# 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 11kW per person for very early settlements to 672 kW per person for well-developed food factory farms, and that solar panel areas will be multiples of farm footprint (see Table 43).**

## 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.
$\Lambda$ = 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
$M$ = total biomass + liquid mass + gas mass per stage in kg

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[1] Member, National Space Society and Saint Louis Space Frontier

$m_a$ = 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/$m^2$

## I. 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 that 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 work[1] 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.

## II. 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. Electricity use increases linearly 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 may 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 from 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.

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

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

$$\mathbf{E_{TOTAL}} = \sum_{\mathbf{i=1}}^{\mathbf{stages}} [\mathbf{E_i}] \tag{2}$$

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 have 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 ($\Lambda$), as in Eq. (3).

$$\mathbf{E_{w,i} = H * A_i / \Lambda} \tag{3}$$

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. $H = 10\ lm/m^2$). 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 ($\Lambda$) |
|---|---|---|---|
| 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.

$$\mathbf{E_{p,h,i} = A_i * 3 * w_{p,h}} \tag{4}$$

**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 $m_a = 1.05$ 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 $w_{p,a} = 12$mW/cm$^2$ (=120 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 $w_{p,a} = 120$ W/m$^2$ may be far lower using modern LEDs or other technologies, but is useful for a worst case.

$$\mathbf{A_{a,i} = L_{tot} * m_a} \tag{5}$$

$$\mathbf{E_{p,a,i} = w_{p,a} * A_{a,i}} \tag{6}$$

### 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 to 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:

$$\mathbf{E_{lq,i} = F_{lq,in,i} * w_{lq} + F_{lq,out,i} * w_{lq} + M_{lq,i}*R_i*w_{lq}} \tag{7}$$

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.

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

| Coefficient | Watts per kg per day | Example |
|---|---|---|
| **Liquids (with or without solids) $w_{lq}$** | 1.151 | 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.

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

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.**

| Coefficient | Watts per kg per day | Example |
|---|---|---|
| **Gases (High Pressure) $w_{gh}$** | 177 | Blue Diamond® Enviro ETK100 [13] |
| **Gases (Low Pressure) $w_{gl}$** | 7.33 | JABSCO® # 35440-0010 [21] |
| **Gases (Fan/High Volume) $w_{gf}$** | 1.77 | 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, and heat is assumed always in 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).

$$\mathbf{E_h = C * V * w_{gl}} \tag{9}$$

### 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 $H_2O$ 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 produce 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]).

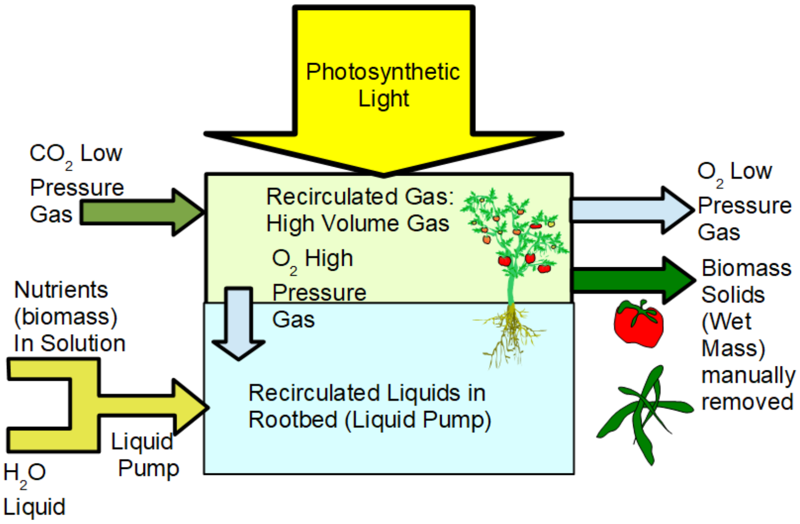

**Fig. 1. Hydroponic net mass and energy flows.** *Note: heat for thermal regulation, and heat from lighting and pumping, are part of the heat rejection schema.*

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 and 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.

