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Supplementary Materials for

A techno-economic assessment for animal cell-based meat tentative title —No Paragraph Breaks

Derrick Risner, Sara Pace, Justin Siegel, …… Edward Spang no paragraph breaks.

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**This PDF file includes:**

Materials and Methods

Supplementary Text

Figs. S1 to S2

Tables S1 to S4

Captions for Data S1 to S2

**Other Supplementary Materials for this manuscript include the following:**

Data S1 to S2

Data S1. Techno-economic analysis excel model for ACBM. Tentative name

Data S2. Techno-economic analysis web-based program for ACBM. Tentative name

Materials and Methods

Methods

To determine the economic viability of animal cell-based meat (ACBM), we developed a model using standard process and chemical engineering methods. The model system is a semi-continuous-batch production system operating at capacity year around and does not account for fill times, sanitation between batches or any operational downtime. Table S2 provides a list of equipment that would likely be necessary for industrial ACBM production. The costs were broadly broken down into annual operating costs and capital expenditures.

Capital Expenditures of an ACBM plant

We accounted for the volume each myoblast/myosatellite cell (MSC) occupies with the operating constraint that the total cell volume cannot exceed bioreactor operating capacity for each batch. Cell volumes are variable, so a reported volume estimate of 5 x 10-15 m3 cell-1 was used 1. Eukaryotic muscle cell density is approximately 1060 kg m-3 and was used to estimate mass of ACBM per batch 2. The actual density of ACBM may be lower due to incorporation of bovine adipose cells or other sources of fat. A decrease or increase in batch time influences economic viability of ACBM production. The batch time is the sum of the cell growth phase and maturation time (equation 1). The cell concentration is considered a variable that can change with technological innovation. Using a given cell concentration, the mass of each batch of ACBM was determined using equations 2-4. The batch time was then used to calculate the annual ACBM batches per bioreactor and the number of bioreactors required to achieve the desired annual ACBM production mass (equations 5 and 6).

Cost estimates of food-grade bioreactors were calculate using a method which accounts for equipment scaling, installation, and inflation (equations 7 and 8) 3. This method applies a set unit cost of $50,000 m-3 for a food grade bioreactor and a common scaling factor of 0.6 3. To account for inflation and changes in cost over time the Chemical Engineering Plant Cost Index (CEPCI) values for heat exchangers and tanks were used to determine an adjusted value factor 4,5. Adjusted value factor of 1.29 was determined dividing the recent CEPCI values with the values from when the set unit cost was referenced. The Lang factor is used to estimate cost associated with installation and piping. This factor can range from 1.35-2.75 for traditional food production operations and to up to 4.80 for fluids processing 6. A Lang factor was estimated to be 2 for all scenarios. For new plant cost the Lang factor value should be increased by 1 6. This estimated the minimum capital expenditures for the required number of bioreactors which are necessary to meet the desired ACBM production mass. This method doesn’t account for any other equipment which would likely be necessary for ACBM production (Table 1) besides the primary bioreactor systems.

Operating costs of an ACBM plant

The potential manufacturing cost of an ACBM plant can be broken into three categories: Fixed manufacturing costs, variable capital costs and indirect (overhead) costs. All fixed manufacturing costs were estimated as a percentage of the fixed equipment costs except loan and equity interest (equation 9) 6. These costs include equipment maintenance, insurance, taxes and royalties costs 6. Indirect costs are not accounted for in our model since these costs are outside of plant operation expenses and will vary company to company. Our model provides an estimate of several variable capital costs related to downstream ACBM production. Costs associated with general meat production such as packaging material and facility lighting are not included. The variable costs estimated in our model include ingredients, raw materials, utilities and labor costs. Equation 10 accounts for all the operating costs associated with the model we have provided.

