Process Summary Examples

This document contains four example process summaries, Process Flow Diagrams, and Stream tables. **THESE EXAMPLES ARE COMPLETELY HYPOTHETICAL AND MEANT TO BE ILLUSTRATIVE ONLY. They may be used as references by teams as they prepare their Phase 1 submissions.**

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Example 1: Macroalgae Growth and Deposition to Deep Ocean

Category: Ocean

Process Summary: The example proposed process entails the growth of macroalgae (i.e. kelp), with initial cultivation and juvenile growth occurring in an on-shore nursery facility, after which sporophytes are transferred to coastal ocean growth habitats where growth occurs in floating farms. Macroalgae is then harvested and transported to deep ocean locations where it can be deposited and sequestered for >100years.

The process is a batch process, with each stage occurring in a sequential batch. Depending on the growing season in selected locations, 1-2 batches can be completed per year.

Process Flow Diagram and Stream Table: Figure 1 provides a process flow diagram indicating the inputs and outputs of each step of the process. Each process step (nursery, growth/farm, harvesting, and sequestration) is identified with all material inputs and outputs, major equipment, energy inputs, and flow rates of each provided for a >1000 tonne/yr CO_2 sequestered (***total sequestered = 1125 tonne/yr*** $\boldsymbol{CO_{2e}}$). The Stream Table (Table 4) provides a summary of the calculated inputs and outputs for each major process stream identified in the PFD.

Assumptions: Several assumptions are made in calculating the required material and energy inputs and outputs. A summary of each assumption, applicable stream, and source of data related to the assumption is provided in Table 1.

Table 1 Macroalgae Example Assumptions

Stream No.	Stream Description	Notable Assumptions	Data Source / Reference
1	Macroalgae Growth Medium	Medium is assumed to be seawater and freshwater (7:3 ratio) plus PES and GeO2 dosed as specified.	N. Flavin, K. Flavin, B. Flahive. Kelp Farming Manual: A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters. Ocean Approved. 2013. https://maineaqua.org/wp-content/uploads/2020/06/OceanApproved_KelpManualLowRez.pdf
2	Macroalgae Spores	Macroalgae spores are from portion of produced stock and require negligible material and energy inputs	Engineering Estimate
6	Sporophytes (impreg. on lines)	(assume weight of sporophytes is 0.1% of final harvested weight)	Engineering Estimate
7	CO2 and nutrients (for photosynthesis)	100% yield CO2 to C in algae; Elemental nutrient inputs required are calculated based on ultimate analysis of algae	Ultimate analysis provided in: J. Milledge and P. Harvey. Potential process hurdles in the use of macroalgae as feedstock for biofuel production in the British Isles. J Chem Technol Biotechnol. August, 2016. 91(8): 2221-2234. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4999046/
8	Fuel / energy for onsite operations & transport to site)	2.15 MJ/kg dryw algae energy input required for nursery functions Assume 60% of energy input is for ocean growth process, 20% for	M. Aresta, A. Dibenedetto, G. Barberio. Utilization of macro-algae for enhanced CO2 fixation and biofuels production: Development of a computing software for an LCA study. Fuel Processing Technology, Volume 86 Issues 14-14, p. 1679-1693. October, 2005. https://www.sciencedirect.com/science/article/pii/S0378382005000299

		nursery cultivation, 20% for transport	
10	Fuel / energy for onsite operations & transport to site)	5.5 MJ/kg dw total Assume 75% for stream 10 and 25% for stream 15)	M. Aresta, A. Dibenedetto, G. Barberio. Utilization of macro-algae for enhanced CO2 fixation and biofuels production: Development of a computing software for an LCA study. Fuel Processing Technology, Volume 86 Issues 14-14, p. 1679-1693. October, 2005. https://www.sciencedirect.com/science/article/pii/S0378382005000299
12	Algae Loss during Processing	10% of algae is lost in harvesting, farming, sequestration	Engineering estimate
13	Algal Loss (naturally transported to Deep Ocean)	11.4% is naturally transported to deep ocean or sequestered in algal shelf	C. Duarte and D Krause-Jensen. Substantial Role of macroalgae in marine carbon sequestration. Nature Geoscience, Vol 9, October , 2016.
14	Algal loss (not sequestered)	89.6% is consumed by biological organisms or temporarily sequestered in shallow waters and decays	C. Duarte and D Krause-Jensen.
15	Algae to sequestration	A) 100% of algae is sequestered; B) Algae is 31% C by dry wt.; C) Algae dry wt to fresh wt = 0.1;	A) Engineering estimate B,C) J. Milledge and P. Harvey.

<u>Mass, Carbon, Energy Balances:</u> Mass and Carbon balances are provided for the overall process as summarized in the PFD in Table 2. Mass balance includes total mass of each major input and each output. For carbon balances, the carbon content of each mass input or output is accounted for. Total carbon mass (C – not CO2e) is calculated for each stream and product, distinguished as a carbon source or sink. For carbon and mass balances, only those processes included in the main process flow are included in calculations. No ancillary processes, such as inputs and outputs of nutrient manufacture or electrical power generation are accounted for as those are considered outside of the process boundary. However, those are to be accounted for in the overall cradle to grave lifecycle carbon emissions analysis.

