www.sphinxsai.com

ChemTech

International Journal of ChemTech Research
CODEN (USA): IJCRGG ISSN: 0974-4290
Vol.8, No.11 pp 237-249, 2015

Modeling of Solar Irradiance, Energy requirement for Microalgae CO_2 Sequestration Using MATLAB-Simulink

Sudharshan K[1], Sudhakar K[2]

[1]Department of Electrical and Electronics, PRIST University, Thanjavur, India

[2]Department of Energy, National Institute of Technology, Bhopal, India

Abstract: This paper presents an attempt of modeling a generalized Microalgae CO_2 Sequestration model using Matlab/Simulink software package, which can be representative for easy use on simulation platform. The proposed model is modeled in such a way with ease to user in handling and a dialog box like Simulink block libraries. This makes the generalized model easily simulated and analyzed in conjunction with power requirement for a maximum power utilized to cater the process of Sequestration at various levels. Taking the effect of solar Irradiance into consideration, the Micro-Algae growth kinetics and CO2 absorption rate of Sequestration model was simulated using the proposed model. This enables the dynamics of pilot plant system to be easily simulated, analyzed.

Keywords: Micro-Algae; CO_2 Sequestration, Solar Energy, MATLAB model.

Introduction:

With raising concerns about fuel deficit, hiking oil prices, global warming, and damage to ambient nature and ecosystem, there comes now promising incentives to develop alternative energy resources with high efficiency and low emission are of great importance. Among the renewable energy resources, the energy through the Solar effect can be considered the most essential and primary sustainable resource because of the abundance. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost. Recently, solar energy in CO_2 Sequestration system by growing Micro bio-Algae species is likely recognized and widely utilized to the forefront in fuel utilities to extract oil out of populated algae in the raceways and open/closed photo bio-reactors. It can generate electricity without environmental impact and contamination when the oil is used in replacement of oil fired power stations, else the co firing of Algae residues in compliment to conventional coal fired power plants. Being biological systems, the Carbon sequestrating Solar System (CCSS) is static, quite, and free of moving parts, and these make it have little operation and maintenance costs. Even though the system is posed to its high capital fabrication cost and low conversion efficiency, the hiking oil prices make solar energy naturally viable energy supply with potentially long-term benefits. CCSS module represents the fundamental natural incubator unit of a bio-chemical system. The output characteristics of the module depend on the Solar Insolation, the CO_2 and assumed standard nutrients (nitrogen, phosphorus, potassium in sols). Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of maximum output for various locality applications. The mathematical models used in computer simulation have been built for over the past four decades. However in MATLAB/Simulink package there is no CCSS model to integrate with simulation technology. Thus, it is difficult to simulate and analyze in the generic modeling of sequestration system. This motivates to develop a generalized model for Carbon sequestration using Simulink. The main contribution of this paper is the implementation of a generalized model in the form of masked block, which has a user-friendly icon and dialog in the same way of Simulink block libraries or other component-based sub-system simulations.

Materials & Methods:

Algae farms on the use of open shallow ponds were CO2 emitted from the power plants are bubbled into the raceway ponds and utilized by algal strains growing the aqueous suspensions. The program targeted coal -fired power plants as the main sources of CO_2. [1] In the traditional raceway design, culture depth and biomass concentrations have to be maintained low to ensure efficient penetration of sunlight. Large-scale raceways for algal cultivation have been operated with depths ranging from 30 to 50 cm. [2]

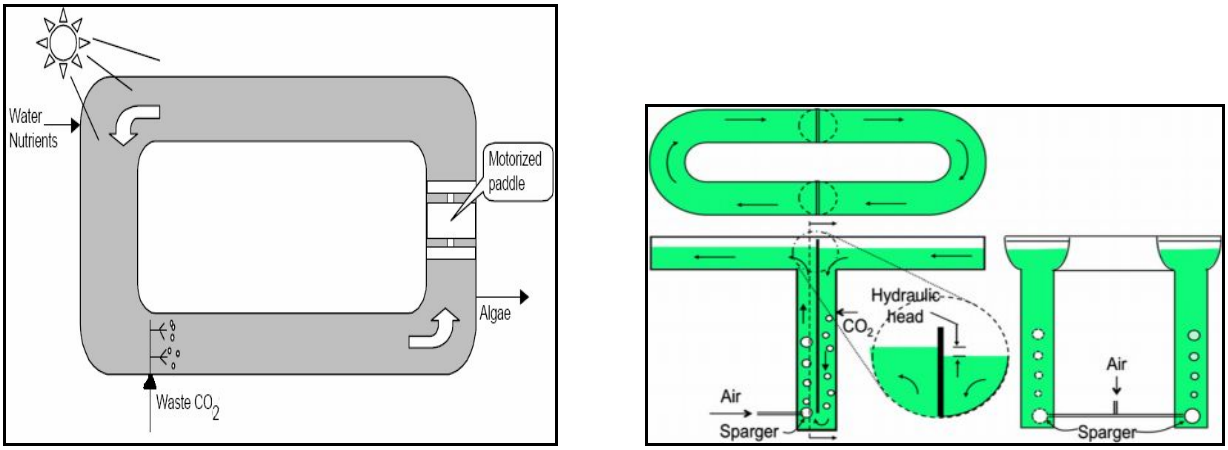


Figure 1: **Sun, Water, Nutrients and CO2 input to raceway ponds** [1] [3]

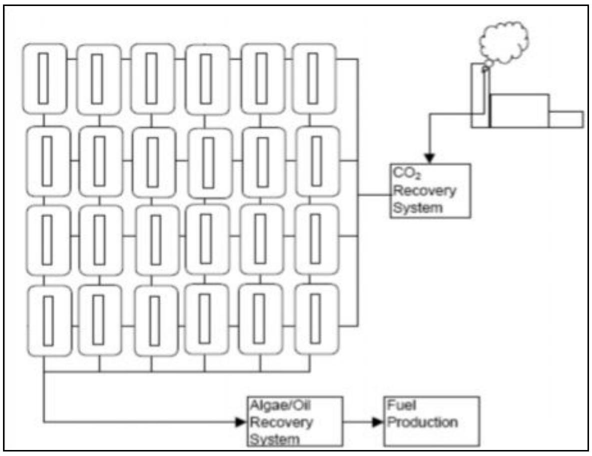


Figure 2: **Array set-up of raceway ponds [1]**

Here are in a position to estimate and model the Pond raceway's intake of various parameters especially sunlight (Photo synthetically active radiation-PAR), Yield of Algae, and auxiliary power consumptions that has to meet out in operating the raceway to maintain the yield as optimum.

i. Modeling of the Solar Insolation over the Micro Algae culture in Raceway:

The Insolation on the Culture depends upon the geometric position (demoted by latitude and longitude), which determines the site getting the interaction with sun (Solar Angle) and the time of the day (denoted by solar hour angle, declination, local solar time).

