Supplementary Information

Technoeconomic Analysis for the Sustainable Production of Fertilizers via the Photosynthetic Recovery of Nutrients in Livestock Waste

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1 Cyanobacteria Light-Limited Growth Model

A Monod growth kinetics model[1] based on the work of Clark[2] was used to describe the the light-limited growth kinetics for PCC 6803. As the mixing time is very short, it has been cosnidered that the cells experience a spatially average irradiance. Thus, the average specific growth rate is determined

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by the specific growth rate for the average irradiance. The model also considers that a photon balance that tracks the energy distribution from absorbed photons can be used to examine how cellular maintenance and the synthesis of secreted products impact growth. Then, the analytical solution to yield expressions for cell density and product concentration as a function of time can be calculated using the following equations:

$$X(t) = X(0)\exp\left(-\kappa t + X_S[1-\exp(-\kappa t])\right) \tag{1.1}$$

$$P(t) = P(0) + \rho[X_s - X(0)][1-\exp\left(-\kappa t]\right) \tag{1.2}$$

$$\kappa = \frac{Y_{X\nu} m_\nu}{1+\rho\frac{Y_{X\nu}}{Y_{P\nu}}} \tag{1.3}$$

$$X_S = \frac{\eta\frac{I_{IN}S}{V}}{m_\nu} \tag{1.4}$$

Where η is the photosynthetic efficiency, I_{IN} is the irradiance at the surface of the reactor, S is the irradiated surface area of the reactor, V is the culture volume, $m\nu$ is the biomass specific photon utilization for maintenance, Y_{X_ν} is the theoretical maximum yield of biomass on photons, and Y_{P_ν} is the theoretical maximum yield of product on photons, X_S is the stationary phase cell density, κ is a characteristic time constant for transition to stationary phase and is equal to the Y_{X_ν} to $m\nu$ ratio, ρ is the growth associated productivity parameter ($molP(gDW)^{-1}$) and P is the specific productivity.

2 Technoeconomic Analysis Methodology

2.1 Capital Cost Estimation

The total capital investment (TCI) of a plant is the level of investment required to acquire all of the elements necessary to begin operating and is divided into two categories, fixed capital investment (FCI) and working capital investment (WCI).[3] The WCI includes the cost of stockpiling raw materials as well as the operating expenditures accrued before the generated product is sold. The FCI covers the expenses of actually building the plant. In this work, we assume that the WCI is negligible compared to the FCI. This is due to the fact that the raw material, livestock waste, is assumed to be provided free of charge, and the scale of the process is small enough that we assume that it can be operational in less than a year. As a result, the terms TCI and FCI will be used interchangeably from here on.

The FCI is divided into four categories inside battery limit (ISBL) costs, outside battery limit (OBSL) costs, engineering and procurements costs, and contingency costs.[4] ISBL costs cover the purchasing and installation costs of the equipment required to build the production infrastructure of the plant. OSBL costs consist of expenses associated with building the non-production sections of the plant such as utility grid connections, office and laboratory spaces, and safety services. Generating the detailed design required to build the plant is an intensive process that is usually assigned to a specialized design team not involved with daily plant operations, the cost of hiring this team is captured by the engineering costs. The contingency is charged to cover unexpected expenses such as transport delays, sudden material price increases, or late-stage modifications to the design.

The ISBL cost is calculated using the installed cost of the various pieces of equipment required and includes the purchase, transport and setup of the production equipment. In this work we use price data reported in the literature or by equipment manufacturers along with the relevant scaling factors (i.e. the six-tenths rule)[5] and price indices[6] to calculate the ISBL cost of the ReNuAl process:

$$c_i = c_i' \left(\frac{S_i}{S_i'}\right)^{y_i} \left(\frac{PI}{PI_i'}\right) \tag{2.5}$$

where c_i is the installed cost of the i^{th} piece of equipment, S_i is its size, and y_i is the appropriate scaling factor; the cost and size of the reference equipment are denoted by c_i' and S_i' respectively. The price index for the year of construction (2020) is given by PI and PI_i' is the price index for the reference. The ISBL cost is then the sum of the installed costs of the N required pieces equipment:

$$c_{is} = \sum_{i=1}^{N} c_i \tag{2.6}$$

The OSBL, engineering, and contingency costs are typically calculated as a fraction of the ISBL as follows:

$$c_{os} = w_{os} c_{is} \tag{2.7a}$$

$$c_{eng} = w_{eng}(c_{is} + c_{os}) \tag{2.7b}$$

$$c_{con} = w_{con}(c_{is} + c_{os}) \tag{2.7c}$$

where c_{os} and w_{os} are the OSBL costs and cost fraction, c_{eng} and w_{eng} are the engineering costs and cost fraction, and c_{con} and w_{con} are the contingency cost and cost fraction. In this work we used 0.4, 0.3, and 0.2 as the values of w_{os}, w_{eng}, and w_{con} respectively.[7] The value of the TCI, C, is calculated by summing these costs:

$$C = c_{is} + c_{os} + c_{eng} + c_{con} \tag{2.8}$$

2.2 Operating Cost Estimation

Total operating cost (TOC), o, is usually expressed in terms of USD/yr and can be split into two categories: fixed operating costs (FOCs) and variable operating costs (VOCs). FOCs are not tied to production and, as a result, must be paid in full every year that the plant operates. Expenses that fall under this category include labor, maintenance, insurance, leasing costs or property taxes, license fees, and any other general overhead costs. Similar to OBSL, engineering and and contingency costs, we set the FOCs to a fraction of the ISBL cost:

$$c_{mt} = w_{mt} c_{is} \tag{2.9a}$$

$$c_{op} = w_{ov} c_{is} \tag{2.9b}$$

$$c_{ov} = w_{ov} c_{is} \tag{2.9c}$$

where c_{mt} and w_{mt} are maintenance cost and cost fraction, c_{op} and w_{op} are the operations costs (insurance, taxes, license fees) and cost fraction, and c_{oh} and w_{oh} are the general overhead costs and cost fraction; w_{mt}, w_{op}, and w_{oh} were assigned values of 0.05, 0.025, and 0.05 respectively.[4] The cost of labor, c_{lb}, was calculated separately and is based on the area of the reactor section, SA, of the ReNuAl process:[8]

$$c_{lb} = c'_{lb}\left(\frac{SA}{SA'}\right) \tag{2.10}$$

where c'_{lb} is the cost of labor at a reference facility and SA' is the area of its reactor section.

The VOC, c_{voc}, refers to the cost of elements that vary along with production levels; these consist of raw material use, utility consumption, and product shipment. As previously stated, the main raw material, manure, is assumed to be provided free of charge, and we did not consider product distribution costs in this study. The main VOCs are then the utilities (electricity, natural gas, amine, etc.) required to operate the process equipment. The utility requirements for the equipment were calculated by scaling reference values found in the literature to the appropriate size. Note that, unlike capital costs, utility requirements were assumed to scale linearly with equipment size.

2.3 Profitability Calculations

The economic gains from investing in ReNuAl were determined using the discounted return on investment (DROI), which is defined as the discount factor or rate that results in a net present value (NPV) of 0 at the end of a project's lifetime.[3] The NPV can be calculated as follows:

$$NPV = C + \sum_{t=1}^{T} P\,(1+i)^{-t} \tag{2.11}$$

where T is the project lifetime (assumed to be 20 years), i is the discount factor, and P is the annual after tax profit (AATP) which is formulated as:

$$P = (1-x)(p_f\dot{m}_f + p_g\dot{m}_g + p_e\dot{w} - o - d) + d \tag{2.12}$$

Here p_f, $\dot{m}_f$, p_g, $\dot{m}_g$, p_e, and $\dot{w}$ are the selling prices and production rates of the fertilizer, biogas, and electricity generated by ReNuAl, x is the tax rate (21% in US), and d is the annual capital asset depreciation. In this study, d was calculated using the straight-line depreciation formula[3] and the salvage value of the purchased equipment was assumed to be 0:

$$d = \frac{c_{is}}{T} \tag{2.13}$$

The profitability of ReNuAl was measured using two approaches. In the first, the DROI was set equal to 15% and the selling price (USD/kg) of the CB fertilizer that resulted in an NPV of 0 after 10 years was calculated; the values of p_g (USD/kg) and p_e (USD/kW-hr) were fixed according to values found in the literature. In the second, the value of the CB fertilizer was assigned based on its N and P content and the DROI was then varied to obtain a final NPV of 0. This allowed allowed us to gauge the degree to which the fertilizer needs to be improved, or costs reduced, to achieve a desirable level of economic performance.