Table 2 Macroalgae Mass & Carbon Balance

Mass and Carbon Balance					
Component	**Carbon Content (wt% dry)**	**Inputs (tonne/yr)**	**Carbon Input**	**Outputs (tonne/yr)**	**Carbon Output**
CO2 (input)	27.3%	1234.6	336.7003	0.0	0.0
N	0	26.1	0	0.0	0.0
P, K, Ca, Mg, etc.	0	262.8	0	0.0	0.0
S	0	7.6	0	0.0	0.0
O	0	0.0	0	503.6	0.0
H	0	40.2	0	0.0	0.0
PES Culture media (nutrients)	negl.	2.0	0	0.0	0.0
GeO2	0	0.2	0	0.0	0.0
Seawater (nursery)	0.0028%	149.6	0.00413	0.0	0.0
Freshwater (nursery)	negl.	62.6	0	0.0	0.0

Macroalgae Spores (nursery)	31%	0.5	0.016835	0.0	0.0
Wastewater (nursery)	0.0019%	0.0	0	203.5	0.0
Macroalgae (Mature) (wet) - to deep ocean sequestration	31%	0.0	0	9899.0	306.9
Macroalgae (Mature) Water Content (to deep ocean)	0	8909.1	0.0	0.0	0.0
Macroalgae (Mature) (wet) - loss	31%	0.0	0.0	962.3	29.8
Macroalgae (Mature) Water Content (loss)	0	866.1	0.0	0	0.0
Total		**11561.3**	**336.7**	**11568.4**	**336.7**
Mass Balance					**100.06%**
Carbon Balance					**99.99%**

A summary of energy inputs is provided in Table 3. However, because energy inputs are converted to mechanical work (propulsion, winches, harvester equipment, etc.) energy outputs are not measured nor estimated. Note that energy required for photosynthesis is also not included, as it is assumed that it is available solar energy or chemical energy that is converted into biomass via photosynthesis and it does not need to be detailed here.

Table 3 Macroalgae Example Energy Balance

Energy Balance		
Component	**Inputs (MJ/yr)**	**Outputs * (MJ/yr)**
Electricity	467036.0	0
Diesel Fuel	233518.0	0
Marine Diesel Fuel	7608341.5	0
Total	**8308895.4**	**0.0**
Energy Balance		**NA**

