Chapter Number

A Contemporary Analysis of the O'Neill – Glaser Model for Space-based Solar Power and Habitat Construction

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1. Introduction

1.1 Purpose of this Chapter

In 1975 Gerard O'Neill published in the journal Science a model for the construction of solar power satellites. He found that the solar power satellites suggested by Peter Glaser would be too massive to launch economically from Earth, but could be financially viable if the workforce was permanently located in free space habitats and if lunar and asteroid materials were used for construction. All new worldwide electrical generating capacity could be then achieved by solar power satellites. The project would financially break even in about 20 years after which it would generate substantial income selling power below fossil fuel prices. Two NASA / Stanford University led studies at Ames Research center during the summers of 1974 and 1976 found the concept technically sound and developed a detailed financial parametric model. Although the project was not undertaken when suggested in the 1970s, several contemporary issues make pursuing the O'Neill – Glaser concept more compelling today.

First, our analysis suggests that if in the first ten years of construction that small habitats (compared to the large vista habitats envisioned by O'Neill) supporting approximately 300 people were utilized, development costs of the program and the time for financial break even could be substantially improved.

Second, the contemporary consensus is developing that carbon free energy is required to mitigate global climate change. It is estimated that 300 GW of new carbon free energy would be necessary per year to stabilize global atmospheric carbon. This is about 4 times greater energy demand than was considered by the O'Neill – Glaser model. Our analysis suggests that after the initial investments in lunar mining and space manufacturing and transportation, that the profit margin for producing space solar power is very high (even when selling power below fossil fuel prices). We have investigated the financial scaling of ground launched versus space derived space solar power satellites. We find that for the carbon mitigation case even modernized ground launched space solar power satellites are not financially viable. For space derived solar power satellites, however, the increased demand makes them break even substantially sooner and yield much higher profit.

Third, current awareness is increasing about the dangers of humanity remaining a single planet species. Our technological power has been increasing relative to the size of the planet Earth. Since the middle of the 20th century our technological power has grown large relative to our planet's size. This presents a very real potential for human self-extinction. We argue that the potential for human self-extinction is increasing with time in proportion to the exponential growth of our technological power making self-extinction likely within this century if humanity remains a single planet species. The O'Neill model of multiple independent free space habitats, it is argued, can protect humanity from extinction in the same way that portfolio diversification protects ones assets from total loss. We show that about 1 million people for the electricity only case, and about 1 billion people for the carbon mitigation case, can be provided with permanent space habitats and transportation from Earth in 30 years and can be funded by the space derived solar power satellite program.

1.2 Scope of this Chapter

The goal of this chapter is to illustrate the power and importance of the O'Neill-Glaser concept in the context of human survival and maintaining a healthy planet Earth. We argue that at this point in human history our technological power is too dangerous to our selves and our home planet for us not to expand into space. We show by the models presented in the chapter that the imminent dangers of global warming and human self-extinction mandate that humanity move aggressively into the solar system in this generation. We show that the production of solar power satellites using space resources and with a work force living in space provides a viable financial model to mitigate CO_2 preventing the worst global warming scenarios, and safeguards humanity against self-extinction by providing hundreds of habitats and a billion people living in space within about 35 years.

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To accomplish this goal we need only consider the classic O'Neill-Glaser model which was parameterized for 1970's technological projections. Only habitat size optimization for the first ten years of production is added. This is a conservative approach since the innovations of the last 30 years will make the financial projections more favorable. However, the classic O'Neill-Glaser model represented a broad technological consensus. The model is well documented in the references and our calculations can be easily reproduced.

If we succeed in our arguments and a serious contemporary re-evaluation of the O'Neill-Glaser plan begins, then the financial technology parameters can be systematically updated. Other options such as laser power transmission from the SPS to Earth (Curreri&Criswell, 1999), materials processing on the Moon versus in microgravity (Curreri, 2007b) or basing the solar cells on the lunar surface (Criswell & Curreri, 1998) can then be assessed and the detailed technology trades made.

In this chapter the economics of the O'Neill – Glaser model is compared with models that rely exclusively on Earth launched materials. Although many studies of Earth launched Solar Power Satellites have been made, we found that the NASA "Fresh Look Study" was the most comprehensive and well documented. It also provided one of the most optimistic Earth launch financial projections. We thus chose it for comparison purposes.

To determine the energy demand for stabilization of CO_2 emissions, we found that Garrett's thermodynamic planetary model most suitable. By limiting consideration of local scenarios, the model is less sensitive to arbitrary assumptions, tracks well with decades of climate data, and provides insight for the correlation of energy use and economic value.

2. O'Neill – Glaser Model for Solar Power Satellite Production

The Solar Power Satellite, SPS, concept introduced by Peter Glaser in 1968 (Glaser, 1974) advocated placing large solar collecting arrays in space and beaming the energy down to Earth by microwave to provide electrical power. The advantage of collection of solar energy in space rather than on the Earth's surface includes 24 hour per day service, utilizing of the full solar irradiance without attenuation due to atmosphere of weather, and unlimited collection area. Thus, SPS could supply all Earth's expanding electrical needs without chemical pollution and with minimal waste heat. The original Glaser design as defined by NASA and DOD studies consisted of satellites 10 by 5 kilometers in size, providing 5 GW power, and requiring the launch of 50,000 metric tons. The economy of Earth launch has made construction of a viable business model for SPS contingent on drastic reductions satellite specific weight or of launch costs to Geosynchronous Earth Orbit, GEO.

O'Neill demonstrated (O'Neill, 1975a) that by utilization of space based (lunar or asteroid) materials and space based labor, the high costs of logistics from Earth could be offset. This enabled economically viable construction of SPS with user energy costs which could achieve complete market penetration for new and replacement electrical power production over several decades after which a very large financial return on investments would be realized. The key concepts are that the moon's gravity is 1/6th that of Earth and that translates to about 1/20th the energy costs to GEO, and that people living their lives near the job in free (non-planetary) space (even after the investment in space habitats) are much more economical than workers ferrying back and forth from Earth. It was determined that 98% of the mass for Glaser SPS could be obtained from lunar materials. After an initial investment in space infrastructure consisting of a lunar mining facility, space transport, and in space manufacturing facilities; free space permanent habitats (to house the people needed to build the SPS) would be constructed in tandem to SPS construction. These workers and their families living in permanent space habitats would number in the tens of thousands, thus, beginning the human settlement of space.

NASA studied the O'Neill – Glaser model through the mid 1970's most notably in two "summer studies" hosted by NASA Ames and California Institute of Technology and chaired by O'Neill. The study reports (Johnson & Holbrow 1977, Billingham et al, 1979) include detailed data used in the SPS financial model first published in the journal Science (O'Neill, 1975a) by O'Neill. The studies found the O'Neill – Glaser concept financially viable and feasible with 1970's technologies.

Although the SPS financial model developed by O'Neill is compelling, the high investments for the establishment of a lunar mining base and other space infrastructure all but necessitated governmental underwriting. Only the United States had the technical capability to place humans on the moon. The concept was presented by O'Neill to the U.S. Senate Science and Technology Committee (O'Neill, 1975b); however, probably due to the high initial costs and long time for financial payback the plan was not adopted by that or as yet by any subsequent U.S. administrations.

2.1 Earth Launch of SPS using More Mature Technology

Many studies (Geuder et al, 2004; Rouge, 2007) since Glaser's have attempted to achieve a viable financial model for Earth launched SPS. For comparison to O'Neill-Glaser, we found that the most comprehensive and best documented financial model was a NASA led study in the 1990's called the "Fresh Look Study" (Mankins, 1997). The study employed more advanced technologies (then Glaser's) that included remote robotic assembly, phase array microwave pointing, state-of-the-art solar cells, and high temperature superconductor bus lines. Figure 1 shows the two leading design concepts the "Solar Disc" and the "Sun Tower" compared to a Glaser era satellite being constructed in the vicinity of an O'Neill habitat. In order to keep the initial costs as low as possible, lunar materials were not considered and the number of humans in space were kept as low as possible. It was found that with these advanced technologies SPS might be financially viable if Earth launch costs could be aggressively reduced.