3 Environmental Analysis

3.1 Greenhouse Gas Emissions and Credits

Greenhouse gas emissions for the various sources (manure, natural gas, electricity), $\dot{E}_i$, were calculated (in terms of tonnes CO_2-eq) using emissions factors as follows:

$$\dot{E}_i = f_i \dot{a}_i, \;\; i \in \{man, g, e\} \tag{3.14}$$

where f_i is the emissions factor for source i and $\dot{a}$ is its activity rate. The net emissions from the ReNuAl are then:

$$\dot{E}_{net} = \dot{E}'_e + \dot{E}'_g - \left(\dot{E}_{man} + \dot{E}_e + \dot{E}_g\right) \tag{3.15}$$

where $\dot{E}'_e$ and $\dot{E}'_g$ are the GHG emissions resulting from the electricity and natural gas demand of the process and $\dot{E}_{man}$, $\dot{E}_e$, $\dot{E}_g$ are the offsets resulting from manure processing, electricity generation, and biogas exportation. Note that the GHG reductions that arise from exporting biogas off-farm as well as on-farm electricity generation are assumed to be equal in value to those that would result from the consumption of these resources.

ReNuAl derives revenue for GHG emissions reductions via the RIN and LCFS credit schemes. RIN credits are applied on an energy content basis at a rate of 17 USD/MMBTU[9,10] (roughly equivalent to 0.84 USD/kg). The total revenue generated from this credit is then:

$$r_{rin} = 0.84 \dot{m}_g \tag{3.16}$$

where $\dot{m}_g$ is again the natural gas export rate of ReNuAl. LCFS credits are earned for emissions offset or avoided at a base of 0.199 USD/kg CO_2-eq.[11] The LCFS credits received are calculated using the emissions factor for natural gas; the revenue generated from methane exportation is then:

$$r_{lcfs} = 0.199 f_g \dot{m}_g \tag{3.17}$$

These revenues can then be incorporated into (2.12) as taxable income and the updated DROI and MSP calculated as detailed in 2.3.

4 Process Costs and Operations Data

Table SI 1: General farm and process information[6,12–16]

Herd size	1000 AU
Manure produced	20832 tonnes/yr
Manure emissions factor	72.5 kg CO_2-eq/tonne
CB P uptake	0.023 kg/kg CB
Operating days per year	365
Light Intensity	350 µmol/m^2·s
Reactor surface area to volume ratio	15.4 m^{-1}
Cost index for 2020	596.2
Electricity price	0.11 USD/kW-hr
Electricity emissions factor	0.4795 tonnes CO_2-eq/MW-hr
Natural gas price	5.84 USD/1000 scf
Natural gas emissions factor	2.75 tonnes CO_2-eq/tonne
Biogas density	1.2 kg/m^3
Diammonium phosphate price	312 USD/tonne
Diammonium phosphate N content	23 wt%
Diammonium phosphate P content	21 wt%

Table SI 2: Mean concentrations of total solids, total nitrogen, total phosphorus and total ammoniacal nitrogen (TAN) for manure in the anaerobic digester and solid liquid separator.[17]

Item	Value	Units	Notes
Manure			
Total P (TP)	7.8	g TP/kg dry manure	Total P in manure
Total N	47		Total N in manure
Total solids (TS)	7.8	%	Total solids fraction in manure
Digestate			
Inorganic N (TAN)	21	kg N/tonne dry manure	fraction of available N in manure that goes into AD digestate
Total solids (TS)	6	%	Total solids fraction in manure
Solid Liquid Separator			
Solid separated manure			
Total P (TP)	30	%	Total P in the solid fraction
Total N (TN)	13	%	Total N in the solid fraction
Total solids	47	%	Fraction of water in the solid product
Liquid separated manure			
Inorganic P (TP)	80	%	Available P in the liquid fraction
Inorganic N (TAN)	50	%	Available N in the liquid fraction

Table SI 3: Economic and environmental variables for the scenarios evaluated. The percentage indicates the change in the MSP relative to the price of diammonium phosphate and the variation in emissions compared to the base case.