Figure 1 Macroalgae Example Process Flow Diagram

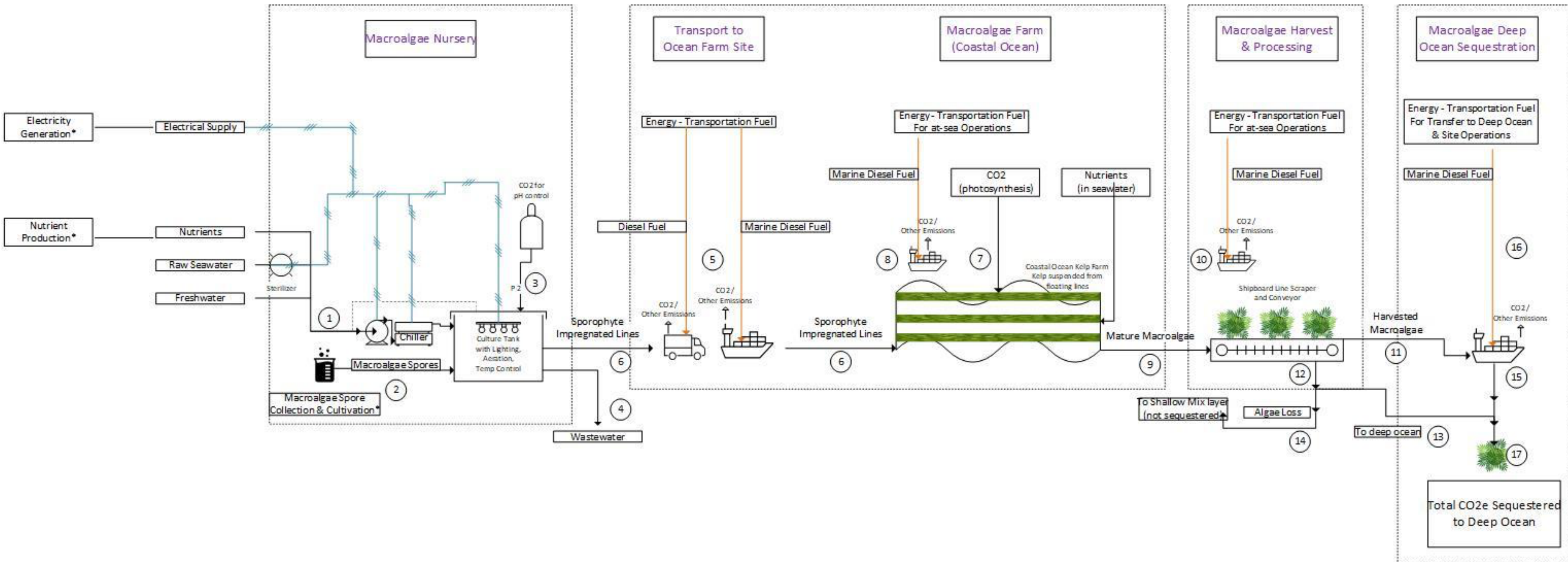

Table 4 Macroalgae Example Stream Table

Stream No.	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Stream Description		Macroalgae Growth Medium	Macroalgae Spores	CO2 (pH Control)	Wastewater from Culture Tank	Fuel for Transport	Sporophytes (impregnated on lines)	CO2 and nutrients (for photosynthesis)	Fuel / energy for onsite operations & transport to site)	Mature Macroalgae (on lines)	Fuel / energy for onsite operations & transport to site)	Macroalgae	Algae Loss during Processing	Algal loss (naturally transported to Deep Ocean)	Algal loss (naturally deposited in algal shelf)	Algae to sequestration	Fuel / energy for onsite operations & transport to site)	Total Sequestered Algae / CO2
Stream Characteristics (i.e. T, P)																		
Component Flow Rates - materials																		
CO2 (input)	tonne/yr			negligible				1234.6										
C (in macroalgae)	tonne/yr									336.7		303.0	33.7	3.8	30.2	303.0		306.9
N	tonne/yr							26.1		26.1		23.5	2.6	0.3	2.3	23.5		23.8
P, K, Ca, Mg, etc.	tonne/yr							262.8		262.8		236.6	26.3	3.0	23.6	236.6		239.6
S	tonne/yr							7.6		7.6		6.8	0.8	0.1	0.7	6.8		6.9
O	tonne/yr							394.3		394.3		354.8	39.4	4.5	35.3	354.8		359.3
H	tonne/yr							40.2		40.2		36.2	4.0	0.5	3.6	36.2		36.6
PES Culture media (nutrient mix)	tonne/yr	2.0																
GeO2	tonne/yr	0.2																
Seawater	tonne/yr	149.6																
Freshwater	tonne/yr	62.6																
Macroalgae Spores or Sporophytes	tonne/yr		0.5				10.8613											
Wastewater (nursery)	tonne/yr				203.5													
Macroalgae (Mature)	tonne/yr (wet)									10861.3		9775.2	1086.1	123.8	962.3	9775.2		9899.0
Macroalgae (Mature)	tonne/yr (dry)									1086.1		977.5	108.6	12.4	96.2	977.5		989.9
Macroalgae (Mature) - Water Content	tonne/yr (dry)									9775.2		8797.7	977.5	111.4	866.1	8797.7		8909.1
CO2e in Macroalgae	tonne/yr									1234.6		1111.1	123.5	14.1	109.4	1111.1		1125.2
Electricity	MJ/yr	467036.0																
Diesel Fuel	MJ/yr					233518.0												
Marine Diesel / Bunker Fuel	MJ/yr					233518.0			1401107.9		4480286.7						1493428.9	

Example 2: Bamboo Growth with Pyrolysis for Production of Biochar

Category: Land (plant)

Process Summary: The example process is the cultivation of bamboo for the production of biochar for application on lands for both improved agricultural uses as well as fallow land enhancement. The growth of bamboo stands is a 5 year process so the production process diagram and balance have been sized for 5000 ton of CO2 uptake which is an average of 1000 tons/year.

The process begins with the collecting of culms or rhizomes for transplant (seeds can be used but are very rare). Regardless of the starting point, the bamboo is reared in a small open wall greenhouse as temperatures are warm enough for growth year round. The young shoots are kept in the green house for one year. Then they are planted in the fields at a spacing of roughly 200 plants/hectare. To achieve the required sequestration approximately 230 hectares are planted, cultivated, thinned, and fertilized over the ensuing four years.

Mature bamboo is harvested and allowed to dry to approximately 10-15% moisture (approximately 1-2 months). Drying the biomass to this range improves the operation of the biochar system. The dried bamboo is then fed into a pre-dryer which is heated by the exhaust of the pyrolysis gas combustion. The dried bamboo is then chipped then pyrolyzed at 500C. Approximately, 40% of the bamboo ends up as biochar, however, there are some losses in the machine and only 96.9% of the biochar is collected. The biochar that is collected is 82% carbon with a majority of the remaining mass being oxygen. The biochar is then milled and pelletized for application on the fields. The bamboo chipping, the biochar milling and pelletizing equipment is powered electrically, while the pyrolysis is heated through the burning of the branches and leaves of the bamboo.

Process Flow Diagram and Stream Table: Figure 2 provides a process flow diagram indicating the inputs and outputs of each step of the process. Each process step (nursery, growth/farm, harvesting, and sequestration) is identified with all material inputs and outputs, major equipment, energy inputs, and flow rates of each provided for a >1000 tonne/yr CO_2 sequestered average (***total sequestered = 5000 tonne/5 yr*** $\boldsymbol{CO_{2e}}$). The Stream Table (Table 8) provides a summary of the calculated inputs and outputs for each major process stream identified in the PFD.

Assumptions: Several assumptions are made in calculating the required material and energy inputs and outputs. A summary of each assumption, applicable stream, and source of data related to the assumption is provided in Table 5.