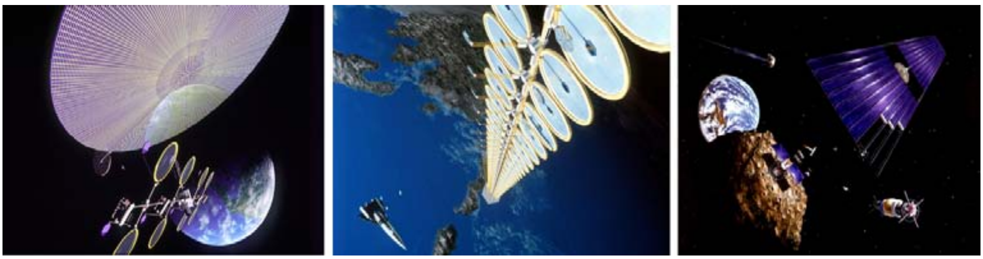

Fig. 1. Artist's conceptions of Solar Disc (left) and Sun Tower (center) Earth launched, and a Glaser era space derived SPS (right) with O'Neill habitat and near Earth asteroid miner (NASA).

2.2 Habitat Size Optimized O'Neill – Glaser Model

In the early studies of the O'Neill – Glaser economics the habitat size was fixed. O'Neill's original model (O'Neill, 1975a) assumed that the permanent in-space habitats would each hold 1 to 5 million people. The NASA studies (Johnson & Holbrow 1977, Billingham et al, 1979) scaled the habitat size down to 40 thousand people. The reason for fixing the large habitat size was to maintain O'Neill's vision of beautiful landscaped large vista habitats (Figure 2) (Johnson & Holbrow 1977) that would be attractive sites to begin the human settlement of space.

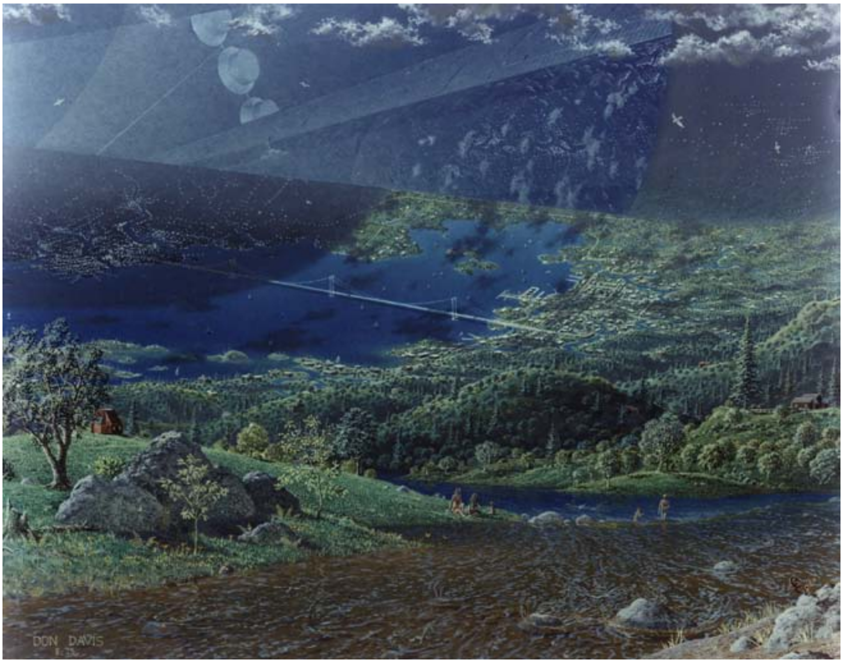

Fig. 2. Artist's conception a four million person cylindrical habitat planned to be located in lunar orbit near the fifth Earth-Moon LaGrange point (NASA).

However, habitats this size during the early part of the program when the in-space manufacturing capability is relatively small would require decades to build. The financial benefits of having the workforce living in permanent in-space habitats is deferred in time until the first of these large habitats can be built, thus increasing the required initial investment and lengthening the time to financial break even.

The concept of optimizing habitat size was applied (Curreri, 2007, Detweiler & Curreri, 2008) to the O'Neill – Glaser financial model by recalculating with habitat size as a free variable. The result was that the optimum habitat was a bolo design with about 300 people (150 in each of the two spheres). The first permanent habitat can then be built in the second construction year reducing the time for financial breakeven by about 1/2 and the total investment by about 3/4. After 10 years of SPS production, the manufacturing capabilities in space grow and the economics become insensitive to habitat size enabling the production, with negligible financial penalty, of the large vista habitats envisioned by O'Neill.

3. Analysis of the O'Neill-Glaser Model

3.1 Methods and Procedures for Habitat Size Optimized O'Neill – Glaser Model

The financial analyses of the O'Neill – Glaser model follows the NASA Ames methodology (Billingham et al, 1979). The model uses an economic parametric approach where costs are estimated relative to system mass by comparison to similar aerospace construction. These costs and benefits are then tracked with an economic model which includes the costs of financing, labor, and energy supply and demand. Ten years are allotted to build lunar and in-space infrastructure after which construction of SPS and free space habitats begin. The model is well documented in (Billingham et al, 1979). The optimization of the model for habitat size is described in (Detweiler & Curreri, 2008). All the costs have been updated according to the inflation rate of 383.42% from the year 1975 to 2005 (Halfhill, 2007).

In the NASA study the first 10 year period was utilized for research and development, lunar base construction, and other initiation costs. To expedite comparison of habitat size, this study assumes the common cost equal to the inflated value derived in the NASA study for the first 10 years and begins the comparison at year 10 of the project. Each of the figures in the Results section thus starts at project year 10. This corresponds to beginning the analysis when the necessary infrastructure is in place to begin building.

A summary of the activity during these ten years as envisioned in the NASA study is as follows: The first five years are devoted to research and basic construction on Earth. At year 5 a temporary habitat for 200 people is created in Low Earth Orbit (LEO). With a 10 Megawatt (MW) nuclear power plant and a material fabrication plant, the station at LEO starts creating products. At year 9 a L5 space station is created along with the transfer of three 20 MW solar power satellites to provide power for the station. Lunar Landers, which have been researched from year three, are then created. On year ten, a 120MW nuclear power plant is landed on the Moon. Also in this year, the Interlibrational Transfer Vehicle (ITV), the mass driver needed to send lunar regolith to lunar orbit, and the mass catcher in lunar orbit are fully developed. These three pieces of equipment take the raw materials from the Moon and transport them to their destination. The Lunar Base begins operation on Year 10. The total cost for this is estimated to be $283 billion in 2005 dollars.

Space Solar Power Satellite construction offsets the costs of large scale human habitation in space and provides return on the investment. To determine how many new SPS per year are required, the growth rate of the demand for electricity in the world is assumed to be a steady 2.4 percent per year. The total demand for electricity during 2004 was 1,875 GigaWatts (Energy Information Administration, 2007; Public Policy Institute of New York, 2006). For this analysis, a nominal start date of 2010 is used, so year 12 of the report (the first year SPS are created) would correspond to the year 2022.

The business plan for the SPS industry is to capture the world growth and replacement market for electricity, so only 2.4% of this electricity is provided by space industry. The replacement market is 4.32 times smaller than the growth market. So the total electrical needs fulfilled by space power are taken to be 2.96% of the total world electricity requirement. The model for market penetration for the first 10 years is as follows: 10, 12, 16, 20, 25, 32, 49, 45, 50, and 60 percent of the world electrical growth and replacement market. For the years after, this market penetration is taken to be 100 percent of the growth and replacement market. This market penetration is achieved by pricing the electricity 20% below all competing Earth based sources.

