

Electrical Requirements for a Spectrum of Multi-Stage Space Farms

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Future long-term space missions and settlements will be energy intensive and will need both biological and mechanical means to recycle carbon dioxide, water, and wastes to oxygen, clean water, and a variety of foods. Missions imply a transient nature, but settlements require a more permanent mindset. Settlements here imply permanent or nearly permanent occupancy. Previous work has shown that space farms, using a diversity of species and stage types including hydroponic, aquatic, photobioreactors, and yeast-bacteria bioreactors, can both recycle air and water, and produce a variety of foods to support a settlement. This work calculated mass flows, stage and species living masses, initial supplies, and volumes for four increasingly complex scenarios to support a 100-person settlement, with a variety of farm species. The most diverse space farm scenario produces enough to feed 61 people per hectare, roughly equivalent to the best production for rice and soybeans in fields on Earth (see Appendix A). However, we need to know energy in addition to mass and volume. Energy demand determines lift mass for solar panels or reactors. Energy demand, particularly electrical power, can be estimated using data for existing industrial equipment used to pump liquids and circulate gases on Earth. Similarly, currently available light sources can be used to predict lighting requirements, both photosynthetic and environmental, for the biomass produced by each species. These estimates, combined with energy for circulation and thermal control, give worst case total energy needs related directly to masses and sizes of biomass for each stage in the farm. This paper will use industrial data to tie energy to mass flow, volume, and footprint, to calculate electrical requirements for each stage in each of four scenarios in a one hundred person evolving space settlement, with attendant solar panel area to supply power. Results show that fluid movement drives energy consumption for most scenarios, with worst case total power needs ranging from 1 kW per person for very early settlements to 117 kW per person for well-developed food factory farms, and that solar panel areas will be multiples of farm footprint (see Table 43). *Note: Pump coefficients were corrected with inputs from reviewers on 2/14/2023.*

I. Nomenclature

A_i	= footprint area in square meters for stage
$A_{a,i}$	= photosynthetic lit area of an algae bioreactor stage i
C	= Circulation rate of the entire farm volume for heat rejection in rotations per day.
E_i	= total energy needed for the stage i in Watts
$E_{w,i}$	= energy needed for work/animal lighting for stage in Watts
$E_{f,i}$	= energy needed for fluid pumping (gas and liquids input, output, recirculation) for stage i in Watts
$E_{lq,i}$	= energy needed to pump liquids
$E_{g,i}$	= energy needed to pump liquids
E_h	= energy needed to circulate the air volume in the farm for heat rejection.
$E_{p,h,i}$	= energy needed for hydroponic photosynthetic light in stage i.
$E_{p,a,i}$	= energy needed for algae photosynthetic light in stage i
E_{TOTAL}	= energy for the space farm.
F	= mass flow in kg/day
F_g	= mass flow for gases in kg/day
F_{lq}	= mass flow for liquids in kg/day
F_s	= mass flow for solids in kg/day
H	= habitat or work lighting needed in lumens per square meter.
Λ	= lumens per watt for (Light Emitting Diode) LEDs for work or animal lighting (visible light).
L_{tot}	= total living population in a stage in mass of wet living biomass
L_{crop}	= total living population in a stage in mass of wet living biomass

¹ Member, National Space Society and Saint Louis Space Frontier

M	= total biomass + liquid mass + gas mass per stage in kg
m_a	= mass of algae cell layer per m^2 in all algae bioreactors for photosynthetic light.
R	= recirculation rate in count of full turnovers per day
w_{lq}	= energy coefficient for liquid pumps in Watts* day/kg
w_{gh}	= energy coefficient for high-pressure gas pumps in Watts* day/kg
w_{gl}	= energy coefficient for low-pressure gas pumps in Watts* day/kg
w_{gf}	= energy coefficient for high volume pumps (e.g. fans) Watts* day/kg
$w_{p,h}$	= energy coefficient for photosynthetic lighting in hydroponic beds in Watts/ m^2
$w_{p,a}$	= energy coefficient for photosynthetic lighting in algae bioreactors (photobioreactors) in Watts/ m^2

II. Introduction

In future missions and settlements, biological and mechanical means of recycling air, water, and waste, will be required. While missions are where space voyagers are in space transiently, a settlement is a place where people go for long term habitation. Due to settlement's long-term mode, it is key to reuse and recycle as much mass as possible to limit the cost of resupply. One space farm concept compartmentalizes species into stages where conditions are optimized to enhance growth and outputs given inputs. This is not to say that growth is always mono-specific, but rather staging allows calculation, even when there are biomes in root beds. Space farms composed of multiple stage types, including: hydroponic, aquatic, photobioreactor, and yeast bacteria bioreactor, are one way to recycle mass, and provide a varied diet for human space settlers and explorers. Prior work [1] calculated mass flows, initial masses, and sizes for space farms for four scenarios. In these farms, mass input after steady state was minimal, and the farm input balanced the outputs from the habitat, and farm outputs met the input needs for the habitat. The four scenarios are: initial settlement (Level 0), where the bioreactors are available, but the rest of the farm is under construction; sustained settlement (Level 1), where a limited set of plants and animals are available, but may require supply of nitrogen-rich materials; steady state settlement with a self-sustaining and minimal resupply farm (Level 2); and a supplying settlement which uses in-situ supplies to create a surplus of key crops, while feeding and supplying itself (Level 3). These scenarios were based on increasing varieties of species and included scenarios with input masses. However, it is not enough to know just biochemistry, species, and masses, if the goal is to build the farms. It is also critical to know the energy consumption to keep the farm, including the variety of machinery required to implement the farm, and keep it running. Fortunately, the space farm in prior work¹ uses many components available using current technology, including pumps, lighting, controls, and thermal regulation. Control systems typically are not the key drivers of energy, leaving pump (i.e. fluid movement and compression) energy for various parts, lighting, and thermal management. Given published data for current equipment from various companies, ratios of electricity consumption to mass flows, total masses, volumes, and species, electrical power requirements can be calculated. Therefore, this paper will use the mass flows, sizes, and species, assuming one hundred adult settlers, with this published industrial equipment data, to determine electrical needs for each stage and scenario.

III. Method

A. Assumptions

1. Energy is used as a proxy for electrical power below, based on context.
2. 100 adult humans occupy the habitat.
3. Linear increase in electricity use with increase in mass flow for pumps and stirring.
4. Circulation of gases with passive means can remove or add heat as required.
5. Photosynthetic efficiency for mass can be tied to mass flow of products (sum of oxygen and dry mass produced).
6. Lights produce optimal wavelengths for plant and algae use, in lumens, though at a lower efficiency than future lighting.
7. No solar lighting is used. All light is provided electrically, to allow the worst case.
8. Lighting days are 24 hours, again for worst case, though in reality there will be cycling.
9. Pumps (or mechanical energy for solids) are required to pull inputs from, and push outputs to, tanks and storage.
10. Human mechanical labor is energy free, i.e. fueled only by food. Also assume macerators and reactors fully expose chemistry such that mass is fully reacted.
11. Mass of a liter is 1 kg for any pumped liquid (allows worst case and simplifies calculations).
12. Fish and shrimp have similar recirculation requirements.
13. All plants have similar photosynthetic needs, that can be linearly tied to planted area.
14. Animals can use light at a similar level to human work lighting (again a worst case).

B. High Level Stage Types

There are four stage types. Each stage type is a method, that maybe be reflected in construction, to isolate the mass flows and power requirements for different elements of the farm. The stage types are: Algae Photobioreactor, Yeast-Bacteria Bioreactor, Hydroponic, and Aquatic. Each type is described in detail below. These types may have multiple stages for each species to allow analysis. At a high level, the Algae Photobioreactor stage type is a complex bioreactor that uses immerse lighting and membrane confined cyanobacteria, algae or water plants to convert nitrogen rich nutrients, water, and carbon dioxide to oxygen and wet biomass. Similarly, the Hydroponic stage type uses soilless technology in sealed chambers to grow vascular food plants, taking in nitrogen rich nutrients in water, carbon dioxide, and light to produce oxygen gas, to clean water, and to produce food biomass. The Aquatic stage type has water organisms, which can be shrimp, fish, mollusks, or other aerobic organisms, in tanks or raceways, taking in biomass in the form of foods composed of algae and wastes, water, and oxygen, to produce food biomass, release solid and nitrogen rich liquid wastes, and carbon dioxide. Each farm also has the Yeast-Bacteria Bioreactor stage type, composed of a single stage, which is a complex array of membrane mediated and open tank bioreactors with genetically tailored bacteria and fungi, connected by complex control systems, pumps, and buffer tanks. The Yeast-Bacteria Bioreactor is a multifunction biochemical balancing system, typically accepting wastes form the farm or habitat in solid, solution, or suspended forms, and using oxygen or via other processes, producing nutrient rich water and carbon dioxide for other stages. These stage types are connected via complex systems of tanks, pumps, and control systems that are assumed to perfectly link the mass products between stages as required to achieve a balance where the habitat and farm are together mass flow neutral. See Appendix B for notional diagrams illustrating connections between stages.

C. Energy Types and Equations

In words, the sum of all major energy requirements for the farm is the sum for all stages plus heat rejection: Energy in a stage + Energy to bring in mass to the stage + Energy to extract mass from the stage + Energy for overall farm thermal management and control. Given this core thesis, the energy in a stage is essentially: energy to input, output, and recirculate gases and liquids, added to energy to provide light for photosynthesis, plus energy to provide work lighting for humans and animals plus energy to control temperature (heat rejection). These equations and the assumptions above, can simplify otherwise very complex calculations to arrive at a linear relationship between commercially available coefficients, mass flows in the farm, and rough estimates of energy consumption.

For single stage, energy needed (E_i) is the sum of energy for fluid movement ($E_{f,i}$), work lighting($E_{w,i}$), photosynthetic lighting (the sum of hydroponic lighting ($E_{p,h,i}$) and algae reactor lighting ($E_{p,a,i}$)), and heat rejection (E_h) as in Eq. (1) below.

$$E_i = E_{f,i} + E_{w,i} + (E_{p,h,i} + E_{p,a,i}) + E_h ; \text{ where } E_{f,i} = E_{lq,i} + E_{g,i} \quad (1)$$

For the total farm's energy (E_{TOTAL}):

$$E_{\text{TOTAL}} = \sum_{i=1}^{\text{stages}} [E_i] \quad (2)$$

The data from the efficiency coefficients, are easily available from corporate technical specifications for a sample set of similar equipment, across a spectrum of sizes, to get a worst-case coefficient for each as described below, in terms of electrical power.

D. Work Lighting and Animal Lighting

Humans need to see to work, and they will be working in the farm at a minimum to repair and maintain the equipment, though also to harvest and process food. Animals need to have light to orient themselves. As a result, part of the energy required in the farm will be for work lighting for humans and animals. Work lighting here is assumed to be a linear relationship between the footprint of a stage (i.e. enclosed area, A_i), the light intensity required in lumens per unit area (H), and the lighting efficiency of commercially available LED bulbs in watts per lumen (Λ), as in Eq. (3).

$$E_{w,i} = H * A_i / \Lambda \quad (3)$$

Work lighting is assumed to be of the same spectrum as in most homes and for most animals and working people, as in table F-1 in OSHA 1915.F [3]. Therefore, for this paper, H will be constant at 10 lumens per square meter (i.e. $H = 10 \text{ lm/m}^2$). This is generally lower than required for plants and algae, so is an add-on for those stages, especially since photosynthetic lights will be in spectra that may cause eye strain to human color vision (personal experience), and some plants need white light to trigger life events. Note that light for animals will need to be balanced with dark, as for day-night cycles on Earth, so 12 hours out of a day could be used, though for worst case power, 24 hours is used here. General Electric data [9] was used for energy for representative visible light data (i.e. daylight or white light) as in Table 1.

Table 1. Visible light efficiency for LED work and animal light.

Model	Electric Watts	Lumens/Color Temp	Lumens/Watt (Λ)
GE® LED Bulb #22824 [9]	13	1140 lm /2850 K	87.7 lm/Watt

E. Energy for Lights for Photosynthesis

Lights optimized for plants and algae are also called ‘grow lights’ and emit energy in the prime photosynthetic spectra, i.e. ranges around 430 nm and 660 nm, seen as a pink-blue by the human eye. In both the algae bioreactor stages and hydroponic stages, grow lights are the primary light source for biochemical conversions. In the algae bioreactor (photobioreactor) stages, the lights are immersed in the solution with the algae/cyanobacteria, while in the hydroponic stages the lights are above the plants.