Table 5 Bamboo Example Assumptions

Stream No.	Stream Description	Notable Assumptions	Data Source / Reference
6	Fertilizer	244 kg N/ha/yr; 196 kg P and K / ha/yr	C. Kim et al. Regular Fertilization Effects on the Nutrient Distribution of Bamboo Components in a Moso Bamboo (Phyllostachys pubescens (Mazel) Ohwi) Stand in South Korea. Forests 2018, 9, 671; doi:10.3390/f9110671 https://www.mdpi.com/1999-4907/9/11/671/pdf
8	CO2 for photosynthesis	Assume 43 t/h/a for culms (an additional 9.5 would go to leaves, limbs, and rhizomes which would not be sequestered so is excluded here)	Carbon storage in a bamboo (Bambusa vulgaris) plantation in the degraded tropical forests: Implications for policy development Md. Shawkat Islam Sohel, Mohammed Alamgir, Sayma Akhter, Mizanur Rahman
9	Energy (Diesel for Operations)	Cultivation and Harvest energy are combined (see Stream 12).	
10	Mature Bamboo	5% Loss of bamboo during harvest, Moisture content = 59.5%	Hamid et al. VARIATION OF MOISTURE CONTENT AND SPECIFIC GRAVITY OF GIGANTOCHLOA SCORTECHINII GAMBLE ALONG THE INTERNODES SIXTH HEIGHT http://www.fao.org/3/XII/0030-B4.htm
11	Harvested bamboo	Bamboo allowed to dry outdoors for 1-2 months to 10-15% moisture	Engineering Estimate
12	Energy (Diesel for Harvest)	20 MJ/kg bamboo	Life Cycle Assessment and Carbon Sequestration; the Environmental Impact of Industrial Bamboo Products P. Van der Lugt, JG Vogtlander, JH van der Vegte, JC Brezet
13	Energy (Electricity for Nursery)	Assumed zero as growth is undertaken in open air greenhouses. Climate controlled greenhouses would incur significant energy usage.	Manual for Sustainable Management of Clumping Bamboo Forest Jayaraman Durai, Trinh Thang Long Energy Consumption Prediction of a Greenhouse and Optimization of Daily Average Temperature Yongtao Shen † ID , Ruihua Wei † and Lihong Xu
14	Dried Biomass	Carbon Content 50%	Technical, Economical, and Climate-Related Aspects of Biochar Production Technologies: A Literature Review Sebastian Meyer, Bruno Glaser, and Peter Quicker
16	Hot Pyrolysis Gases and Biochar	Assume 40% to biochar	Slow Pyrolysis of Bamboo Biomass: Analysis of Biochar Properties Laidy E. Hernandez-Mena, Arai A. B. Pécora, Antonio L. Beraldo
17	Biochar	96.9% capture rate for biochar 82% carbon content of biochar	Saucier, David Shane (2013). Cyclone Performance for Reducing Biochar Concentrations in Syngas. Master's thesis, Texas A & M University. Available electronically from https : / /hdl .handle .net /1969 .1 /150963. Slow Pyrolysis of Bamboo Biomass: Analysis of Biochar Properties Laidy E. Hernandez-Mena, Arai A. B. Pécora, Antonio L. Beraldo
18	Milled/Ground Biochar	Assume minimal losses in milling	Engineering Estimate
21,22	Biochar in Soil	Assume 97% of biochar is stable (500 year time line) 3% lost to organic processes	Industrial biochar systems for atmospheric carbon removal: a review Samer Fawzy · Ahmed I. Osman · Haiping Yang · John Doran · David W. Rooney
24	Energy (chipping biomass)	1.13 L/ton dried biomass	Throughput Rate and Energy Consumption During Wood Chip Production in Relation to Raw Material, Chipper Type and Machine Setting Daniel Kuptz, Hans Hartmann

25	Pelletizing	10.8 MJ/tonne	Effects of binders on the properties of bio-char pellets Qiang Hu, Jingai Shao, Yang Haiping, Dingding Yao, Xianhua Wang, Hanping Chen

Mass, Carbon, Energy Balances: Mass and Carbon balances are provided for the overall process as summarized in the PFD in Table 6. Mass balance includes total mass of each major input and each output. For carbon balances, the carbon content of each mass input or output is accounted for. Total carbon mass (C – not CO2e) is calculated for each stream and product, distinguished as a carbon source or sink. For carbon and mass balances, only those processes included in the main process flow are included in calculations. No ancillary processes, such as inputs and outputs of nutrient manufacture or electrical power generation are accounted for as those are considered outside of the process boundary. However, those are to be accounted for in the overall cradle to grave lifecycle carbon emissions analysis. The balance is not fully closed as the fate as the oxygen carried via input CO_2 is unknown. Bamboo exhausts an unknown/unmeasured amount of oxygen through plant respiration, this amount could be estimated, however, could really only be found via difference. Since oxygen is a carbon free molecule this leads to a much better carbon balance than total mass balance.

Table 6 Bamboo Example Mass & Carbon Balance

Mass and Carbon Balance					
Component	**Carbon Content (wt% dry)**	**Inputs (tonne/yr)**	**Carbon Input**	**Outputs (tonne/yr)**	**Carbon Output**
CO2 (input)	27.3%	37857.0	10324.63	0.0	0.0
Biochar	82.0%	0.0	0	6286.1	5154.6
Bamboo	20.3%	103.2	20.89577	0.0	0.0
Pyrolysis Gas	34.1%	0.0	0	12047.8	4112.9
Fertilizer - N	0.0%	61.5	0	0.0	0.0
Fertilizer P, K	0.0%	107.9	0	0.0	0.0
Water	0.0%	0.0	0	0.0	0.0
Total		**38129.6**	**10345.5**	**18333.9**	**9267.5**
Mass Balance					**48.08%**
Carbon Balance					**89.58%**

A summary of energy inputs is provided in Table 7. However, because energy inputs are converted to mechanical work (propulsion, spreaders, harvester equipment, etc.)

energy outputs are not measured nor estimated. Note that energy required for photosynthesis is also not included, as it is assumed that it is available solar energy or chemical energy that is converted into biomass via photosynthesis and is does not need to be detailed here.

Table 7 Bamboo Example Energy Balance

Energy Balance		
Component	**Inputs (MJ/yr)**	**Outputs (MJ/yr)**
Electricity	67,890.4	
Diesel Fuel	5,301,655.2	
Pyrolysis Gas		103.9
Total	**5369545.6**	**103.9**
Energy Balance		**NA**