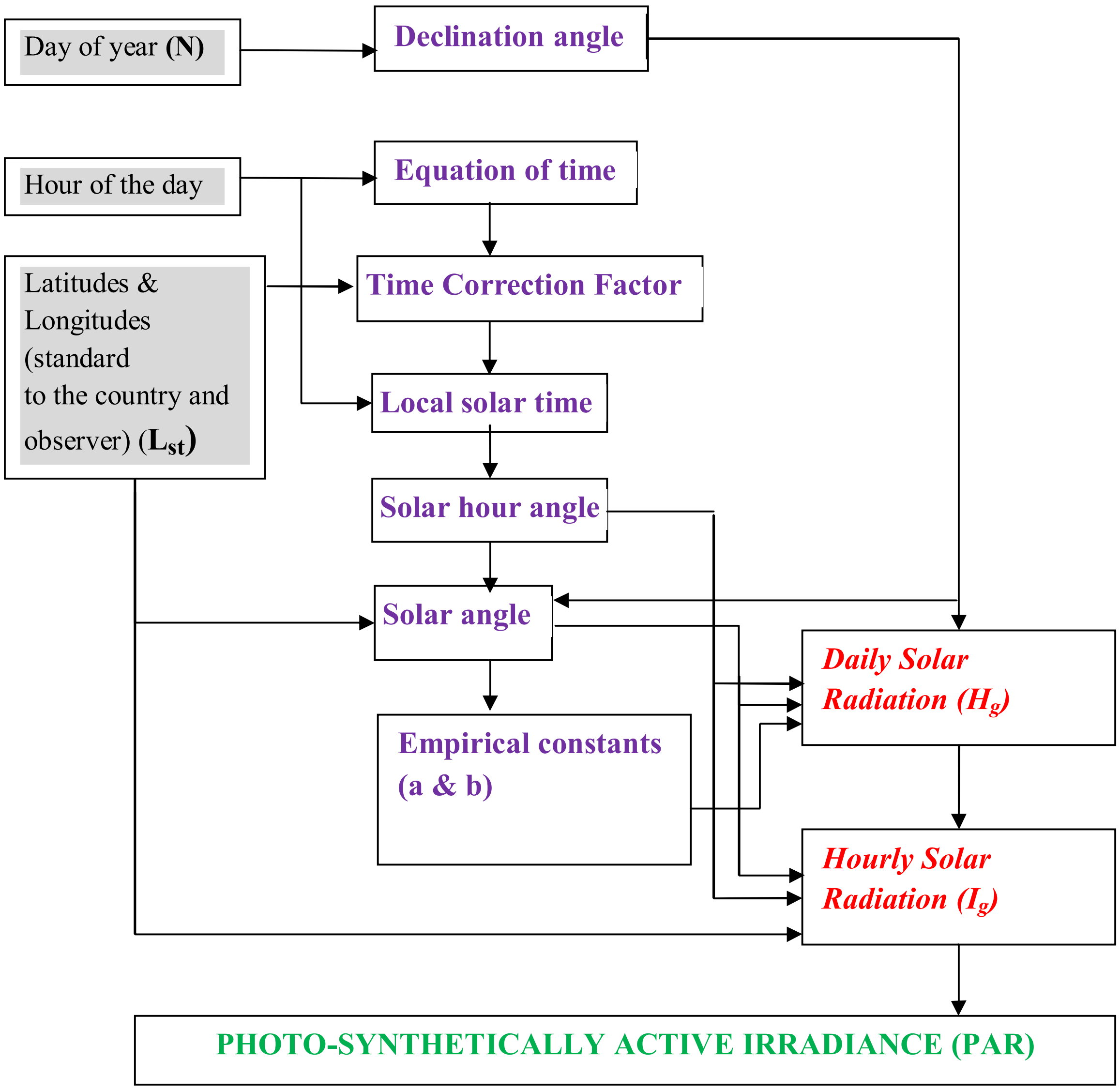


Figure 3: Model for Photosynthetically active Irradiance

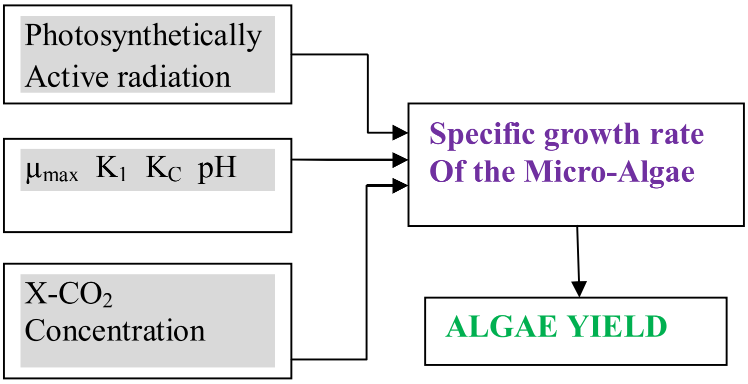
Table 1: Design for modeling the Solar Insolation over the Micro Algal Culture

