LUNAR POWER SYSTEM
SUMMARY OF STUDIES FOR THE LUNAR ENTERPRISE TASK FORCE
NASA - OFFICE OF EXPLORATION

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1 INTRODUCTION

The capacity of global power systems must be increased by a factor of ten to provide 20,000 GW of electric power by the year 2050 to support the needs of 10 billion people at 2 kWe/person. Solar power bases can be expeditiously constructed on the moon to supply the majority of the needed power (Waldron and Criswell 1985, 1989).

The Lunar Power System (LPS) would collect solar energy at power bases (1 & 2, figure 1) located on opposing limbs of the moon as seen from Earth. Each base would contain tens of thousands of individual systems, each consisting of solar converters and microwave transmitters that transform the solar power to microwaves. Hundreds to thousands of low-intensity microwave beams will be directed from each base to rectifying-antenna (rectennas) on Earth (4 & 5, figure 1) and in space (8) that convert the microwaves back to electrical power. Additional sunlight can be reflected by mirrors (3) in orbit about the moon to bases #1 and #2 during lunar night. Microwave reflectors (6) in mid-altitude, high-inclination orbits about Earth can redirect microwave beams to rectennas that can not directly view the moon. The sunlight and microwave reflectors can eliminate the need for power storage on the moon or Earth, permit the LPS to follow the power output needs of each receiver, and minimize the need for long-distance power transmission lines on Earth. The complete LPS consists of the power bases (1 & 2), orbital mirrors (3 & 6), and rectennas (4, 5 & 7). Space rectennas (8) can have a low mass per unit of received power (< 1 Kg/Kw) and can enable high performance electric-rockets and rugged facilities.

LPS can provided dependable, economic, renewable, and environmentally benign solar energy to Earth. LPS requires far less equipment, land area, people, and net investment to construct and maintain than any of the other options for planetary-scale power systems. A vigorous Apollo-like program could start the construction of LPS on the moon early in the 21st Century (Mueller 1984) and thereby build on the United States journeys to the moon (Aldren & McConnell 1989).

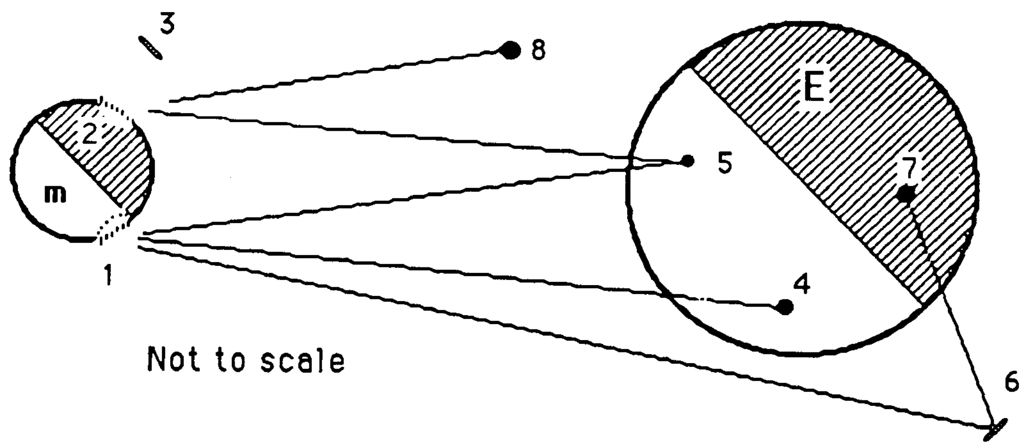

Figure1 Major Components of the Lunar Power System

A preliminary engineering and cash flow model of the LPS has been developed. Results are shown for a system scaled to a peak capacity of 355 GWe on Earth and to provide 13,600 GWe-Yrs of energy over a 70-year life-cycle of construction and full operation. This is approximately the level of electric power now required by the United States and the total quantity of electric energy consumed by the United States since the start of the electric industry in the 1880s.

Figure 2 shows the growth in capacity of the reference system from start of installation on the moon in 2005 to completion of its nominal life-cycle in the year 2070. The Lunar Enterprise Study assumes the average price of electric power will be 0.25$/kW-Hr in the 21st Century. However, a selling price of 0.1 $/kW-Hr is assumed in the LPS reference model. This yields a net revenue for the mature LPS of approximately 300 B$/Yr. The Reference model projects operating costs of the reference LPS to be approximately 5 B$/Yr or 1/60th of revenue. Due to the low projected operating costs the LPS profit is roboust aginst increases in near-term inflation and maintenance, especially with advances in the technology of LPS components. Total life-cycle costs would be approximately 560 B$.

Government development of the transportation system and space facilities to establish a small scientific research facility on the moon could reduce the life-cycle-costs by approximately 125 B$ and cover the initial R&D expenditures for a manned return to the moon. Government development of the initial base is likely to be essential. The initial lunar base would be extremely difficult to organize and finance privately.