The demand formula is then

$$D = 1{,}875 \cdot 1.024^{y-2004} \cdot \left(0.024 + {}^{0.024}\!/_{4.32}\right) \cdot p \qquad (1)$$

To find the number of 10 GW SPS that are created each year, the demand found by Equation (1), is divided by 10 GW, and then rounded to the nearest whole number. These SPS then generate income. The business plan is to charge 80% of the current industrial average price for electricity. The average price in the United States is 891 mils (where 1 mil =0.01¢), and so 80% of this is 712 mils (Public Policy Institute, 2007). The economic benefit, b, in billions, of the SPS program could then be calculated as the total population of SPS, p_s, times the 10 million kilowatt-hours they produce multiplied by their operational time (95%) times the amount of hours per year they are operational, times the price per kilowatt-hour (in billions).

$$b = p_s \cdot 10^7 \cdot 0.95 \cdot 24 \cdot 365 \cdot 0.0712 \times 10^{-9} \qquad (2)$$

The Solar Power Satellites (modelled after the Glaser design) are made of 80 kt of material and take 2,950 worker-years to complete. Some of this material is purchased on Earth and transported to L5. The cost of this material is $17.67 billion to purchase and $11.04 billion to transport. The amount of material required from Earth is assumed to decrease at an 80% learning curve, decreasing the purchase and transport cost. The amount of labor required is taken to stay the same as a worst case scenario, except when otherwise stated. When these SPS learning curves are incorporated into the model, a more conservative learning curve of 90% is used to account for the differing levels of expertise of the crews working on the Satellites. There is also a maintenance cost for the SPS. This fee is $115 million per year, which can be approximated over the lifetime of the satellite by multiplying by 10. So the total maintenance cost per satellite is $1.15 billion. The learning curve can be produced using the formula:

$$w = a \cdot u^{\ln(c)/\ln(2)} \qquad (3)$$

The standard learning curve of 80% (c = 0.8) which has been found to be a reliable model in airplane construction (Asher, 1956). This means that each time the amount of machines created doubles, the work and price decrease by 80%.

The bulk of the material for the construction of the satellites and the habitats must be transported from the Moon. The cost of the transportation to L5 and the cost of construction (inflated to 2005 dollars) at L5 are taken from the 1975 NASA study (Johnson & Holbrow, 1977). The costs associated with the transportation of material come from the Mass Driver, the Mass Catcher, and the Interlibrational Transfer Vehicle (ITV). These are the machines which move the material. The Mass Driver launches the lunar soil or regolith from the surface of the Moon, the Mass Catcher collects this material at L2, and the ITV transports the regolith to L5. The ITV, the Mass Driver, and the Mass Catcher each have costs associated with them. Every year, there must be enough of each to handle the mass needs of that year. But since these continue working, only as many need to be created each year to handle the increase in tonnage over the last greatest tonnage requirement. These costs as well as the mass transfer capacity of each machine are reproduced in Table 1. The transportation costs from the Earth to the place of construction are estimated at $1,840 per kilogram ($480/kg in 1975 dollars), which is taken from the NASA study for transfer from Earth to L5. Even though current launch costs are higher this rate was considered reasonable when the required increase in launches per year is considered.

Since the radius of the bolo spheres are small compared to the length of the rotation tether between them, most of the bolo volume is between 0.8 and 1 gravity. The volume of the bolo can thus be divided into decks in the classic metallic view of space stations. Our proposed bolo design consists of one double sphere on each end of a rotation tether. The outer compartment would be shielded for habitation. Each of these inhabited spheres would be next to another sphere, this one shielded for agriculture. The tonnage of lunar material needed for a bolo can be found the same way as for two spheres, since only two of the spheres are shielded for humans. The structural weight of the agricultural spheres obtained using the structural weight of a 33.3m bolo in the 1975 NASA Ames study (Johnson & Holbrow, 1977). The population of a bolo can be found by calculating the volume of the habitable spheres and dividing it by $35m^2$ * 3.1m. Thirty five m^2 is the amount of space an individual needs in a high density environment (not including space for food production) and 3.1m is a reasonable height for each deck. After financial break even, as will be discussed later, habitats can economically be built assuming $47m^2$ for the amount of space an individual needs corresponding to a low density "large vista" environment. The two habitation spheres with their high shielding mass would act as the primary counterweights allowing for the rotation of the bolo. Some figures use models with a learning curve for the habitats. For these, an 80% learning curve is used on the labor required. However, the learning curve is assumed to stop after a 75% decrease.

The concept for an Interlibrational Transfer Vehicle in the 1975 NASA study (Johnson & Holbrow, 1977) uses some cargo (lunar regolith) for reaction mass to achieve propulsion. A round trip requires a quarter of the cargo for propellant. Thus 625 kt must be put in an ITV for it to transport 500 kt of material to L5. Therefore the Mass Drivers and Mass Catchers must move 1.25 times the amount of material needed.

Each Mass Driver requires power from a lunar rectenna which receives power from a solar power satellite orbiting the Moon. Each Mass Driver requires 0.1071 of the power received by the rectenna. Each rectenna costs $8.7 billion. The price and labor decrease with an 80% learning curve based on how many are produced. Given the amount of mass drivers for a year, the amount of rectenna needed and their operating costs can be calculated.
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TABLE 1. Costs and Mass Transfer Capacity of In Space Transfer Machines

Machine Name	Transfer Capacity (kt/yr)	Cost Per Unit (in Millions, 2005 Dollars)	Transportation Costs (in Millions, 2005 Dollars. At $1840 per kg).
Interlibrational Transfer Vehicle	500	11.5	9.2
Mass Catcher	313	2.3	1.84
Mass Driver	625	172.81	228.7

The regolith is processed and turned into usable products at L5 in the Material Processing and Fabrication Plants. Each of these is sized to process 1 Mt of lunar rocks per year. The number of plants built each year is that required for the construction of the SPS and habitats. While the first of these plants comes from Earth, each of the following will be built using material from the Moon. Each plant is made of 10.8 kt of material that must be transported from the Moon to L5.

To develop a scenario that could begin implementation with current launch systems, we studied an initial 50 space worker startup that begins by building smaller 384 person habitats (compared to the 5000 space worker start-up prior to the construction of the 10,000 person habitats used in the NASA study). In the case of habitats that cannot be built in a single year, it is assumed that there are no extra workers brought in, and the number of workers stays at 50. Once a habitat is complete, all workers live in the habitat and there are no Earth-based workers that require 6 month rotation between Earth and space. To maximize the economic payback, there must be just enough total workers in space each year to construct the SPS for that year, as well as to build habitats to keep up with the increased demand for SPS. As was assumed in the 1975 NASA study, the settlers are paid in materials constructed on the habitats, as well as by 100 kg/year from Earth. The materials from Earth are assumed to be purchased at $19.2 per kilogram, and transported to L5 at $1,840 per kilogram.

To maintain the operations on the Moon, 70 workers are needed to create each mass driver and 75 workers are required for the maintenance of the mass drivers. The amount of workers decreases at an 80% learning curve. Also, new lunar rectennas need to be built by lunar workers. Each lunar rectenna requires 277 workers for construction. Twenty percent of the workers on the Moon are assumed to be working on other lunar base related tasks. The lunar base could hold agriculture, and be mostly independent from Earth; thus lunar workers are assumed to be paid the same as settlers.

The cost of the initial supplying of the habitats is taken from the 1975 NASA study. This calculation is for the transportation of nitrogen and hydrogen from Earth, the transportation of plants and animals, the purchase and transportation of some equipment from Earth, and for the transport of the settlers from Earth. The 1975 NASA study concludes that this is $29.02 billion (2005 dollars) for every 10,000 people. Since this cost is directly proportional to the amount of settlers, to find the cost per habitat, multiply the $29.02 billion times the amount of settlers in the habitat over 10,000.

Using the above, the cost and benefit per year can be calculated when given the tonnage and personnel capacity of a certain space habitat. But these factors must be calculated as well. For this, simple geometry as well as previous models done by the 1975 Ames sponsored NASA study are used.