Symbol	**Parameter**	**Design particulars:**	**Units**:	**Cited from**
N	*Day of year*	0 to 365	No units	[4]
ø	*Latitude angle*	Specific to site of location Assumed from literature	degree	[4]
β	*Angle of ground elevation*	Specific to site of location Assumed from literature	degree	[5]
δ	*Declination angle*	$\delta = 23.45 \text{ Sin}\left(\frac{360(284+N)}{365}\right)$	degree	[5]
LST	*Local solar time*	$\text{local Solar time} = \text{Standard time} \pm \left[\frac{TCF}{60}\right]$	minute	[5]
E	*Equation of time*	$E = 9.87(\text{Sin}2B) - 7.53(\text{Cos}B) - 1.5(\text{Sin}B)$	minute	[5]

		$B = \frac{360(N-81)}{364}$		
TCF	*Time Correction Factor*	$TCF = 4(L_{st} - L_{oc}) + E$	minute	[5]
ω	*Solar hour angle*	$\omega = 15\ (\text{Local Solar time} - 12)$	degree	[6]
ω_s	*Solar angle*	$\omega_s = \cos^{-1}(-\tan\delta\tan(\emptyset - \beta))$ $\omega_s = \cos^{-1}(-\tan\delta\tan(\emptyset))$	degree	[5,6]
θ	*Angle of incidence*	$\theta = \cos^{-1}(\sin\emptyset\sin\delta\cos\beta - \sin\delta\sin\beta\cos\emptyset\ \cos$	degree	[4]
θ_z	*Zenith angle*	$\theta_z = \cos^{-1}(\cos\emptyset\ \cos\delta\ \cos\omega - \sin\beta\sin\emptyset)$	degree	[5]
t_s	*Total Sunshine hours*	$t_s = \left(\frac{2}{15}\right)\cos^{-1}(-\tan\delta\tan(\emptyset))$	hour	[4]
a & b	*Empirical constants*	$a = 0.409 - (0.5016\sin(\omega_s - 60))$ $b = 0.6609 - (0.4767\sin(\omega_s - 60))$	No units	[7]
H_g	*Daily Solar Radiation*	$H_o = \left(\frac{24 I_{sc}}{\pi}\right)\left(1.0 + 1.033\cos\left(\frac{360N}{365}\right)\right)\left((\cos\emptyset\cos\delta\sin\omega_s) +\right.$ $H_g = H_0\ \left(a + b\left({}^{n}/_{N}\right)\right)$	$kJ\ m^{-2}d^{-1}$	[7,8,9]
n	*measured number of sunshine hours*	Specific to site of location Assumed from literature Taken as 11.99978208	hour	[8.9]
N	*number of sunshine hours calculated*	Specific to site of location Assumed from literature Taken as 13.71448293	hour	[8.9]
${}^{n}/_{N}$	*Atmospheric clarity*	Specific to site of location Assumed from literature Taken as 0.874971528	no units	[8,9]
I_{sc}	*solar constant energy received from sun for a unit time on a area perpendicular to sun rays*	Assumed from literature Taken as 1.367	$kJ\ m^{-2}d^{-1}$	[8,9]
I_r	*Hourly Solar Radiation*	$= \left(\frac{3.142\ H_g}{24}\right)(a + b\cos\omega_s)\left\lvert\frac{\cos\omega_s - \cos\omega}{\sin\omega_s - \omega_s\ \cos\omega_s}\right\rvert$	$kJ\ m^{-2}hr^{-1}$	[8,9]
E_f	*Photosynthetic efficiency*	Assumed from literature Taken as 1.74± 0.09 ×10−6	EJ^{-1}	[8,9]
I	*Photosynthetic active irradiance*	$I = [(I]_r) * (E_f)$	$\mu Em^{-2}\ s^{-1}$	[8,9]

ii. Modeling of the Algae Growth Yield:

The growth of the Micro-Algae is modeled by the First order growth kinetics given by the famous Monod Equation , which requires the input parameters such as specific growth rate of the Algae, Inhibition level, concentration level of CO_2, Photo synthetically active irradiance and the alkalinity of the water



.

Figure 4: Model for Algae Growth Yield

Table 2: Design for modeling the growth yield of Micro Algal Culture

Symbol	Parameter	Design particulars:	Units:	Cited from
$x_{CO_2,g}$	*initial molar fraction of CO_2*	Assumed from literature Taken as 0.009	gram	[10]
pH	*Acidity/ Alkalinity*	Assumed from literature Taken as 8.08	No units	[10]
C_{tot}	*total dissolved carbon in the liquid phase*	$C_{tot} = (10^{-1.5}x_{CO_2,g}) + \left[\left(\frac{10^{-7.8}}{10^{-pH}}\right)x_{CO_2,g}\right] + \left[\left(\frac{10^{-28.1}}{10^{-2pH}}\right)x_{CO_2,g}\right]$	No units	[10]
K_1	*inhibition constants*	Assumed from literature Taken as 69.86	k mol Cm^3	[12]
K_c	*half-saturation constant*	Assumed from literature Taken as 0.0002	k mol Cm^3	[12]
μ_{max}	*maximum specific growth rate*	Specific to each Individual Micro-Algal Strains Assumed from literature Taken as	h^{-1}	[12]
μ	*Algae specific growth rate*	$\mu = \mu_{max}\left(\frac{I_t}{I_t + K_1}\right)\left(\frac{C_{tot}}{K_c + C_{tot} + \frac{C_{tot}^2}{K_1}}\right)$	degree	[12]
X_0	*Initial concentration*	Assumed from literature Taken as	g drycell m^{-3}	[13,14]
X	*Cell Concentration*	$X = X_0(e^{\mu t})$	g drycell m^{-3}	[13,14]

iii. Engineering aspects for carbon sequestration designing the limits for CO_2 intake:

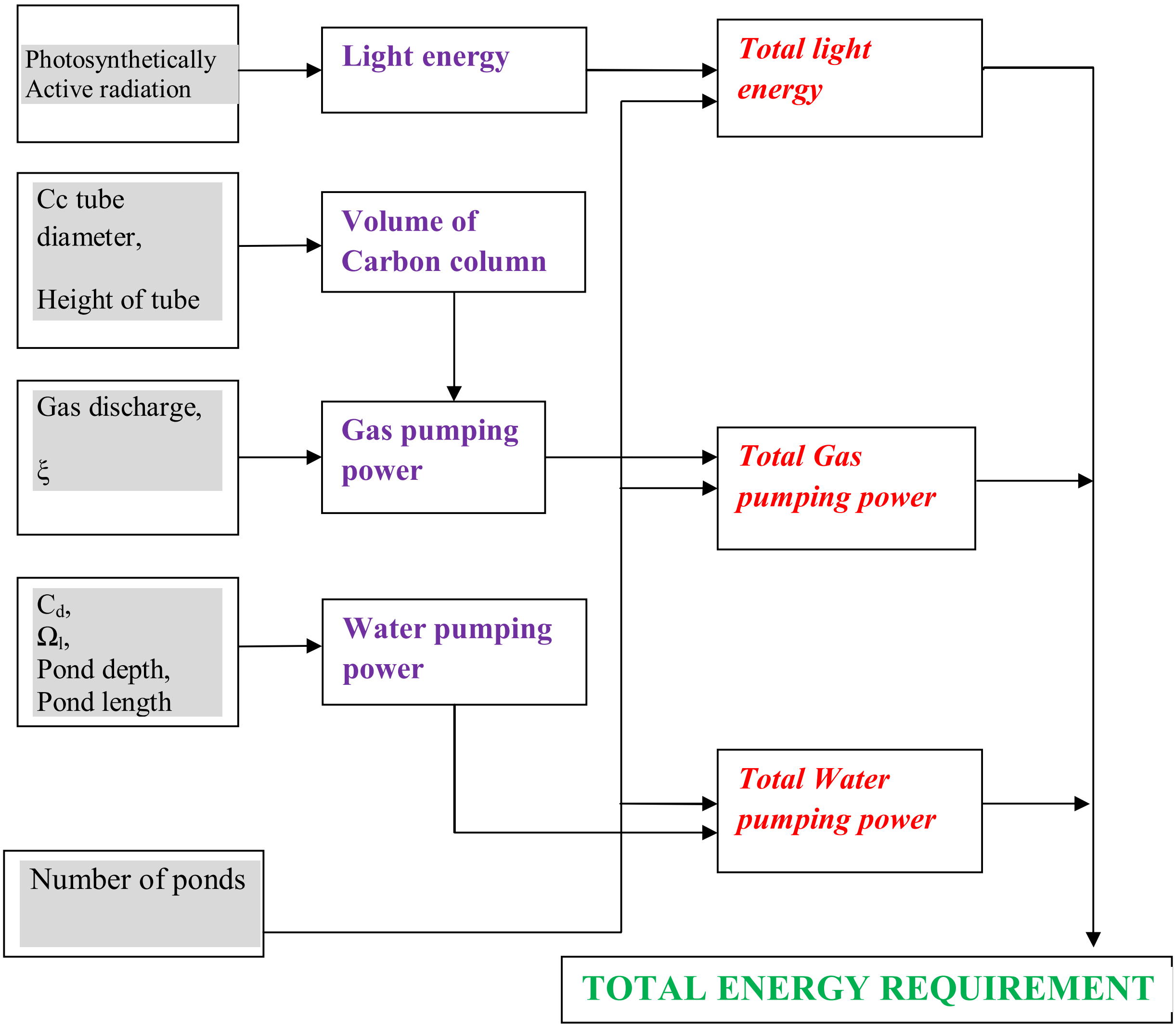


Figure 5: Model for Energy Intake by the Culture

Table 3: Design for modeling the Energy Intake by the Culture

Symbol	**Parameter**	**Design particulars:**	**Units**	**Cited from**
k_L	*the liquid-phase mass transport coefficient*	Assumed from literature Taken as 0.00016	ms^{-1}	[15]
C_S	*saturation concentration of* CO_2	$C_S = 28 \times P_1$	mol	[15]
P_A, P_1, P_2	*the partial pressure of* CO_2	Assumed from literature Taken as 90%	atm	[16]
k_H	*Henry's Law constant for* CO_2 *at 30 °C*	Assumed from literature Taken as 2000	atm mol^{-1}	[16]
ρ_m	*molar density of water (in)*	Assumed from literature Taken as 56,000	mol m^{-3}	[15]
C	*at 30 °C the concentration of* CO_2	$C = P_A \rho_m k_H$	mol	[15]
$C_S - c$	*the saturation concentration of* CO_2	Assumed from literature Taken as 0.1	mol	[15]
R	*Transport rate of* CO_2	$R = k_L(C_s - C)$	L min^{-1}	[17]

V_m	*the molar volume of ideal gas at 30° C*	Assumed from literature Taken as 41	mol m^{-3} atm	[15]
V_g	*volume of the gas bubble*	Assumed from literature Taken as 0.25	m^3	[15]
A_g	*Area of gas bubble*	Assumed from literature Taken as 0.52	cm^2	[18]
A_c	*area of column cross-section*	$A_c = 10A_g$	cm^2	[18]
Q_g	*CO_2 gas flow rate*	Assumed from literature Taken as 0.93	L min^{-1}	[18]
v_g	*bubble rise velocity*	Assumed from literature Taken as 0.3	m s^{-1}	[18]
a,co_2	*the mass of CO_2 fixed by unit biomass*	Assumed from literature Taken as 1.833	gram	[19]
$C_{f.b}$	*final dry biomass concentrations*	--	g L^{-1}	[20]
$C_{i.b}$	*initial dry biomass concentrations*	--	g L^{-1}	[20]
T	*batch test period T*	--	day	[20]
P_b	*Biomass productivity*	$P_b = \frac{1}{T}\left(C_{f.b}/C_{i.b}\right)$	dry g L^{-1} day^{-1}	[20]
W_h	*average harvested dry biomass per day*	--	dry g day^{-1}	--
V_R	*working volume of the reactor*	--	m^3	--
P_c	*Biomass productivity*	$P_c = \frac{W_h}{1000\ V_R}$	dry g L^{-1} day^{-1}	[19]
R	*hydraulic Radius of the algae pond*	Assumed from literature Taken as 0.115385	m	[21]
V_{racewa}	*Velocity of the water in raceway*	$V_{raceway} = \frac{1}{n} R^{2/3} s^{1/2}$ Assumed from literature Taken as 3	m^3	[21]
s	*Head loss per unit length of raceway*	$s = \frac{n^2 V^2_{raceway}}{R^{4/3}}$	m	[21]
H_R	*Total head loss in raceway*	$H_R = \frac{n^2 L_R\ V^2_{raceway}}{R^{4/3}}$	m	[22]
n	*Manning fraction*	Assumed from literature Taken as 0.008	no units	[23]
Q_L	*volume flow rate of liquid in raceway*	Assumed from literature Taken as 9.81	$m^3 s^{-1}$	[23]
ρ_L	*the density of the water*	Assumed from literature Taken as 998.2	kg m^{-3}	[22]
g	*Constant gravitational acceleration*	Assumed from literature Taken as 9.81	ms^{-2}	[22]
P_R	*Power required for maintaining flow in raceway*	$P_R = \frac{Q_L \rho_L g\ n^2 V^2_{raceway}}{R^{4/3}}$	Kilowatt	[23]
v_p	*velocity of paddle relative to water*	----	ms^{-1}	[23]
C_D	*the drag coefficient for flat paddles*	Assumed from literature Taken as 1.8	no units	[23]
A_P	*the area of the paddle in a plane perpendicular to the direction of motion*	Assumed from literature Taken as 0.72	m^2	[23]
P_P	*power required for mixing by the paddlewheel*	$P_P = \frac{C_D \rho_L A_P v_P^3}{2}$	Kilowatt	[24]