Figure 2 Bamboo Example Process Flow Diagram

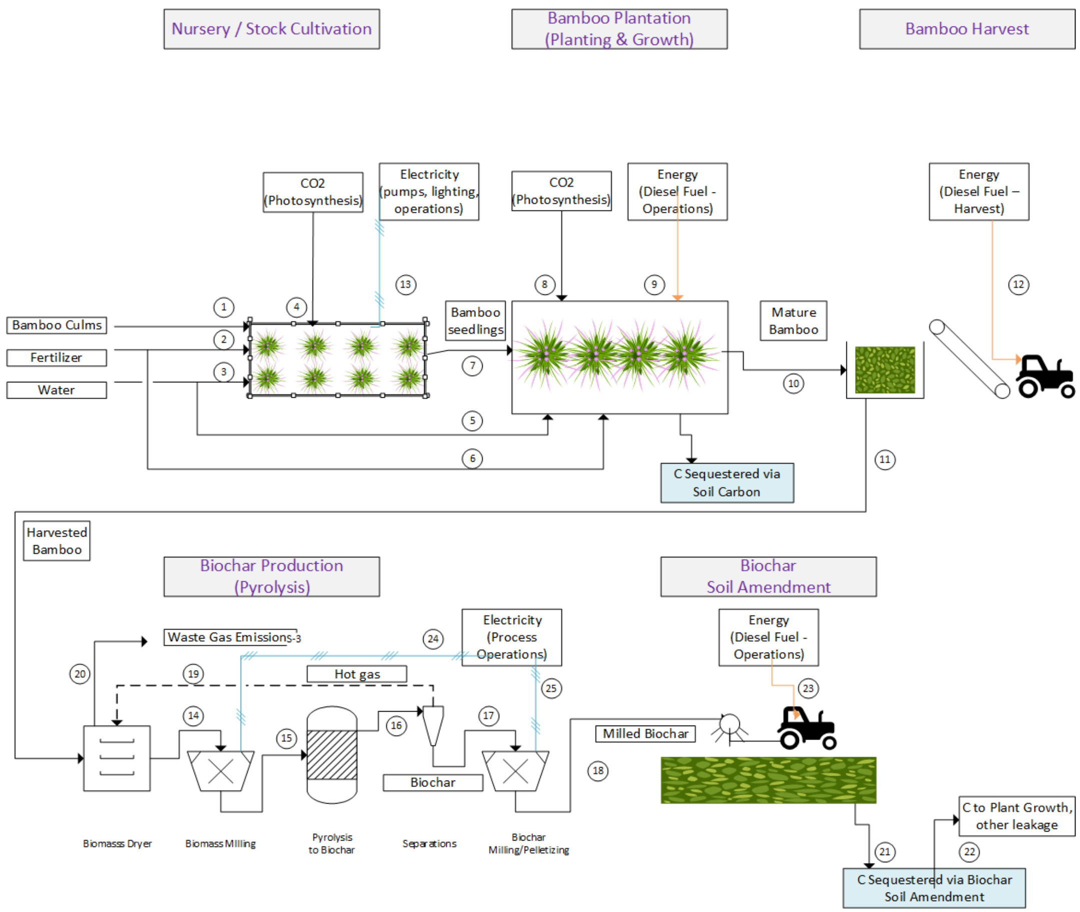

Table 8 Bamboo Example Stream Table

Stream No.	Units	1	2	3	4	5	6	7	8	9	10	11	12
Stream Description		Bamboo culms, seeds, propagules (from existing crop)	Fertilizer N,P,K 14-14-14 or equivalent	Water	CO2 (for photosynthesis)	Water	Fertilizer N,P,K 14-14-14 or equivalent	Bamboo Seedlings	CO2 (for photosynthesis)	Fuel / energy for onsite operations & transport to site)	Mature Bamboo	Harvested Mature Bamboo	Fuel / energy for harvesting
Stream Characteristics (i.e. T, P)													
Component Flow Rates - materials													
CO2 (input)	tonne/yr				1,702.6				36,154.4				
Biochar	tonne/yr												
Bamboo	tonne/yr	103.2						1,031.9			48,174.1	20,594.4	
C	tonne/yr	51.6			464.4			515.9	9,860.3		9,755.3	9,267.5	
CO2e (tpy)	tonne/yr												
Pyrolysis Gas	tonne/yr												
Fertilizer - N	tonne/yr		5.6				56.0						
Fertilizer P, K	tonne/yr		18.0				89.9						
Water	MJ/yr			0.0		1,513,438.8							
Electricity	MJ/yr												
Diesel Fuel	MJ/yr									see 12			4,449,999.6

Stream No.	Units	13	14	15	16	17	18	19	20	21	22	23	24	25
Stream Description		Electricity (nursery activities)	Dried Biomass (dry)	Shredded Biomass (dry)	Hot Pyrolysis Gases and BioChar	Biochar	Milled / ground biochar	Hot pyrolysis gases (for drying)	Pyrolysis gas emissions (flared)	Biochar in soil (amount C sequestered)	Biochar in soil (amount C leaked / re-utilized)	Diesel Fuel (Biochar transport & Applacation)	Chipping	Pelletizing
Stream Characteristics (i.e. T, P)														
Component Flow Rates - materials														
CO2 (input)	tonne/yr													
Biochar	tonne/yr				6,487.3	6,286.1	6,286.1			6,097.6	188.6			
Bamboo	tonne/yr		18,535.0	18,535.0										
C	tonne/yr		9,267.5	9,267.5	9,267.5	5,154.6	5,154.6	4,112.9	4,112.9	5,000.0	154.6			
CO2e (tpy)	tonne/yr													
Pyrolysis Gas	tonne/yr				12,047.8			12,047.8	12,047.8					
Fertilizer - N	tonne/yr													
Fertilizer P, K	tonne/yr													
Water	MJ/yr								2,059.4					
Electricity	MJ/yr													67,890.4
Diesel Fuel	MJ/yr											80,896.1	770,759.5	

Example 3: Direct Air CO_2 Capture with Saline Aquifer CO_2 Sequestration

Category: Rocks

Process Summary: The example proposed process consists of state-of-the-art direct air capture (DAC) of CO_2. This process captures the CO_2 utilizing a KOH solution and the solution undergoes is regenerated with calcium hydroxide in the pellet reactor. The $CaCO_3$ is precipitated onto seed pellets and once large enough are removed from the system. Calcination of the $CaCO_3$ to release the CO_2 is achieved with an oxygen fired circulating fluidized bed. The resulting CaO is then sent to a steam slaking reactor for conversion back to calcium hydroxide. The heat and power of the system is generated by burning methane in a turbine. The emissions from the turbine are collected in a standard countercurrent CO_2 scrubber with the tail gas also fed into the air contactor for further capture and sequestration. The CO_2 liberated from the calcium carbonate in the calciner is mostly pure and it is then compressed and injected into a deep subterranean saline aquifer. The integrity of the saline aquifer is then monitored through annual 3D seismic time lapse surveys. Monitoring of subsurface freshwater aquifers will be conducted to detect breakthrough.