3. Habitat Size Optimization of the O'Neill-Glaser Model

A model was created to directly compare habitat sizes with the 1975 Ames hosted NASA study model. In order to fix variables other than habitat size, this initial calculation relies on the NASA study data completely, and uses all the data corresponding to a 1975 start date including using 1975 dollars. The in space society productivity is also calculated based on the NASA study value of 44% per habitat working on SPS and new permanent habitation. The shield weight is 5 tons per square meter. A learning curve similar to that found in the NASA study is applied to the work required for SPS. Eighty percent learning curves are used for the habitats, and are added to the cost for buying the material for the Mass Catchers, Mass Drivers, and ITVs. The benefit from the SPS is reduced to the 1975 value of 141 mills per kilowatt hour. Following the 1975 NASA study, the cost of transportation is reduced in year 22 from $480 per kilogram (in 1975 dollars) to $110 per kilogram. While there was not enough information to duplicate all the details of the NASA report we believe that the calculation has fidelity within 5 %.

Figure 3 shows the comparison between small bolo habitats and the large torus habitats built using temporary space workers housed in orbital construction shacks. The bolo program relies solely on permanent space labor and use no temporary space construction shacks after the first year. The results given in Figure 3 show that the small bolos, relative to the large vista cylinders, require only about one quarter of the investment, and reach economic break-even 10 years sooner.

3.2 Analysis for Earth Launch Advanced Technology SPS

The financial models for Earth launched satellites (“Sun Towers” and “Solar Discs”) follows the NASA Advanced Technology Office supported “Fresh Look” studies (Mankins, 1997).
In the Sun Towers plan begins with 7 years of research after which 18 satellites launched over 10 years, each of which provides 4 GW of power. The Sun Tower SPS begins with 6 years of research followed by 18 years of SPS Construction. For model comparison the data was extrapolated to 38 years.

The ground launch financial model assumes a launch cost of $400 per kg to GEO, compared to O’Neill – Glaser model cost of about $1690 only to LEO. Most of the financial burden for satellites launched from Earth is in launch costs. The aggressive decrease in launch costs is necessary to make the plan viable. It can be argued that the very high launch volume required by an Earth material based SPS plan would result in a “Progress Rate Cost” decrease (Xin et al, 2009) that is a function of total mass launched. Thus, it was decided to maintain the assumption used in the "Fresh Look" study that for Earth launched SPS the launch costs will be $400/lb. The space based case, however, maintains the more conservative $1600/lb Earth to LEO costs.

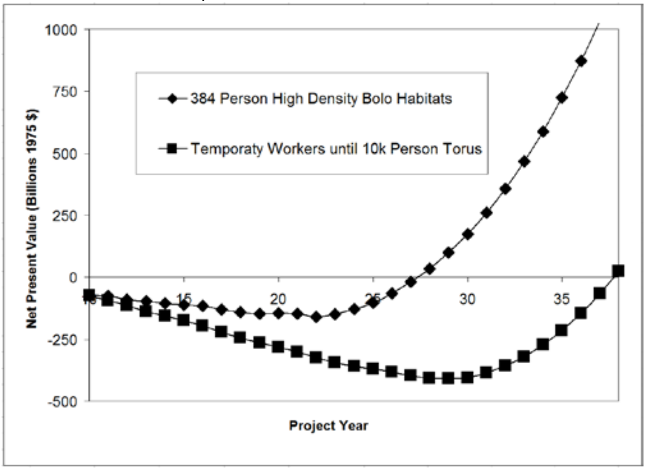

Fig. 3. A Comparison of small bolos to the 1975 NASA Ames study using an almost identical model (1975 economics). This shows the economic benefit of early spaced based labor achieved through smaller permanent habitats.

The Solar Disk plan begins with 6 years of research followed by construction of six 5GW Solar Disks over 30 years.

The ground launched models assume a selling price of electrical power at 21 cents per kilowatt hour, while O'Neill – Glaser model assumes a price of 7.12 cents. To enable a competitive comparison the income of the satellites were normalized to 7.12 cents per kilowatt hour.

4. Results and Discussion

4.1 Comparison of the Economics of Earth Launch and Space Derived SPS

The evolution of the economics of the two Earth derived (Sun Tower and Solar Disc) models and the space derived Optimized O'Neill – Glaser model is shown in Figure 3. The Earth launch models after six or seven years of relatively low cost research and development the SPS launching begins. However, even assuming the optimistic launch costs of $400/kg, the 78 GW Sun Tower program requires 30 program years to break even after which there is only a modest projected profit. The 30 GW Solar Disc program is even less favorable economically, with financial outlays of over $100 Billion and projected financial break even after 37 years.

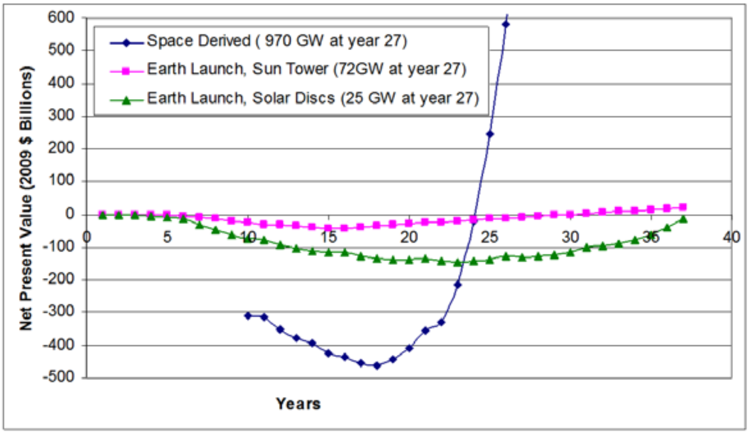

Fig. 3. Economics versus time for proposed Earth Launch and Space Derived SPS construction models

The space derived (optimized O'Neill – Glaser) model requires an investment of $300 Billion to build the infrastructure on the Moon and in space to allow utilization of lunar materials and space based labor. Once the infrastructure is in place, however, the SPS are constructed more than an order of magnitude cheaper than by Earth launch. These inexpensive SPS have a very large profit margin even when selling electricity below Earth market values. The peak investment of about $460 Billion is paid back at program year 24 and by program year 27 the project is projected to realize $600 Billion in profits.

4.2 Economic Comparison of SPS Models for Mitigation of Global Warming

Figure 4 gives the net present values versus time for "Sun Towers" for power demand levels up to 1.4 TW. It can be seen that as the demand increases the system cost increases and the time to financial break even lengthens. The 1.44 TW curve will be running a deficit of hundreds of billions of dollars 40 years into the program while supplying only about ½ of the required electrical power demand. The carbonless power at year 25 needed to stabilize CO_2 is about a factor of 6 higher (Garrett, 2009), thus, utilizing Earth launch SPS to achieve the carbon stabilization believed to be needed to mitigate global warming does not appear to be financially practical.

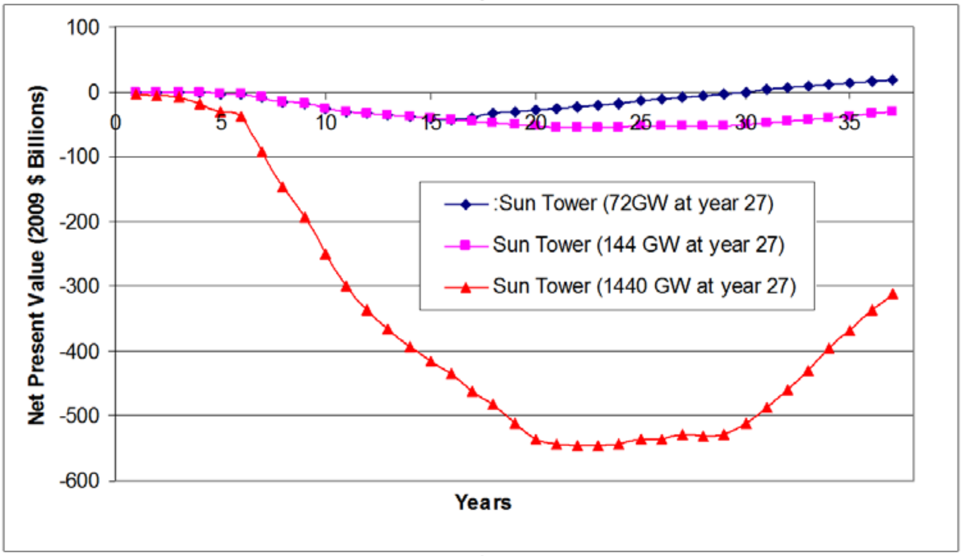

Fig. 4. Economics versus time for proposed Earth Launch and Space Derived SPS construction models

Next we calculate the economics of the Optimized O'Neill – Glaser model at the demand level (Garrett, 2009) required to stabilize global green house gases. It is assumed in this model that excess electricity would be converted into non-carbon producing fuels such as hydrogen or into non-carbon emitting energy storage devices such as batteries or fuel cells.