Δd	*Change in depth in the pond*	Assumed from literature Taken as 0.075	m	[25]
d	*Raceway Pond depth*	Assumed from literature Taken as 0.12	m	[25]
w	*Raceway Pond width*	Assumed from literature Taken as 6	m	[25]
V	*mixing velocity*	Assumed from literature Taken as 30	ms^{-1}	[25]
L	*length of the pond*	$L = \left(\frac{\Delta d \left(d \times w / (w + 2d) \right)^{4/3}}{V^2 \times n^2} \right)$	m	[25]
A	*mixable area*	$A = L\,W$	m^2	[25]
γ	*the specific weight of the broth*	Assumed from literature Taken as 9810	$N\ m^3$	[26]
H	*Height of the carbon column tube*	Assumed from literature Taken as 3.1	m	[26]
A_R	*mixable area receiving the PAR*	---	m	[26]
I_L	*PAR*		$kJ\ m^{-2}hr^{-1}$	[26]
E_L	*Light energy input per unit reactor volume*	$E_L = \frac{0.22\, I_L\, A_R}{V_R}$	$kJ\ m^{-2}d^{-1}$	[26]
E_G	*Mechanical energy input per unit reactor volume*	$E_G = \frac{Q_G \gamma\, H}{V_R}$	$W\ m^{-3}$	[26]
P_{TOTAL}	*Total power input to the Culture*	$P_{TOTAL} = (E_G + E_L + P_P)$	W	[26]