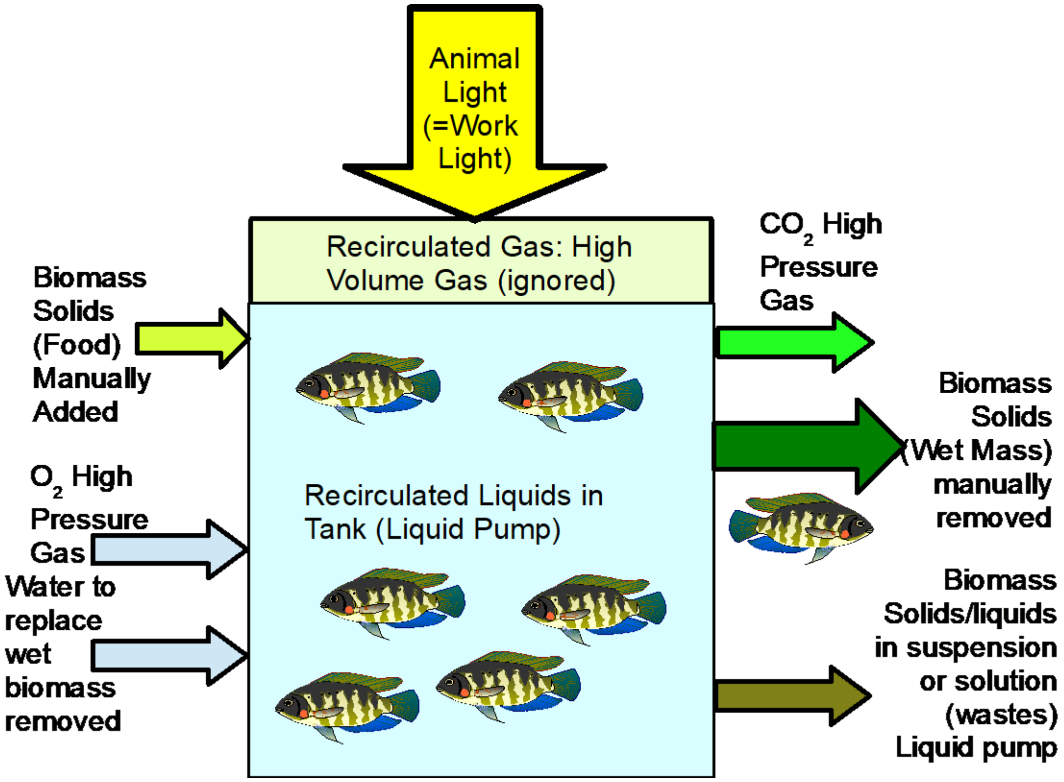

**Fig. 2. Aquatic stages net mass and energy flows.** *Note: heat for thermal regulation of the tank, and heat from lighting and pumping, are part of the heat rejection schema.*

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.