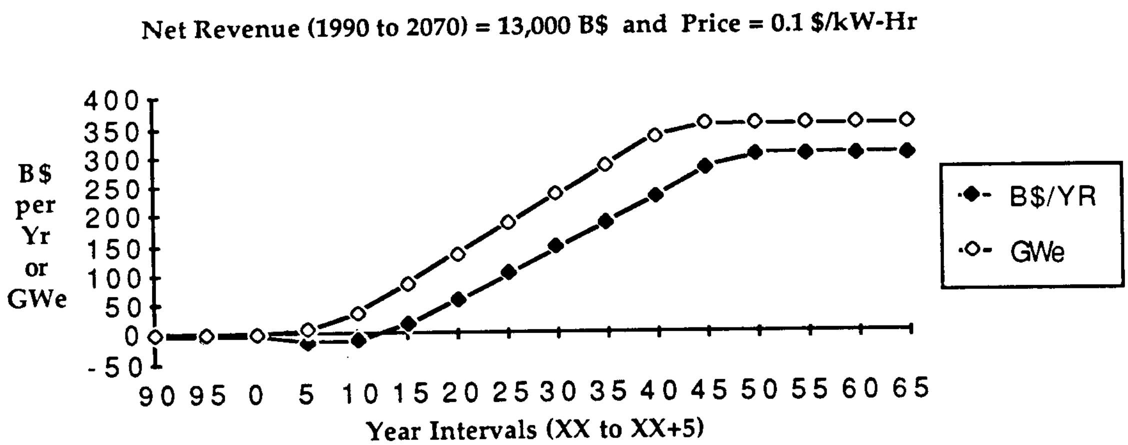

Figure 2 LPS Capacity and Revenue

World needs for power could be accommodated by expansion in capacity of the reference LPS beyond 355 GWe. This would be done by steadily incorporating newer technology during full operation and by establishing additional bases. The major expenditures are for expansion in size and power capacity of the receivers (rectennas) on Earth. Most of those costs can be paid for through local sale of power. Each receiver can operate while undergoing expansion beyond 10s MWe output. For a world demand of 20,000 GWe and a price of 0.1$/kW-Hr, power sales could approach 15,000 B$/Yr by Y2050.

2 LUNAR POWER SYSTEM

As envisioned, the mature LPS consists of several bases on the moon. Figure 3 is a montage of one concept for a demonstration LPS (lower half) and the beaming of power from mature LPS bases to Earth (upper half, scale and perspective both distorted). Bases near sunrise or sunset are illuminated by orbital mirrors such depicted on the middle right.

The dominant features of a lunar base are the plots of photovoltaic converters placed directly on the lunar surface and the large number of objects that look like billboards placed at the end of each plot. In the foreground, one small power plot is under construction. The plot consists of a relatively small area of photovoltaic cells that are made from lunar materials. See Hanak et al. (1986) and Hubbard (1989) for reviews of relevant solar cell technologies. The moon is a far better location for intrusive, large-area solar collectors (SC) than is Earth. There, sunlight is completely dependable and more intense. Compared to collectors on Earth, the lunar collectors can:

- have <0.1% the mass per unit area and therefore ultimately be produced faster because the lunar materials and environment are uniquely suitable to the production and emplacement of large area and thin film, solid state devices;

- have far longer life because of the lack of air, water, and disturbances; and
- be immune to the environmental variations and catastrophes (e.g., weather and earthquakes) of Earth.

Most of the components of each plot can be formed of local lunar materials. Initially only 0.1 tonne (T=1 E 3 kg) of components and consumables will be required from Earth to emplace one megawatt of received power on Earth. No component imports may be required as industrial experience is acquired on the moon or with further creative research on Earth preceding a return to the moon. Very likely the majority of the mass of emplacement equipment and supplies could eventually be derived from lunar resources.

The photovoltaic cells in each power plot feed electric power to sets of solid state MMIC (monolithic microwave integrated circuits; Abita 1988) transmitters at the end of each plot. Each set of MMICs projects many individual sub-beams of microwave power at their "billboard-like" reflector on the anti-Earthward end of their plot. Every sub-beam is reflected backward toward Earth. Subsets of sub-beams from every reflector are mutually phased to form one power beam directed toward Earth.

Each "billboard" is constructed of foamed or tubular glass beams that support a microwave reflective surface consisting of a cross grid of glass fibers coated with a metal such as aluminum or iron. The billboards of one LPS base are arranged over an area near the limb of the moon so that when viewed from Earth they appear to merge, through foreshortening, into a single large synthetic aperture of diameter "l" kilometers. The local subunits of this microwave phased array of sub-arrays is distributed over zones 1 & 2 (figure 1; zone length= l = 30 km to 100 km and wavelength= w = 10 cm; $l/w > 10^6$). Each zone projects 100s to 1000s of tightly collimated power beams (<MWe to many GWe). The beams are convergent (near field), but slightly defocused, like a spotlight, to distances (= l*l/w) many times that of the Earth-moon distance. Power is combined in free space in the electromagnetic field of the transmitted beams rather than in large physical conductors as occurs in most power systems. The enormous composite antennas are possible because the moon is extremely rigid and non-seismic, there are no external disturbances, and antenna construction requires only modest amounts of local materials.

Each LPS beam can be fully controlled in intensity across its cross-sectional area to a scale of a few 100 meters at Earth. This allows the LPS beams to uniformly illuminate rectennas on Earth that are larger than 200-300 meters across. The microwave beams projected by the LPS should have very low sidelobe intensity and not have grating lobes. The stray power level should be very low and incoherent. LPS could probably operate economically at a lower power density (~ 1 milliwatt/cm^2) than the leakage allowed under Federal Guidelines (5 mW/cm^2) from microwave ovens used in homes. A beam intensity of 23 mW/cm^2, which produces little sensible heating in animals, will allow delivery of power at costs lower than those now associated with established hydroelectric dams.