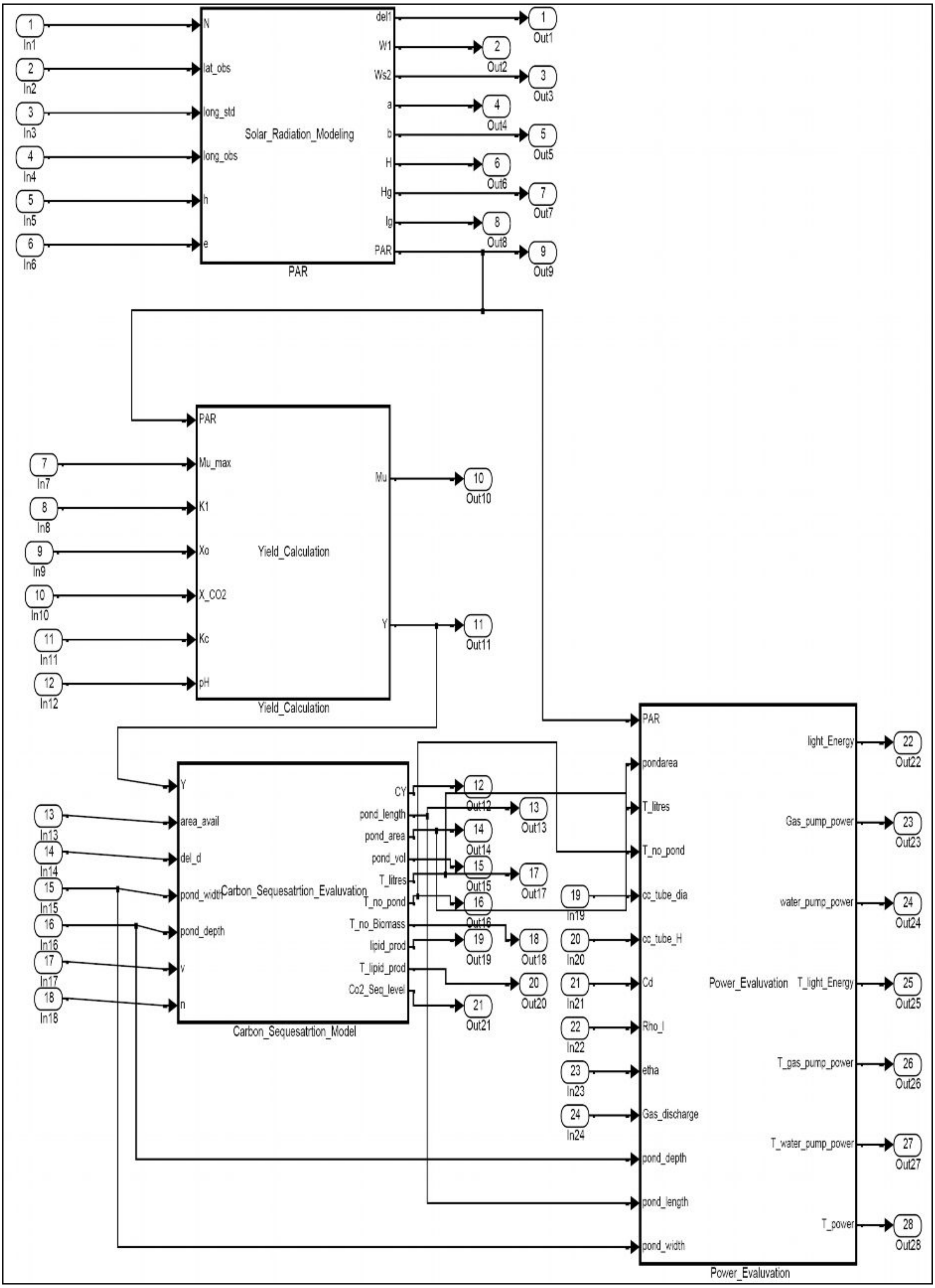
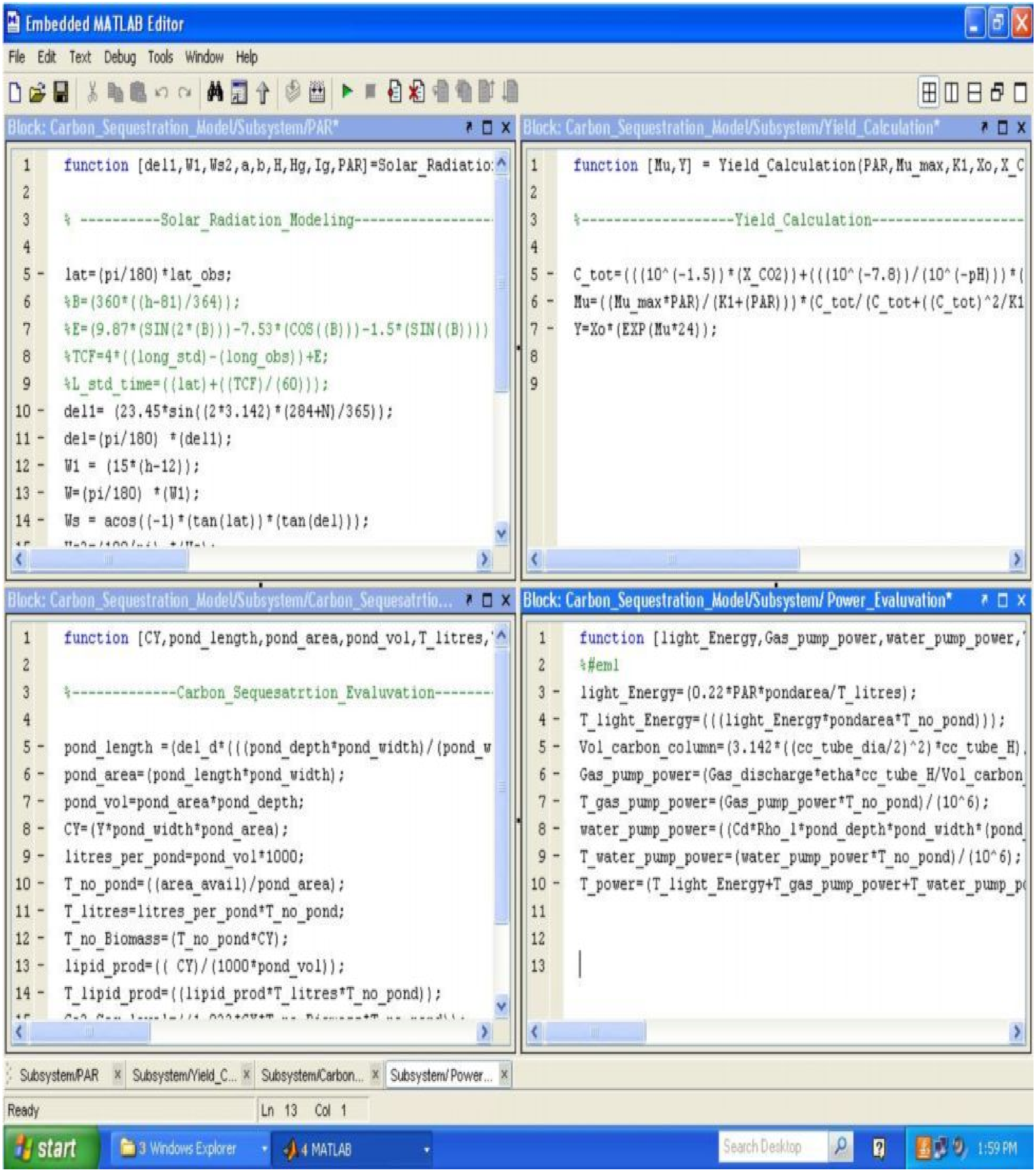


Figure 7: Embedded MATLAB Subsystem for Carbon Sequestration Model



```
function [del1,W1,Ws2,a,b,H,Hg,Ig,PAR]=Solar_Radiatio

% ----------Solar_Radiation_Modeling-----------------

lat=(pi/180)*lat_obs;
%B=(360*((h-81)/364));
%E=(9.87*(SIN(2*(B)))-7.53*(COS((B)))-1.5*(SIN((B))))
%TCF=4*((long_std)-(long_obs))+E;
%L_std_time=((lat)+((TCF)/(60)));
del1= (23.45*sin((2*3.142)*(284+N)/365));
del=(pi/180) *(del1);
W1 = (15*(h-12));
W=(pi/180) *(W1);
Ws = acos((-1)*(tan(lat))*(tan(del)));
```

```
function [Mu,Y] = Yield_Calculation(PAR,Mu_max,K1,Xo,X_C

%-------------------Yield_Calculation-------------------

C_tot=(((10^(-1.5))*(X_CO2))+(((10^(-7.8))/(10^(-pH)))*(
Mu=((Mu_max*PAR)/(K1+(PAR)))*(C_tot/(C_tot+((C_tot)^2/K1
Y=Xo*(EXP(Mu*24));
```