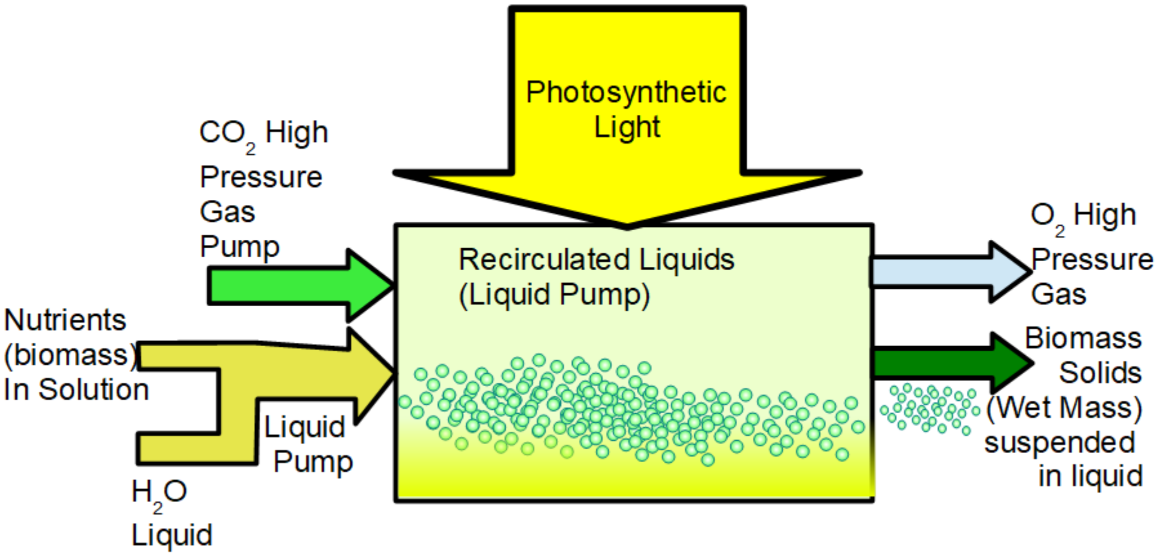

**Fig. 3. Photobioreactor net mass and energy flows.** *Note: heat is required in photosynthesis, and heat is generated due to the lighting and pumping, both part of the heat rejection schema.*

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.

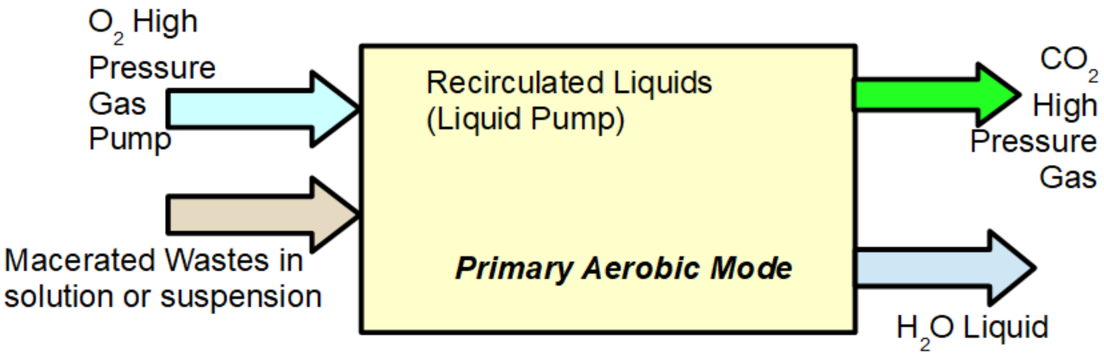

**Fig. 4. Yeast-Bacteria Bioreactor net mass and energy flows, in primary mode.** *Note: heat is produced due to aerobic metabolism,and pumping, though both are assumed part of the heat rejection schema.*

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 were 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 $m^2$ or about a third of a US football field in area) and requires very little enclosed volume (~5,900 $m^3$ 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** | *$m^3$* | *metric tons* | *metric tons* | *hectares* | *kg* | *kg* |
| 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)** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **$CO_2$** | **$H_2O$** | **$O_2$** | **Biomass in (total)** | **$CO_2$** | **$H_2O$** | **$O_2$** | ***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.* |
| 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.**

| | | RECIRCULATION (kg/day) | | | |
|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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** | *m³* | *metric tons* | *metric tons* | *hectares* | *kg* | *kg* |
| 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 $CO^2$ without producing food biomass.

**Table 13. Scenario 1B net mass flows.**

| | | **INPUTS (kg/day)** | | | | **OUTPUTS (kg/day)** | | | |
|---|---|---|---|---|---|---|---|---|---|
| From Table 20 in Ref. [1] | | **$CO_2$** | **$H_2O$** | **$O_2$** | **Biomass in (total)** | **$CO_2$** | **$H_2O$** | **$O_2$** | **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.* |
| 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.**

| | | **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 | 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.**

| | | 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 | 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.**

| | | RECIRCULATION (kg/day) | | | |
|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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** | *$m^3$* | *metric tons* | *metric tons* | *hectares* | *kg* | *kg* |
| **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) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$ | $H_2O$ | $O_2$ | Biomass in (total) | $CO_2$ | $H_2O$ | $O_2$ | *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.* |
| **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.**

| | | INPUTS (kg/day) | | | | |
|---|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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.**

| | | 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 | - | 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.**

| | | RECIRCULATION (kg/day) | | | |
|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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** | *$m^3$* | *metric tons* | *metric tons* | *hectares* | *kg* | *kg* |
| **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 then in 2A, and the addition of the grain and 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) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$ | $H_2O$ | $O_2$ | **Biomass in (total)** | $CO_2$ | $H_2O$ | $O_2$ | ***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.* |
| **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.**