Process Flow Diagram and Stream Table: Figure 3 provides a process flow diagram (PFD) indicating the inputs and outputs of the process. The process consists primarily of the DAC, the transmission pipeline and the booster pump at the wellhead. The PFD identified all material inputs and outputs, major equipment, energy inputs, and flow rates of each provided for a >1000 tonne/yr CO_2 sequestered (***total sequestered = 1Mtonne/yr CO_{2e}***). The Stream Table (Table 12) provides a summary of the calculated inputs and outputs for each major process stream identified in the PFD.

Assumptions: Several assumptions are made in calculating the required material and energy inputs and outputs. A summary of each assumption, applicable stream, and source of data related to the assumption is provided in Table 9.

Table 9 Direct Air Capture Example Assumption

Stream No.	Stream Description	Notable Assumptions	Data Source / Reference
1	Air Flow	ambient conditions of 20C and 64% relative humidity	A Process for CapturingCO2from the Atmosphere David W. Keith, Geoffrey Holmes, David St. Angelo,and Kenton Heidel
2	Tail gas	The contactor is the heart of CE's air capture technology. It is the unit that diverges farthest from industrial precedent in that cross-flow cooling-tower components are used for a chemical gas-exchange process	A Process for CapturingCO2from the Atmosphere David W. Keith, Geoffrey Holmes, David St. Angelo,and Kenton Heidel
3	Methane	Assume 100% methane pipeline gas	A Process for CapturingCO2from the Atmosphere

			David W. Keith, Geoffrey Holmes, David St. Angelo,and Kenton Heidel
5	Oxygen	quote from major ASU vendor for 95% purity delivered at 120 kPa	A Process for CapturingCO2from the Atmosphere David W. Keith, Geoffrey Holmes, David St. Angelo,and Kenton Heidel
8	Water	plant needs 4.7 tons of water per ton CO2 captured from the atmosphere	A Process for CapturingCO2from the Atmosphere David W. Keith, Geoffrey Holmes, David St. Angelo,and Kenton Heidel
9	Make up $CaCO_3$	Equals amount removed for disposal	A Process for CapturingCO2from the Atmosphere David W. Keith, Geoffrey Holmes, David St. Angelo,and Kenton Heidel
11	Fines for Disposal	plant discharges 1% of the circulating Ca each cycle as waste	A Process for CapturingCO2from the Atmosphere David W. Keith, Geoffrey Holmes, David St. Angelo,and Kenton Heidel
14	Pipeline transmission losses	Transmission losses were estimated to be the same as theoretical transmission losses of a trunk gas pipeline since this pipeline would not be sugject to some of the issues associated with NG pipeline (theft, variable pipe stack, etc) The value used was 0.21% of input CO_2.	Calculation of theoretical transmission loss in trunk gas pipeline Ying Xie, Xingzhi Wang, Fangrui Mai Advances in Mechanical Engineering Volume: 11 issue: 12, December 2019
15	CO_2 injected	Equals DAC output minus transmission losses. Escape is not anticipated, however, monitoring will be conducted to verify. Booster pump energy costs depend on pressure drop through pipeline (currently unknown).	Engineering Estimate

<u>Mass, Carbon, Energy Balances:</u> Mass and Carbon balances are provided for the overall process as summarized in the PFD in Table 10. Mass balance includes total mass of each major input and each output. For carbon balances, the carbon content of each mass input or output is accounted for. Total carbon mass (C – not CO2e) is calculated for each stream and product, distinguished as a carbon source or sink. For carbon and mass balances, only those processes included in the main process flow are included in calculations.

Table 10 Direct Air Capture Example Mass and Carbon Balance

Mass and Carbon Balance					
Component	**Carbon Content (wt% dry)**	**Inputs (tonne/hr)**	**Carbon Input**	**Outputs (tonne/hr)**	**Carbon Output**
CO2 (input)	27.30%	229.8	62.726	229.2	62.573
Methane	74.88%	6.3	4.717	0	0.000
Oxygen	0	64,093.3	0	64,246.6	0
Nitrogen	0	185,199.2	0	185,804.8	0
H2O	0	2,067.2	0	1,890.5	0
CaCO3	12.00%	3.4	0.408	3.4	0.408
Ca(OH)2	0	0	0	0	0

Total		**251,599.2**	**67.9**	**252,174.4**	**63.0**
Mass Balance					**100.23%**
Carbon Balance					**92.82%**

A summary of energy inputs is provided in Table 11. However, the size of the turbine and subsequent methane input was selected to match the electrical needs of the DAC, therefore electricity is netted as zero and methane is the only energy input. Note that energy required for the booster pump is also not included, as it is and unknown quantity at this time and is dependent on the pressure drop losses accumulated along the length of pipeline, co-locating the DAC at the well would eliminate this requirement.