It may be possible to make the stray, incoherent power levels on Earth of a 20,000 GWe LPS less than a human, or the Earth, radiates thermally in the microwave. If so, the power-beaming system can be completely safe.

LPS beams can efficiently service rectennas on Earth once they are more than 200 meters in diameter and several 10s of megawatts in power output. Thus, as rectennas are enlarged beyond a diameter of 200 meters, the additional growth can be paid for out of present cash flow derived from power sales.

A given lunar base is adequately illuminated only 13.25 of the 29.5 days of the lunar month. Several complementary methods are available to provide a steady stream of power to users on Earth. Pairs of bases built on opposite limbs of the moon could supply power for 26.5 out of 29.5 days of the lunar month. Favorable siting of the bases on slopes in the limb regions of the moon may also decrease the period of lunar dusk below three days. Approximately three days of power storage could be provided at each plot of a lunar power base to ensure an uninterrupted flow of power. Or, power storage can be provided on Earth and the LPS system scaled up to provide the additional three days of power every 29.5 days. However, with present technology, power storage is very expensive. Even with pumped hydro-storage on Earth using one surface and one deep (1 Km) reservoir, the storage of 300 GWe of power for three days would exceed all other costs. The preferred solution is to keep the lunar bases illuminated and delivering power continuously. Large mirrors, "lunettas," can be placed in orbit about the moon and oriented to reflect sunlight to the bases.

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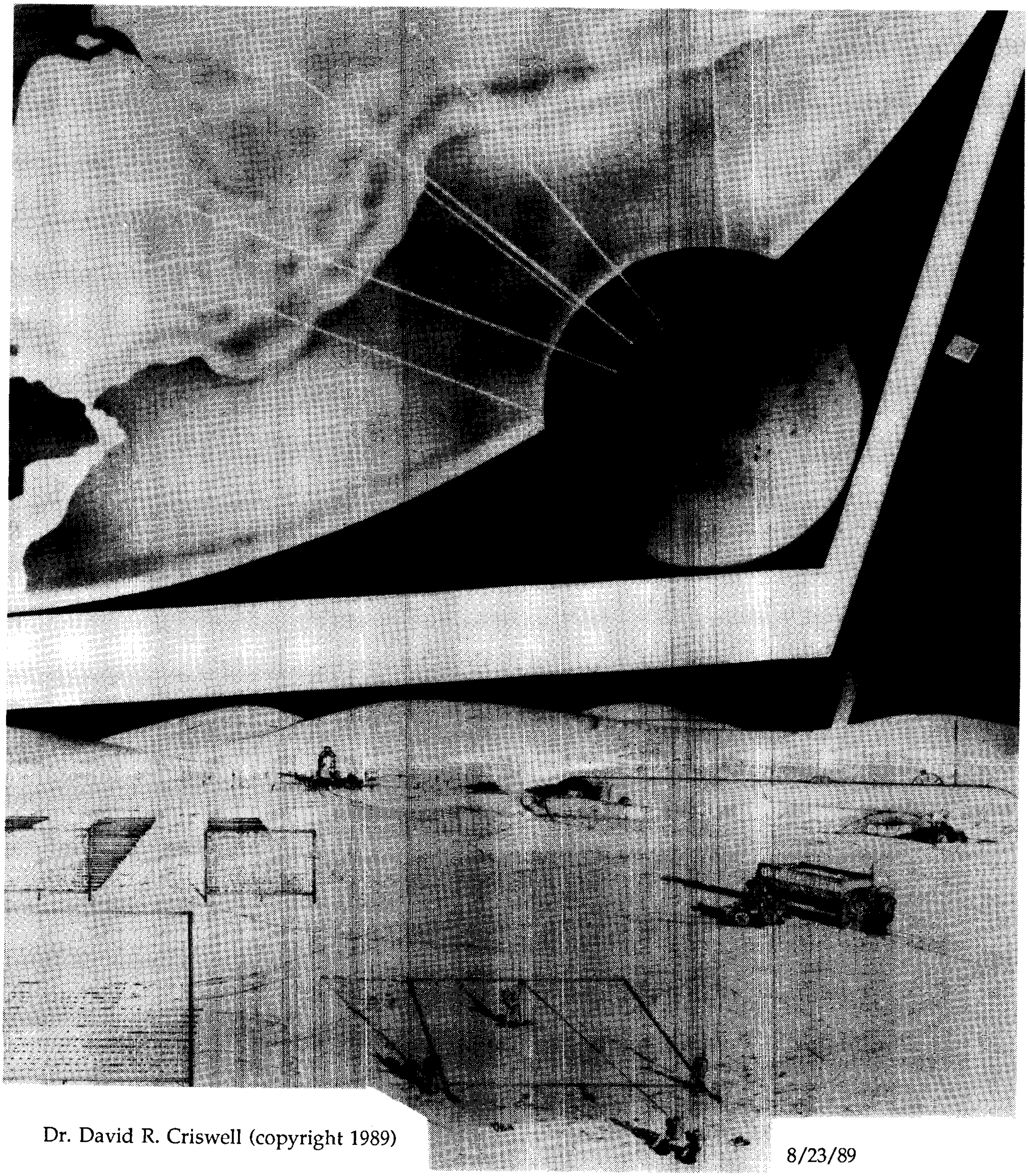
Figure 3 Montage: Beaming power from moon to Earth (top part, not to scale) and LPS Demonstration Base (lower part) (by D. R. Fosdick)



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Lunettas, a version of solar sails (Garvey and Adkisson 1988, Criswell 1979), can have a low mass per unit area, be of low optical quality (no convergence), and be constructed primarily of glass fibers and trusses and a thin film of reflective metal such as aluminum. The masses and costs of lunettas are considered in section 3. The estimates assume the lunettas are evenly spaced along a polar orbit about the moon. The plane of the orbit is coincident with the terminator of the moon during the middle of the period of new moon. In the model no credit is taken for sunlight delivered to the solar converters outside the three-day period about new moon.