1. Hydroponic Photosynthetic Calculations

To simplify calculations for hydroponic beds, it was assumed all plants can use the same types of light (i.e. the combination of photosynthetic lights and work lighting as referenced before) and are the same distance from the light to tray canopy. In practice there would be surrounding light adjusted in intensity, spectrum, and cycle time, for species and life cycle, but for energy estimation, a single overhead light was used, and its coverage estimated using beam angle. In the previous work it was assumed in sizing roughly 3 stacks of beds, 1 m high each, would be in each m^2 footprint (A_i), so the footprint of the hydroponic bed was tripled, then multiplied by hydroponic photosynthetic electrical power coefficient ($w_{p,h}$) as in the Eq. (4) below, using the coefficient from the example light in Table 2.

$$E_{p,h,i} = A_i * 3 * w_{p,h} \quad (4)$$

Table 2. Hydroponic photosynthetic coefficient light.

Example	Electric Watts Used	Energy/Area $w_{p,h}$ (W/m ²)	Notes
VividGro [®] V2 [5,6]	588	168.78	65° Beam Angle, 76.2 cm above tray

2. Algae Photobioreactor Photosynthetic Light Calculations

Like the hydroponic calculations above, the algae bioreactor stages have light energy input to an area of algae slime layer or confined algae cells. To find the affected area for lighting ($A_{a,i}$), the total living biomass for each Algae Bioreactor stage in each scenario (L_{tot}) is used to compute light affected surface. Assuming a double layer of 2mm cells (i.e. 4mm layer), use a computed mass per area of $m_a = 1.05 \text{ kg/m}^2$ as in Eq. (5), then was used with data from Lee and Palsson [15] to find a (pessimistic) energy coefficient per unit live algae area of $w_{p,a} = 12 \text{ mW/cm}^2 (=120 \text{ W/m}^2)$ in Eq. (6) below. The coefficient is multiplied by the effective area to find the energy for photosynthetic light for the stage ($E_{p,a,i}$). Note that it is likely this coefficient $w_{p,a} = 120 \text{ W/m}^2$ may be far lower using modern LEDs or other technologies, but is useful for a worst case.

$$A_{a,i} = L_{tot} * m_a \quad (5)$$

$$E_{p,a,i} = w_{p,a} * A_{a,i} \quad (6)$$

F. Pumping Liquids, Solutions, and Suspended Solids in Liquids

Liquids including water, water with solutes, and water with suspended solids, are pumped into each stage, out of each stage, and circulated inside the stage (recirculated). There are many mechanisms that are used to buffer flow between stages, and efficiently separate fluids by chemical composition, so it will be assumed for this paper that pumps need to pull in all liquids in inputs, push out for all extraction, and circulate inside the stage. Energy for inputs and outputs can be calculated by multiplying the liquid pump efficiency in energy used per rate of mass moved (w_{lq}), times the mass of input ($F_{lq,in,i}$) or output ($F_{lq,out,i}$), all per day, by type of liquid moved. Circulation inside the stage will be the mass of liquids in the stage ($M_{lq,i}$) * recirculation turnover rate (R_i) * liquid pump efficiency (w_{lq}), all as in Eq. (7) below:

$$E_{lq,i} = F_{lq,in,i} * w_{lq} + F_{lq,out,i} * w_{lq} + M_{lq,i} * R_i * w_{lq} \quad (7)$$

For suspended solids, for example macerated animal or human wastes, F_{lq} will include the mass of the water solution and solids, and M_{lq} a solution with suspended or dissolved solids. After examining several pumps, a commercially available pump was selected as an exemplar, and its listed data was converted to energy per day for w_{lq} as in Table 3. *Several of these coefficients have been corrected 14 Feb 2023 to estimate energy more realistically in regular use.*

Table 3. Liquid pump coefficient (w_{lq}) used. (Corrected)

Coefficient	Watts per kg per day	Example
Liquids (with or without solids) w_{lq}	0.00151	Little Giant [®] 514420 [12]

G. Gas High Pressure, Low Pressure, and High-Volume Circulation

While in many ways moving gases is like the liquid calculations above, there are additional considerations due to compressibility and pressure. Simply circulating gases, as with a fan or blower, is a low-pressure operation where large volumes (and masses) are pushed using efficient means. Pushing gases in at atmospheric pressure as used in HVAC is a similarly high efficiency operation. However, pushing gases into a liquid as in aeration, pulling gases from a liquid using a vacuum, or simple high-pressure pumping, require far greater energy pumps. As a result, Eq. (8) below is more complex than Eq. (7) above. Each type of gas input or output is allocated to either high pressure (using w_{gh}) or low-pressure pump (using w_{gl}). Gases being recirculated inside the stage (which may be mixes of gas types) are allocated to high pressure, low pressure, or high-volume pumps (i.e. fans, w_{gf}). Then calculations are similar to those for liquids above, where input masses ($F_{g,in,t,i}$) or output masses per day ($F_{g,out,t,i}$) are multiplied by the high pressure or low pressure coefficient to get energy required, and recirculated gases are multiplied by mass ($M_{g,t,i}$) and recirculation rate ($R_{t,i}$) and allocated coefficient for high pressure, low pressure, or high volume pumps.

$$E_{g,i} = \sum_{t=1}^{\text{gas types}} \{ (F_{g,in,t,i} * [w_{gh} \text{ or } w_{gl}]) + (F_{g,out,t,i} * [w_{gh} \text{ or } w_{gl}]) + (M_{g,t,i} * R_{t,i} * [w_{gh} \text{ or } w_{gf} \text{ or } w_{gl}]) \} \quad (8)$$

The nature of the machinery for the stage determine which efficiency, high or low pressure, to use. When to use each is shown in the stage descriptions below. Aeration pumps are assumed to be high pressure gas pumps. Coefficients used here, derived from common commercial pumps, are listed in Table 4 below. It is possible by the time the settlement is built, far more efficient and durable devices will exist, but for a worst-case energy estimate, current devices were used.

Table 4. Gas pump coefficients and commercial pump examples. (Corrected using values and equations from contributors at NASASpaceFlight.com)

Coefficient	Watts per kg per day	Example
Gases (High Pressure) w_{gh}	0.452	Blue Diamond® Enviro ETK100 [13]
Gases (Low Pressure) w_{gl}	0.010	JABSCO® # 35440-0010 [21]
Gases (Fan/High Volume) w_{gf}	0.0031	Schaefer® Versa-Kool® Greenhouse Circulation Fan — 8in., 450 CFM, Model# VK8 [22]

H. Temperature Adjustments and Heat Rejection

Ideally, every watt used will express as heat, and a series of calculations based on maintaining ideal temperatures for the plants, microorganisms, and animals in each stage would be used. One consideration is the energy to heat and cool a mass and volume from the wide temperature swings of space. However, another consideration is the need to cool a stage and the farm due to numerous heat-generating activities in the stage. There is another source of heat too, that of respiration in living things. Animals and aerobically respiring bacteria and yeast release heat, while plants and algae consume it. Liquid volumes can use heat exchanging fins as part of existing recirculation schemes [2]. That said, many organisms have ideal temperatures, and in the stage, temperature may be offset by heat from lighting and mechanical work and light. To avoid complexity, for this paper it is assumed as in Soilleux [2] that a passive radiator system is used, heat is assumed always excess. The heat must be moved to the radiator system using a low-pressure pump to blow air across fins and coolers, rotating the entire volume of the farm's air. Estimates for factories and similar facilities [14] recommend a general circulation of 15 times per hour (360 times per day), which is used here as a multiplier, as in Eq. (9) below to find energy for heat rejection (E_h), where C is circulation rate (i.e. $C=360$) of the volume of the sum of farm stages (V).

$$E_h = C * V * w_{gl} \quad (9)$$

I. Manual Solid Movement Between Stages

For the sake of this paper, and to simplify calculation, it is assumed that human labor is solely fueled by the food generated, and therefore not considered in the calculations herein. It is likely that robots will be performing much of the work in the farms, however, food fueled human work is assumed, and heat from the humans is ignored. Further, it is assumed that non-suspended movement of solids is either a manual process of human labor or is conducted outside the calculations here. So harvesting, pruning, tending of fish and shrimp, feeding of animals, and other operations are not added to the energy sum, except that manually removed items are added to the mass processed as suspended solids and solutions by the Yeast-Bacteria Bioreactor stage, after being processed mechanically or consumed by animals or humans (i.e. as human or animal wastes as in black water).

J. Human Mass Flow Model

While the energy use in the human habitat for the 100 settlers is not considered, human mass inputs and outputs are used to compute the processing needs of the Yeast-Bacteria Bioreactor. Since the gas distribution system is assumed to be very efficient and use the pressures to and from the other stages, oxygen and carbon dioxide are pulled into stages and pushed out of stages, for the purposes of this paper, the first place the balance from the human habitat is seen is the Yeast-Bacteria Bioreactor. Oxygen consumed is subtracted from that available to the Yeast-Bacteria Bioreactor, carbon dioxide is subtracted from the output needs for the bioreactor in aerobic mode, the metabolic water fraction produced by the habitat is removed from the water production requirement of the Yeast-Bacteria Bioreactor, and the biomass available to the reactor is decremented by a mass fraction sent to and received from the habitat. As a result, the following model is considered in Table 5 below:

Table 5. Assumed human habitat effects on mass flow for the Yeast-Bacteria Bioreactor. *These are derived from prior work [1], with budgeting (worst case) to allow electrical power calculation for the bioreactor.*

Habitat Effects on Yeast-Bacteria Bioreactor Mass Flow (kg/day) for 100 people				
Inputs to Bioreactor (Subtracted from Inputs)		Outputs from Bioreactor (Subtracted from Outputs)		
O ₂	Biomass	CO ₂	Metabolic H ₂ O Net	Biomass
59	46.9	81.1	21.4	24.8

K. Stage Type Description: Hydroponic Stages

Hydroponic stages are focused on vascular plants. The term ‘hydroponic’ here may mean hydroponic, aeroponic, or aquaponic methods, with root beds that may or may not contain root media. Regardless of method, plants are assumed grown in soil-less conditions. The plants are surrounded by lighting from above and possibly along the side, in a carbon dioxide rich atmosphere maximized for growth of edibles. Lights are assumed to be optimized for growth and may vary from white light at times to photosynthetic optimums as required by the plants. Roots are grown in a semi-sealed bed inoculated with bacteria and fungi selected or engineered to facilitate the uptake of nutrients and nitrogen compounds from the root bed environment, using nitrogen compounds supplied in nutrient solution to the roots (i.e. not assumed to use atmospheric nitrogen gas). The root environment will be aerated and will vary from the aerial stem and leaf volumes. The trays of plants are stacked and arranged tightly to minimize volume, but still allow servicing by humans or robots.

In terms of net mass flow and allocation (See Fig. 1), the stage takes in carbon dioxide as a gas, input using low pressure gas pumps, water as a liquid pumped in, and nutrients dissolved into water, which produces wet biomass manually harvested and oxygen pumped out by low pressure pumps. Carbon dioxide is added by low pressure pump to the atmosphere of the hydroponic stage, as needed and controlled by the sensor and control system. Oxygen for the root bed biome is extracted from the hydroponic aerial atmosphere, calculated as part of high volume gas recirculation (assumed 10% of the mass recirculated) and pushed using high pressure gas pumps into the root bed media. High volume recirculation rate is derived loosely from Bartok, 2005 [16] to be 12 times per day for the entire aerial volume. The nutrient water solution is pumped into the root bed and aerated by the oxygen high pressure injection, likely using an aeration column, or spiral gas injection manifold, controlled and optimized by the control system and sensors. The solution may be fed in using distributed hoses directly to the root ball and extracted centralized or by distributed taps or another schema not covered here. Oxygen beyond that needed by roots or fruit is extracted from the hydroponic

aerial atmosphere around the leaves and sent out as an output from the stage. The root bed solution is recirculated at 126.4 times per day rotation rate (as derived and calculated from Fifth Season Co. recommendations [17]).