Table 11 Direct Air Capture Example Energy Balance

Energy Balance		
Component	**Inputs (MJ/hr)**	**Outputs * (MJ/hr)**
Electricity	0	0
Methane	315,000	0
Total	**315,000**	**0.0**
Energy Balance		**NA**

Figure 3 Direct Air Capture Example Process Flow Diagram

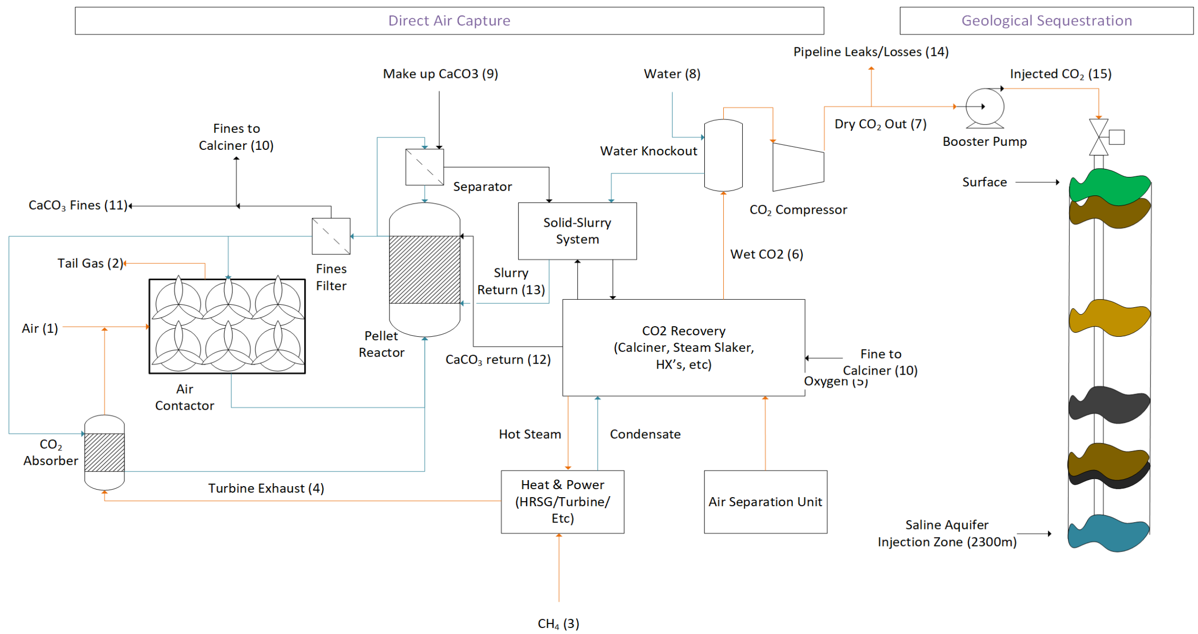

Table 12 Stream Table

Stream No.	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Stream Description		Air	Tail Gas	Methane	Turbine Exhaust	Oxygen	Wet CO2	Dry CO2 Out	Water In	Make up CaCO3	Fines to Calciner	CaCO3 Fines waste	CaCO3 Return	Slurry Return	Transmission Losses	Injected CO2
Stream Characteristics (i.e. T, P)																
Component Flow Rates - materials																
Total Mass Flow	tonne/hr	251000.0	252000.0	6.3	121.0	58.5	201.0	171.0	531.0	3.4	21.5	3.4	6.0	773.0	0.4	170.6
CO2	tonne/hr	229.8	61.6	0.0	26.4	0.0	183.7	167.6							0.4	167.3
Methane	tonne/hr	0.0	0.0	6.3	0.0	0.0	0.0	0.0							0.0	0.0
Oxygen	tonne/hr	64,037.1	64,244.9	0.0	1.2	56.2	1.9	1.7							0.0	1.7
Nitrogen	tonne/hr	185,197.0	185,803.1	0.0	83.9	2.3	1.8	1.7							0.0	1.7
H2O	tonne/hr	1,536.2	1,890.5	0.0	9.5	0.0	13.6	0.0	531.0					769.2	0.0	0.0
CaCO3	tonne/hr									3.4	21.5	3.4	6.0			
Ca(OH)2	tonne/hr													3.5		
Electricity	MW	9.2		-55.8	3.0	13.3		22.0			3.4		4.4	0.5		Variable
Methane	MJ/hr			315000.0												

Example 4: Enhanced Weathering of Mining Fines

Category: Rocks

<u>Process Summary:</u> The example proposed process takes advantage of mining fines which would otherwise be considered a waste and utilizes them to capture CO_2 directly from the air. These materials would be selected based upon their silicate content with a target CO_2 capacity, or R_{CO2} ,of 0.25, which means the materials can hold 0.25 tonnes of CO_2 per tonne of material. This materials would be further milled to a particle size of approximately 0.01 mm, which would increase the surface area to about 1 m^2/g. This fine powder would then have enhanced reactivity with ambient CO_2 in the atmosphere. This material could then be applied to crop lands with a loading of roughly 2.5 tonnes/hectare. Testing of ground materials will be tested for CO_2 uptake over time to determine annual capacity.

<u>Process Flow Diagram and Stream Table:</u> Figure 4 provides a process flow diagram (PFD) indicating the inputs and outputs of the process. The process shows the entire process from the mines all the way to land application, however, the demonstrated technology would focus on the process after acquisition of the mining fines. The PFD identified all material inputs and outputs, major equipment, energy inputs, and flow rates of each provided for a >1000 tonne/yr CO_2 sequestered (***total net sequestered = 1tonne/yr CO_{2e}***). The Stream Table (Table 16) provides a summary of the calculated inputs and outputs for each major process stream identified in the PFD.

<u>Assumptions:</u> Several assumptions are made in calculating the required material and energy inputs and outputs. A summary of each assumption, applicable stream, and source of data related to the assumption is provided in Table 13.