A given station on Earth can receive power directly from the moon when the moon is approximately 10 degrees above its local horizon and over a daily angular sweep of approximately 120 degrees. For equatorial stations the lunar power beam could be received for one-third the time. At poleward locations the moon would be sufficiently high above the local horizon about one-third of the year. Most power usage on Earth occurs between 30 and 60 degrees of latitude.

The final space components of the LPS are microwave mirrors (MM) in low altitude (<5,000 km) and high inclination (30 to 90 degree) orbits about Earth. They can economically reflect power beams to rectennas that are blocked by Earth or attenuated by long paths through the atmosphere as would occur for rectennas at high latitudes. Each MM is approximately 1 kilometer in diameter and is continuously reoriented to reflect a microwave beam from the moon to a rectenna on Earth. The MMs also provide a means for multiple power beams to be delivered to a given rectenna. The MMs have a very low mass per unit area and per unit of reflected power. The major components are a rigid frame, a microwave reflective grid of fibers held in place by the frame, and an orientation system. Drag make-up and orientation can be supplied by ion-thrusters that are powered by electricity tapped from the reflected beam. Momentum control devices (momentum wheels or moment-of-inertia controllers) and gravity gradient tethers can also be used for attitude control. The fine pointing of the reflected beam can be done electronically at the moon by shifting between transmitters at the periphery of the beam.

MM components would be made on Earth and assembled in orbit. Little if any mass will be required from Earth for operation of the MMs. An MM would have approximately 1/300th the mass per kW of "handled" power of a Space Solar Power Satellite (SPS; Glaser 1977; NRC 1981). The costs of these reflectors are not explicitly calculated in the LPS model but are included in a 10% allowance of the costs of building space manufacturing facilities discussed in sections 3 and 4.

3 MODEL

P. Glaser (1977) introduced the concept of establishing huge solar power satellites (SPS) in space that could collect solar power, convert it to microwave energy, and beam the power to rectennas on Earth. Each SPS would operate for 30 years or more. Approximately 30 M$ was spent by NASA and DoE between 1977-1981 studying the technical, economic, and environmental feasibility of building a fleet of such satellites. The results are extensively reported (OTA 1981, NRC 1981). Transport of SPS from Earth to orbit was a major challenge. Very large rockets would be needed to launch the components into space. The billions of components would have to be built to tolerate terrestrial, launch, and space conditions and assembly. An immense scale-up of photovoltaic, microwave, and space engineering over prior efforts and the use of components of high efficiency and low specific weight to off-set high transport costs to orbit would be required. O'Neill (1975) proposed that SPS be built out of materials gathered on the moon and transported to space. This would reduce the impact of high transport costs and allow the establishment of production processes optimized for zero-gravity and vacuum.

NASA funded studies on the production of Space Solar Power Satellites from lunar materials (LSPS). General Dynamics (Bock 1979) developed systems level models for the production of one 10 GWe LSPS per year over a period of 30 years. MIT (Miller 1979) examined the production and design of LSPS and factories for LSPS in geosynchronous orbit. Both drew on previous studies at the Lunar and Planetary Institute that examined the feasibility of producing engineering materials from lunar resources (Criswell 1980, 1979). General Dynamics (GD) formulated a system level infrastructure model for the systematic analysis three lunar production options. A NASA reference model for a 10 GWe SPS to be deployed from Earth was used to establishing the performance requirements (JSC 1978) and reference costs (JSC 1977) for the LSPSs. The GD studies explicitly included estimates of costs of research and development, deployment, and operation of a fleet of 30 LSPS. Case D of the GD study assumed extensive production of chemical propellants (Al and O2) and LSPS components on the moon. Case D is similar in type and mass of equipment and the number of people off Earth to an LPS system with the capacity to emplace approximately 30 MWe(=MWs received at earth) of power every 24 hours. General Dynamics estimated the total program costs to be 620 B$ for LSPS Case D.

A spread sheet model based on the GD results was developed for the mass of equipment and components, number of people, and costs of establishing a Lunar Power System of arbitrary size (Criswell 1989 a, b & c). The LPS model includes the major materials-handling and production operations on the moon and in orbit about the moon. These are: smoothing the soil and forming the north-south ridges; beneficiating iron from the soil; producing dense and foamed glass components for stabilizing ridges, forming frames of microwave reflectors, and producing the glass (metal-coated) fiber grid stretched across the frames; producing amorphous silicon solar cells, producing most of the microwave production system, shipping mirror material from the moon to lunar orbit, and producing mirrors in lunar orbit. Table 1 gives the key parameters.