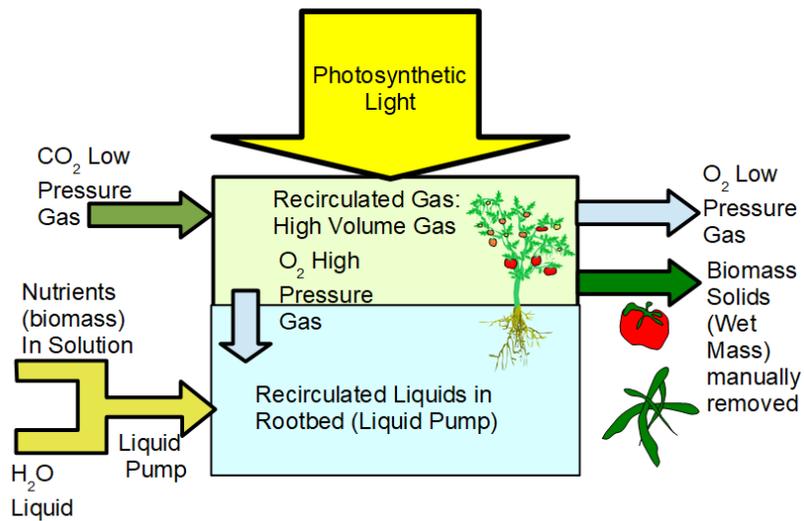


Fig. 1. Hydroponic net mass and energy flows. *Note: heat for thermal regulation, and heat from lighting and pumping, are part of the heat rejection schema.*

Ideally, pulsing pumps for the root-bed as needed would clear any clogs (not calculated here). Water is also pulled from the root bed and settled to send cleaned water to other stages, replaced by nutrient rich water in input, though this flow is not added to calculations for energy, as such flow is assumed as part of the overall mass flow. Continuous harvest, timed by lighting and planting to assure continuous food production, is assumed here to be human labor. Plant biomass is removed from the stage, the inedible portions either fed to animals in other stages or dehydrated then fed to the Yeast-Bacteria Bioreactor stage.

L. Stage Type Description: Aquatic Stages

Aquatic Stages are focused on growth of aquatic animals including fish and shrimp. A series of tanks hold the organisms in various stages of growth, from larvae to adults to harvest, and breeders. A set of buffer tanks for liquids and gases precede and follow the animal tanks. Above the tanks, a human-breathable atmosphere allows for human labor to access the tanks for maintenance and harvest, and work lighting doubles as light for the animals in the tank. In low gravity or micro-gravity, light will also be required to orient animals. Aquatic animals orient using current (personal observation) and light (see Johnson [25]) as cues. Automatic feeders send semi-liquid and dried foods to the animals. A pipe and pump from the algae photobioreactor could also be used to feed algae infused water to the tanks. Additional foods may include waste food, plant trimmings, yeast biomass, and wastes processed by the Yeast-Bacteria Bioreactor. Non-algae foods are macerated and sterilized before use. Solid wastes suspended or slushed from the animals are pulled and filtered/settled from the tank, while wastes in solution (ammonia and urea, et al.) are pulled, concentrated, and forwarded, from the tank to photosynthetic stages (i.e. hydroponic stages and algae bioreactors). The walls of the tanks, and other structures in the tank and filters hold aerobic bacteria to maintain chemical balance in the tank, as may a media bed on the bottom of the tank, or bacteria-seeded filter body. It is possible that some plants may be grown in the tank to enhance fish growth or in breeder tanks (part of L_{tot}) for reproduction.

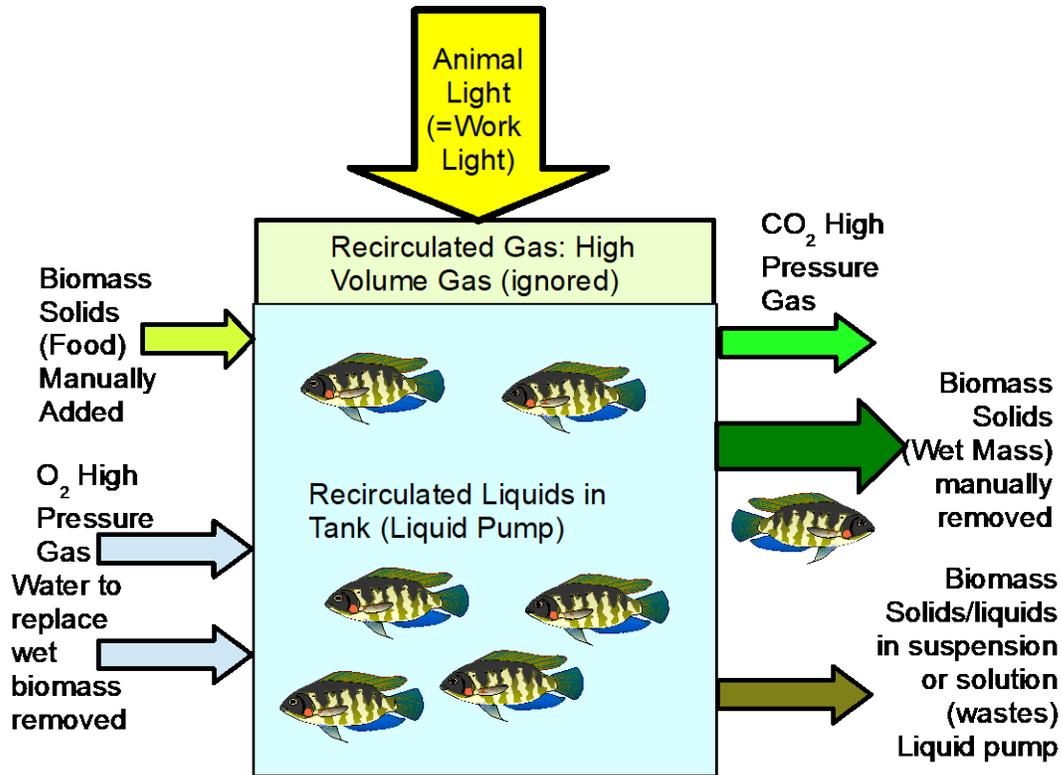


Fig. 2. Aquatic stages net mass and energy flows. *Note: heat for thermal regulation of the tank, and heat from lighting and pumping, are part of the heat rejection schema.*

In terms of net mass flow (See Fig. 2), the stage takes in oxygen and biomass. Water is added to replace any net mass lost in wet biomass removed in wastes or organisms, minus any in the food or produced aerobically. Oxygen must be injected using high pressure gas pumps into the tank water at the proper concentrations for the organism. Biomass is manually added for food for the fish and shrimp. The animals aerobically metabolize the biomass and oxygen, releasing water, carbon dioxide, liquid wastes, and solid wastes which must be removed from the tank water and sent to other stages. Carbon dioxide must be extracted from the water using separators (i.e. high-pressure gas pump energy), and excess water is filtered (possibly including very efficient reverse osmosis) at pressure (liquid pump). The aquatic stage also produces fish or shrimp wet biomass, a fraction of which is harvested continuously for human food, by humans or robots as manual solid mass. Excess water from animal biomass is returned to the tank eventually by human processing and excretion, or other processes that eventually involve the Yeast-Bacteria Bioreactor. The animals harvested are processed outside the stages into edible biomass using human or robot labor, and it is assumed the entire organism is edible once processed, where meals are made from less edible parts (and eaten or put into the yeast-bacteria bioreactor, e.g. shells, bones, scales) and choice portions (e.g. fillets, meat) are directly cooked and eaten by humans. The tank water is recirculated by liquid pumps, at a rate of roughly 1,446 kg/day tank water solution per kilogram of live animal (loosely via Rakocy [18]) and assumed the same rate for all species, while the air above the tanks is circulated slowly using small high-volume fans, though this is ignored for energy calculations as small, or accounted for in heat rejection circulation. Temperature is controlled in the tank, and networks of sensors monitor animal health using motion and visual sensors, and sensors track chemical composition of the water, which controls inputs (food, oxygen, water), though due to the heat-rejection system, thermal control energy is ignored except for the heat rejection schema herein.

M. Stage Type Descriptions: Algae Bioreactors

The Algae Bioreactor stages (a.k.a. photobioreactors) use high surface area structures and submerged lights to grow cyanobacteria and algae or aquatic plants like *Elodia* et al. For the microorganisms, a combination of open volume and cells confined in a layer to thin materials, with light in tubes and strips arranged to maximize exposure of nutrients and light to the cells is used, while allowing the pulsing of pumps to pull clumps of algae away for harvest.

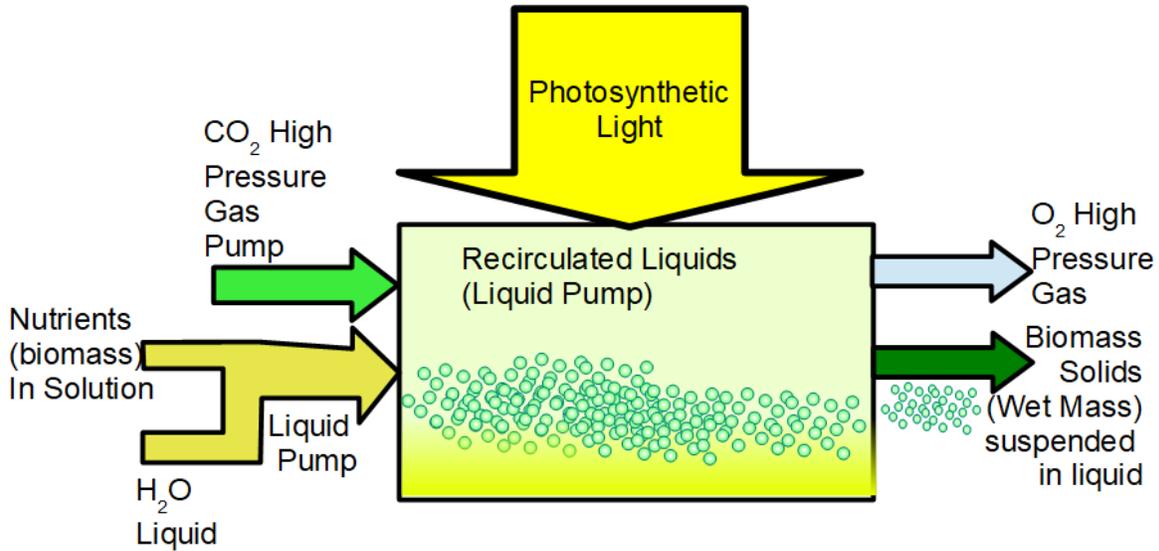


Fig. 3. Photobioreactor net mass and energy flows. *Note: heat is required in photosynthesis, and heat is generated due to the lighting and pumping, both part of the heat rejection schema.*

In terms of net mass flow (see Fig. 3), the stages require water, carbon dioxide dissolved in water, and nitrogen and mineral rich nutrients in solution in the water. Carbon dioxide must be aerated into the water using a high-pressure gas pump. Nutrients and water are brought in as liquids by liquid pumps. The stage produces in net mass terms wet algae biomass (the whole organism/cell, all of which is assumed edible), and oxygen. Oxygen is extracted by filter/vacuum (i.e. high-pressure gas pump). The solution of water, gases, and nutrients is recirculated an assumed rate of four times per minute by liquid pumps, and loose algae cell clumps are settled and filtered out (i.e. liquid pumped) for use in other stages or the habitat as wet biomass. Ideally, a soft circulation pumping method would be used to preserve cells, though here the energy is assumed to come from the liquid pump for recirculation.

Light energy is required to grow the algae crop using photosynthesis, using methods shown in the algae section above, though some work light is around the bioreactor to allow human servicing of the machinery. Very careful control of light intensity and spectrum, of temperature, of pressures, and of chemical composition, requires a wide diversity of sensors and control systems. Heat from the lights will be extracted if it results in overheating of algae as part of the heat rejection schema.

N. Stage Type Descriptions: Yeast-Bacteria Bioreactor

Each farm has a complex set of chemical bioreactor machinery, the Yeast-Bacteria Bioreactor, that has a host of species of both fungi and bacteria, in tanks and confined to membranes, that are used to balance the biochemistry of the total farm. This mechanism is common now for chemical production on Earth, and it is expected that advancements will make this machinery very efficient in the future. Inputs and outputs vary with each scenario, though in most cases, the bioreactor takes in dissolved oxygen and wastes macerated and suspended in water, to produce carbon dioxide and water. Until the Hydroponic or Aquatic Stages are built, wet yeast biomass can be produced for human food. Yeast in these early settlements would be clumps of cells, pulsed away from the membranes in the bioreactor, and settled or centrifuged out. Any mass produced for consumption is included as liquid pumped out for calculation of energy needs and was included for sizing in prior work.

