. the so called "Redfield ratio") was assumed to be constant.

Amounts of carbon, nitrogen and phosphorus required to produce 50.00 metric ton of microalgae are given in Table A.1.

Current atmospheric CO_2 concentration is at 390 ppm (i.e. 0.209 g C m^{-3} air). Assuming microalgae consume only 50% of C from the added air roughly 131 m^3 of air should be pumped per m^2 of BUMC per day to get biomass yield of 50 t $ha^{-1}y^{-1}$. At this pumping rate an apparent rise velocity of air bubble is around 0.003 m s^{-1} which indicates a need for additional mixing to keep microalgae in suspension (see A.1.6. Machinery Expenses).

Municipal wastewater contains 20.00 to 85.00 mg N L^{-1} and 4.00 to 15.00 mg P L^{-1}; there is enough P in municipal wastewater to provide all P to MCO2SF but not enough N [27, 49]. Assuming that 50% of N and P found in domestic wastewater are readily available for microalgal growth one needs to pump 37.4 to 402 liters of the wastewater per m^2 of BUMC to get microalgae yield of 50 t $ha^{-1}y^{-1}$ (Table A.1.). It follows that addition of N and P fertilizers, or industrial effluents rich in N like: a) agricultural wastewater, b) food industry wastewater (145 to 2,700 mg N L^{-1}), c) fertilizer production wastewater (200 to >6,000 mg N L^{-1}), or d) explosives industry wastewater that contains from 1500 to more than 12,500 mg N L^{-1} [35], will be required to produce 100 and more tons of microalgae per hectare per year.

CO_2 could be provided from air or by using CO_2 emissions from industry. Municipal or industrial wastewater could serve as source of N and P but one can also use N, P fertilizers. The use of CO_2, N and P that come as byproducts of other processes will have impact on microalgae production costs but here we did not discuss allocation of costs/benefits between parties involved because of it is impossible to know a priori positions and strategic interests of the parties involved.

Table A.1. Microalgae yield and daily C, N, P demands

Microalgae Yield		Carbon	Nitrogen	Phosphorus
$(t\ ha^{-1}\ y^{-1})^T$	$(g\ m^{-2}\ d^{-1})^G$	$(g\ m^{-2}\ d^{-1})^C$	$(g\ m^{-2}\ d^{-1})^N$	$(g\ m^{-2}\ d^{-1})^P$
50	13.70	11.41	2.01	0.28

T = Microalgae yield in metric ton dry weight per hectare per year; G = Microalgae yield in grams dry weight per meter square per day; C = Carbon demand in grams dry weight per meter square per day; N = Nitrogen demand in grams dry weight per meter square per day; P = Phosphorus demand in grams dry weight per meter square per day; Microalgal Biomass Mw $C_{106}N_{16}P$ =1527, C weight % =83.30, N weight % =14.67, P weight % = 2.03.

Comparison of prices of N and P fertilizers shows that the most economic N-fertilizer is anhydrous ammonia at $607 per ton N and the most expensive N-fertilizer is $(NH_4)_2SO_4$ at $1,538.00 per ton N; most economic P fertilizer is superphosphate at $1,555.00 per ton P and the most expensive $(NH_4)_2HPO_4$ at $2,157.00 per ton P [38].

E1) Maximal N&P expenses: Nitrogen supply in form of anhydrous ammonia, and phosphorus supply in form of superphosphate were assumed; estimate maximal N&P expenses per metric ton of microalgae are $120.81 (see Tables 1 and Appendix A).

E2) Minimal N&P expenses: To calculate minimal N&P expenses we assumed that domestic or industrial wastewater will be used as source of nitrogen and phosphorus. Negative expenses of -$0.00289\$ m^{-3} of wastewater was assumed; estimated minimal N&P expenses per metric ton of microalgae was calculated at -$10.00 t $ha^{-1}y^{-1}$ (see Tables 1, and Appendix A).

F1) Maximal CO_2 expenses were calculated for the BUMC at $ 7,634.00 (assuming CO_2 costs of $25 ton^{-1} and 50% CO_2 utilization rate). Estimate maximal CO_2 expenses per metric ton of microalgae are $152.68 (Tables 1 and Appendix A)

F2) Minimal CO_2 expenses were calculated at -$3,053.60 assuming negative cost of carbon (i.e. -$20 ton^{-1} CO_2); negative expenses were assumed because of the impending carbon tax, estimated minimal CO_2 expenses per metric ton of microalgae are -$61.07. It should be added that carbon tax of -$20.00 t^{-1} CO_2 is quite conservative since the cost for geo-sequestering of CO_2, without transportation costs, is estimated at $50.00 ton^{-1} CO_2 [10].