Table1 Major Parameters for Modeling LPS Production and Operation

	LPS TECHNOLOGY LEVEL	
Engineering Factors	Reference(1980s)	Advanced(2000s)
LPS System Factors		
Electric to microwave conver. eff.	0.4	0.9
Solar Cell Efficiency	0.1	0.35
Mass of orbital mirrors (T/Km**2)	10	3
Solar exposure per day	1/Pi	1
Wavelength of power beam (cm)	10	2
Diffract. beam width Earth (Km)	0.5	0.2
Productivity Factors		
Equip. work hours per 24 hours	12	23
Beneficiation equip.(T/T/Hr)	1	0.01
Excavation equipment (T/T/Hr)	0.1	0.01
Hot forming equip. (T/T/Hr)	10	.03
Terrestrial components (T/MWe)	0.1	0.01
Habitat mass per person	5	1
Constant or Minor Adjustment*		
Free iron in soil (weight fraction)	0.001	0.001
Weight fraction adhered glass	1	1
Height of solar cell supports (m)	0.3	0.3
Thickness reflector frames(m)	0.2	0.2
Electric collection efficiency*	0.9	0.99
Assembly of macro-parts (T/T/Hr)	100	100
Micro-parts production (T/T/Hr)	3000	3000
Chemical refining (T/T/Hr)	100	100
Electric mass driver (T/T/Hr)	500	500
System availability*	0.9	0.99
Rectenna collection efficiency*	0.95	0.98
Beam inten. rectenna (mW/cm**2)	23	23
Growth, Costs, & Sales	**Ref.**	**Range**
Growth rate (GWe/Yr/Yr)	1	0 & 1
Steady production (GWe/Yr)	10	1 to 100
Period steady construction (Yrs)	30	1 to 100
Installed capacity (GWe)	355	1 to 10,000
Near-term inflation (1990$/1977$)	1.7	1 to 80
Maintenance factor	0.5	0 to 90
Price of electric power ($/kWe-Hr)	0.1	0.005 to 0.3

4 Results

The model was exercised over a wide range of the parameters listed in Table 1. The two sets of parameters selected were judged to represent levels of technology corresponding both to the 1980s time frame (Reference) and the level of advanced technology that is expected to be available in the year 2000.

Table 2 presents the results for both sets of assumptions applied to the construction of 27.3 MWe/24 hours or 10 GWe/Yr over a 30 year period, approximately 2005 to 2035. The General Dynamics study was done assuming 1977 dollars. Table 2 makes no adjustment for inflation between 1977 and 1989.

TABLE 2 Reference & Advanced

ITEM	TECHNOLOGY LEVEL	
	Reference(1980s)	**Advanced(2000)**
Sunlight to Earth Power	**0.01**	**0.20**
Materials mined (T/Yr)		
Scraping	160,000,000	8,000,000
Beneficiation	35,000,000	7,900,000
Others (glass, iron,...)	2,040,000	1,970,000
Equipment on Moon (T)		
Mining	11,600	52
Processing	33,000	4,100
Support & habitats	3,900	140
Space Facilities (T)		
Low Earth Orbit	20,000	2,000
Low Lunar Orbit	3,000	300
Materials to Space (T/Yr)		
Moon to LEO	90,000	16,627
Earth to Moon	5,400	400
People		
Moon	500	50
Low Lunar Orbit	100	10
Low Earth Orbit	50	5
Total Costs(B$)	320	140
R&D, Production, & Space Operations B$	220	40
Rectennas on Earth B$	100	100
Power Costs ($/kWe-Hr)	**0.009**	**0.004**
Earth Mass(T) shipped to moon (T/GWe-Yrs)	**20**	**1.5**

Technology advancement decreases both the area of the lunar surface and of mirrors in orbit about the moon that are necessary to capture and transmit a unit of solar power. This greatly reduces the size of machinery and number of people necessary to install and maintain the bases. A scientific lunar base would require approximately the same scale of transportation as an advanced LPS (Lovelace et. al. 1989).

Cost of power is projected to be low in both cases, 0.9 and 0.4 ¢/kW-Hr. The cost of power from the Advanced System does not drop further because no technology advancement is assumed for the rectennas on Earth. Lower costs rectennas may be possible. Neither the time value of money, except as allowed for in the General Dynamics study, nor regulatory expenses or taxes are included in the costs.

The General Dynamics study estimated the expenditures (1977$) for research and development (R&D), production, and maintenance of all elements of the LSPS and the production system. A total expenditure was presented for each item of the infrastructure analysis. A 1990 - 2070 life-cycle model was produced for the LPS by distributing each of the LPS expenditures derived from the General Dynamics model over their relevant portion of LPS life cycle. For example, rectenna R&D was taken to be 1% of the total expenditure on rectennas and was spread evenly over the 1990 - 2005 period. R&D for space transportation was concentrated in the 1990 -2000 time frame and production in the 2000 - 2005 period just before a return to the moon.

Figure 4 depicts the projected expenditures for the 1980's technology case. The expenditures are separated into space elements of the Lunar Power System (LPS), the rectennas on Earth (RECTN), all aspects of the space transportation system (Trnsp. - rockets, propellant depots, facilities on Earth), and the Lunar Base (LunB). Research and development is concentrated in the 1990 to 2000 time frame, production of space transportation elements, lunar and space habitats, and emplacement machinery in 2000-2005 and their deployment and initial operation in 2005 - 2010. The federally funded scientific lunar base is completely installed in 2005. Beginning in 2005 the lunar base expenditures (LunB) include only purchases of power and services at a rate of 75$/kW-Hr and for a quantity of power that increases from 25kW in 2005 to 4.2 MW in 2015. In 2015 the price of power to the lunar base decreases to 0.1 $/kW-Hr and becomes insignificant. The majority of the power is embedded in lunar-derived propellants and materials to support operations of the scientific lunar base.