Ingredients and raw materials

A key material for animal serum-free ACBM production is the specialized media required for myoblasts/MSCs growth. Our model examines the use of Essential 8, an animal free growth medium which contains over 50 ingredients including ascorbic acid 2-phosphate, sodium bicarbonate, sodium selenite, insulin, transferrin, fibroblast growth factor-2 (FGF-2), and transforming growth factor beta (TGF-b§) 1. A report from the Good Food Institute provides an excellent breakdown of the individual components of Essential 8 media and the 2019 pricing of each media component 1. Cell glucose consumption rates can vary based upon several factors including glucose concentration present in the growth medium and the metabolic pathways being utilized by the cell 7,8. Glucose consumption rates have been reported to be between 2 to 20 nmol1 million cell-1 min-1 in human stem cells 8. While there can be many limiting factors in a complex medium system; glucose consumption and the total number of cells in the bioreactor were used to estimate the media requirements and expense per batch. The starting glucose concentration is reported to be 1.78x10-2 mol L-1 1. Only media used in the main bioreactor was accounted for. An oxygen supply is also critical for aerobic cell culture and is also considered an operating expense for ACBM production. Equation 11 was used to determine total amount of myoblasts/MSCs in the bioreactor at a given time. During the growth phase, the glucose consumption rate changes as time changes and this was accounted for using equation 12. The total glucose required for the growth phase was determined by equation 13. The total glucose required per batch was determined by adding the total glucose used in the maturation and growth phase (equations 14 and 15).

The media requirement was then determined by examining the total amount of glucose in the Essential 8 media. To understand the volume requirement per batch, a charge was deemed the equivalent to the working volume of the bioreactor. This assumption was done to account for any innovations related to vascularization and does not account for the volume of the cells. The total media volume required per batch/year and total annual media costs were determined by equations 16-19.

An oxygen supply is critical for aerobic cell cultures and is also considered an operating expense for ACBM production. The oxygen levels in the bioreactor were assumed to be kept in a steady state concentration of 2% for optimal cell growth 9,10. This is expressed by equation 20 11. The initial oxygen needed for the bioreactor system was determined by equation 21. The annual oxygen requirement was determined in the same manner as the media requirement and is calculated using equations 11 and 22-27.

Utility related expenses

Our model accounts for some bioreactor operating expenses. These should be viewed as theoretical minimum estimates based upon conventional thermodynamic equations. The energy requirements for heating the media, cooling the bioreactors and cooling of the ACBM mass leaving the bioreactor systems were estimated. The water/media was assumed to enter the facility at approximately 20 ˚C. The media is also assumed to have an isochoric specific heat of approximately water. The density of the media was assumed to be 1 kg L-1 and would be heated to 37 ˚C. The minimum energy required to heat the media was calculated using equation 28. The metabolic consumption of glucose and oxygen produces heat which must be removed from the system. Approximately 470 kJ of heat is released per mol of O2 consumed during glucose combustion (equation 29) and this value was used to approximate cellular heat generation 11. The minimum energy required to be removed from the system to ensure cell health was calculated using equation 30. The ACBM mass leaving the bioreactor must be cooled from 37 ˚C to 4 ˚C to ensure food safety standards are maintained 12. The specific heat of ACBM is assumed to be the same as beef which is 2.24 kJ kg-1 ˚C-1 13. An estimation of energy used during the cooling process (equation 31) was made based on the efficiency of the heat exchanger system.

Energy costs can be variable depending upon the location, time of day and amount used. A yearly national grid average for industrial electricity and natural gas prices was obtained from the United States Energy Information Administration (EIA) from 1999-2019 14. One thousand cubic feet of natural gas contains approximately 303.6 kWh of potential energy and the cost per kWh was determined using this value 15. The average costs were normalized to January 2019 prices using the CPI inflation calculator (Table S3 and S4) 16. To estimate the energy/electricity cost a comparison of the industrial price of natural gas and electricity was made from 1999-2019 (Fig. S3). Equation 32 was derived from a linear relationship of the cost of electricity and natural gas (Fig. S4). Equation 32 was then used to estimate energy/electricity costs from a public supplier. Natural gas was chosen since it is the most used source of energy for electricity production in the United States in 2019 17. The costs of energy/electricity produced via an onsite boiler-turbine system was estimated by equation 33. A steam pressure of 42.5 bar is assumed because it is used as a reference pressure for cost of steam production and is adequate for steam turbine electricity production 18,19. Solar generation of electricity was considered as well and was estimated to have a negligible operating cost for the facility. The equipment costs for solar are not accounted for since this is a facility dependent item. Equation 34 estimates the minimum cost of energy at an ACBM production facility.