The world electricity consumption was about 1966 GW in 2005 and it is projected to be about 4,000 GW by the year 2036, which would be about year 27 of these analyses. Figure 5 gives the economics of the space derived (O'Neill – Glaser) SPS construction model for meeting world electrical power growth requirements and that for stabilization of CO_2 emissions. Figure 6 gives the corresponding SPS power delivered to Earth. The "electricity" plan will create 970 GW by year 27, which is 24 percent of the world electricity demand. The higher demand plan will create 8660 GW by year 27, meets the requirements of Garret's thermal dynamic global warming model (Garrett, 20009) by replacing 2.1% percent of the total energy consumed each year by non-carbon-emitting sources in order to stabilize world CO_2 emissions.

From comparison of the curves in Figure 5 it is apparent that the economics of space derived SPS for the higher demand level needed to stabilize global CO_2 are even more favorable than for the new electrical demand model. This occurs because after the space infrastructure is in place, there is a high profit margin on SPS production. Ramping up to this higher production requires greater initial investment (about $800 billion at year 17) however program break even occurs 4 years sooner at, at year 20. The profit projected by program year 25 is over $8 trillion.

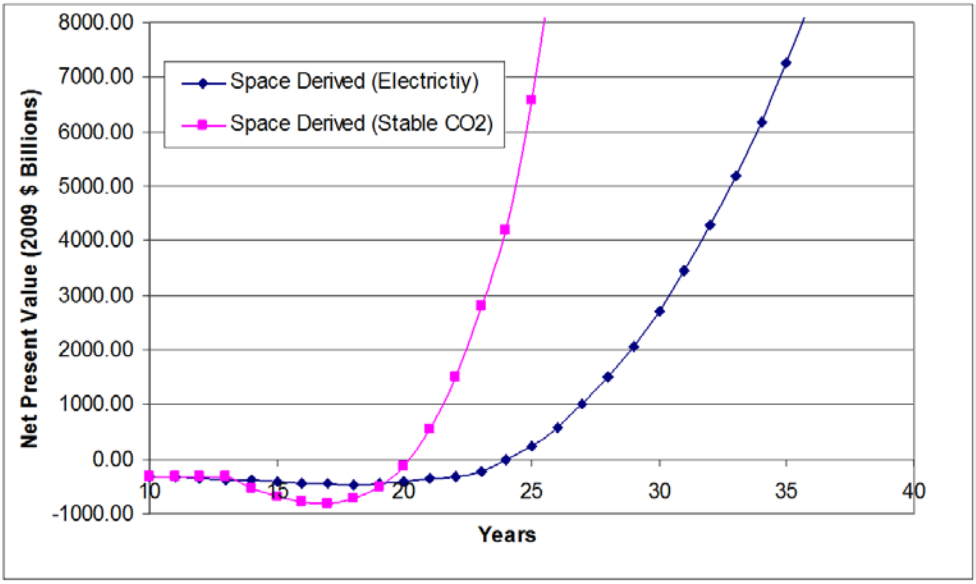

Fig. 5. Economics of space derived SPS scaled to stabilize CO2 emissions.

As far as the authors are aware, this is the first study to apply the financial models for SPS construction to the global warming scenario. The results are quite dramatic. While the ground based approach does not appear to be financially practical, the space based approach is financially compelling, promising extraordinary profit if implemented.

As a mechanism to stabilize CO_2 emissions and avert global warming space derived SPS have a singular advantage over other potential solutions, in that they have an economically favorable rate of return even when compared to fossil fuels. Since the materials (during the construction phase) are mainly derived from space, a program should be possible which is very friendly to the Earths environment while maintaining the historic rates of increase in global economic growth.

4.3 Population in Space

By design the O'Neill – Glaser model has the unique ancillary benefit of establishing a significant human population living in free (non-planetary) space. By project year 35 for the electrical power scenario 40 thousand people and for the climate change mitigation scenario 520 thousand people would be living in space. These people, and their families, represent 1.25 times the projected work force needed to construct the SPS and associated infrastructure.

In O'Neill's early writing (O'Neill, 1974), the potential of free space habitation to absorb the natural human population increase was discussed in the context of allowing maintenance of some limited population for Earth. He estimated that more than half of the human

population could be living in in-space habitation within 130 years. However, this potential was not related to his subsequent economic model (O'Neill, 1975).
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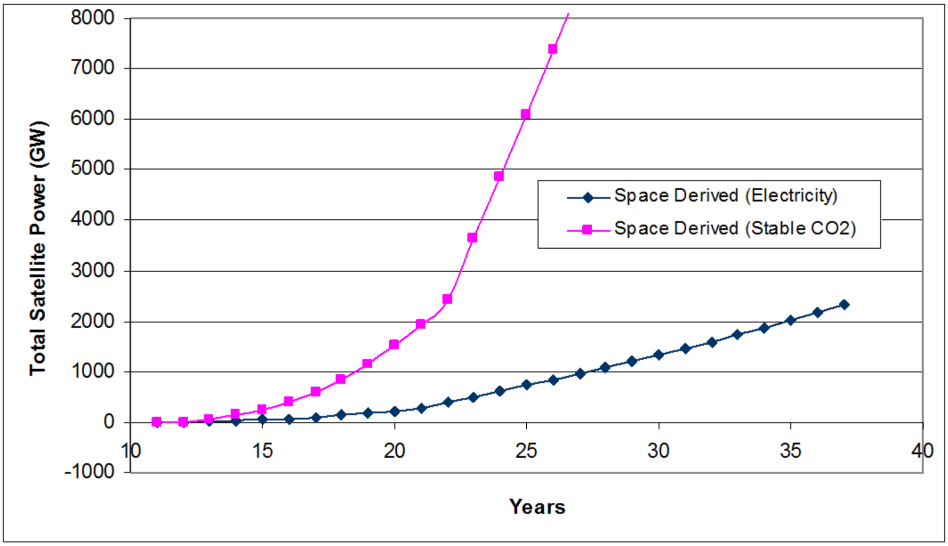

Fig. 6. Space derived SPS power delivered to Earth corresponding to the economic curves in Fig. 5.

The economic potential of the space derived SPS program to populate space can be examined by modifying the model to reinvest the profits from the program in additional space habitation. This model represents a transition in the space economy from one driven by space power production to one that is also driven to maximize space real estate production. As shown in Figure 7, the space derived SPS program is capable of financing in the first 35 years 800 thousand people for the electricity scenario and 1.1 billion people in space for the CO2 stabilization scenario. This includes construction of large vista O'Neill habitats, transportation of the population from Earth to the space habitation, and the population's living expenses in space. Again 80% of the population is employed in building SPS or habitation. After this space real estate focus the space population can be naturally deployed to develop a solar system based economy. The solar system economy would have little near term limits to growth since the carrying capacity of the asteroid belt alone utilizing O'Neill habitats is estimated to be greater than 10-100 trillion people (Billingham et al, 1979).

4.4 Criticality of O'Neill-Glaser for Human Survival

4.4.1 Human Propensity for Self-Extinction

Let us begin with a thought experiment that we will call the "Red Button" scenario. Suppose that each person on Earth is given at 12 midnight GMT a "Red Button" which if pressed would essentially destroy all human life on Earth. How much longer would we last? The answer is almost certainly about 20 milliseconds after midnight which approximates the response time of the human thumb. With six billion people, we know that someone, probably quite a few people, would push the button immediately.