Emplacement of the LPS on the moon begins in 2005 at the rate of 1 GWe/Yr and the installation capacity is increased every year by 1 GWe/Yr from 2005 through 2015. After 2005 the LPS section includes both the habitats and emplacement machinery. The expenditures in Figure 4 assume the Federal government does the R&D for the establishment of a lunar base and the associated transportation system. Thus, the LunB and Trnsp. items between 1990 and 2005 are Federal expenditures. The organization that establishes the lunar power system pays for LPS and RECTN items between 1990 and 2005 and after 2005 it also pays for all transportation and manned production activities on and off the moon. Rectennas expenditures are primarily for R&D during the 1990 - 2005 period. Rectenna expenditures increase sharply in 2005-2010 as construction of demonstration antennas begins. Power begins to be received from the moon in the latter part of 2005 and revenue begins to grow quickly.

Advances in technology can sharply decrease expenditures during all phases of the LPS program. Factors of 2 to ten decrease in annual cash flow can result for the Transportation, Lunar Base and LPS categories. Rectenna construction is assumed to remain unchanged.

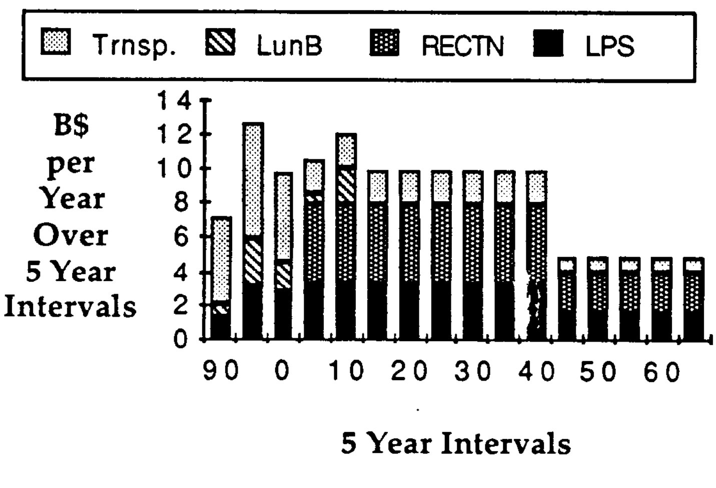

Figure 4 LPS Expenditures for Reference System

Analyses by other reseachers will differ, especially of costs for such a large and complex project over 85 years. To encourage more research, the models were run to determine the ranges of near-term inflation (1990$/1977$) and maintenance for which the LPS would provide a cumulative net revenue that was positive (B$ net at Y2070). Figure 5 shows the effects of near-term inflation. Near-term inflation can be taken as an actual correction for inflation between 1977 and the start of the project or as a multiplier to all the costs of establishing and maintaining the LPS. Thus, zero inflation corresponds to an LPS that costs nothing to build or operate. An inflation of "one" means the cost of money is the same as in 1977 over the life of the project.

Maintenance = 0.5 & 0.1 $/KWe-Hr

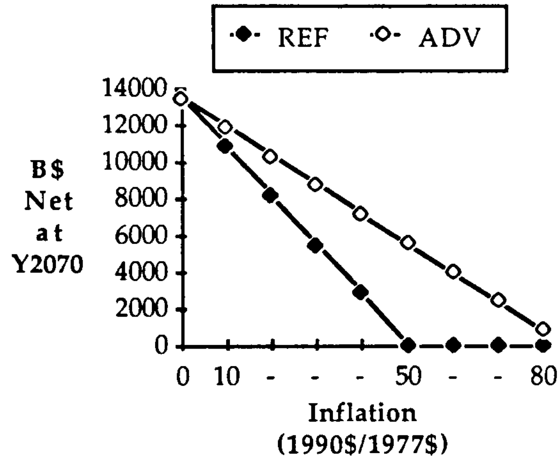

Figure 5 Net profit versus inflation

Figure 5 assumes that power is sold at an average price of 0.1 $/kW-Hr and that maintenance is conducted at a high enough level to rebuild 50% of the lunar and space installations over the last 25 years of operation. Figure 5 reveals that the costs presented in Table 2 must increase for the 1980s case by a factor of 50 (5000%) before the net revenue goes to zero. For the case of advanced technology the inflation must increase by a factor of 83 (8300%).

Figure 6 shows the results of similar calculations in which the inflation is held constant at 1.7 and the maintenance factor is changed. A maintenance factor of 1, or 100%, corresponds to rebuilding the lunar and terrestrial components once over the last 25 years of operation. For the REF case (1980s technology) the maintenance must increase by a factor of 55 and by 110 for the ADV case before the cumulative revenue at 2070 goes to zero.