Our model assumes media will be produced onsite given the scale of the operation. All water used for media production is considered process water, however it should be noted that deionized water could be required due to the operational sensitivity of myoblasts/MSCs. Compressed air is a common utility in food production facilities; however, it is not estimated in this analysis due to being a site specific consideration. Cost of sterile filtration of the water for media production is not accounted for. The spent media is considered wastewater and must be treated to comply with environmental regulations 20. The wastewater is assumed to be treated by a filtration and biological oxidation step. Cost estimates have been made for process water and wastewater treatment and these estimates have been adjusted to January 2019 values to account for inflation (Table 4) 16,18. It should be noted that this does not account for water used for sanitation or for losses during the production process. Equation 35 is used to estimate the annual process and wastewater costs.

Labor related expenses

Our scenarios assume that the ACBM production facility is operating 24 hours/day and year around. It is assumed the facility is fully staffed and no overtime is required. Each shift is assumed to be an 8-hour shift. The facility is also assumed to be in the United States in an area of standard income. The required production operators (required manpower) for the ACBM production facility per shift is estimated by amount and type of processing equipment in the facility (Table S2) 3,18. This processing equipment could include centrifugal pumps, plate filters, media holding vessels, heat exchangers, bioreactor seed train, positive displacement pumps and bioreactors. In the four scenarios, this equipment was deemed site specific and only the main bioreactors were accounted for. However, these factors are adjustable in our model. The labor cost were determined using the mean hourly rate, $13.68 (USD h-1) for a meat packer 21. The labor costs were estimated using a factorial method with a labor cost correction factor (equations 36-38) 18.

Finance related expenses

Our model accounts for the expenses related to equity recovery and debt using a standard finance calculation (equations 39-46) 22. For all scenarios, the input variables were kept constant. Equations 39-46 convert the capital expenditures to an annual cost which is used to calculate the total annual minimum costs in conjunction with the annual operating costs (equation 47).

Sensitivity analysis

The sensitivity analysis was conducted by individually increasing and decreasing each model variable by 25% and comparing the new capital costs and annual operating costs with original model parameters.

Supplementary Text

Model limitations

In human pluripotent stem cells, as the cells exit pluripotency and enter the initial differentiation phase a metabolic shift to mitochondrial OXP occurs 23,24. A similar shift occurs as myoblasts fuse differentiate into myotubes 25. As myoblasts differentiate into myotubes it has been reported that the metabolic rate is maintained despite a greater reliance on OXP pathway for ATP production25,26. However, it is not known if this metabolic rate will be maintained during the undefined scaffolding and maturation process. During this undefined scaffolding and maturation process, the myotubes diameter could potentially increase 20-fold27–29. Our model assumes glucose and oxygen uptake rate are maintained during this process; however, these values could change to meet the metabolic needs of the maturing myotubes. Once the myotubes mature, they rely upon OXP to meet their metabolic needs and this shift may require an adjustment to operation factors such as an increased or decreased media or oxygen supply.

Our model did not account for amino acid uptake rates due to glucose being the most consumed nutrient in cell culture, however amino acid (AA) metabolism should be a consideration for commercial scale up. An example of the importance of this consideration is that stem cell amino acid metabolism can vary species to species 30,31. Bovine and mouse embryonic stem cells are sensitive to extrinsic deprivation of threonine, whereas human embryonic stem cells are not sensitive extrinsic deprivation of threonine, but require increased levels of methionine 31–33. This extrinsic threonine requirement does not apply to other mouse or bovine cells which are proliferating30. This illustrates how these requirements can vary by species and by cell type.

Glutamine is utilized as both a nitrogen donor and energy substrate in proliferating myosatellite/myoblast cells 34,35. Glutamine is the second most consumed nutrient in animal cell cultures and contributes to nucleic acid, protein and lipid production 36. Glutamine concentration has been show to influence the myoblasts proliferation rate with 300 µM being reported as the optimal conditions for human myoblasts proliferation 35. This indicates that amino acid levels in the media could potentially influence operating costs via increased or decreased doubling times. This would likely be cell line dependent and should again be a consideration for companies wishing to develop multiple products from different cell lines.