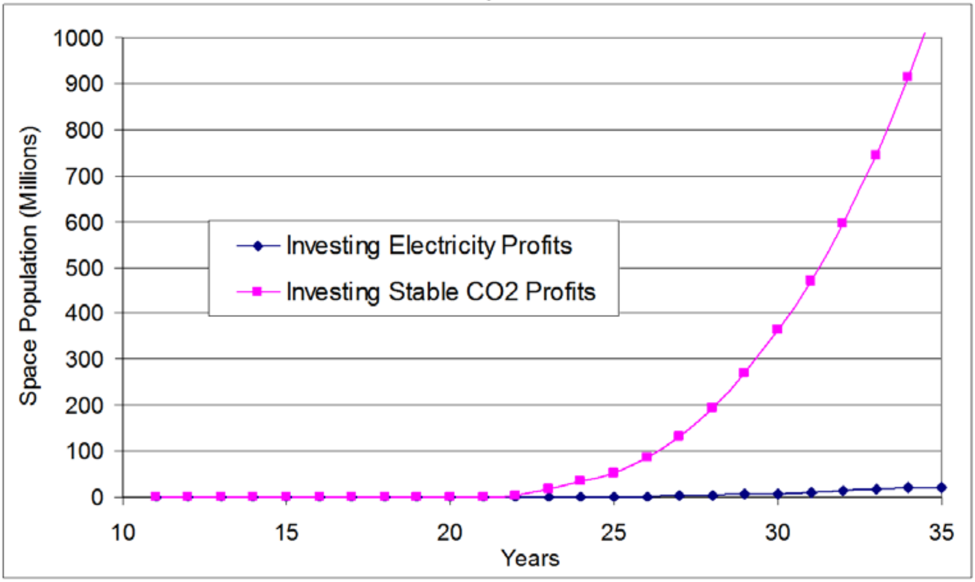

Fig. 7. Population in space for space derived SPS if profits are reinvested in additional in-space habitation.

What makes this thought experiment pertinent is that since 1950's there have been a number of people who have had the capability to initiate human self-extinction. How safe are we? To answer this question we must consider two things, the growth with time of technological power and the human propensity for self annihilation.

During the 1950's there were perhaps 10 people (about 5 in the U.S. and 5 in the U.S.S.R.) who had the power to initiate the global destruction of human society. What was our probability of self extinction at that time? One (perhaps conservative) estimate of the human propensity for self-extinction is the murder-suicide rate. The human murder-suicide rate (Eliason, 2009) has remained relatively constant from 0.2 to 0.3 per 100,000 people per year. This would be about 15 thousand per year for a population of 6 billion or a probability of $2.5*10^{-6}$. With these assumptions we can estimate the probability of human self-extinction during the 1950's. Where (for a single habitat) the probability of self-extinction is given by equation (4) where, P_0 is

$$P_0 = P_R \ N_C \tag{4}$$

P_R is the probability that someone would initiate self-extinction and N_C is the number of people that have the capability to initiate extinction. Thus, P_0 in the early 1950's would be estimated as $2.5*10^{-5}$. Because of the relatively low propensity for murder-suicide our chances for survival in the early 1950's were good. However, the number of people with apocalyptic capability has grown substantially during the last 60 years. Thus, in order to understand our current and future self-extinction risks, we must consider the growth of N_C with time.

4.4.2 Exponential Growth of Technology and N_C with Time

The current number of people who possess the capability to initiate human extinction, N_C, is not easy to determine directly. There are now at least 10 nations that have nuclear weapons (FAS, 2008), stock piles have existed of biological weapons capable of destroying all humans 10,000 times over (John Hopkins, 2002), genetic engineering is becoming cheep and easy enough for a graduate student to do in a garage (Boutin, 2006) with unknown hazards, nano technologies and artificial intelligence are expected to have the potential for globally lethal events. Certainly, a serious comprehensive study of N_C with time is warranted, since the consequence of ignorance is to risk extinction.

With the above uncertainties stated, it is worthwhile to make a reasonable estimate for the trend of N_C. There is an impressive body of data (Kurzweil, 2005) that documents the exponential growth of knowledge and technology over the past centuries. Not only has the technological power increased exponentially but the costs of the technologies have tended to decrease exponentially with time. The growth N_C would be expected to follow the growth of technology in general. Thus, we can assume that N_C increases proportionately with the growth of technology. Following Kurzweil's model for technology growth, N_C as a function of time, t, is

$$N_C = N_{C0}\, e^{(C\,t)} \qquad (5)$$

where N_{C0} is N_C at time zero and C is a constant. If we assume N_{C0} was 1 in 1945 and 10 at t = 1950, we could determine a value for C if with an estimate of N_C at 2010. Since a direct count of N_C is not available, we will make an indirect estimate. The increase in technological availability should be proportional to the increase in wealth and inversely proportional to the decrease in cost of the technology. For simplicity we will use nuclear weapon development and gross world product, GWP. Since 1945 the GWP has increased by a factor of 10 (Berkeley, 1998). Development of the first nuclear bomb in 1945 (The Manhattan Project) cost 20 billion (1996 dollars) (Brookings Institution, 2009). Development of the Pakistan nuclear bomb in 1998 was estimated to cost about $150 million. Thus the development cost of a nuclear weapon has decreased by about 100 times. Thus, a rough guess based on the increase in world wealth and the decrease in the costs of destructive technology for of the present value of N_C is 1000 at 2010.

If we use $N_C = 10$ for 1950 and $N_C = 1000$ for 2010 in equation (5) we determine a value for C of 0.77. This allows us to calculate a projection for N_C versus time. P_0 can then be calculated by equation (4) assuming P_R to be equal to the murder-suicide probability. The result is given in Figure 8. What should be noted from this exercise is the increase in extinction probability over time, P_0, due to the exponential growth of technological power. In the given scenario P_0 was 1 in 100,000 in 1950, 1 in 500 in 2010, but will become 1 in 10 in 2060 and approach 1 in 2090. If these calculations hold then the children born today would be the last humans to enjoy a full life span before self induced extinction becomes all but inevitable. The above analysis assumes that humanity remains a one planet society. Next we shall examine the effect on extinction probability if humanity adapts to multiple independent habitats beyond the Earth.

4.4.3 Multiple Independent Habitats and Survival Probabilities

Next we will examine the survival probabilities of a self-extinction capable society with multiple independent habitats. Let us define the subset of those who could produce an extinction event, N_C, which actually would initiate human self-extinction as N_R. If $N_R \geq 1$ we have extinction of a one habitat society. Next let us define N_H as the number of independent habitats that humans inhabit. In this context, independent means that the habitat has sufficient separation in space with other habitats that for the current technological level, a self extinction event in one habitat will not significantly affect the survival probability of another independent habitat.

Because of human nature (Eliason, 2009; Curreri, 2010) we cannot reliably predict who is or will become a subset of N_R. (But by the analysis in Figure 8 it is very likely that the condition $N_R > 1$ will occur within one human lifespan from the present.) So for the analysis we assume that N_R is randomly distributed among N_H. Now we can analyze the probability of self extinction, P_0, as a function of N_R and N_H. This analysis is similar to that for portfolio diversification or for fault tolerant computing.

An everyday analogy of this probability calculation is given as follows. Consider that a deck of cards represents an independent habitat, N_H, and the Aces are extinction events, N_R. The probability that we have an Ace in the deck (extinction) is 100%. If we cut the cards into two piles the probability of extinction, P_0, is less than 100 % since all the Aces could be in one pile. If we make 5 piles then the probability that each pile has one of the 4 Aces is zero ($P_0 = 0$). Let us apply this method with the assumption that humanity can establish habitats beyond Earth ($N_H > 1$).