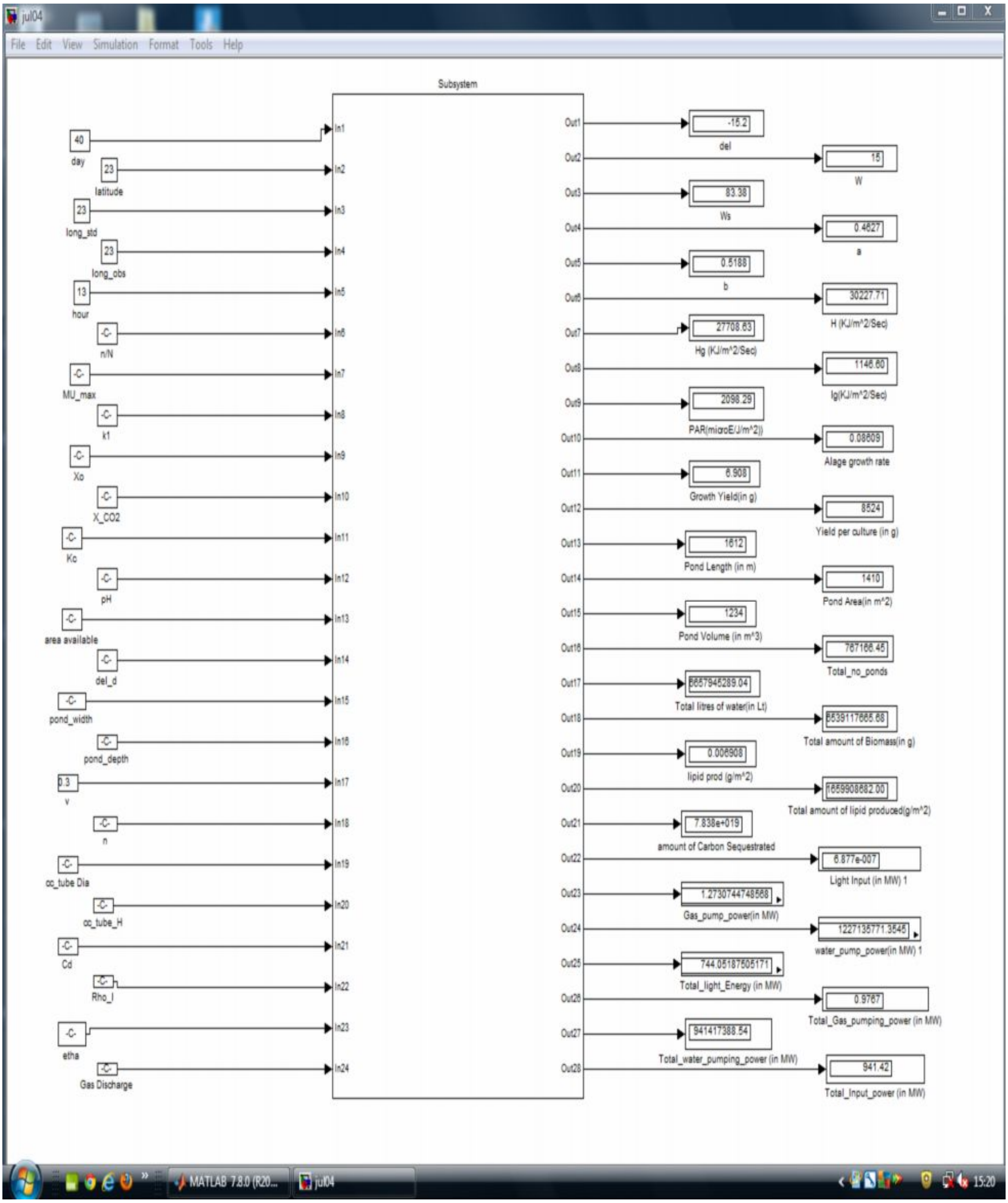
```
function [CY,pond_length,pond_area,pond_vol,T_litres,'

%-------------Carbon_Sequesatrtion_Evaluvation-------

pond_length =(del_d*(((pond_depth*pond_width)/(pond_w
pond_area=(pond_length*pond_width);
pond_vol=pond_area*pond_depth;
CY=(Y*pond_width*pond_area);
litres_per_pond=pond_vol*1000;
T_no_pond=((area_avail)/pond_area);
T_litres=litres_per_pond*T_no_pond;
T_no_Biomass=(T_no_pond*CY);
lipid_prod=(( CY)/(1000*pond_vol));
T_lipid_prod=((lipid_prod*T_litres*T_no_pond));
```

```
function [light_Energy,Gas_pump_power,water_pump_power,'
%#eml
light_Energy=(0.22*PAR*pondarea/T_litres);
T_light_Energy=(((light_Energy*pondarea*T_no_pond)));
Vol_carbon_column=(3.142*((cc_tube_dia/2)^2)*cc_tube_H).
Gas_pump_power=(Gas_discharge*etha*cc_tube_H/Vol_carbon_
T_gas_pump_power=(Gas_pump_power*T_no_pond)/(10^6);
water_pump_power=((Cd*Rho_l*pond_depth*pond_width*(pond_
T_water_pump_power=(water_pump_power*T_no_pond)/(10^6);
T_power=(T_light_Energy+T_gas_pump_power+T_water_pump_pc
```

Figure 8: Coding in Embedded MATLAB Subsystems for Carbon Sequestration Model



40 day
23 latitude
23 long_std
23 long_obs
13 hour
-C- n/N
-C- MU_max
-C- k1
-C- Xo
-C- X_CO2
-C- Kc
-C- pH
-C- area available
-C- del_d
-C- pond_width
-C- pond_depth
0.3 v
-C- n
-C- cc_tube Dia
-C- cc_tube_H
-C- Cd
-C- Rho_l
-C- etha
-C- Gas Discharge

-15.2 del
15 W
83.38 Ws
0.4627 a
0.5188 b
30227.71 H (KJ/m^2/Sec)
27708.63 Hg (KJ/m^2/Sec)
1146.60 Ig(KJ/m^2/Sec)
2098.29 PAR(microE/J/m^2))
0.08609 Alage growth rate
6.908 Growth Yield(in g)
8524 Yield per culture (in g)
1612 Pond Length (in m)
1410 Pond Area(in m^2)
1234 Pond Volume (in m^3)
767166.45 Total_no_ponds
8657945289.04 Total litres of water(in Lt)
8539117665.68 Total amount of Biomass(in g)
0.006908 lipid prod (g/m^2)
1659908682.00 Total amount of lipid produced(g/m^2)
7.838e+019 amount of Carbon Sequestrated
6.877e-007 Light Input (in MW) 1
1.2730744748568 Gas_pump_power(in MW)
1227135771.3545 water_pump_power(in MW) 1
744.05187505171 Total_light_Energy (in MW)
0.9767 Total_Gas_pumping_power (in MW)
941417388.54 Total_water_pumping_power (in MW)
941.42 Total_Input_power (in MW)