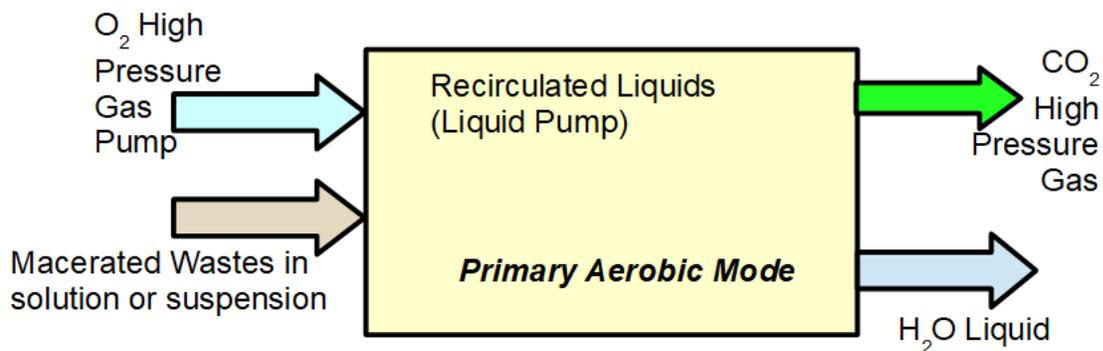


Fig. 4. Yeast-Bacteria Bioreactor net mass and energy flows, in primary mode. *Note: heat is produced due to aerobic metabolism, and pumping, though both are assumed part of the heat rejection schema.*

Net mass and energy flow are simplified as shown in Fig.4 for calculations. Gas inputs are high pressure gas pumped into liquids, while the remainder is liquid pumped into the stage. Gas outputs are extracted using separators with high pressure gas pumps, while liquid and biomass outputs are liquid pumped from the stage. A series of pumps in the stage move liquids between various components of the stage. To find recirculation power needs, it is assumed all the mass of the farm is circulated through the reactor roughly 60 times per day derived and calculated roughly from Agulanna et.al. [23], as pumped liquid. Heat generated from, or needed by, the bioreactors in the stage is managed using complex sensors and controls but is ignored in energy calculation except as part of the heat rejection schema.

O. Scenario Descriptions and Masses/Volumes Used, with Allocated Fluid Flows

The mass and species data for the energy calculations for each scenario is extracted from prior work, to support 100 adults. However, flows for the Yeast-Bacteria Bioreactor was recomputed for scenarios 2-4, to allocate mass to gas and liquid pump energy. It was assumed for scenarios 2-4 that the balance is largely aerobic as shown in tables far below.

The species used for each scenario are shown in Table 6 (pulled from Table 12 in prior work [1]).

Table 6. Species for each scenario.

SPECIES	STAGE TYPE	SCENARIO				
		1A	1B	2A	2B	3+4
Barley	Hydroponic					X
Bell Peppers	Hydroponic			X	X	X
Chlorella	Algae Bioreactor	X	X	X	X	X
Pinto Beans	Hydroponic			X	X	X
Potatoes	Hydroponic			X	X	X
Rice	Hydroponic				X	X
Shrimp	Aquatic					X
Silver Carp	Aquatic					X
Soybeans	Hydroponic					X
Spirulina	Algae Bioreactor	X	X	X	X	X
Tilapia	Aquatic			X	X	X
Tomato	Hydroponic		X	X	X	X
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	X	X	X	X	X

3. Scenario 1A

The first scenario set (1A and 1B) assume an early 100-person space settlement, where bioreactors produce all or nearly all food, and recycle all wastes, from the habitat. Scenario 1A assumes all food is bioreactor produced, while

Scenario 1B adds tomatoes from a small Hydroponic stage. The resultant menu for either scenario is dull, though minimally nutritious. The mass flows, masses, and volumes for Scenarios 1A are shown below. Note that this is a very small footprint farm (around 1,900 m² or about a third of a US football field in area) and requires very little enclosed volume (~5,900 m³ or less than many small office buildings).

Table 7. Scenario 1A sizes.

TOTAL STAGE VALUES		Derived from Tables 14 and 15 in Ref [1]					
		Volume	Mass	Water (Liquid) Mass	Footprint Area	Living Biomass Total	Living Biomass Crop
Species	Stage Type	<i>m</i> ³	<i>metric tons</i>	<i>metric tons</i>	<i>hectares</i>	<i>kg</i>	<i>kg</i>
Chlorella	Algae Bioreactor	1617	1.87	1.35	0.05	300	220
Spirulina	Algae Bioreactor	1617	1.62	1.16	0.05	300	75
Yeast-Bacteria	Yeast-Bacteria Bioreactor	2675	5.62	4.45	0.09	100	50

Note that yeast is produced by this farm for food, at 50 kg/day of wet mass.

Table 8. Scenario 1A net mass flows.

From Table 16 in Ref [1]		INPUTS (kg/day)				OUTPUTS (kg/day)			
		CO ₂	H ₂ O	O ₂	Biomass in (total)	CO ₂	H ₂ O	O ₂	Biomass out (total)
Species	Stage Type	<i>gas</i>	<i>liquid</i>	<i>gas</i>	<i>suspended/dissolved in liquid</i>	<i>gas</i>	<i>liquid or in biomass</i>	<i>gas</i>	<i>dry mass suspended in liquid or as org.</i>
Chlorella	Algae Bioreactor	61	372	-	5	-	357	45	37
Spirulina	Algae Bioreactor	49	312	-	5	-	299	35	31
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	676	253	3	349	253	-	331

The values in Table 7 and Table 8 were used with the methods in the sections above to allocate mass flow to pump types to calculate energy for fluid flow by stage as shown in Table 9 to Table 11 below. Note that due to mass allocations into categories to get energy needs, masses may no longer balance between input and output for all scenarios. The Yeast-Bacteria Bioreactor also produces nutrient biomass as part of its output, and extra biomass processed is forced as a large mass output into liquid pump energy for the purposes of finding energy as worst case.

Table 9. Net mass flows allocated to inputs for energy.

		INPUTS (kg/day)				
Species	Stage Type	Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/ solution	Solids Manually Added
Chlorella	Algae Bioreactor	61	-	372	5	-
Spirulina	Algae Bioreactor	49	-	312	5	-
Yeast-Bacteria	Yeast-Bacteria Bioreactor	253	-	676	3	-
TOTAL		363	-	1,360	13	-

Note that all the gas flow is high pressure, injected into liquids pushed into the bioreactors.

Table 10. Net mass flows allocated to outputs for energy.

		OUTPUTS (kg/day)				
Species	Stage Type	Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/ solution	Solids Manually Removed (Wet Mass)
Chlorella	Algae Bioreactor	45	-	-	394	-
Spirulina	Algae Bioreactor	35	-	-	330	-
Yeast-Bacteria	Yeast-Bacteria Bioreactor	349	-	684	331	-
TOTAL		429	-	684	1,055	-

Note that all the gas flow is high pressure, extracted from liquids pulled from the bioreactors, while the water may be pushed out or recirculated. Solids (i.e. clumps of living cells) are settled out of the liquids recirculated using gravity or centrifuge and filter.

Table 11. Net mass flows allocated in recirculation.

Species	Stage Type	RECIRCULATION (kg/day)			
		Gases (high pressure)	Gases (low pressure)	Gases (high volume)	Liquids
Chlorella	Algae Bioreactor	-	-	-	222,995
Spirulina	Algae Bioreactor	-	-	-	191,611
Yeast-Bacteria	Yeast-Bacteria Bioreactor	-	-	-	234,602
TOTAL		-	-	-	649,208

Note that all mass in the bioreactors is recirculated as liquids at a high rate.

4. Scenario 1B

Like Scenario 1A, Scenario 1B flows were allocated as in Table 12-Table 16 below. Scenario 1B also assumes a small tomato Hydroponic Stage, as for a growing new settlement, though again the bioreactors provide much of the nutrition to the habitat.

Table 12. Scenario 1B sizes.

From Tables 18 and 19 in Ref. 1		Volume	Mass	Water (Liquid) Mass	Footprint Area	Living Biomass Total	Living Biomass Crop
Species	Stage Type	<i>m</i> ³	<i>metric tons</i>	<i>metric tons</i>	<i>hectares</i>	<i>kg</i>	<i>kg</i>
Chlorella	Algae Bioreactor	1617	1.87	1.35	0.05	300	220
Spirulina	Algae Bioreactor	539	0.54	0.39	0.02	100	25
Tomato	Hydroponic	1616	2.06	0.33	0.05	1500	1364
Yeast-Bacteria	Yeast-Bacteria Bioreactor	1724	3.93	2.84	0.06	50	25

The addition of hydroponics adds volume and mass, but results in a similar area footprint to 1A, due to the smaller *Spirulina* photobioreactor. A smaller mass of yeast is produced for food, offset by the tomato crop. Note that total living biomass for yeast does not include the yeast and bacteria to aerobically produce CO² without producing food biomass.

Table 13. Scenario 1B net mass flows.

From Table 20 in Ref. [1]		INPUTS (kg/day)				OUTPUTS (kg/day)			
		CO ₂	H ₂ O	O ₂	Biomass in (total)	CO ₂	H ₂ O	O ₂	Biomass out (total)
Species	Stage Type	<i>gas</i>	<i>liquid</i>	<i>gas</i>	<i>suspended/dissolved in liquid</i>	<i>gas</i>	<i>liquid or in biomass</i>	<i>gas</i>	<i>dry mass, suspended in liquid or as org.</i>
Chlorella	Algae Bioreactor	61	372	-	5	-	357	45	37
Spirulina	Algae Bioreactor	16	104	-	2	-	100	12	10
Tomato	Hydroponic	7	42	-	-	-	39	5	5
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	338	68	1	92.9	104.6	-	166

Why is the mass output larger than the crop biomass? Because of the reproduction rate of yeast, which produces multiples of wet biomass in the same day, and used to find a worst case for energy calculations. Note that in the energy tables there is a small shift to low pressure gases due to the hydroponic stage.

Table 14. Net mass flows allocated to inputs for energy.

Species	Stage Type	INPUTS (kg/day)				
		Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/solution	Solids Manually Added
Chlorella	Algae Bioreactor	61	-	372	5	-
Spirulina	Algae Bioreactor	16	-	104	2	-
Tomato	Hydroponic	-	7	42	-	-
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	68	-	338	1	-
TOTAL		145	7	856	8	-

Table 15. Net mass flows allocated to outputs for energy.

Species	Stage Type	OUTPUTS (kg/day)				
		Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/ solution	Solids Manually Removed (Wet Mass)
Chlorella	Algae Bioreactor	45	-	-	394	-
Spirulina	Algae Bioreactor	12	-	-	110	-
Tomato	Hydroponic	-	5	-	-	5
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	93	-	105	166	-
TOTAL		150	5	105	670	5

In Scenario 1B we see the beginning of manual harvesting of crops (i.e. tomatoes) as wet biomass solids manually removed.

Table 16. Net mass flows allocated in recirculation.

Species	Stage Type	RECIRCULATION (kg/day)			
		Gases (high pressure)	Gases (low pressure)	Gases (high volume)	Liquids
Chlorella	Algae Bioreactor	-	-	-	222,995
Spirulina	Algae Bioreactor	-	-	-	64,421
Tomato	Hydroponic	247	-	24,720	41,580
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	-	117,211
TOTAL		247	-	24,720	446,207

Due to the tomatoes, there is a need to recirculate gases, to rotate the atmosphere of the hydroponic garden, and a portion of the rotation as high-pressure gas to push oxygen into the root bed environment for the root biome.

5. *Scenario 2A*

The second scenario set (2A and 2B) assumes a more mature 100-person settlement than scenario set 1, where a substantial set of hydroponic stages provide the bulk of food stuffs, with a developing tilapia aquatic stage. The mass flows, masses, and volumes for scenarios 2A are shown in Table 17-Table 21 below.

Table 17. Scenario 2A sizes.

		Volume	Mass	Water (Liquid) Mass	Footprint Area	Living Biomass Total	Living Biomass Crop
Species	Stage Type	<i>m</i> ³	<i>metric tons</i>	<i>metric tons</i>	<i>hectares</i>	<i>kg</i>	<i>kg</i>
Bell Peppers	Hydroponic	543	1.78	0.02	0.02	1600	77
Chlorella	Algae Bioreactor	7546	8.72	6.3	0.25	1400	1027
Pinto Beans	Hydroponic	3068	3.82	0.22	0.1	3200	136
Potatoes	Hydroponic	2676	10.42	0.23	0.09	9200	697
Spirulina	Algae Bioreactor	3774	3.77	2.7	0.13	700	175
Tilapia	Aquatic	17	11.92	8	<0.01	200	12
Tomato	Hydroponic	3232	4.12	0.66	0.11	3000	2727
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	2453	5.59	4.04	0.08	N/A	N/A

The hydroponic stages produce a diversity of starch, protein, and fibrous crops, and the aquatic stage produces a small quantity of tilapia, in a total farm area a little over twice the size of a US football field.

Table 18. Scenario 2A net mass flows.