A.1.4. Harvesting Equipment Expenses

G1) *Maximal expenses of harvesting equipment (Figure A.1.0.A)* consist of: a) settling tank construction expenses (i.e. capacity of up to 5,000 m^3 microalgae suspension per day), b) flocculation/dissolved air flotation construction and machinery expenses, c) separation/centrifugation expenses, and iv) capital expenses for "a+b+c" are estimated at 60% of the maximal construction expenses (see 2.2.1) which yields $837,366.90; the

sum was divided by 3,345 to get $250.34 t ha^{-1}y^{-1}; the sum of $250.34 was used to calculate maximal harvesting cost of microalgae (see Table 1, Section 2, and Appendix A).

G2) *Minimal expenses of harvesting equipment (Figure A.1.0.B)* To estimate microalgae minimal harvesting costs we assumed that: a) microalgal suspension will be harvested in a low tech settling tank of 2,000 m^3, b) harvesting efficiency will be in range 50 to 90%, c) after harvesting microalgal slurry will be sold/used as is, and d) supernatant will be returned to BUMC. Construction and capital expenses for harvesting equipment were estimated at $279,066.60; the sum was divided by 6,690 to get $41.71 t ha^{-1}y^{-1} which was used to calculate minimal harvesting expenses of microalgae (see Table 1, Section 2, and Appendix A).

A.1.5. Labor Expenses

To estimate labor expenses we consulted local companies for wages in Bemidji area; to calculate hourly wages outside the USA data on GPN per capita in the USA and sub-Saharan Africa were taken from "The World Factbook" [22]; it was assumed that wage ratio (i.e. wage in Country A / wage in the USA) is roughly equal to GNP per capita ratio (i.e. GNP per capita in Country A/ GNP per capita in the USA). An estimated average hourly wages for sub-Saharan Africa are roughly 45 times smaller than in the USA; such low hourly wages will yield negligible labor expense. We used instead 6 to 9 times smaller hourly wages than in the USA to calculate minimal labor expenses.

Assumptions pertinent to maximal and minimal labor expenses are given in Table A.2.; maximal labor expenses of microalgae production were estimated at $71.17 t ha^{-1}y^{-1}, minimal labor expenses of microalgae production were estimated at $6.55 t ha^{-1}y^{-1}.

Table A.2. Assumptions pertaining to minimal and maximal labor expenses

Function	Employees per hectare of BUMC		Wages ($/hour)	
	Minimum	Maximum	Maximum	Minimum
Plant manager	0.002	0.003	35.00	4.00
Shift supervisors	0.008	0.010	28.00	3.00
Operators	0.038	0.050	14.00	2.00
Technicians	0.008	0.010	21.00	2.60
Electricians	0.003	0.004	21.00	2.60
Mechanics	0.003	0.004	21.00	2.60
Accountant	0.002	0.003	18.00	2.10
Logistics & Supply	0.003	0.004	18.00	2.20
Adm. Assistant	0.002	0.003	12.00	1.80

A.1.6. Machinery Expenses

These expenses include: paddle wheels, CO_2 compressor, diffusers, piping and valves, cables, pumps, measuring and control equipment, other instrumentation, and associated capital expenses.

Maximal machinery expenses (Figure A.1.0.A.) are estimated at 40% of maximal construction expenses of BUMC (see section 2.1.) and are equal to $558,244.60; the sum

was divided by 3,345 to get \$166.89 t $ha^{-1}y^{-1}$; the sum was used to calculate maximal machinery expenses of microalgae production (see Table 1, Section 2.1., and Appendix A).

Minimal machinery expenses (Figure A.1.0.B) are estimated at 25% of maximal construction expenses for BUMC and are equal to \$348,902.90; the sum was divided by 6,690.00 to get \$52.15 t $ha^{-1}y^{-1}$ that was used to calculate minimal machinery expenses of microalgae production (see Table 1, Section 2.1., and Appendix A).

A.1.7. Operation and Maintenance

O&M expenses include: working capital expenses, power expenses (i.e. electricity and gasoline/gas for: mixing, harvesting, water pumping, CO_2 pumping), flocculants costs, and other expenses.

Maximal O&M expenses are estimated at \$139,561.15 (i.e. 10% of maximal construction expenses) the sum was divided by 3,345 to get \$41.72 t $ha^{-1}y^{-1}$ that was used to calculate maximal machinery expenses of microalgae production (see Table 1, Section 2, and Appendix A).