The standard formula for the number of combinations of n and k where order is not important is

$$nCk = \frac{n!}{k!(n-k)!} \tag{5}$$

Examining the probability for extinction, P_0, as a function of N_R and N_H we obtain

$$P_0 = \frac{(N_R - 1)C(N_H - 1)}{(N_H + N_R - 1)C\,N_R} \tag{6}$$

For the case where $N_R = N_H$ this simplifies to

$$P_0 = \frac{1}{(N_H + N_R - 1)C\,N_R} \tag{7}$$

Examining equation (7), we see that when N_R exceeds 1 the probability of human extinction can be greatly reduced with a small increase in the number of independent habitats. With one habitat by definition the probability of extinction is one, but with just two additional (Moon and Mars for example) the probability drops to one in ten per year. For five, nine, and ten habitats the probability of extinction per year drops to one in 100, 1,000 and 10,000 respectively.

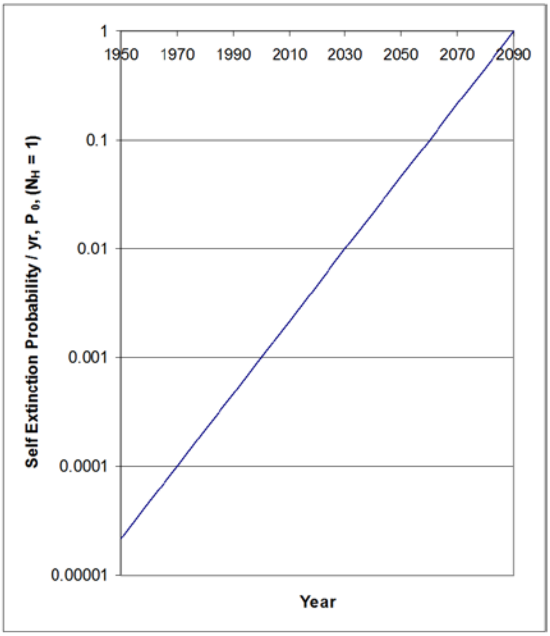

Fig. 8. Calculation of Self Extinction Probability versus time for a single habitat if $N_C = 10$ in 1950 and $N_C = 1000$ in 2010.

The probability of extinction, however, tells only part of the story since it does not give information regarding surviving population. Multi habitat civilization design will need to consider the probability rate for outcomes of partial population loss. Equation (8) gives a general formula for calculating the probabilities for all outcomes.

$$P_{(N_H, N_R)} = \sum_{K=1}^{K=(N_H V N_R)\min} \frac{(N_H C K)((N_R - 1) C (K-1))}{(N_H + N_R - 1) C N_R} \quad (8)$$

Equation (8) states that the probabilities for a N_H, N_R pair are given by the sum for k = 1 to the value of N_H or N_R whichever is lower acting on the ratio of the combinations to the right. The results for pairs of N_H and N_R from 1 to 6 are given in Table 2.

For example if N_H and N_R = 2, then the probability outcome (for that time step) for zero population is one out of three, and the probability for survival of one half the initial habitats is 2 out of three. Examining Equation 4, it is apparent the complexity of the possible outcomes increases as N_R and N_H become greater. It is also evident that if $N_R \geq N_H$ then $P_0 > 0$, and if $N_R < N_H$ then $P_0 = 0$.

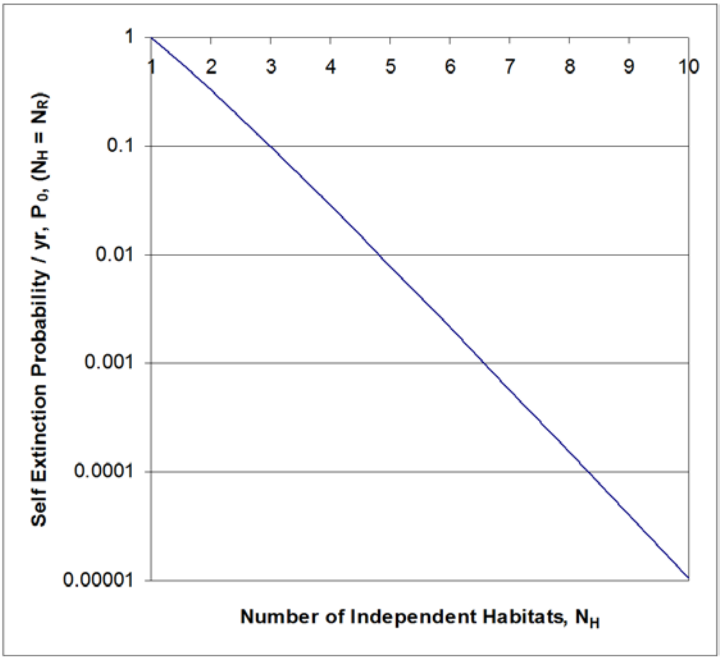

Fig. 8. Self Extinction Probability for 1 to 10 Habitats when $N_H = N_R$

4.5 Escaping Human Self-extinction Probability with Multiple O'Neill Habitats

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Now let us examine the scenario shown in Figure 3 where we have a total human population, N_P, of 1 billion people living in space in O'Neill habitats. Since the O'Neill habitats are fragile relative to the inhabitants technological capabilities we assume that all the people have the ability to destroy all life in their habitat that is $N_C = N_P$. If we assume each of the billion people has the technical capacity to destroy their habitat, N_R then equals N_C times the murder-suicide rate which gives N_R = 2,334. We now can utilize Equation 4 to calculate extinction probability, P_0, versus the number of habitats, N_H, for N_R = 2,334.

Because of the difficulties in calculating factorials of large numbers, an optimized tool was used (Shipway, 2008).

Table 2. Probability Matrix for N_H, and N_R values of 1 to 6.

	$N_R=1$	$N_R=2$	$N_R=3$	$N_R=4$	$N_R=5$	$N_R=6$
$N_H=1$	$P_0=1$	$P_0=1$	$P_0=1$	$P_0=1$	$P_0=1$	$P_0=1$
$N_H=2$	$P_{1/2}=1$	$P_0=1/3$; $P_{1/2}=2/3$	$P_0=2/4$; $P_{1/2}=2/4$	$P_0=3/5$; $P_{1/2}=2/5$	$P_0=4/6$; $P_{1/2}=2/6$	$P_0=5/7$; $P_{1/4}=2/7$
$N_H=3$	$P_{2/3}=1$	$P_{1/3}=3/6$; $P_{2/3}=3/6$	$P_0=1/10$; $P_{1/3}=6/10$; $P_{2/3}=3/10$	$P_0=3/15$; $P_{1/3}=9/15$; $P_{2/3}=3/15$	$P_0=6/21$; $P_{1/3}=12/21$; $P_{2/3}=3/21$	$P_0=10/28$; $P_{1/3}=15/28$; $P_{2/3}=3/28$
$N_H=4$	$P_{3/4}=1$	$P_{2/4}=6/10$; $P_{3/4}=4/10$	$P_{1/4}=4/20$; $P_{2/4}=12/20$; $P_{3/4}=4/20$	$P_0=1/35$; $P_{1/4}=12/35$; $P_{2/4}=18/35$; $P_{3/4}=4/35$	$P_0=4/56$; $P_{1/4}=24/56$; $P_{2/4}=24/56$; $P_{3/4}=4/56$	$P_0=10/84$; $P_{1/4}=40/84$; $P_{2/4}=30/84$; $P_{3/4}=4/84$
$N_H=5$	$P_{4/5}=1$	$P_{4/5}=5/15$; $P_{5/5}=10/15$	$P_{2/5}=10/35$; $P_{3/5}=20/35$; $P_{4/5}=5/35$	$P_{1/5}=5/70$; $P_{2/5}=30/70$; $P_{3/5}=30/70$; $P_{4/5}=5/70$	$P_0=1/126$; $P_{1/5}=20/126$; $P_{2/5}=60/126$; $P_{3/5}=40/126$; $P_{4/5}=5/126$	$P_0=5/210$; $P_{1/5}=50/210$; $P_{2/5}=100/210$; $P_{3/5}=50/210$; $P_{4/5}=5/210$
$N_H=6$	$P_{5/6}=1$	$P_{4/6}=15/21$; $P_{5/6}=6/21$	$P_{3/6}=20/56$; $P_{4/6}=30/56$; $P_{5/6}=6/56$	$P_{2/6}=15/126$; $P_{3/6}=60/126$; $P_{4/6}=45/126$; $P_{5/6}=6/126$	$P_{1/6}=6/252$; $P_{2/6}=60/252$; $P_{3/6}=120/252$; $P_{4/6}=60/252$; $P_{5/6}=6/252$	$P_0=1/462$; $P_{1/6}=30/462$; $P_{2/6}=150/462$; $P_{3/6}=200/462$; $P_{4/6}=75/462$; $P_{5/6}=6/462$

The result, shown in Figure 8, is somewhat surprising. If human population of 1 billion, all with habitat destroying technology, are dispersed in 50 or less habitats self-extinction within a decade is highly probable. However, with just 160 habitats the chances of self-extinction per year decrease to about one in a million.