		INPUTS (kg/day)				OUTPUTS (kg/day)			
		CO ₂	H ₂ O	O ₂	Biomass in (total)	CO ₂	H ₂ O	O ₂	Biomass out (total)
Species	Stage Type	<i>gas</i>	<i>liquid</i>	<i>gas</i>	<i>suspended/dissolved in liquid</i>	<i>gas</i>	<i>liquid or in biomass</i>	<i>gas</i>	<i>dry mass, suspended in liquid or as org.</i>
Bell Peppers	Hydroponic	20	170	-	1	-	162	16	14
Chlorella	Algae Bioreactor	286	1,734	-	24	-	1,664	208	171
Pinto Beans	Hydroponic	1,189	424	-	52	-	147	865	653
Potatoes	Hydroponic	350	682	-	234	-	802	254	210
Spirulina	Algae Bioreactor	113	728	-	12	-	698	82	72
Tilapia	Aquatic	-	16	5	330	7	16	-	328
Tomato	Hydroponic	91	558	-	6	-	521	73	62
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	1,434	808	1,961	281	-	-

Starting in Scenario 2A, and for remaining scenarios (i.e. 2B, 3, 4), the Yeast-Bacteria Bioreactor does not produce human edible food, and instead, for the purposes of this paper, is used to aerobically digest biomass to produce carbon dioxide and water for the photosynthetic stages.

Table 19. Net mass flows allocated to inputs for energy.

Species	Stage Type	INPUTS (kg/day)				
		Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/solution	Solids Manually Added
Bell Peppers	Hydroponic	-	20	170	1	-
Chlorella	Algae Bioreactor	286	-	1,734	24	-
Pinto Beans	Hydroponic	-	1,189	424	52	-
Potatoes	Hydroponic	-	350	682	234	-
Spirulina	Algae Bioreactor	113	-	728	12	-
Tilapia	Aquatic	5	-	16	-	330
Tomato	Hydroponic	-	91	558	6	-
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	1,434	-	-	808	-
TOTAL		1,838	1,650	4,312	1,137	330

As in the tables here, aquatic stages take in oxygen for the animals that must be injected (aerated) into the water solution in the tanks, and manually provided food biomass (which will have dry solids and water to moisten the foods).

Table 20. Net mass flows allocated to outputs for energy.

Species	Stage Type	OUTPUTS (kg/day)				
		Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/solution	Solids Manually Removed (Wet Mass)
Bell Peppers	Hydroponic	-	16	-	-	176
Chlorella	Algae Bioreactor	208	-	-	1,835	-
Pinto Beans	Hydroponic	-	865	-	-	800
Potatoes	Hydroponic	-	254	-	-	1,012
Spirulina	Algae Bioreactor	82	-	-	770	-
Tilapia	Aquatic	7	-	7	325	12
Tomato	Hydroponic	-	73	-	-	583
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	1,961	-	281	-	-
TOTAL		2,258	1,208	288	2,930	2,583

Wastes produced by the tilapia fish consists of nitrogen compounds in solution, metabolic water, and solids in suspension (i.e. feces). These waste products need to be extracted and passed to other stages. Living tilapia are harvested whole as a crop for human food (shown as solids manually removed as wet mass). Carbon dioxide from the aerobic respiration of the fish must be extracted by high pressure gas pump (or equivalent) from the water in the tank to prevent poisoning the fish.

Table 21. Net mass flows allocated in recirculation.

Species	Stage Type	RECIRCULATION (kg/day)			
		Gases (high pressure)	Gases (low pressure)	Gases (high volume)	Liquids
Bell Peppers	Hydroponic	80	-	7,982	2,520
Chlorella	Algae Bioreactor	-	-	-	1,040,644
Pinto Beans	Hydroponic	451	-	45,100	27,720
Potatoes	Hydroponic	393	-	39,337	28,980
Spirulina	Algae Bioreactor	-	-	-	445,990
Tilapia	Aquatic	-	-	-	289,121
Tomato	Hydroponic	475	-	47,510	83,160
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	-	1,113,699
TOTAL		1,399	-	139,929	3,031,833

The larger Yeast-Bacteria Bioreactor stage requires substantial recirculation, as do the photobioreactors, and the fish tanks. The root beds for the hydroponic beds also require liquid recirculation, though at a much smaller rate.

6. *Scenario 2B.*

Scenario 2B is like 2A, also with 100 settlers as in all scenarios. Scenario 2B also adds an extra hydroponic stage with a grain, i.e. rice. The sizes, mass flow and allocations for pump energy are in Table 22-Table 26.

Table 22. Scenario 2B sizes.

		Volume	Mass	Water (Liquid) Mass	Footprint Area	Living Biomass Total	Living Biomass Crop
Species	Stage Type	<i>m</i> ³	<i>metric tons</i>	<i>metric tons</i>	<i>hectares</i>	<i>kg</i>	<i>kg</i>
Bell Peppers	Hydroponic	475	1.56	0.0138	0.016	1,400	67
Chlorella	Algae Bioreactor	4,851	5.61	4.05	0.162	900	660
Pinto Beans	Hydroponic	1,630	2.03	0.12	0.054	1,700	72
Potatoes	Hydroponic	145	0.57	0.01	0.005	500	38
Spirulina	Algae Bioreactor	2,156	2.16	1.54	0.072	400	100
Tilapia	Aquatic	33	23.8	16	0.001	400	24
Tomato	Hydroponic	2,154	2.75	0.44	0.072	2,000	1,818
Rice	Hydroponic	5,863	2.71	0.34	0.195	2,100	70
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	5,090	4.62	3	0.17	N/A	N/A

Scenario 2B’s fish population is larger than in 2A, and the addition of the grain, rice, adds a substantial footprint, though improving the menu for settlers. Rice also results in a large amount of inedible biomass in straw, roots, and leaves, for each mass of edible rice grains. The inedible biomass for the plants in the farm is largely cellulose, which must be digested by the Yeast-Bacteria Bioreactor to extract the carbon, or a substantial portion of the carbon in the farm system will eventually be cellulose.

Table 23. Scenario 2B net mass flows.

		INPUTS (kg/day)				OUTPUTS (kg/day)			
		CO ₂	H ₂ O	O ₂	Biomass in (total)	CO ₂	H ₂ O	O ₂	Biomass out (total)
Species	Stage Type	<i>gas</i>	<i>liquid</i>	<i>gas</i>	<i>suspended/ dissolved in liquid</i>	<i>gas</i>	<i>liquid or in biomass</i>	<i>gas</i>	<i>dry mass suspended in liquid or as org.</i>
Bell Peppers	Hydroponic	18	149	-	1	-	142	14	12
Chlorella	Algae Bioreactor	184	1,115	-	15	-	1,070	134	110
Pinto Beans	Hydroponic	632	225	-	28	-	78	459	347
Potatoes	Hydroponic	19	37	-	13	-	44	14	11
Spirulina	Algae Bioreactor	65	416	-	7	-	399	47	41
Tilapia	Aquatic	-	31	10	660	13	31	-	656
Tomato	Hydroponic	60	372	-	4	-	347	49	41
Rice	Hydroponic	765	319	-	15	-	39	572	489
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	1,220	875	1,649	493	-	-

As noted before, the carbon dioxide inputs for the photosynthetic crops must be offset by aerobic respiration from the Yeast-Bacteria Bioreactor.

Table 24. Net mass flows allocated to inputs for energy.

		INPUTS (kg/day)				
Species	Stage Type	Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/ solution	Solids Manually Added
Bell Peppers	Hydroponic	-	18	149	1	-
Chlorella	Algae Bioreactor	184	-	1,115	15	-
Pinto Beans	Hydroponic	-	632	225	28	-
Potatoes	Hydroponic	-	19	37	13	-
Spirulina	Algae Bioreactor	65	-	416	7	-
Tilapia	Aquatic	10	-	31	-	660
Tomato	Hydroponic	-	60	372	4	-
Rice	Hydroponic	-	765	319	15	-
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	1,220	-	-	875	-
TOTAL		1,479	1,494	2,664	958	660

Oxygen input as high-pressure gas to the Yeast-Bacteria Bioreactor, and water supplied by liquid pump to the *Chlorella* Algae Bioreactor, drive mass inputs.

Table 25. Net mass flows allocated to outputs for energy.

		OUTPUTS (kg/day)				
Species	Stage Type	Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/ solution	Solids Manually Removed (Wet Mass)
Bell Peppers	Hydroponic	-	14	-	-	154
Chlorella	Algae Bioreactor	134	-	-	1,180	-
Pinto Beans	Hydroponic	-	459	-	-	425
Potatoes	Hydroponic	14	-	-	-	55
Spirulina	Algae Bioreactor	47	-	-	440	-
Tilapia	Aquatic	13	-	13	650	24
Tomato	Hydroponic	-	49	-	-	388
Rice	Hydroponic	-	572	-	-	528
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	1,649	-	493	-	-
TOTAL		1,857	1,094	506	2,270	1,574

As shown in Table 25, the diversity of plant crops, and the animal crop, require significant manual harvest.

Table 26. Net mass flows allocated in recirculation.

Species	Stage Type	RECIRCULATION (kg/day)			
		Gases (high pressure)	Gases (low pressure)	Gases (high volume)	Liquids
Bell Peppers	Hydroponic	70	-	6,983	1,739
Chlorella	Algae Bioreactor	-	-	-	668,985
Pinto Beans	Hydroponic	240	-	23,961	15,120
Potatoes	Hydroponic	21	-	2,132	1,260
Spirulina	Algae Bioreactor	-	-	-	254,380
Tilapia	Aquatic	-	-	-	578,241
Tomato	Hydroponic	317	-	31,664	55,440
Rice	Hydroponic	862	-	86,186	42,840
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	-	874,656
TOTAL		1,509	-	150,925	2,492,660

Again, the largest masses in circulation are liquids.

7. *Scenario 3.*

Scenario 3 assumes a fully mature 100 person supporting space farm, with a diversity of plant and animal species of all stage types. The mass flows, masses, and volumes for scenario 3 is shown in Table 27-Table 31 below.

Table 27. Scenario 3 sizes.

		Volume	Mass	Water (Liquid) Mass	Footprint Area	Living Biomass Total	Living Biomass Crop
Species	Stage Type	<i>m</i> ³	<i>metric tons</i>	<i>metric tons</i>	<i>hectares</i>	<i>kg</i>	<i>kg</i>
Barley	Hydroponic	18,512	6.15	0.57	0.62	5,000	67
Bell Peppers	Hydroponic	781	2.56	0.02	0.03	2,300	111
Chlorella	Algae Bioreactor	2,695	3.12	2.25	0.09	500	367
Pinto Beans	Hydroponic	1,918	2.39	0.14	0.06	2,000	85
Potatoes	Hydroponic	407	1.59	0.04	0.01	1,400	106
Rice	Hydroponic	1,954	0.9	0.11	0.07	700	23
Shrimp	Aquatic	733	524	357	0.02	3,400	258
Silver Carp	Aquatic	128	91.4	60.01	<0.01	3,000	75
Soybeans	Hydroponic	8,982	6.85	0.71	0.3	5,400	144
Spirulina	Algae Bioreactor	2,696	2.69	1.93	0.09	500	125
Tilapia	Aquatic	83	59.6	40	<0.01	1,000	61
Tomato	Hydroponic	1,508	1.92	0.31	0.05	1,400	1,273
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	8,157	19	13	0.27	N/A	N/A

The diversity of foodstuffs in Scenario 3 drive a much larger farm than in previous scenarios, which further increases the size of the Yeast-Bacteria Bioreactor stage due to inedible biomass produced, including plant matter from the hydroponics, and animal wastes from the three animal crops. The total footprint, 1.62 hectares (~4 acres) is still efficient in area compared to Earth farms to feed 100 people, see Appendix A.

Table 28. Scenario 3 net mass flows.

		INPUTS (kg/day)				OUTPUTS (kg/day)			
		CO ₂	H ₂ O	O ₂	Biomass in (total)	CO ₂	H ₂ O	O ₂	Biomass out (total)
Species	Stage Type	gas	liquid	gas	suspended/ dissolved in liquid	gas	liquid or in biomass	gas	dry mass suspended in liquid or as org.
Barley	Hydroponic	1,447	817	-	38	-	300	1,052	950
Bell Peppers	Hydroponic	29	244	-	2	-	233	22	20
Chlorella	Algae Bioreactor	102	619	-	8	-	594	74	61
Pinto Beans	Hydroponic	743	265	-	32	-	92	540	408
Potatoes	Hydroponic	53	104	-	36	-	122	39	32
Rice	Hydroponic	255	106	-	5	-	13	191	163
Shrimp	Aquatic	-	535	431	676	593	535	-	514
Silver Carp	Aquatic	-	250	463	538	636	511	-	103
Soybeans	Hydroponic	3,729	4,233	-	493	-	2,828	2,208	3,418
Spirulina	Algae Bioreactor	81	520	-	8	-	499	59	52
Tilapia	Aquatic	-	78	24	1,650	33	78	-	1,641
Tomato	Hydroponic	42	260	-	3	-	243	34	29
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	3,242	3,858	5,138	1,962	-	-

The Yeast-Bacteria Bioreactor values here are different than in prior work, to allow a worst-case allocation to energy sources, and assume aerobic digestion. Note that soybeans in this scenario drive carbon dioxide needs for the farm.