Minimal O&M expenses are estimated at \$69,780.60 (i.e. 5% of maximal construction expenses) the sum was divided by 6,690.00 to get \$10.43 t $ha^{-1}y^{-1}$ that was used to calculate minimal machinery expenses of microalgae production (see Table 1 - Section 2, and Appendix A).

A.1.8. Total Crude Production Costs of Microalgae

Table A.3. Examples of known production-specific expenses and associated total crude production costs of microalgae (TCPCM)

MS No.	Variable = Known Production-Specific Expense ($ t^{-1} ha^{-1}y^{-1})							TCPCM
	CE	CO2E	NPE	HE	LE	ME	OME	$ t^{-1} ha^{-1}y^{-1}
97	44.83	-61.07	-10.00	41.71	6.55	52.15	10.43	84.60
105	44.83	-61.07	-10.00	41.71	6.55	52.15	41.73	115.90
74	44.83	-61.07	-10.00	41.71	71.17	52.15	10.43	149.22
86	44.83	-61.07	-10.00	41.71	71.17	52.15	41.73	180.52
72	44.83	-61.07	-10.00	41.71	6.55	166.89	10.43	199.34
6	417.23	152.69	120.82	250.35	71.17	52.15	41.73	1106.14
89	417.23	152.69	120.82	250.35	6.55	166.89	10.43	1124.96
90	417.23	152.69	120.82	250.35	6.55	166.89	41.73	1156.26
93	417.23	152.69	120.82	250.35	71.17	166.89	10.43	1189.58
29	417.23	152.69	120.82	250.35	71.17	166.89	41.73	1220.88

MS No. = Modeling Scenario Number out of 152 tested. Known Production-Specific Expenses: CE = Construction expenses, CO2E = carbon dioxide expenses, NPE = nitrogen and phosphorus expense, HE = Harvesting expenses, LE = Labor expenses, ME= Machinery expenses, OME = Operation and maintenance expenses, and TCPCM = Total Crude Production Costs of Microalgae.

A.1.9. Crude and Adjusted Production Costs

Table A.4. Total crude and adjusted total production costs of microalgae

MS No.	TCPCM ($ t^{-1} ha^{-1} y^{-1})	ATPCM ($ t^{-1} ha^{-1} y^{-1})
97	84.60	73.60
105	115.90	143.72
74	149.22	158.17
86	180.52	234.68
72	199.34	151.50
6	1106.14	1095.08
89	1124.96	1451.20
90	1156.26	1503.14
93	1189.58	1142.00
29	1220.88	1428.43

MS No. = Modeling Scenario Number out of 152 scenarios tested. TCPCM = Total Crude Production Costs of Microalgae; ATPCM Adjusted Total Production Cost of Microalgae = (TCPCM * Random Number in range 0.7 to 1.3).

A.1.10. Analysis of Variance for Model

Table A. 5. Analysis of variance for Central Composite Design Response Surface Model

	S^2	dF	M^2	FV	pV	Note
MODEL	$8.109*10^6$	9	$9.010*10^5$	67.30	<0.0001	SI
CE	$4.294*10^6$	1	$4.294*10^6$	320.70	<0.0001	
CO2E	$1.119*10^6$	1	$1.119*10^5$	83.54	<0.0001	
NPE	$7.600*10^5$	1	$7.600*10^5$	56.76	<0.0001	
HE	$1.134*10^6$	1	$1.134*10^6$	84.70	<0.0001	
LE	$1.790*10^5$	1	$1.790*10^5$	13.37	<0.0001	
ME	$5.593*10^5$	1	$5.593*10^5$	41.78	<0.0001	
OME	$3.441*10^4$	1	$3.441*10^4$	2.57	0.0042	
CE*HE	$3.004*10^4$	1	$3.004*10^4$	2.24	0.2954	
CO2E*NPE	3.430	1	3.430	$2.56*10^{-4}$	0.8665	
RESIDUAL	$1.901*10^6$	142	$1.339*10^4$			
Lack of Fit	$1.879*10^6$	133	$1.413*10^4$	5.68	0.3691	NS
Pure Error	$2.239*10^4$	9	$2.488*10^3$			
Cor Total	$1.001*10^7$	151				

S^2=Sum of squares; dF = degree of freedom; M^2 =Mean square; FV = F value; pV = p value; SI = significant; NS = not significant. Mean = 658.81; St.Dev.= 115.71; R^2 = 0.8101; Adj R^2 = 0.7980; C.V. % = 17.56; Construction expenses (CE), Carbon dioxide expenses (CO2E), Nitrogen and phosphorus expense (NPE), Harvesting expenses (HE), Labor expenses (LE), Machinery expenses (ME, Operation and maintenance expenses (OME).