| | | RECIRCULATION (kg/day) | | | |
|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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** | *m³* | *metric tons* | *metric tons* | *hectares* | *kg* | *kg* |
| **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) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$ | $H_2O$ | $O_2$ | Biomass in (total) | $CO_2$ | $H_2O$ | $O_2$ | 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 then 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.**

| | | INPUTS (kg/day) | | | | |
|---|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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.**

| | | **RECIRCULATION (kg/day)** | | | |
|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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** | *m³* | *metric tons* | *metric tons* | *hectares* | *kg* | *kg* |
| **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) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$ | $H_2O$ | $O_2$ | Biomass in (total) | $CO_2$ | $H_2O$ | $O_2$ | ***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 | 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.**

| | | INPUTS (kg/day) | | | | |
|---|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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.**

| | | OUTPUTS (kg/day) | | | | |
|---|---|---|---|---|---|---|
| **Species** | **Stage Type** | **Gases (High Pressure)** | **Gases (Low Pressure)** | **Liquids** | **Solids in suspension/ solution** | **Solids Manually Removed (Wet Mass)** |
| **Barley** | Hydroponic | - | 1,558 | - | - | 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.**

| | | RECIRCULATION (kg/day) | | | |
|---|---|---|---|---|---|
| **Species** | **Stage Type** | **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 for each scenario is as in Table 37 below.

**Table 37. Electricity for fluid flow by scenario.**

| 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** | 140,016 | - | - | 750,722 | 890,738 |
| **1B** | 95,836 | 88 | 43,708 | 515,402 | 655,034 |
| **2A** | 971,481 | 20,960 | 247,414 | 3,499,156 | 4,739,011 |
| **2B** | 856,561 | 18,980 | 266,856 | 2,876,038 | 4,018,435 |
| **3** | 2,807,917 | 90,542 | 885,327 | 17,006,656 | 20,790,442 |
| **4** | 4,387,218 | 104,296 | 1,818,609 | 48,156,207 | 54,466,330 |

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 38.

**Table 38. 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 |
| *Hydroponic area is footprint area in $m^2$ * 3 (assumes 1m between shelves stacked to 3m tall)* | | | | | | | |

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 39 below.

**Table 39. Photosynthetic electricity requirements by species and scenario.**

| Species | Stage Type | Scenario<br>*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 in 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 40 below.

**Table 40. 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 41 below.

**Table 41. Fluid flow electricity for heat rejection.**

|  | Farm Volume | Energy |
|---|---|---|
| **Scenario** | *$m^3$* | *Watts* |
| **1A** | 5,910 | 74,774 |
| **1B** | 5,496 | 69,536 |
| **2A** | 23,308 | 294,896 |
| **2B** | 22,399 | 283,396 |
| **3** | 48,554 | 614,313 |
| **4** | 102,446 | 1,296,163 |

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.

## III. Results

### A. Energy Consumption by Scenario and Type

Summing all energy sources by scenario results in Table 42 below. Note that the largest power consumer in all scenarios is fluid movement.

**Table 42. Electrical needs from all sources by scenario.**

|  | FLUID MOVEMENT | PHOTOSYNTHETIC LIGHT | WORK LIGHT | CIRCULATION FOR HEAT REJECTION | TOTAL | TOTAL per Person |
|---|---|---|---|---|---|---|
| **Scenario** | *kW* | *kW* | *kW* | *kW* | *kW* | *kW/person* |
| **1A** | 891 | 117 | 0.23 | 75 | **1,083** | ***10.83*** |
| **1B** | 655 | 315 | 0.21 | 70 | **1,040** | ***10.40*** |
| **2A** | 4,739 | 1,973 | 0.89 | 295 | **7,008** | ***70.08*** |
| **2B** | 4,018 | 1,945 | 0.86 | 283 | **6,247** | ***62.47*** |
| **3** | 20,790 | 4,448 | 1.85 | 614 | **25,854** | ***258.54*** |
| **4** | 54,466 | 11,470 | 3.89 | 1,296 | **67,236** | ***672.36*** |

Fluid movement (i.e. gas and liquid with or without suspended solids) is between just below two-thirds to over three quarters of the energy need in all scenarios. This implies that recirculation of liquids is a driver for the energy needs in all the farms, and that methods to reduce the energy required for recirculation should be examined in future settlements.