If the 1 billion people were separated into 200 O'Neill habitats, each would house 5 million people, which is the lower population density (O'Neill, 1974) for the original double cylindrical habitat design. This migration could be accomplished in about 35 years, be completely financed by profits from SPS while stabilizing Earth's global carbon emissions. The probability of human self-extinction during the natural life span of a child born today would decrease from some number uncomfortably close to 1 to a probability less then 1 in ten million.

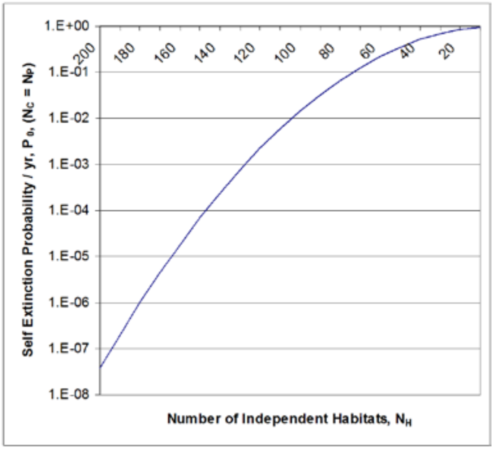

Fig. 8. Probability of self-extinction for 1 billion people in O'Neill habitats.

5. Discussion

5.1 Energy, Climate Change and World Economy

The analysis in this chapter shows that by using extraterrestrial materials and space based labor we can provide enough carbon free energy from Solar Power Satellites to stabilize CO_2 emissions at costs below fossil fuel prices. Would it not be better to decrease our energy consumption? Better understand this we will examine Gannett's thermodynamic planetary model (Gannett, 2009, 2011) in the context of the O'Neill-Glaser energy production model.

Gannett finds that the global primary energy consumption, a, is directly related to the global economic value, C, through a constant λ.

$$a = \lambda C \tag{9}$$

Thus, as our energy consumption goes to zero the value of our civilization would also go to zero. The creation of wealth from the exponential growth of knowledge (equation 5) is naturally associated with an exponential growth in energy consumption.

$$a = a_0 \exp(\eta t) \tag{10}$$

In Equation (10) a_0 is the energy consumption at time, t_0, and η is the "rate of return" representing the instantaneous rate of civilization's growth or decay. If the rate of return is negative, eventually our civilization will collapse.

World CO_2 emissions, E, are directly related to our global economic value as

$$E = \lambda \, c \, C \tag{11}$$

where c is the carbonization of the fuel supply. Garrett (Garrett, 2011) calculates a number of likely forecast scenarios for economic growth and carbon emission. All the forecasts lead to either economic collapse or to dangerous levels of atmospheric CO_2 followed by economic collapse before 2100. He also finds that conventional analysis underestimates the cost and the overestimates the associated wealth of society for low emission levels.

This is in contrast space derived solar power. Here the power is beamed from space by microwaves to a ground receiving rectifying antenna; with the SPS produced in space from extraterrestrial materials the total carbonization of this energy is very low. As Earth launch is eliminated the system allows the accelerating growth of the world's wealth with minimum atmospheric carbon production.

5.2 Calibration of the "Doomsday Clock"

After the first hydrogen bomb tests, it became obvious to many that our species had attained the ability to ability to destroy ourselves. In 1947 the Bulletin of Atomic Scientists began to publish the "Doomsday Clock" which began at 7 minutes to midnight. Each year it is subjectively adjusted in response to events such as arms control treaties or countries that newly attain atomic weapons. The clock was set as far back as 17 minutes to midnight in 1991 and was at 5 minutes to midnight in 2007. We believe that the calculations given in section 4 of this chapter provide a framework to estimate, with some veracity, the probability with time for human self-extinction. This is critical since credible responses to the danger require a finite time as we illustrate with the 30 year O'Neill-Glaser example.

That said, the models given in this chapter provide only a framework. The details must be refined. For example the current value of N_c, the number of people capable of initiating a human self-extinction event, should be precisely evaluated. The growth rate of technological power (for nuclear, biological and nano-technologies etc.) should be precisely determined. Some of these technologies may be growing at doubly exponential rates (Kurtzweil, 2005). The O'Neill-Glaser model technological parameters should also be updated and the plan optimized. Then we must begin timely implementation.

5.2 Comparison with Other Proposed Models for our Future

There have been many models proposed predicting human societies collapse due to population increase and the exhaustion of Earth's resources. For example von Hoerner (von Hoerner, 1975) projected human population growth continuing at 2% and argued that even star travel would not be adequate to alleviate the problem. Gerard O'Neill believed that the justification for his space habitats was to avert the depletion of Earth's resources as was predicted by the "Club of Rome" financial models (O'Neill, 1977). These arguments based on limited resources have not been predictive because they fail to account for the counter balancing effect of the exponential growth of technoligical power in an energy rich environment.

Sagan (Sagan, 1973), argued that when a society gains the technical ability for self-extinction it enters a Technological Adolescence during which time there is a good possibility for self-extinction. Lemarchand (Lemarchand, 2002) considers the historical trends for violent conflicts, population growth, and the growth of democracies and calculates that our period of Technological Adolescence will be 150- 200 years. This is similar to the 140 years from atomic bomb development to self-extinction that we calculated in section 4.4.4. However, these authors then conjecture that societies, if they survive, will then enter a Technical Mature Age in which the species would learn to live in harmony. This is wishful thinking, since there is no evidence or precedence for such a change in human nature. On the contrary (Curreri, 2010) the diverse points-of-view that comprise human nature (including the extremes that we might term very good and very evil) are what powers the engine of multiple hypothesises essential for the scientific method. Thus, we argue that any technically vital society must maintain diversity of thought. A species will not attain harmony without technical stagnation. This would also include artificial intelligences. Thus, we contend that expansion into multiple independent habitats separated by sufficient space is a requirement for successful technological societies to survive after Technological Adolescence is reached.

Another prediction (Smith, 2009) is that intelligent species continue the compression of microelectronics to the limit where their planets become an informational singularity. These societies do not expand into space, since expanding inward is more informationally rich. The models presented in this chapter strongly suggest that such an intelligent society would achieve self-extinction long before they achieve an informational singularity if they do not expand in space to multiple habitats beyond their home planet.

6. Conclusion

To solve the main problems of our age, we must embrace the Copernican principle that "the Earth is not central or in specially favored position." We must tap into the infinity beyond our home planet. Space based Solar Power can solve our energy, economic, and climate change issues if and only if we use the materials and living space beyond Earth to build them.

Since the mid 20th century we had the technological power to destroy our species and our home planet. This technological power and its associated risks continue to grow at an exponential rate. When the human propensity for self destruction and the growth of the availability of technologies of mass destruction are considered, our self-extinction probability can be expected to approach 1 well before the end of this century.

If, on the other hand, a few hundred artificial worlds (as advocated by O'Neill) are placed in the solar system with enough space between them that if one self destructs its neighbor would not be directly affected then the chances of human self-extinction would fall to about 1 chance in 1 million per year.

Further, it is shown that 1 billion people could be placed in space within 35 years completely funded by income from Solar Power Satellites needed to stabilize planetary CO_2 emissions.

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