The volume of animal cells also plays an important factor in our modeling which accounts for the volume of each cell. Animal myoblasts cells volume are orders of magnitude larger than common prokaryotic or single cell fungi 37. This places hard constraints on the number of cells a single bioreactor can produce per batch i.e. bioreactor with a working volume of 20 m3 can only produce the number of cells whose total volume is 20m3. This does not account for repulsive forces or for the media within bioreactor. While this was done to account for any innovations in vascularization it makes the model less conservative and should be a consideration for any company considering scale up. It also does not account for cellular volume increases during the unknown scaffolding and maturation phase. The diameter of the myotube can increase up to 20 times it’s original size as contractile protein is formed 27–29. This increase in size of the cells during maturation could make the bioreactor more efficient, however it was not included in our model due to the unspecified nature of the commercial process.

Figure 2 represents a potential upstream production system for ACBM, however the capital expenditures that were estimated by our model only estimate the cost of a series of 20,000 L continuous stirred bioreactors designated by letter A. We did not adjust the maximum bioreactor operating capacity of the bioreactors in any scenario due to fragility of animal cells which lack a cell wall and cannot withstand the hydrostatic pressures which yeast or prokaryotic organisms can 38. Innovations in bioreactor design could potentially increase the maximum working capacity. An increase in bioreactor working capacity would potentially lower capital expenses and annual operating costs. However, this would initially increase the base cost ($50,000/m3) of the bioreactor measured in our model. In a more detailed analysis as the metrics we have outlined are achieved, interest rate and learning curve equations could be applied to estimate capital and operating expenses in finer granularity. We also assume that the unknown scaffolding and maturation process could be accomplished within the bioreactors. If a separate bioreactor or maturation vessel is needed this would also increase capital expenditures. We did not account for the other equipment since this will be a site-specific variable. The Lang factor is used to estimate actual cost of equipment by accounting for installation related expense. A Lang factor of 2 was chosen for all scenarios to represent a food/bioprocessing facility that could be easily configured to accommodate ACBM production. However, a Lang factor of 2 is considered to be low by general conventions for a brand new facility or novel technology; a Lang factor of 3 to 5 would be more appropriate 3. We anticipated that once the ACBM is cooled it will be processed in a manner similar to other ground meat products. We also did not account for any additional ingredients being added to the product. Cellular propagation technology could potentially be applied for myoblasts/MSC propagation. Cytodex® 1 microcarriers have been employed for bovine myoblasts proliferation and achieved a cell concentration of approximately 9x106 cells/ml 39. Our model does not account for this technology or any additional propagation technology which may increase capital or operating expenses. It has also been reported that bovine muscle satellite cells have been cultured with hemoglobin and myoglobin40. Costs associated with additional ingredients or media supplementation have not been accounted for and could substantially increase the annual operating expenses

Variables list

Variables are listed in the order they appear in the equations.

= time of batch (h)

= Time growth phase ends (h)

= Time of maturation phase (h)

= Final concentration of cells in bioreactor (cells L-1)

= Bioreactor working volume (L)

= Total number of cells in bioreactor (cells)

= Volume of single cell (m3 cell-1)

= Volume (m3)

= Density of muscle cell (kg m3)

= mass of ACBM produced per batch (kg batch-1)

= Number of batches a single bioreactor can produce in year (batches year-1)

= Mass of ACBM a bioreactor can produce in a year (kg year-1)

= Desired annual mass of ABCM (kg)

= Total number of bioreactors required to annual production goal

= Total equipment costs (USD)

= Fixed equipment cost (USD)

= Adjusted value factor for equipment j

= Unit costs for equipment j

= Base unit for equipment j

= Actual unit for equipment j

= Scale factor for equipment j

= Lang factor

= Fixed manufacturing cost factor

= Fixed manufacturing costs (USD)

= Annual operating costs (USD)

= Total annual costs of media (USD)

= Total annual costs of oxygen (USD)

= Minimum energy required to heat media (kWh)

= Minimum energy required bioreactor heat removal (kWh)

= Minimum annual energy required for ACBM heat removal (kWh)