Item	Units	ReNuAl1	ReNuAl2
MSP (No incentives)	$/kg	4.73 (+151 %)	4.21 (+134 %)
MSP (Incentives)	$/kg	2.37 (+75 %)	1.32 (42 %)
GWP	Tonnes CO_2-eq	1041 (- 40%)	795 (- 54%)

Table SI 4: Capital costs of ReNuAl units

Item	c_i'	Units	PI_i'	Size Ratio	y_i	Notes
Anaerobic Digester (AD)[18]	$937.1\,(m_{in})^{0.6} + 75355$	USD	539.1	–	–	m_{in} denotes unit capacity (tonne/yr)
Solid-Liquid Separator (SLS)[18]	$14.9 m_{in} + 1786.9 \log(m_{in}) - 9506.6$	USD	556.7	–	–	m_{in} denotes unit capacity (lb/hr)
Electricity Generator[18]	$0.67 c_{AD} x_{CH4}$	USD	539.1	–	–	c_{AD} denotes cost of AD (USD) x_{CH4} denotes fraction of biogas produced used for electricity
H_2S Scrubber[19]	348	USD	521.9	2.59×10^{1}	0.6	–
CO_2 Scrubber[20]	13.1	MMUSD	444.2	4.37×10^{-4}	0.8	–
Photobioreactors[8,21]	279	USD	556.8	1.08×10^{5}	0.6	cost of structural system, bag costs are included in TOC
Flocculation Tank[22]	0.115	MMUSD	585.7	1.57×10^{-3}	0.6	Scaling is in terms of CB mass
Lamella Clarifier[22]	2.50	MMUSD	585.7	1.57×10^{-3}	0.6	Scaling is in terms of CB mass
Pressure Filter[23]	0.137	MMUSD	381.8	2.39×10^{-1}	0.6	–
Dryer[23]	0.706	MMUSD	539.1	2.20×10^{3}	0.6	–

Table SI 5: Variable operating costs and utility sources for ReNuAl units

Item	Operating Cost	Units	Utilities	Notes
Anaerobic Digester[18]	$0.096c_{AD}$	USD/yr	electricity	c_{AD} denotes cost of AD (USD)
Solid-Liquid Separator[18]	$0.488m_{in} + 0.1c_{SLS}$	USD/yr	electricity	m_{in} and c_{SLS} denote capacity and cost of SLS (USD)
H_2S Scrubber[19]	66.7	USD/tonne biogas	activated carbon	gas removal via carbon bed adsorption
CO_2 Scrubber[20]	40.0	USD/tonne CO_2	amine solution, steam	gas removal via amine scrubbing
Photobioreactors[8]	12100	USD/acre/yr	electricity, bags, urea, water	–
Flocculation Tank[22]	100	USD/tonne CB	electricity	source includes cost of chemical flocculant
Lamella Clarifier[22]	0.43	USD/tonne CB	electricity	–
Pressure Filter[23]	2.06	USD/tonne CB	electricity	–
Dryer[23]	19.3	USD/tonne water	natural gas	basis is in terms of water removed

Table SI 6: Product yield factors

Product	Unit	Yield	Notes
CH_4[15]	Anaerobic Digester	3.09×10^{-2} kg/kg manure	CH_4 from biogas production
CO_2[15]	Anaerobic Digester	1.66×10^{-2} kg/kg manure	CO_2 from biogas production
H_2S[15]	Anaerobic Digester	1.14×10^{-4} kg/kg manure	H_2S from biogas production
Electricity[24]	Electricity Generator	4.33 kW-hr/kg CH_4	assumes gas turbine efficiency of 0.3 and CH_4 energy content of 1000 BTU/scf
Bedding[13]	Solid-Liquid Separator	0.09 kg/kg manure	P and N are assumed to be uniformly distributed in digestate liquid and solid fractions
Cyanobacteria[2]	Photobioreactors	4.98E-3 kg/L	titer achieved after 30 days and 350 µmol/m^2·s light intensity
Primary Dewatering Product[22]	Lamella Clarifier	1.60×10^{-2} kg/L	–
Secondary Dewatering Product[23]	Pressure Filter	0.27 kg/L	–