### 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 43, driven by pump energy for fluid movement. 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, these space farms 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 43. Comparison of energy values for various estimates.**

| | **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** *(via email, Al Globus, Aug 2018)* | 35-60 kW |
| **Scenario** *(this paper)* | **1A** | 11 kW |
| | **1B** | 10 kW |
| | **2A** | 70 kW |
| | **2B** | 62 kW |
| | **3** | 259 kW |
| | **4** | 672 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 is an order of magnitude less than scenarios 3+4, and 12%-20% of scenarios 1+2. However, add in the free sunlight at a rate of roughly 1kW/m$^2$, and the results are roughly comparable in most scenarios. 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 m$^2$ of solar panel area (i.e. 0.286 kW/m$^2$) at 1 AU without Earth obstruction, to get an equivalent solar panel area as in Table 44 below. It was assumed in calculations that solar power is provided 24 hours a day. The resulting solar panel sizes in Table 44 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 44. Estimated solar panel areas for power requirements by scenario.**

| | **TOTAL ENERGY** | **Solar Panel Area** | **Solar Panel Area** | **Farm Total Footprint** *(for Comparison)* |
|---|---|---|---|---|
| **Scenario** | *kW* | *m*$^2$ | *hectares* | *m*$^2$ *(hectares)* |
| **1A** | **1,083** | *3,784* | **0.38** | 2,000 (0.2) |
| **1B** | **1,040** | *3,634* | **0.36** | 1,800 (0.18) |
| **2A** | **7,008** | *24,492* | **2.45** | 7,800 (0.78) |
| **2B** | **6,247** | *21,835* | **2.18** | 7,470 (0.747) |
| **3** | **25,854** | *90,365* | **9.04** | 16,100 (1.61) |
| **4** | **67,236** | *235,001* | **23.50** | 34,000 (3.4) |

As noted above, the energy needs listed in Table 42 linearly drive solar panel areas which are many multiples of the size of the farm itself. Solar panel areas run from almost double in Scenario 1A to nearly seven times 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 based 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.

## IV. 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. 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.

## Acknowledgements

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## 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 Kg[1] | 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.