Table 29. Net mass flows allocated to inputs for energy.

Species	Stage Type	INPUTS (kg/day)				
		Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/solution	Solids Manually Added
Barley	Hydroponic	-	1,447	817	38	-
Bell Peppers	Hydroponic	-	29	244	2	-
Chlorella	Algae Bioreactor	102	-	619	8	-
Pinto Beans	Hydroponic	-	743	265	32	-
Potatoes	Hydroponic	-	53	104	36	-
Rice	Hydroponic	-	255	106	5	-
Shrimp	Aquatic	431	-	535	-	676
Silver Carp	Aquatic	463	-	250	-	538
Soybeans	Hydroponic	-	3,729	4,233	493	-
Spirulina	Algae Bioreactor	81	-	520	8	-
Tilapia	Aquatic	24	-	78	-	1,650
Tomato	Hydroponic	-	42	260	3	-
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	3,242	-	-	3,858	-
TOTAL		4,343	6,298	8,031	4,483	2,864

Soybean carbon dioxide needs drive low pressure gas and liquid pump inputs, while the Yeast-Bacteria Bioreactor stage drives high pressure gas inputs, though also requires substantial liquid pump inputs for the solids in suspension.

Table 30. Net mass flows allocated to outputs for energy.

		OUTPUTS (kg/day)				
Species	Stage Type	Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/solution	Solids Manually Removed (Wet Mass)
Barley	Hydroponic	-	1,052	-	-	1,250
Bell Peppers	Hydroponic	-	22	-	-	253
Chlorella	Algae Bioreactor	74	-	-	655	-
Pinto Beans	Hydroponic	-	540	-	-	500
Potatoes	Hydroponic	-	39	-	-	154
Rice	Hydroponic	-	191	-	-	176
Shrimp	Aquatic	593	-	342	450	258
Silver Carp	Aquatic	636	-	455	84	75
Soybeans	Hydroponic	-	2,208	-	-	6,246
Spirulina	Algae Bioreactor	59	-	-	655	-
Tilapia	Aquatic	33	-	32	1,626	61
Tomato	Hydroponic	-	34	-	-	272
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	5,138	1,962	-	-	-
TOTAL		6,533	6,048	829	3,470	9,245

Carbon dioxide produced by the Yeast-Bacteria Bioreactor pulled out at high pressure by gas pumps from solution is fed largely to soybeans, while most mass in output is manually removed by human or robot effort.

Table 31. Net mass flows allocated in recirculation.

Species	Stage Type	RECIRCULATION (kg/day)			
		Gases (high pressure)	Gases (low pressure)	Gases (high volume)	Liquids
Barley	Hydroponic	2,721	-	272,126	71,820
Bell Peppers	Hydroponic	115	-	11,481	2,520
Chlorella	Algae Bioreactor	-	-	-	371,658
Pinto Beans	Hydroponic	282	-	28,195	17,640
Potatoes	Hydroponic	60	-	5,983	5,040
Rice	Hydroponic	287	-	28,724	13,860
Shrimp	Aquatic	-	-	-	4,915,049
Silver Carp	Aquatic	-	-	-	4,336,808
Soybeans	Hydroponic	1,320	-	132,035	89,460
Spirulina	Algae Bioreactor	-	-	-	318,800
Tilapia	Aquatic	-	-	-	1,445,603
Tomato	Hydroponic	222	-	22,168	39,060
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	-	3,133,355
TOTAL		5,007	-	500,711	14,760,674

Liquids are by far the largest mass recirculated, due to the rates required to support the animals in the aquatic stages, and due to the Yeast-Bacteria Bioreactor to efficiently digest biomass into carbon dioxide for plant crops.

8. *Scenario 4.*

The mass flows, masses, and volumes for Scenario 4 are shown in Table 32-Table 36 below. Scenario 4 is an export food factory, that also supports a 100-person habitat. This farm has a full diversity of crops, takes in 50 kg per person in additional mass, and exports 50 kg per person to other settlements, as part of a web of trade. As a result, it is vastly larger than the habitat balancing farms in scenarios 1-3.

Table 32. Scenario 4 sizes.

		Volume	Mass	Water (Liquid) Mass	Footprint Area	Living Biomass Total	Living Biomass Crop
Species	Stage Type	<i>m</i> ³	<i>metric tons</i>	<i>metric tons</i>	<i>hectares</i>	<i>kg</i>	<i>kg</i>
Barley	Hydroponic	27,398	9.1	0.85	0.91	7,400	99
Bell Peppers	Hydroponic	10,051	32.9	0.29	0.34	29,600	1,424
Chlorella	Algae Bioreactor	2,156	2.49	1.8	0.07	400	293
Pinto Beans	Hydroponic	7,863	9.8	0.57	0.26	8,200	349
Potatoes	Hydroponic	3,054	11.89	0.26	0.1	10,500	795
Rice	Hydroponic	7,259	3.35	0.42	0.24	2,600	87
Shrimp	Aquatic	2,891	2,065	1,410	0.1	13,400	1,015
Silver Carp	Aquatic	333	237	156	0.01	7,800	194
Soybeans	Hydroponic	2,495	1.9	0.2	0.08	1,500	40
Spirulina	Algae Bioreactor	1,617	1.62	1.16	0.05	300	75
Tilapia	Aquatic	291	209	140	0.01	3,500	212
Tomato	Hydroponic	11,849	15.12	2.42	0.39	11,000	10,000
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	25,190	65.42	47	0.84	N/A	N/A

The mass input-output nature of the farm in scenario 4 drives a farm double the size (3.4 hectares) of scenario 3, and the inedible mass not exported must be processed in a very large Yeast-Bacteria Bioreactor, which is 25% of the total footprint. Again, the mass flow for the Yeast-Bacteria Bioreactor is allocated to allow energy calculation.

Table 33. Scenario 4 net mass flows.

		INPUTS (kg/day)				OUTPUTS (kg/day)			
		CO ₂	H ₂ O	O ₂	Biomass in (total)	CO ₂	H ₂ O	O ₂	Biomass out (total)
Species	Stage Type	<i>gas</i>	<i>liquid</i>	<i>gas</i>	<i>suspended/ dissolved in liquid</i>	<i>gas</i>	<i>liquid or in biomass</i>	<i>gas</i>	<i>dry mass suspended in liquid or as org.</i>
Barley	Hydroponic	2,142	1,210	-	56	-	444	1,558	1,406
Bell Peppers	Hydroponic	378	3,146	-	19	-	2,996	288	260
Chlorella	Algae Bioreactor	82	495	-	7	-	475	59	49
Pinto Beans	Hydroponic	3,047	1,085	-	133	-	377	2,215	1,673
Potatoes	Hydroponic	399	779	-	268	-	915	290	240
Rice	Hydroponic	947	395	-	19	-	48	708	605
Shrimp	Aquatic	-	2,109	1,698	2,663	2,335	2,109	-	2,026
Silver Carp	Aquatic	-	651	1,203	1,398	1,654	1,328	-	269
Soybeans	Hydroponic	1,036	1,176	-	137	-	786	613	950
Spirulina	Algae Bioreactor	49	312	-	5	-	299	35	31
Tilapia	Aquatic	-	273	85	5,775	116	274	-	5,742
Tomato	Hydroponic	332	2,045	-	21	-	1,909	268	228
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	2,989	2,932	4,226	1,695	-	-

In this scenario, the animals produce more of the carbon dioxide needed in the system than in prior scenarios, nearly equaling the carbon dioxide contribution from the Yeast-Bacteria Bioreactor.

Table 34. Net mass flows allocated to inputs for energy.

Species	Stage Type	INPUTS (kg/day)				
		Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/solution	Solids Manually Added (Dry Mass)
Barley	Hydroponic	-	2,142	1,210	56	-
Bell Peppers	Hydroponic	-	378	3,146	19	-
Chlorella	Algae Bioreactor	82	-	495	7	-
Pinto Beans	Hydroponic	-	3,047	1,085	133	-
Potatoes	Hydroponic	-	399	779	268	-
Rice	Hydroponic	-	947	395	19	-
Shrimp	Aquatic	1,698	-	2,109	-	2,663
Silver Carp	Aquatic	1,203	-	651	-	1,398
Soybeans	Hydroponic	-	1,036	1,176	137	-
Spirulina	Algae Bioreactor	49	-	312	5	-
Tilapia	Aquatic	85	-	273	-	5,775
Tomato	Hydroponic	-	332	2,045	21	-
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	2,989	-	-	2,932	-
TOTAL		6,106	8,281	13,676	3,597	9,836

The larger animal presence in this farm also drives the need to manually (via auto-feeder or human) provide feed for shrimp and fish, though the largest input masses are liquid pumped (as solids in suspension/solution or as other liquids).

Table 35. Net mass flows allocated to outputs for energy.

Species	Stage Type	OUTPUTS (kg/day)				
		Gases (High Pressure)	Gases (Low Pressure)	Liquids	Solids in suspension/ solution	Solids Manually Removed (Wet Mass)
Barley	Hydroponic	-	1,558	-	-	1,850
Bell Peppers	Hydroponic	-	288	-	-	3,256
Chlorella	Algae Bioreactor	59	-	-	524	-
Pinto Beans	Hydroponic	-	2,215	-	-	2,050
Potatoes	Hydroponic	-	290	-	-	1,155
Rice	Hydroponic	-	708	-	-	653
Shrimp	Aquatic	2,335	-	1,348	1,772	1,015
Silver Carp	Aquatic	1,654	-	1,183	221	194
Soybeans	Hydroponic	-	613	-	-	1,736
Spirulina	Algae Bioreactor	35	-	-	330	-
Tilapia	Aquatic	116	-	115	5,689	212
Tomato	Hydroponic	-	268	-	-	2,137
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	4,226	-	1,695	-	-
TOTAL		8,425	5,940	4,340	8,536	14,258

The largest output component for energy is the manually removed portion, which does not add to energy needs for the farm. The largest output mass contributing to energy cost is the liquid pumped combination of liquids and solids in suspension (together around 13 metric tons per day).

Table 36. Net mass flows allocated in recirculation.

Species	Stage Type	RECIRCULATION (kg/day)			
		Gases (high pressure)	Gases (low pressure)	Gases (high volume)	Liquids
Barley	Hydroponic	4,028	-	402,751	107,100
Bell Peppers	Hydroponic	1,477	-	147,750	36,540
Chlorella	Algae Bioreactor	-	-	-	297,327
Pinto Beans	Hydroponic	1,156	-	115,586	71,820
Potatoes	Hydroponic	449	-	44,894	32,760
Rice	Hydroponic	1,067	-	106,707	52,920
Shrimp	Aquatic	-	-	-	19,371,076
Silver Carp	Aquatic	-	-	-	11,275,701
Soybeans	Hydroponic	367	-	36,677	25,200
Spirulina	Algae Bioreactor	-	-	-	191,611
Tilapia	Aquatic	-	-	-	5,059,609
Tomato	Hydroponic	1,742	-	174,180	304,920
Yeast-Bacteria Bioreactor	Yeast-Bacteria Bioreactor	-	-	-	4,987,337
TOTAL		10,285	-	1,028,544	41,813,919

In Scenario 4, liquids are by far the largest recirculated component, due to both the large animal crops in aquatic stages, and the Yeast-Bacteria Bioreactor stage.

P. Fluid Flow Energy Calculations by Scenario

Using the above per scenario data, and the calculation methods in the sections above, coefficients for fluid electrical power as above in Table 3, fluid flow and fluid energy for each scenario is as in the tables below.