Inflation = 1.7 & 0.1$/KWe-Hr

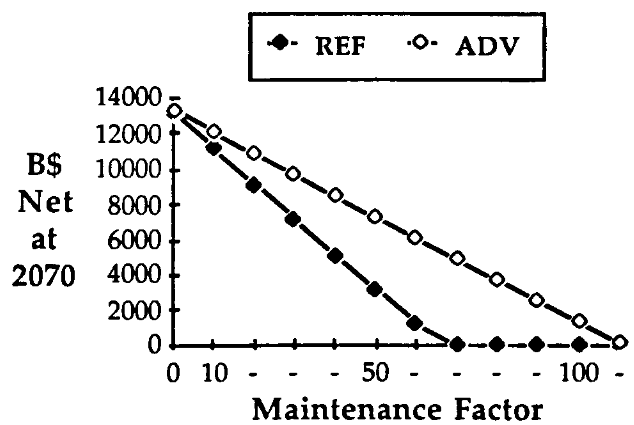

Figure 6 Net Profit versus maintenance

The inflation and maintenance calculations indicate that the net revenue of the LPS will be positive in the face of major increases in construction and maintenance expense. Technology advancement should strongly increase the probability that LPS will provide net positive returns at a price of electric power competitive with prices today. If the average selling price of electricity increases above 0.1 $/kW-Hr then the LPS becomes even more viable. Figures 5 and 6 make it clear that

LPS provides an unusually robust concept for the acquisition and delivery of power that should receive additional analysis.

5 GLOBAL POWER SYSTEMS

Table 3 provides a high-level summary of the scale of equipment and consumables that must be organized and used to support various types of 300 GW power systems based in space (Space Systems) and on Earth (Terrestrial Systems) over a 70 year life-cycle. The LPS and SPS avoid the burning of both fossil and radioactive fuels within the biosphere. In addition, but not included here, the LPS and SPS systems can redirect power about the world without the use of power lines or the shipping of fuels. "Total Equip." refers to the total mass of machinery, habitats, components, and equipment that must be shipped to space from the Earth over the 70 years of power production. Thus, the smaller the "Total Equip." the smaller the overall mass of launch and production equipment required on Earth. Small values of "Specific Mass" are preferred. Neither include the mass of rockets or propellant.

Table 3 Scale of 300 GW Power Systems Over 70 Years & Gross Energy Produced Over 70 Years

SPACE SYSTEM (Mass from Earth)	First Year Equip. (T)	Total Equip. (T)	Total Energy (GWe-Yr)	Specific Mass (T/GWe-Yr)
Advanced LPS	**500**	**20,000**	**13,620**	**1.5**
He3 (fused on Earth)	2,000	90,000	10,200	10
Reference LPS	6,000	280,000	13,620	20
Advanced SPS (~1 T/MWe)	2,000	400,000	9,300	40
Lunar-derived SPS (GD study) with these transport means off the moon				
.....lunar Al fuel & LO2	300,000	700,000	9,300	80
Earth SPS (NASA Ref., 10 T/MWe)	30,000	4,500,000	9,300	500

TERRESTRIAL SYSTEMS	Fuel(70 Yrs) (T)	Equip & Plant(T)	Tot Energy (GWe-Yrs)	Specific Mass (T/GWe-Yr)
SPS Rectenna Pedestals	-	6 E 7	(13,650)	4,000
(Electrical elements*2)	-	(3 E 5)	(13,650)	(20)
Coal Plants, Mines, & Trains	4 E 10	9 E 7	9,000	10,000
Nuclear fission	1. E 5	3 E 8	9,300	30,000
Hydro* & TSP (w/out storage)	*1.4 E 15	1.2 E 9	13,650	900,000

( ) - Counted in preceding row

Both the LPS and SPS require rectennas on Earth. Their mass is shown in Terrestrial Systems. Note that E "X" means 10 to the Xth power. Rectenna mass is dominated by simple pedestals that support the receiving antennas. This estimate assumes the pedestals are made of concrete. The LPS rectenna should have a pedestal mass that is 1/2 or less that of the reference SPS. Only 5,000 T of electrically active elements of are required in a 10 GWe rectenna. The rectennas are much less massive structures and simpler systems than those associated with coal, nuclear, hydroelectric, or terrestrial solar power facilities (TSP). The TSP do not store power.

Another option is to obtain from the moon the He3 present in the soil at a weight fraction of 5 E-9. Theoretical models indicated that He3 fusion reactors might be approximately the same mass as present fission reactors of equal power capacity (NASA 1988). Fusion of deuterium (D) and He3 induces far less radioactivity than does fusion of D and tritium (T). Fusion R&D programs must be reoriented and expanded to enable the production of commercial He3 fusion reactors by the 2020s.

A 300 GWe nuclear fission system would consume approximately 350 T/yr of uranium. Operational nuclear plants convert only 2% of their nuclear fuel into energy; thus, the order of 17,000 T/yr of nuclear fuels must be recovered, reprocessed, and transported (Cohen 1980).

Remember that Table 3 applies to the production of only 9,300 to 13,620 GWe over the 70 year life-cycle of the various power systems and a peak capacity of 300 to 355 GWe for the last 25 to 40 years. Human needs must be considered on a global scale (Criswell 1985). A world-wide system for supporting 20,000 GWe would require approximately 70 times more equipment and consumables every 70 years. In the case of coal this would imply the consumption of 40 E 9 T/Yr. At present, world industrial consumption of carbon is 5 E 9 T/Yr, and the net increase in atmospheric carbon is 3 E 9 T/Yr. Also, all the world's living plants only convert 50 E 9 T/Yr of atmospheric CO2 back into burnable carbon (Houghton and Woodwell 1989). Neither coal nor renewable plants can support the production of 20,000 GWe. World agricultural needs, pollution control, pollution, greatly increasing atmospheric CO2 (which drives the green-house effect), and increasing competition for fossil fuel will sharply drive up energy costs.