= Estimated annual labor costs (USD)

= Cost of energy (cents kWh-1)

= Annual process water and wastewater costs (USD)

= Total number of cells at time (t)

= Total number of cells present in inoculum (cells)

Doubling time (h)

= Time (h)

= Glucose consumption rate within the bioreactor (mol h-1)

= Glucose consumption rate per cell (mol h-1 cell-1)

=Total moles of glucose required for growth phase (mol)

= Total moles of glucose required for maturation phase (mol)

= Total moles of glucose required per batch (mol)

= Total media charges per batch (charge)

= Moles of glucose per charge (g)

= Total volume of media required per batch (L)

= Volume of charge or bioreactor (L)

= Total media volume per year (L year-1)

= Batches per year

=Cost of media per liter (USD L-1)

= Oxygen uptake rate in bioreactor (mol s-1)

= Oxygen transfer rate in bioreactor (mol s-1)

= mass transfer coefficient (m s-1)

= mean bubble specific interfacial surface area (m2)

= equilibrium concentration (mol m-3)

= actual dissolved oxygen concentration (mol m-3)

= Initial oxygen in required in the system (mol)

= Density of media (kg L-1)

= Percentage of oxygen (O2) in media by weight (%)

= molar mass of O2 (kg mol-1)

= rate of oxygen consumption per cell mol cell-1 h-1

= Total oxygen required for growth phase per batch (mol)

=Total oxygen required for maturation phase per batch (mol)

= Total oxygen used per ACBM batch (mol)

= Total amount of oxygen required per year (mol)

= Total annual costs of oxygen (USD)

= Cost of oxygen (USD mol-1)

=Mass of media used per year (kg)

= Temperature difference (˚C)

= Specific heat of water at constant volume (kWh kg-1 ˚C-1)

= Energy efficiency of heating system (%)

= Oxygen required annually (mol)

= Heat released per mol of oxygen consumed (kWh mol-1)

= Cooling system energy efficiency (%)

= Specific heat of ACBM (kWh kg-1 ˚C-1)

= Energy efficiency of cooling system (%)

= cost of electricity from a public supplier (USD kWh-1)

= Cost of natural gas (USD 1000 ft-3)

= Cost of energy from onsite boiler-turbine system (USD kWh-1)

= natural gas price (USD kWh-1)

= boiler-turbine system efficiency (%)

= percentage of electricity produced by from a public supplier (%)

= percentage of energy produced by on site boiler-turbine system (%)

= Process water costs (USD m-3)

= Wastewater filtration costs (USD m-3)

= Biological oxidation of wastewater costs (USD m-3)

= required manpower (production workers)

= production worker required for single piece of equipment

= Individual piece of equipment

= All downstream equipment used in downstream ACBM production

= Labor cost correction factor

= Country effect

= Supervising and clerical assistance

= Advanced technological and automating

= Skilled and qualified level of the personnel

= Social benefits

= Overtime work

= Estimated annual labor costs (USD)

= Annual operating time (h)

= Production worker hourly rate (USD h-1)

= Equity ratio

= Total debt costs (USD)

= debt ratio (%)

= Total equity costs (USD)

= Capital recovery factor for debt

= Capital recovery factor for equity

= Annual debt payment (USD)

= Annual equity recovery (USD)

= Minimum annual cost of capital expenditures (USD)

= Total minimum annual costs (USD)

Equation list

All cost values are in United States dollar amounts (USD).