Table 13 Enhanced Weathering Example Assumptions

Stream No.	Stream Description	Notable Assumptions	Data Source / Reference
1	Sequestered CO_2	Assume complete reaction with material	The potential of enhanced weathering in the UK Renforth, P IJGGC 2012
2	Onland Product	Total material required for sequestration of 1000 tonne/yr CO2 plus emission associated with process. Assumed 400 gCO2/kWh	The potential of enhanced weathering in the UK Renforth, P IJGGC 2012
3	Brought to Field	Assumed max delivery distance of 100 km via heavy trucks	Estimate
4	Milled	Energy required calculated via Bond Work Index	The potential of enhanced weathering in the UK Renforth, P IJGGC 2012
5	Crushed	80/20 split between product and fines	The potential of enhanced weathering in the UK Renforth, P IJGGC 2012

6	Raw Rocks	Material has R_{CO2} of 0.25-0.3	The potential of enhanced weathering in the UK Renforth, P IJGGC 2012
7	Product Stones	Product stones are between 2-4mm, however, this is beyond the scope of our process	The potential of enhanced weathering in the UK Renforth, P IJGGC 2012

Mass, Carbon, Energy Balances: Mass and Carbon balances are provided for the overall process as summarized in the PFD in Table 14. Mass balance includes total mass of each major input and each output. For carbon balances, the carbon content of each mass input or output is accounted for. Total carbon mass (C – not CO2e) is calculated for each stream and product, distinguished as a carbon source or sink. For carbon and mass balances, only those processes included in the main process flow are included in calculations.

Table 14 Mass and Carbon Balance

Mass and Carbon Balance					
Component	**Carbon Content (wt% dry)**	**Inputs (tonne/hr)**	**Carbon Input**	**Outputs (tonne/hr)**	**Carbon Output**
CO2 (input)	27.30%	1,195.1	326.262	0.0	0.000
Rocks	0.00%	4780.4	0	0	0
Carbonated Rocks	5.46%	0.0	0.000	5,975.5	326.262
Total		**5,975.5**	**326.3**	**5,975.5**	**326.3**
Mass Balance					**100%**
Carbon Balance					**100%**

A summary of energy inputs is provided in Table 15. However, the size of the turbine and subsequent methane input was selected to match the electrical needs of the DAC, therefore electricity is netted as zero and methane is the only energy input. Note that energy required for the booster pump is also not included, as it is and unknown quantity at this time and is dependent on the pressure drop losses accumulated along the length of pipeline, co-locating the DAC at the well would eliminate this requirement.

Table 15 Energy Balance

Energy Balance		
Component	**Inputs (MWh)**	**Outputs * (MWh)**
Electricity	487.6	0
Total	**487.6**	**0.0**
Energy Balance		**NA**

Figure 4 Enhanced Mineralization Example Process Flow Diagram

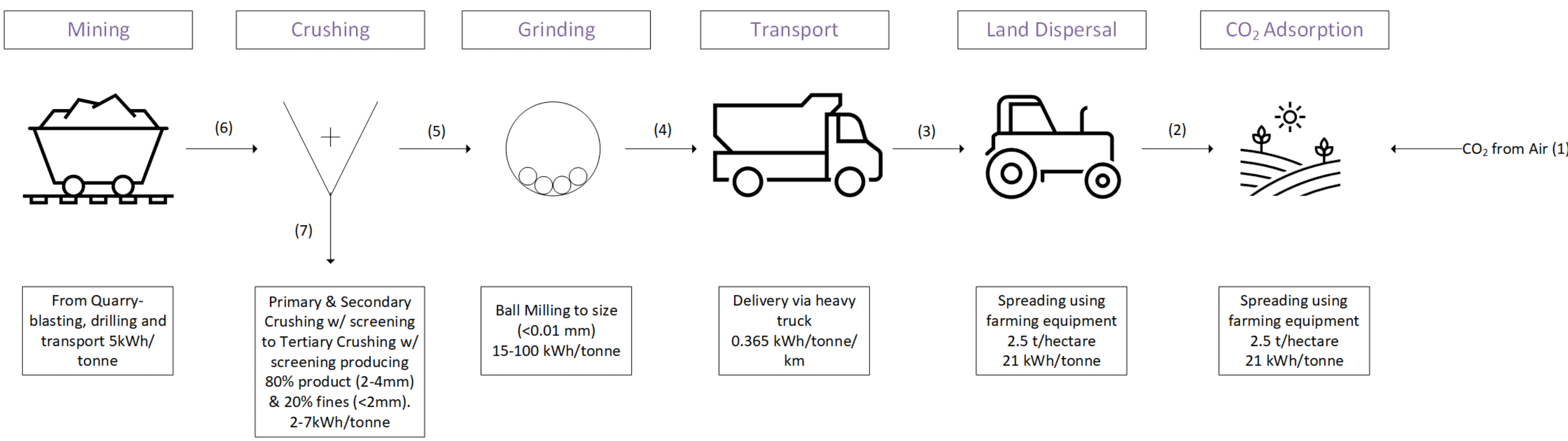

Table 16 Stream Table

Stream No.	Units	1	2	3	4	5	6	7
Stream Description		CO2 in	Onland Product	Brought to Field	Milled	Crushed	Raw Rocks	Product Stones
Stream Characteristics (i.e. T, P)								
Component Flow Rates - materials								
Total Mass Flow	tonne/yr	1163.2						
CO2	tonne/yr	1,195.1						
Rock	tonne/yr		4,780.4	4,780.4	4,780.4	4,780.4	23,902.0	19,121.6
Electricity	MWh		100.4	174.5	71.7	21.5	119.5	