Table 37. Total Mass Flows Allocated for Energy

Scenario	TOTALS FOR ENERGY (kg/day)				
	Gases (High Pressure)	Gases (Low Pressure)	Gases (high volume)	Liquids w/Solids	Manual Solids
1A	792	0	-	652,320	0
1B	537	14	24,720	447,935	0
2A	5,495	2,858	139,929	3,040,500	2,913
2B	4,845	2,588	150,925	2,499,058	2,234
3	15,883	12,346	500,711	14,777,487	12,109
4	24,816	14,221	1,028,544	41,844,068	24,094

Table 38. Electricity for fluid flow by scenario. (Corrected)

TOTAL ELECTRICITY USED FOR FLUIDS (Watts)					
Scenario	Gases (High Pressure)	Gases (Low Pressure)	Gases (High Volume)	Liquids (and solids in suspension or solution)	TOTAL ELECTRICITY FOR FLUID FLOW
1A	358	0	0	985	1,343
1B	245	0	77	676	998
2A	2,484	29	434	4,591	7,537
2B	2,190	26	468	3,774	6,457
3	7,179	123	1,552	22,314	31,169
4	11,217	142	3,188	63,185	77,732

Given the data in the scenarios for liquid recirculation, it is not surprising that liquid pumps are the largest fluid flow energy need. In Scenario 4, recirculation of liquids is over 99% of the liquid fluid flow energy need versus input plus output.

Q. Photosynthetic Light Calculations by Scenario

Using the above per scenario data, and the calculation methods in the sections above, the following photosynthetic areas were computed by scenario as in Table 39.

Table 39. Effective photosynthetic areas.

Areas in m ²		Scenario					
Species	Stage Type	1A	1B	2A	2B	3	4
Barley	Hydroponic	-	-	-	-	18,600	27,300
Bell Peppers	Hydroponic	-	-	600	480	900	10,200
Chlorella	Algae Bioreactor	286	286	1,333	857	476	381
Pinto Beans	Hydroponic	-	-	3,000	1,620	1,800	7,800
Potatoes	Hydroponic	-	-	2,700	150	300	3,000
Rice	Hydroponic	-	-	-	5,850	2,100	7,200
Shrimp	Aquatic	N/A	N/A	N/A	N/A	N/A	N/A
Silver Carp	Aquatic	N/A	N/A	N/A	N/A	N/A	N/A
Soybeans	Hydroponic	-	-	-	-	9,000	2,400
Spirulina	Algae Bioreactor	286	95	667	381	476	286
Tilapia	Aquatic	N/A	N/A	N/A	N/A	N/A	N/A
Tomato	Hydroponic	-	1,500	3,300	2,160	1,500	11,700
<i>Hydroponic area is footprint area in m² * 3 (assumes 1m between shelves stacked to 3m tall)</i>							

These areas were used with coefficients and used in Eqs. (4), (5), and (6) to find energy values for photosynthetic light needs by scenario as in Table 40 below.

Table 40. Photosynthetic electricity requirements by species and scenario.

Species	Stage Type	Scenario					
		Electrical Power in Watts					
		1A	1B	2A	2B	3	4
Barley	Hydroponic	-	-	-	-	3,139,231	4,607,581
Bell Peppers	Hydroponic	-	-	101,266	81,012	151,898	1,721,514
Chlorella	Algae Bioreactor	34,286	34,286	160,000	102,857	57,143	45,714
Pinto Beans	Hydroponic	-	-	506,328	273,417	303,797	1,316,452
Potatoes	Hydroponic	-	-	455,695	25,316	50,633	506,328
Rice	Hydroponic	-	-	-	987,339	354,429	1,215,186
Shrimp	Aquatic	N/A	N/A	N/A	N/A	N/A	N/A
Silver Carp	Aquatic	N/A	N/A	N/A	N/A	N/A	N/A
Soybeans	Hydroponic	48,222	16,074	112,517	64,296	80,369	48,222
Spirulina	Algae Bioreactor	34,286	11,429	80,000	45,714	57,143	34,286
Tilapia	Aquatic	N/A	N/A	N/A	N/A	N/A	N/A
Tomato	Hydroponic	-	253,164	556,960	364,556	253,164	1,974,677
TOTAL		116,793	314,952	1,972,765	1,944,507	4,447,807	11,469,959
Subtotals	Algae Bioreactors	68,571	45,714	240,000	148,571	114,286	80,000
	Hydroponics	48,222	269,238	1,732,765	1,795,936	4,333,521	11,389,959

Hydroponic stages drive photosynthetic light needs is all but Scenario 1A.

R. Work Light Calculations by Scenario

Energy for work lighting (with is also animal lighting in aquatic stages) is found using the areas (footprints) for the stages in each scenario and Eq. (3) above, and coefficients for work lighting above, as shown in Table 41 below.

Table 41. Work light electricity by scenarios.

Scenario	Total Footprint in hectares	Lit Area m ²	Lumens Required	Watts
1A	0.20	2,000	20,000	228
1B	0.18	1,800	18,000	205
2A	0.78	7,800	78,000	889
2B	0.75	7,500	75,000	855
3	1.62	16,200	162,000	1,847
4	3.41	34,100	341,000	3,888

Since work light is tied linearly to footprint, it is not a surprise that bigger farms need more light.

S. Heat Rejection Flow Calculations by Scenario

Using the assumptions in Methods Section H, the volume of the stages for each scenario are summed, used in Eq. (9) above with the coefficient for low pressure gas pumps, to compute the energy required for circulating air past the passive heat rejection equipment to get the values in Table 42 below.

Table 42. Fluid flow electricity for heat rejection. (Corrected)

Scenario	Farm Volume	Energy
	<i>m</i> ³	<i>Watts</i>
1A	5,910	8,060
1B	5,496	7,495
2A	23,308	31,786
2B	22,399	30,547
3	48,554	66,216
4	102,446	139,711

Like work light, size drives the need for heat rejection circulation due to assumptions. As a result, the bigger the farm, the bigger the need for circulation energy.

T. Control Systems Power Assumption

After an initial set of calculations using the Emerson Ovation™ architecture [19] it was found that the control system is a minor power consumer in all scenarios compared to other energy sources, so ignored.

IV. Results

A. Energy Consumption by Scenario and Type

Summing all energy sources by scenario results in Table 43 below. Note that the largest power consumer in vascular crop scenarios is light, though in bioreactor scenarios the consumer is fluid flow.

Table 43. Electrical needs from all sources by scenario. (Corrected)

Scenario	FLUID MOVEMENT	PHOTOSYNTHETIC LIGHT	WORK LIGHT	HEAT REJECTION	TOTAL	TOTAL per Person
	<i>kW</i>	<i>kW</i>	<i>kW</i>	<i>kW</i>	<i>kW</i>	<i>kW/person</i>
1A	1.34	117	0.23	8.06	127	1.27
1B	1.00	315	0.21	7.50	324	3.24
2A	7.54	1,973	0.89	31.79	2,013	20.13
2B	6.46	1,945	0.86	30.55	1,983	19.83
3	31.17	4,448	1.85	66.22	4,547	45.47
4	77.73	11,470	3.89	139.71	11,691	116.91

Fluid movement (i.e. gas and liquid with or without suspended solids, and fans for heat rejection), is a tenth to a fifth of the energy needed in all scenarios. This implies that recirculation and injection of liquids is a driver for the energy needs in all the farms, though light is a larger driver for hydroponic crops, and that methods to reduce the energy required for heat rejection and light should be examined in future settlements. Other fluid movements might be larger to implement farm footprints that are spread out in volume and area though.

B. Comparison to Other Settlement Concepts

In comparison to other settlement energy calculations, energy for Scenarios 2-4 is greater than those estimated per person from other sources as in Table 44, driven by fluid flow including heat rejection, and primarily lighting. This is driven by mass calculations from prior papers, and worst-case assumptions. The electrical power required also increases with mass processed in the farm scenarios and is correlated to diversity of food sources. Many of the other settlements in Table 44 also include the human habitat, and a few are not truly closed cycle (e.g. McMurdo Station). While the ECLSS [2] is closest in analysis, the space farms in this paper assume no solar lighting, and a 24-hour lighting cycle, which account for some differences. Other differences may resolve as future work defines more detailed designs and tighter assumptions. The space farms also use bioreactors, and all stages resemble chemical factories in complexity and power use in lieu of traditional farms, which explains the fluid movement driver. Scenario 4 is an example of a food factory, as it accepts mass input and produces food for export from the settlement. Chemical factories on Earth are major power consumers, typically in the tens of megawatts and up, which may lead to better future comparisons.

Table 44. Comparison of energy values for various estimates. (Corrected)

	Settlement /Farm	Power per Person
Ref [2], p.1	ECLSS	26.4 kW
Via Table A2, Ref [2] except as noted	Biosphere 2	88 kW
	McMurdo Station	6.8 kW
	Hadley VI	30 kW
	ISS	9-13 kW
	Stanford Torus	3 kW
	Kalpana One <i>(via email, Al Globus, Aug 2018)</i>	35-60 kW
Scenario <i>(this paper)</i>	1A	1 kW
	1B	3 kW
	2A	20 kW
	2B	20 kW
	3	45 kW
	4	117 kW

An additional comparator was the Cornell CUAES Greenhouse facility [24], with 127,000 sq. ft. consuming 17,986,668 kWh per year, which works out to 1740 kW/hectare, which more than these farms. However, add in the free sunlight at a rate of roughly 1kW/m², and the results are roughly comparable. This illustrates the need to use available sunlight when possible.

C. Solar Cell Implications

Using the electrical power summation above for all scenarios, we can assume an equivalent solar cell area to satisfy these needs, plus a 5% transmission loss, using DAWN data in para.2.2 in NASA work [8]: 10.3 kW using 36 m² of solar panel area (i.e. 0.286 kW/m²) at 1 AU without Earth obstruction, to get an equivalent solar panel area as in Table 45 below. It was assumed in calculations that solar power is provided 24 hours a day. The resulting solar panel sizes in Table 45 require a much larger area for the farm and power than just the farm alone, especially if the farms were to be placed on a surface such as the Moon or Mars. Given this, nuclear power or other power sources should be examined for Scenarios 3 and 4.

Table 45. Estimated solar panel areas for power requirements by scenario. (Corrected)

	TOTAL ENERGY	Solar Panel Area	Solar Panel Area	Farm Total Footprint
				<i>(for Comparison)</i>
Scenario	<i>kW</i>	<i>m²</i>	<i>hectares</i>	<i>m² (hectares)</i>
1A	127	443	0.04	2,000 (0.2)
1B	324	1,132	0.11	1,800 (0.18)
2A	2,013	7,039	0.70	7,800 (0.78)
2B	1,983	6,933	0.69	7,470 (0.747)
3	4,547	15,899	1.59	16,100 (1.61)
4	11,691	40,879	4.09	34,000 (3.4)

As noted above, the energy needs listed in Table 43 linearly drive solar panel areas which are multiples of the size of the farm itself. Solar panel areas run from 20% in Scenario 1A to nearly equal to the farm’s area in Scenario 4. This would indicate when selecting planetary body sites for settlements, primary consideration would be for land for solar panels. In space station bases settlements, the increased solar area implies added mass for solar panels. Solar panels in free space must use mass that is lifted from Earth or other sources, and this area and inertia must be included in station keeping thrust calculations.

V. Conclusion

In conclusion, energy needs are a critical area for examination and will influence the shape of future settlements in orbit, or on planetary bodies. It is not enough to just find mass needs, balance mass flow, or find footprint. Analysis using six scenarios and four stage types used balancing farms of minimal footprint and mass, and using available pumps and data, found energy needs. As found, even with very footprint efficient farms that balance mass, electrical power needs may multiply the total footprint due to solar panels or other energy sources. Food production requires energy, especially for fluid movement and light. Designs for such settlements should include detailed energy analysis, especially once equipment is selected for each of the systems in the settlement and farm. This analysis must include fluid movement and recirculation, in addition to lighting and heat rejection. Further work in space settlement should also examine better pumps specialized for space use to reduce power needs for fluids.