Equation 1. Time of batch

Equation 2. Total number of cells in a single bioreactor after maturation

Equation 3. Total volume occupied by cells

Equation 4. Cell mass in bioreactor per batch

Equation 5. Annual ACBM production per bioreactor

Equation 6. Bioreactors needed to match desired annual beef production

Equation 7. Equipment costs equation

Equation 8. Fixed equipment costs

Equation 9. Fixed manufacturing costs

Equation 10. Minimum annual operating costs

Equation 11. Cells in bioreactor during growth phase

Equation 12. Glucose consumption rate during growth phase

Equation 13. Total glucose required for growth phase per ACBM batch

Equation 14. Total glucose required for maturation phase per ACBM batch

Equation 15. Total glucose required per batch

Equation 16. Total required media charges per batch

Equation 17. Total media volume required per batch

Equation 18. Total media volume per year

Equation 19. Total annual costs of media

Equation 20. Oxygen uptake rate

Equation 21. Initial oxygen in the for the system

Equation 22. Oxygen uptake rate changing with time

Equation 23. Total oxygen required for growth phase per ACBM batch

Equation 24. Total oxygen required for maturation phase per ACBM batch

Equation 25. Total oxygen required per ACBM batch

Equation 26. Total amount of oxygen required per year

Equation 27. Total annual costs of oxygen

Equation 28. Estimation of energy to heat media to required temperature

Equation 29. Glucose combustion reaction

C6H12O6 + 6 O2 → 6CO2 + 6 H2O + heat

Equation 30. Estimation of energy usage for bioreactor cooling per ACBM batch

Equation 31. Estimation of annual energy usage for cooling of ACBM

Equation 32. Cost of energy per kWh from public supplier

Equation 33. Cost of self-generated electric/energy per kWh from a boiler-turbine system

Equation 34. Cost of energy per kWh

Equation 35. Annual process water and wastewater costs

Equation 36. Required manpower for operation

Equation 37. Labor cost correction factor

Equation 38. Estimated annual labor costs

Equation 39. Equity ratio

Equation 40. Total debt costs

Equation 41. Total equity costs

Equation 42. Capital recovery factor for debt

Equation 43. Capital recovery factor for equity

Equation 44. Annual debt payment

Equation 45. Annual equity recovery

Equation 46. Minimum annual cost of capital expenditures

Equation 47. Total minimum annual cost

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Fig. S1. Sensitivity analysis of variables influencing capital expenditures

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Description automatically generated

Sensitivity analysis of variables influencing capital expenditures. Variables were individually increased and decreased by 25%.

Fig. S2. Sensitivity analysis of variables influencing annual operating expenses

A screenshot of a cell phone

Description automatically generated

Sensitivity analysis of variables influencing capital expenditures. Variables were individually increased and decreased by 25%.

Fig. S3. Costs comparison of the average United States industrial electricity and natural gas (USD kWh-1)1999-2019

A close up of a map

Description automatically generated

Costs comparison of the average United States industrial electricity and natural gas (USD kWh-1) 1999-2019. Information was obtained from the United States EIA and average costs were normalized to January 2019 US currency14,16.

Fig. S4. Linear relationship between electricity and natural gas cost.

A close up of a map

Description automatically generated

Linear relationship between electricity and natural gas cost. This relationship was used to determine equation 32. Information was obtained from the United States EIA and average costs were normalized to January 2019 US currency14,16.

Table S1. Model inputs for key variables for ACBM production

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenarios | **Achievable cell concentration (cells/ml)** | **Bioreactor working volume (m3)** | **FGF-2 conc. (g/L)** | **FGF-2 cost (USD/g)** | **Glucose concentration in basal media (mol/L)** | **Glucose consumption rate per cell (mol/ h cell)** | **Hours per doubling (h)** | **Maturation time (h)** |
| 1 | 1.00x107 | 20.0 | 1.00x10-4 | 4.01x106 | 1.78x10-2 | 4.13x10-13 | 24.0 | 240 |
| 2 | 9.5x107 | 20.0 | 5.00 x10-5 | 2.10x106 | 2.67x10-2 | 2.07x10-13 | 16 | 156 |
| 3 | 9.5x107 | 20.0 | 5.00 x10-5 | 0 | 2.67x10-2 | 2.07x10-13 | 16 | 156 |
| 4 | 2.00x108 | 20.0 | 0 | 0 | 3.56x10-2 | 4.13x10-14 | 8 | 24 |

Model inputs for key variables for ACBM production. These variables were identified as most impactful by a sensitivity analysis.