A nuclear electric economy requires the breeding of fissile fuels. A 20,000 GWe nuclear power system would be approximately 500 times larger than the nuclear industry which now meets 15% of the world's electrical needs (Foley 1987). Proliferation of weapons-grade materials and disposal of spent fuels and the contaminated plants would be a rapidly growing and long-term problem (100s to 100,000s years).

The world hydroelectric resource (> 5 MWe installations) is estimated to be only 2,200 GWe and by 1983 20% was harnessed (Twidell and Weir 1986). Hydroelectric generation of 20,000 GWe through a 100-meter head at 50% efficiency would require the flow of 1.3 E 15 T/Yr of water. Ocean thermal plants and facilities for hydro-storage of terrestrial acquired solar energy would manipulate far greater flows of water.

6 LPS SUMMARY

Why is the LPS so attractive as a large scale power system? There are at least twenty-four fundamental reasons. The sun is a completely **dependable** fusion reactor that supplies **free** and **ashless** high-quality **energy** at high concentrations within the inner solar system, where we live. The LPS primarily handles this free solar power power in the form of photons. Photons weigh nothing and travel at the speed of light. Thus, **passive** and **low-mass equipment** (thin-films, diodes, reflectors, and antennas) can collect and channel enormous flows of energy over a **great range** to end uses as and **where** the energy is **needed** and **without physical connections**. The LPS is a **distributed** system that can be **operated continuously** while being **repaired** and **evolving**. All other power systems require massive components to contain and handle matter under intense conditions or require massive facilities to store energy. Low mass and passive equipment in space and on the moon will be **less expensive per unit of delivered energy** to make, maintain, decommission, and recycle at the end of its useful life than massive and possibly contaminated components on Earth.

The **moon** is a uniquely **suitable** and **available natural platform** for use as a power station. It has the right materials, environment, mechanical stability, and orientation and remoteness with respect to Earth. The major non-terrestrial components of LPS can be made of lunar materials and the large arrays can be sited on the moon.

The **rectennas** on Earth are simple and can be constructed as needed at **minimum up-front costs**. The LPS can be far **less intrusive**, both in the physical and electromagnetic sense, than any other large power system. Most of the power can be delivered close to where it is needed. LPS can **power its own net growth** and establish **new space** and **Earth industries**. Finally, all of this can be done with **known technologies** within the period of time that the people of Earth need a new, clean, and dependable source of power that will generate **new net wealth**.

7 PACE OF DEVELOPMENT

LPS can be developed expeditiously. Many of the key technologies for LPS are developing rapidly because of their value in the terrestrial market place. Thin-film solar arrays and MMICs are two examples. Other areas such as processing of lunar materials with minimal use of reagents and manufacturing techniques appropriate to lunar and space conditions will only be done under special funding. There will be intense interaction between LPS design and the list of key technologies in Table 1. Undoubtedly, the LPS design presented in this paper can be improved.

New vehicle concepts, such as being developed for the United States Advanced Launch System (ALS), can reduce the costs of transportation from Earth to orbit. Criswell (1989d) has presented a

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broader systems concept. It has long been known that single-stage-to-orbit (SSTO) rockets can transport modest payloads (~1% of gross vehicle weight) of fixed size from Earth to orbit. However, SSTO rockets could be linked together, provided with propellant cross-feed, and operated as parallel burn-step rockets to loft arbitrarily large payloads (internal, external cannisters/facilities, or rugged manned vehicles) to orbit (>5% of gross vehicle weight). Conceivably, one or two types of SSTO rockets could replace the present fleet of many different types of multiple-stage rockets and also perform deep space missions. Many possible advances in transportation (tethers, mass drivers, solar sails,lunar derived heat shields) can greatly increase the capacity and and improve the economics of space transportation. The United States space station program, *Freedom*, might be able to contribute habitats and production facilities for LPS.

Of course, much more extensive and refined financial and engineering analyses must be done of LPS than were possible under this study. They can be started immediately. They can draw far more deeply than did this study on the results of the 30 M$ invested in 1977-1981 NASA/DoE investigations of the SPS, the 28 B$ invested in the Apollo program, the 100 M$ invested in post-Apollo research on lunar samples and lunar geophysics, and the extensive and accelerating achievements in electronics technologies that have occurred since LPS was first conceived approximately a decade ago. All the key elements in transportation, power beaming, lunar operations, rectenna construction, microwave reflectors, and solar sails are well within the detailed expertise of the relevant technical communities. No aspects of LPS require fundamental research. Technology advancement can bring down the costs shown in Figure 4 and speed the implementation of LPS.

LPS can grow to meet the energy needs of people on Earth and establish space industry. Bases on the moon can grow to project many 10,000s GWe. The rectennas on Earth can range in size from 10 MWe to many 10s GWe. Rectenna production and operation could be done by local private or public organizations. Developing countries could install rectennas as fast as needed by the local economy. Because small rectennas would be economical it would not be necessary to build extensive high-tension transmission systems. Use of trees for fuel and of water for power production could be greatly reduced. Power from the moon could provide energy without depleting natural resources. LPS can create new wealth on Earth and eliminate major sources of pollution of the biosphere.

The results of this study encourage consideration of a faster paced program than assumed in Figures 2 and 4. After all, Apollo was done in 9 years out of a sense of fear and adventure using the limited technologies of the 1950s. To accomplish LPS the nation can now draw on far more knowledge and capabilities and know that the rewards can be great for the people of America and the world.

ENJOY!

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