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References

- [1] Meyer, B. L. Meyer, B. L., “Mass and Volumes for a Spectrum of Multistage Evolving Space Farms.”, *NSS Space Settlement Journal*, Issue #3, November 2017.
- [2] Soilleux, R. J., Gunn, S.D., “Environmental Control and Life Support (ECLSS) for Large Orbital Habitats: Ventilation for Heat and Water and Management.” *NSS Space Settlement Journal*, Issue #3, Nov 2017.
- [3] Occupational Safety and Health Administration, United States Department of Labor, 29 CFR 1915-part F, Lighting (1915.82) found at: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=190
- [4] FEIT Electric® 2ft LED Grow Light Specifications <https://www.homedepot.com/catalog/pdfImages/de/dec0217d-cd76-4cec-8324-fb3161f36278.pdf>
- [5] VividGro® V2 Specifications at http://vividgro.com/wp-content/uploads/2018/01/VividGro_V2_SpecSheet_RevF.pdf
- [6] VividGro® V2 Technical Report at <http://vividgro.com/wp-content/uploads/2015/12/LM-79-VividGro-V2-RSZ150907501-10-Lighting-Science-VGROHB-600W-P26-MVOLT-CLR-PND-BLK-LM-....pdf>
- [7] Runkle, E., Bugbee, B., “Problems with Foot-candles, Lux and Lumens” Michigan State University, online at: <http://flor.hrt.msu.edu/assets/Uploads/Footcandles-lux-lumens2.pdf>
- [8] Bailey, S and Landis, G., “Solar Power for Future NASA Missions” at <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150002114.pdf>
- [9] GE HD Light at: <https://www.gelighting.com/led-bulbs/product-family-hd>
- [10] Urrestarazu, M. “Effects of spectral quality, intensity of LEDs”, *HortScience*, American Society for Horticultural Science, 09 May 2016, at: <https://phys.org/news/2016-05-effects-spectral-quality-intensity.html>
- [11] Zijfeers, I.J.F., “The Green Solar Collector; converting sunlight into algal biomass”, Jun 2008, OSPT, from NARCIS, at <https://www.narcis.nl/research/RecordID/OND1310000/Language/en>
- [12] Little Giant® Pumps Technical data at: <http://littlegiant.com/>
- [13] Blue Diamond® Pumps, at: <http://bluediamondpumps.com/>
- [14] Air Change Rates in typical Rooms and Buildings, Engineering ToolBox, (2005). Air Change Rates in typical Rooms and Buildings. [online] Available at: https://www.engineeringtoolbox.com/air-change-rate-room-d_867.html
- [15] Lee, C.-G., Palsson, B. O. “High-Density Algal Photobioreactors Using Light-Emitting Diodes” *Biotechnology and Bioengineering*, vol. 44, no. 10, Nov 20, 1994
- [16] Bartok, J.W. Jr, Natural Resources Mgt. & Engr. Dept, U. Of Conn., “Horizontal Air Flow is Best for Greenhouse Air Circulation, May 2005” found on-line at: <https://ag.umass.edu/greenhouse-floriculture/fact-sheets/horizontal-air-flow-is-best-for-greenhouse-air-circulation>
- [17] “The Hydroponic Chronicles Part Two: Ebbing and Flowing”, Dec. 2010, Fifth Season Gardening Co., found online at: <https://fifthseasongardening.com/the-hydroponic-chronicles-part-two-ebbing-and-flowing>
- [18] Rakocy, J.E., “Tank Culture of Tilapia”, L-2409 SRAC Publication No. 282, Southern Regional Aquaculture Center, Sep. 1989.
- [19] Emerson Ovation™ Controller Model OCR1100 Data Sheet, Emerson Corp. Online at: <http://www.emerson.com/documents/automation/ovation-controller-model-ocr1100-en-67350.pdf>
- [20] Globus, A, Covey, S.,Faber,D. “Space Settlement: An Easier Way”, *NSS Space Settlement Journal*, Issue #2, July 2017.
- [21] JABSCO® Model 35440-Series Manual, © 2011 Xylem Inc Form: 43000-0403 Rev B 11/2012, found online at: http://www.xylemflowcontrol.com/files/35440_43000-0403.pdf
- [22] “Schaefer Versa-Kool Deep Guard Circulation Fans”, Model VK8, Pinnacle Climate Technologies copyright 2018, found at: <http://www.schaeferventilation.com/products/versa-kool-deep-guard-circulation-fans/>
- [23] Agulanna, C.N., Onuoha, G.N., Anyanwu, E.F., Ejike, E.N.O., Ogueke, N.V., “Experimental Studies of Anaerobic Digestion of Organic Fraction of Municipal Solid Waste Using a Bioreactor

- with Integral Flow Features”, *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS)* 3 (3): 461-469, © Scholarlink Research Institute Journals, 2012 (ISSN: 2141-7016).
- [24] CUAES Greenhouses - Energy Consumption and Equivalents, Cornell University, CALS, Found at: <https://cuaes.cals.cornell.edu/sites/cuaes.cals.cornell.edu/files/shared/documents/Greenhouse-energy-consumption-2014-03-21.pdf>
- [25] Johnson, David S., “The First Fish in Orbit”, *Scientific American*, Guest Blog. 12/22/2016. Found at <https://blogs.scientificamerican.com/guest-blog/the-first-fish-in-orbit/>
- [26] Personal Communication, Michel Lamontagne and inputs from the NASASpaceFlight.com team, used 14 Feb 2023.

**APPENDIX A: Annual Productivity of Food Grains in Earth Fields:
Best Production in Fields for Four High Calorie Crops**

Crop	Bushels Per Hectare Per Year (Best) 4,5,6,7,8,9,10,11,12	Kg Food Per Bushel 2,3	Kcal Per Kg¹	Kcal Per Bushel	Kcal Per Hectare Per Year	Kcal Per Hectare Per Day	People Per Hectare **
Corn	501.62	25.40	961	24,412	12,245,403	33,549	16.77
Rice	570.81	20.41	3,560	72,665	41,478,078	113,639	56.82
Soybeans	422.55	27.20	4,460	121,312	51,260,365	140,439	70.22
Wheat	299.00	27.22	3,320*	63,095	18,865,238	51,686	25.84
* kcal/kg for flour, wheat flour is 42 lbs/bushel ⁶ .							
** assumes 2000 kcal/day/person							

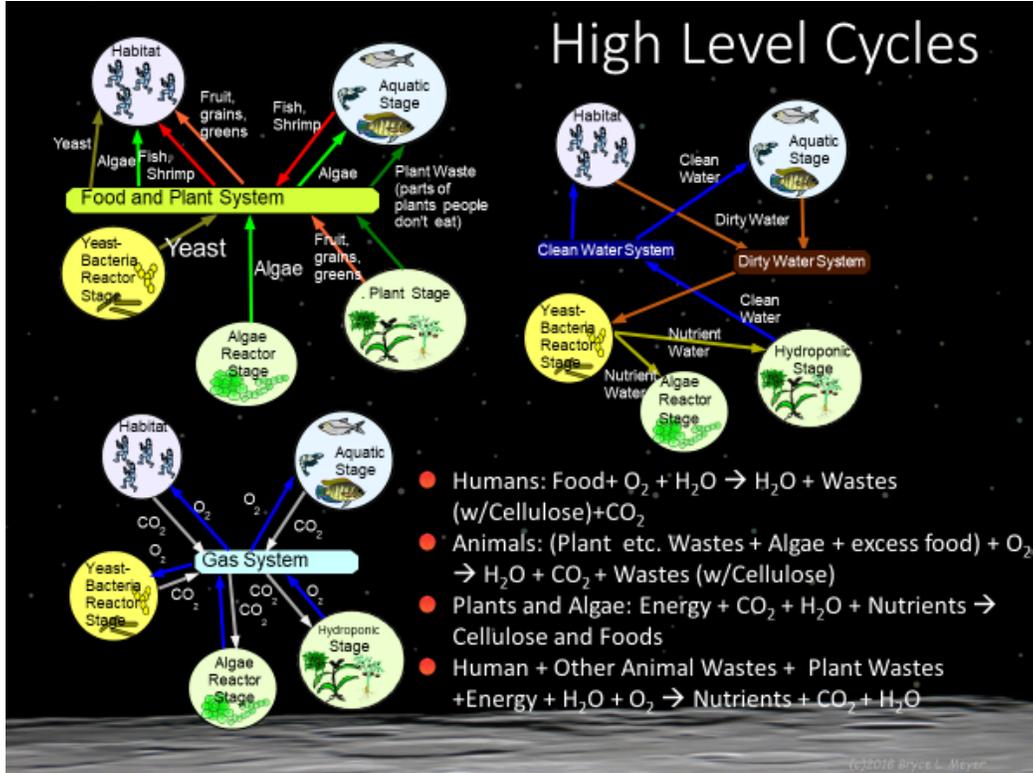
Note: See *Space Settlements: A Design Study*¹³ for comparison for space farms, where rice in Table 5-20, p.113 is grown at roughly 10 times the efficiency of the table above.

Sources:

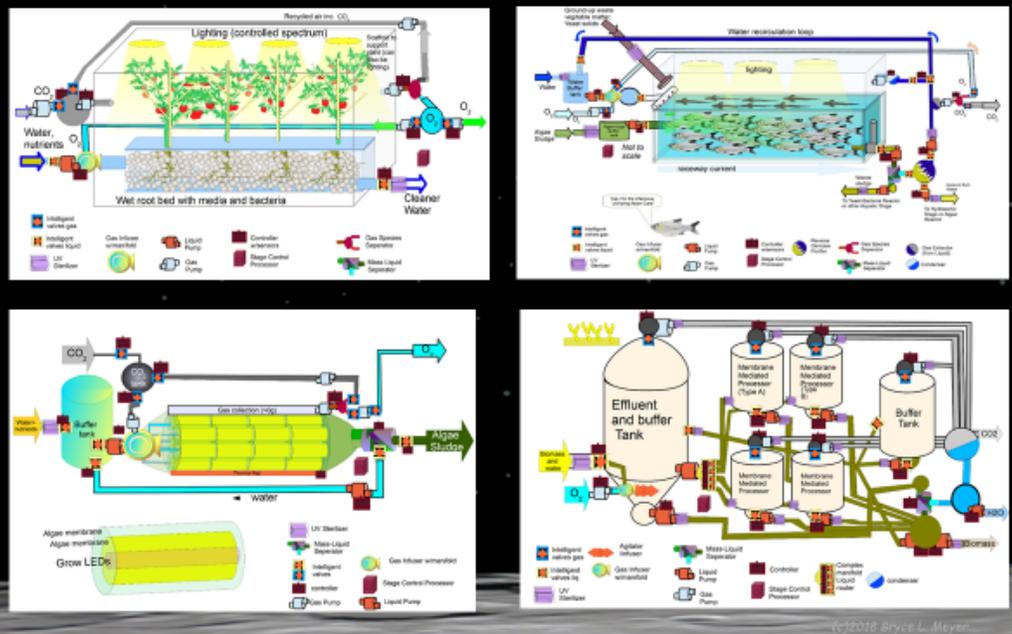
- 1 USDA Food Composition Databases, United States Department of Agriculture Agricultural Research Service found at: <https://ndb.nal.usda.gov/ndb/>
- 2 FGIS Inspection Handbook found at <https://www.omicnet.com/reports/past/archives/ca/tbl-1.pdf>
- 3 Illinois General Assembly, Joint Committee on Administrative Rules, TITLE 8: AGRICULTURE AND ANIMALS, CHAPTER I: DEPARTMENT OF AGRICULTURE, SUBCHAPTER p: WEIGHTS AND MEASURES, PART 600 WEIGHTS AND MEASURES ACT, SECTION 600.TABLE B STANDARD WEIGHT PER BUSHEL FOR AGRICULTURAL COMMODITIES found at <ftp://www.ilga.gov/jcar/admincode/008/00800600ZZ9998bR.html>
- 4 Missouri Corn Facts, Missouri Crop Resource Guide, UNIVERSITY OF MISSOURI EXTENSION, found at <http://crops.missouri.edu/audit/corn.htm>
- 5 Iowa Ag News – United States Department of Agriculture National Agricultural Statistics Service, 2017 Crop Production, found at: https://www.nass.usda.gov/Statistics_by_State/Iowa/Publications/Crop_Report/2018/IA_Crop_Production_Annual_01_18.pdf
- 6 Missouri Wheat Facts, Missouri Crop Resource Guide, UNIVERSITY OF MISSOURI EXTENSION, found at <http://crops.missouri.edu/audit/wheat.htm>
- 7 <https://www.missouriruralist.com/wheat/back-back-100-bushel-wheat-years>
- 8 Missouri Soybean Facts, Missouri Crop Resource Guide, UNIVERSITY OF MISSOURI EXTENSION, found at <http://crops.missouri.edu/audit/soybean.htm>
- 9 <https://www.cornandsoybeandigest.com/soybeans/georgia-producer-sets-new-world-soybean-yield-record>
- 10 Missouri Rice Facts, Missouri Crop Resource Guide, UNIVERSITY OF MISSOURI EXTENSION, found at <http://crops.missouri.edu/audit/rice.htm>
- 11 <https://www.deltafarmpress.com/231-bushels-acre-rice-grower-sets-verification-record>
- 12 <http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-1112/HLA-6019web.pdf>
- 13 edited by Johnson, R.D and Holbrow, C., *Space Settlements: A Design Study*, 1977, NASA. University Press of the Pacific, reprinted 2004.

APPENDIX B: Assembling the Stages

The stages in the space farm are connected by systems of pumps, tanks, and separators, which are accounted for herein and in prior work. Below are mass flows between stages showing the systems in simplified form, and notional assemblies.



Notional Stage Types



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