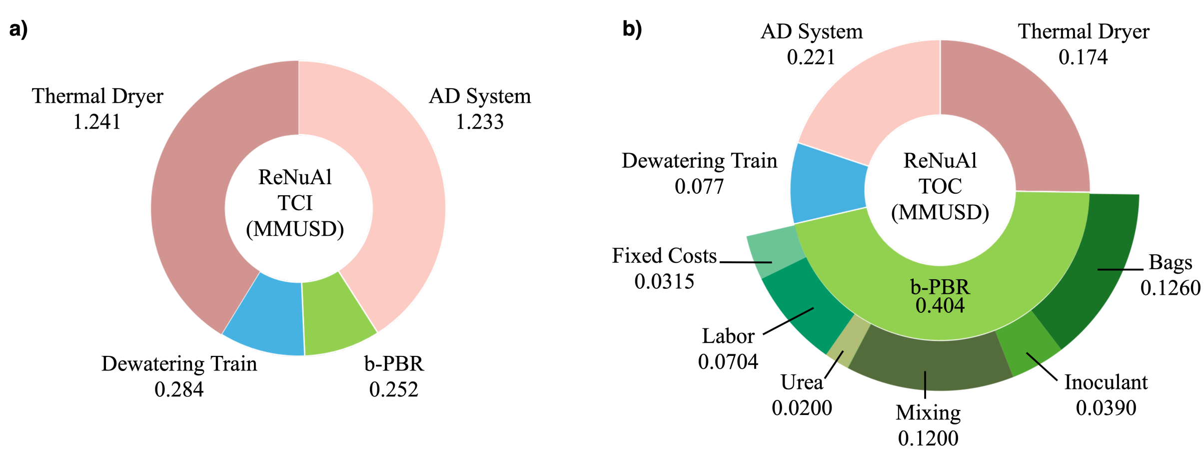

Figure SI 1: Distribution of the total capital investment (right), in MMUSD, and total operating costs (left), in MMUSD/yr, for ReNuAl1 across the different sections of the process.

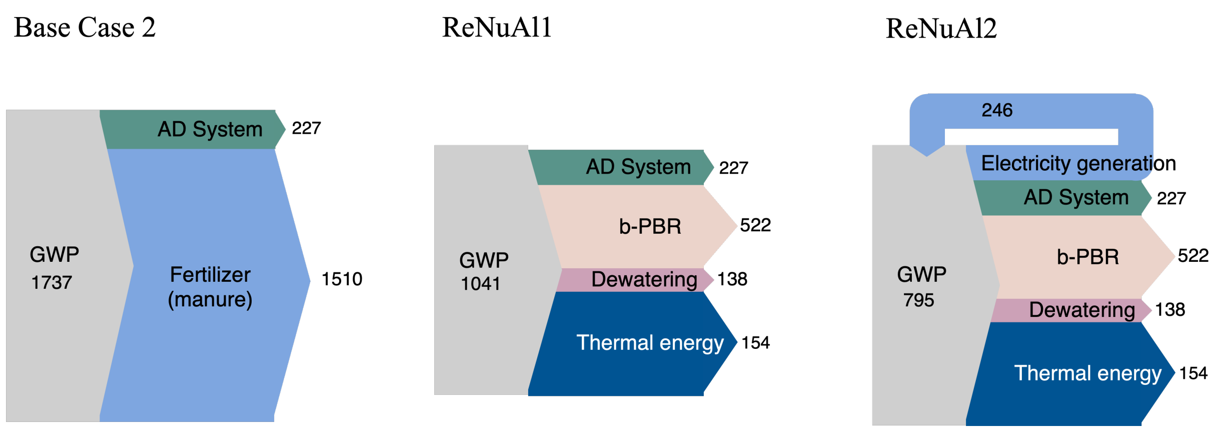

Figure SI 2: Global Warming Potential (GWP) in tonnes of CO_2 per year for the evaluated scenarios.

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