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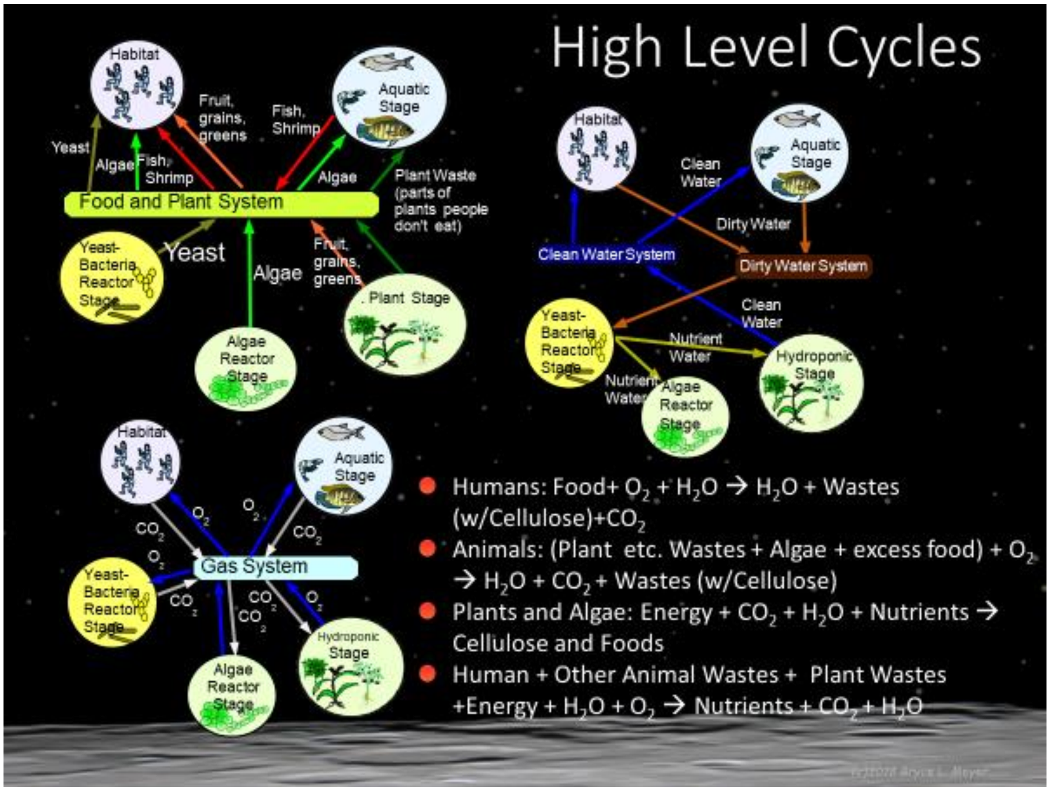
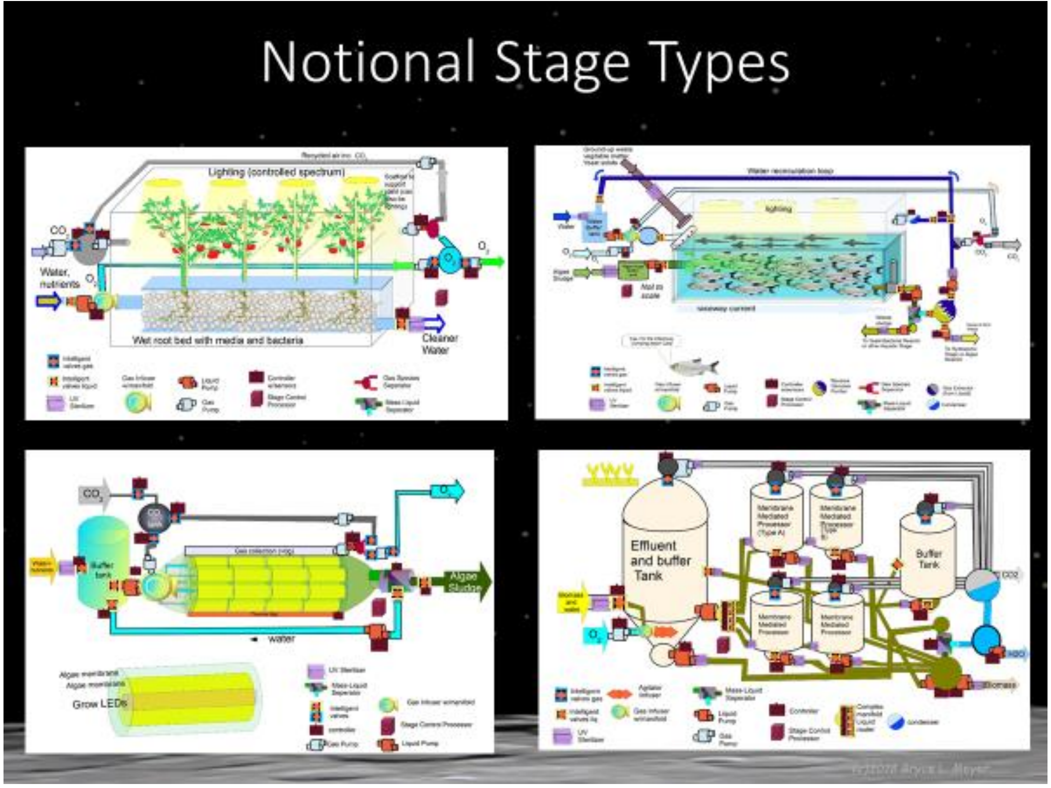
# APPENDIX B: Assembling the Stages

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.



## High Level Cycles

- Humans: Food+ $O_2$ + $H_2O$ → $H_2O$ + Wastes (w/Cellulose)+$CO_2$
- Animals: (Plant etc. Wastes + Algae + excess food) + $O_2$ → $H_2O$ + $CO_2$ + Wastes (w/Cellulose)
- Plants and Algae: Energy + $CO_2$ + $H_2O$ + Nutrients → Cellulose and Foods
- Human + Other Animal Wastes + Plant Wastes +Energy + $H_2O$ + $O_2$ → Nutrients + $CO_2$ + $H_2O$



## Notional Stage Types