Table S2. Potential industrial scale equipment for ACBM production.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Equipment** | **Unit** | **Unit costs ($1000’s)** | **Scale index** | **Production Operators required (P)** | **Adjusted value factor (fAj)** | **Accounted for in equipment cost analysis** |
| Centrifugal pumps | Power (kW) | 5 | 0.60 | 0.1 | 1.42 | - |
| Plate filters | Area (m2) | 3 | 0.75 | 1.0 | 1.64 | - |
| Media holding vessel | Volume (m3) | 10 | 0.50 | 0.2 | 1.29 | - |
| Heat exchanger | Area (m2) | 3 | 0.65 | 0.5 | 1.29 | - |
| Inoculum bioreactor | Volume (m3) | 50 | 0.60 | 1.0 | 1.29 | - |
| Seed bioreactor | Volume (m3) | 50 | 0.60 | 1.0 | 1.29 | - |
| Bioreactors | Volume (m3) | 50 | 0.60 | 1.0 | 1.29 | + |
| Positive displacement pump | Power (kW) | 5 | 0.60 | 0.1 | 1.42 | - |

Potential industrial scale equipment for ACBM production. Created using information from *Food Plant Economics* and CEPI 4,5,18.

Table S3. Annual United States national industrial grid electricity costs 1999-2019

|  |  |  |
| --- | --- | --- |
| **Year** | **Average nominal consumer cost per year (cents kWh-1)** | **Inflation adjusted cost (cents kWh-1)** |
| 1999 | 4.42 | 6.77 |
| 2000 | 4.63 | 6.9 |
| 2001 | 5.04 | 7.25 |
| 2002 | 4.88 | 6.94 |
| 2003 | 5.11 | 7.08 |
| 2004 | 5.25 | 7.14 |
| 2005 | 5.72 | 7.59 |
| 2006 | 6.15 | 7.81 |
| 2007 | 6.39 | 7.95 |
| 2008 | 6.95 | 8.29 |
| 2009 | 6.83 | 8.14 |
| 2010 | 6.76 | 7.85 |
| 2011 | 6.81 | 7.78 |
| 2012 | 6.66 | 7.4 |
| 2013 | 6.88 | 7.52 |
| 2014 | 7.09 | 7.63 |
| 2015 | 6.90 | 7.43 |
| 2016 | 6.75 | 7.17 |
| 2017 | 6.87 | 7.12 |
| 2018 | 6.92 | 7.03 |

Annual United States industrial national grid electricity costs 1999-2019. Information was obtained from the United States EIA and average costs were normalized to January 2019 US currency14,16.

Table S4. Annual United States national industrial natural gas costs 1999-2019

|  |  |  |
| --- | --- | --- |
| **Year** | **Average nominal cost per year (USD thousand cubic feet-1)** | **Inflation adjusted cost (cents kWh-1)** |
| 1999 | 3.08 | 1.55 |
| 2000 | 4.45 | 2.19 |
| 2001 | 5.08 | 2.40 |
| 2002 | 4.02 | 1.88 |
| 2003 | 5.91 | 2.70 |
| 2004 | 6.51 | 2.92 |
| 2005 | 8.67 | 3.77 |
| 2006 | 7.82 | 2.58 |
| 2007 | 7.65 | 3.13 |
| 2008 | 9.66 | 3.79 |
| 2009 | 5.23 | 2.05 |
| 2010 | 5.44 | 2.08 |
| 2011 | 5.12 | 1.93 |
| 2012 | 3.85 | 1.41 |
| 2013 | 4.64 | 1.67 |
| 2014 | 5.58 | 1.98 |
| 2015 | 3.91 | 1.39 |
| 2016 | 3.49 | 1.22 |
| 2017 | 4.08 | 1.39 |
| 2018 | 4.17 | 1.42 |

Annual United States national average natural gas costs 1999-2019. Information was obtained from the United States EIA and average costs were normalized to January 2019 US currency14,16.

Table S5. Cost of process and wastewater treatment

|  |  |
| --- | --- |
| **Utility** | **Cost (USD m-3)** |
| Process water | 0.63 |
| Wastewater filtration treatment | 0.51 |
| Biological oxidation of wastewater | 0.57 |

Cost of process and wastewater treatment. Cost were reported in *Food Plant Economics* and were adjusted to account for inflation reported in January 2019 US currency 16,18.

Data S1. (separate file)

Techno-economic analysis excel model for ACBM. Tentative name

Data S2. (separate file)

Techno-economic analysis web-based program for ACBM. Tentative name