Figure 9: MATLAB-Simulink Model for Carbon Sequestration-with the Executed Results

Conclusion:

Micro Bio-Algal production systems with thermal power plants depends on several factors that were taken into account in this analysis: (1) PAR; (2) algal growth rate; (3) algal concentration in growth system; (4) energy requirement and, most importantly for India, (5) cost of the growth system. Based on current algal productivities alone, a large fraction of the CO_2 from the power plant could potentially be sequestered. Availability of PAR , favourable climatic conditions ,adequate land demonstrates that raceway ponds may be the best method to cultivate algae. The assumptions made for this analysis are based on current techniques, productivities, and processes for mass algal cultivation. The recommendations revealed by this assessment are corroborated by the fact that, presently, nearly all algal biomass production facilities are operated in temperate or tropical locations. Despite the fact that algal biofuels may not yet be economically achievable in northern India, algae show great promise for the remediation of CO_2 point sources. Integrated CO_2 sequestration with power plants will, nonetheless, be an important step toward positive publicity of both CO_2 reduction and microalgal biomass production. Although biofuel production from microalgae in India is currently economically unfavorable,algae cultivation remains a very realistic goal provided certain key barriers to commercialization can be overcome. We believe that this work is best applied as a guide for areas of research and improvement required to allow algal production in conjunction with thermal power plant to become fully viable.

References:

1. NREL Technical Report on “A Look Back at the U.S. Department of Energy’s Aquatic Species Program: Biodiesel from Algae” NREL/TP-580-24190.
2. Brennan, L., Owende, P., 2010. Biofuels from microalgae – a review of technologies for production, processing, and extractions of biofuels and co-products. Renew. Sustain. Energy Rev. 14, 217–232.
3. Balachandran Ketheesan et al,”Feasibility of microalgal cultivation in a pilot-scale airlift-driven raceway reactor”; Journal of Bioresource Technology; 108 (2012) 196–202
4. T. M. Wrigley, R. Richels, and J. A. Edmonds, Economic and environmental choices for the stabilization of atmospheric CO_2 concentration,Nature, vol. 379,pp. 240–243, 1996.
5. Liu,B.Y.H.,Jordan,R.C.,1960.The interrelationship and characteristic distribution of direct, diffuse and total solar radiation.SolarEnergy7,53–65.
6. E.Molina al. “Photobioreactors;light regime, mass transfer, and scale-up”. Journal of Biotechnology. Vol-70, no1-3,pg;231-247,1999
7. Duffie,J.A.,Beckman,W.A.,1980.Solar Engineering of Thermal Processes. Wiley, New York, p. 762
8. Rudras et al..“Sustainable algae Biodisel Production in cold climates. International Journal of chemical engineering”. Article Id 102179, 2010
9. E.Molina al. “Photobioreactors; light regime, mass transfer, and scale-up”. Journal of Biotechnology. Vol-70, no1-3,pg;231-247,1999
10. David Michael Wogan .“An Integrated Resource and Biological Growth Model for Estimating Algal Biomass Production With Geographic Resolution”, Master of Science Thesis report-The University of Texas at Austin , December 2010.
11. Benemann, J.R., CO_2 Mitigation with Microalgae Systems. Energy Convers. Mgmt, 1997. 38: p. 475-479.
12. David Michael Wogan .“An Integrated Resource and Biological Growth Model for Estimating Algal Biomass Production With Geographic Resolution”,Master of Science Thesis report-The University of Texas at Austin . December 2010.
13. Dunn, I.J., E. Heinzle, and J. Ingham, Biological Reaction Engineering. 2003, Weinheim: Wiley-VCH.
14. Goldman, J.C., Outdoor algal mass cultures--II. Photosynthetic yield limitations. Water Research, 1979. 13(2): p. 119-136.
15. Shah,Y.,Kelkar,B.,Delker,W.,1982.Design parameters estimations for bubble columnreactors. AIChEJ. 28(3), 353–379.
16. Emmert,R.,Pigford,R.,1963.Section14,Gasabsorptionandsolventextraction.In:Perry’sChemicalEngineers’Handbook.McGraw-Hill,NewYork,p.14-4.
17. Pirt,S.J.,1975.Principles of Microbe and Cell Cultivation. Blackwell Scientific Publications Ltd., Oxford.

18. RonPutt, Manjinder Singh, Senthil Chinnasamy, K.C.Das, "An efficient system for carbonation of high-rate algaepond water to enhance CO_2 mass transfer", Bioresource Technology 102(2011) 3240–3245.
19. Becker,E.W.,1994. Microalgae:Biotechnology and Microbiology, firsted. Cambridge University Press, NewYork.
20. Herzog, H., "What future for carbon capture and sequestration, Environmental Science and Technology", 35, 148A-153A, 2006.
21. B.Ketheesan, N.Nirmalakhandan, "Development of an new airlift-driven raceway reactor for algal cultivation", Applied Energy: 88(2011)3370–3376
22. Anderson RA.Algal culturing techniques.Elsevier Academic Press;2005
23. Water pollution control federation and ASCE. Design and construction of sanitary and storm sewers. WPCF manual of practicen o9. Washington;1970.
24. Rouse H. Elementary mechanics of fluids. NewYork: John Willey and Sons;1946.
25. Yan Li et al. "Utilization of carbon dioxide from Coal-fired power plant for the Production of value-added products", Thesis report for Design Engineering of Energy and Geo-Environmental Systems Course (EGEE 580), April 27, 2006
26. Balachandran Ketheesan, Nagamany Nirmalakhandan, "Feasibility of microalgal cultivation in a pilot-scale air lift- driven raceway reactor", Bioresource Technology 108(2012)196–202 .

*****