

LUNAR SYSTEM TO SUPPLY SOLAR ELECTRIC POWER TO EARTH

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ABSTRACT

The capacity of global electric power systems must be increased tenfold by the year 2050 to meet the energy needs of the 10 billion people assumed to populate the Earth by then. Few studies directly address this enormous challenge. Conventional terrestrial renewable, nuclear, and coal systems can not provide the power. Solar power collected on the moon can meet these needs. It would be collected by large area, thin-film photovoltaics and converted into thousands of low intensity microwave beams. These beams would be projected from shared, large diameter synthetic apertures on the moon to receivers located anywhere on Earth. Engineering and cost models indicate that the Lunar Power System (LPS) is economically robust and can be built at a faster rate than all other power systems. Internal rates of return in excess of 40% per year may be feasible. LPS uses understood technology. It can be environmentally supportive rather than simply benign or damaging. LPS implementation can immediately channel national and world R&D aerospace and electronics capabilities into completely peaceful directions and enable human prosperity.

1. GLOBAL POWER NEEDS: Now and to 2070

In 1980 approximately 4.43 billion Earthlings used 10,300 GW of power at an average of 2.33 kW/person. Citizens of the United States, Europe, and Japan (1.11 billion) used most of the energy at 6.3 kW/person while the rest of the world averaged 1.0 kW/person [1].

kWe/person). Electricity is the energy of choice in a modern society. Since its introduction in the 1880s electricity has continued to take an increasing fraction of the delivered energy product [2], even through the oil embargoes of the 1970s. Considerable benefits accrue if the source of the electricity is environmentally benign or even enhancing and also cost effective.

If the average rate of increase of the world population were to drop immediately to 1%/year there would be 10^{10} Earthlings in 2050. As technology advances, 2 kWe per person could sustain a higher level of affluence worldwide than now exists in the developed countries [1,2,3]. This would mean a worldwide need for 20,000 GWe of clean and reasonably priced electric power. That is more than 10 times the 1,800 GWe now provided by the world's electric power stations.

Figure 1 is a simple model of the growth of new electrical generation capacity that must be installed to supply the world in 2050 with clean, environment-enhancing electric power. As will be discussed, a new type of system must be developed. A ten year period of research, development, testing, and engineering (RDT&E) is indicated. That program would have to start now and focus on clearly defined and reasonable engineering problems. A vigorous ramp-up effort must build up installation capacity from demonstration to production level. Installation would begin at 50 GWe/year in 2000. Ten years into the program the installation rate of new power would stabilize between 500 and 600 GWe/year and

continue until the year 2040. From 2040 on, the emphasis would be on maintenance of the complete system until the end

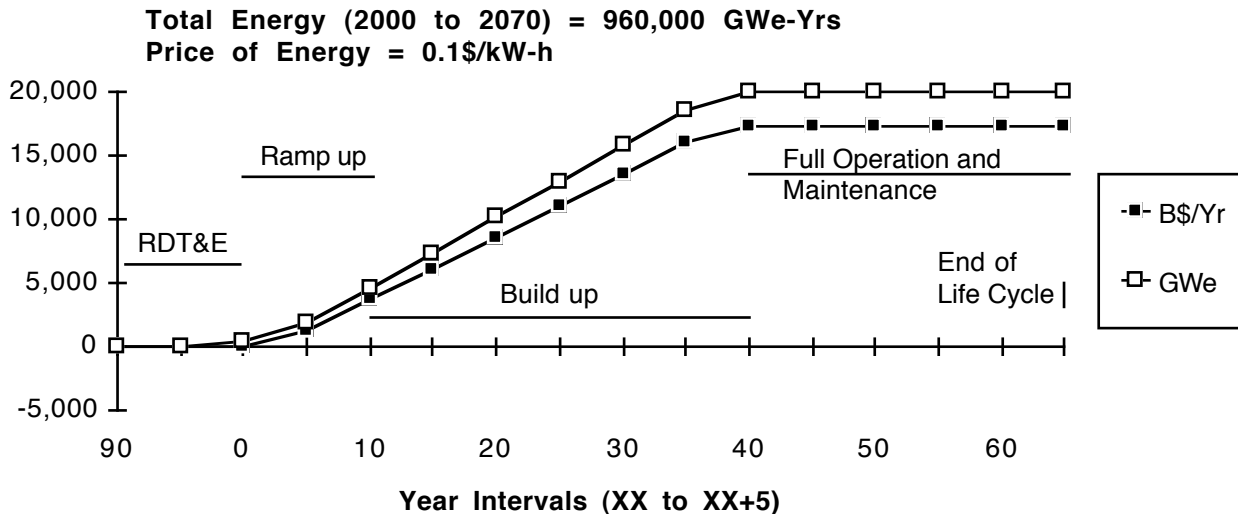


Figure 1 Capacity and Revenue of a New Planetary Power System

The United States converted approximately 25% of its input energy (2632 GW) into delivered electric power (235 GWe or 1

of the life cycle of its major elements in the year 2070. By 2020 another program might come on line to replace the early generation units. This would phase out obsolete elements so

that the mature system would continue to function after 2070. Presumably, these replacement units would be cheaper because the R&D would not have to be repeated if the original approach and technology were chosen correctly. Figure 1 shows that the electric power is sold to end users at 0.1 \$/kWh. Unadjusted for inflation, the mature cash flow approaches 20,000 B\$/year. This is approximately the present Gross World Product (GWP). The accumulated gross return would exceed 840,000 B\$. Note that Figure 1 is independent of a particular engineering approach.

2. LUNAR POWER SYSTEM

P. Glaser [4] 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. NASA and DoE spent approximately 30 M\$ between 1977–1981 studying the technical, economic, and environmental feasibility of building a fleet of such satellites [5,6]. Transport of SPS components from Earth to orbit was a major challenge and expense. Very large rockets would be needed. 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 was required. Components of high efficiency and low weight were required. There was little incentive to develop components with low unit costs because of the high costs that transportation would add. SPS busbar costs were estimated to be in the range of 0.08 to 0.44 \$/kWh [5] for a system the order of 300 GWe.

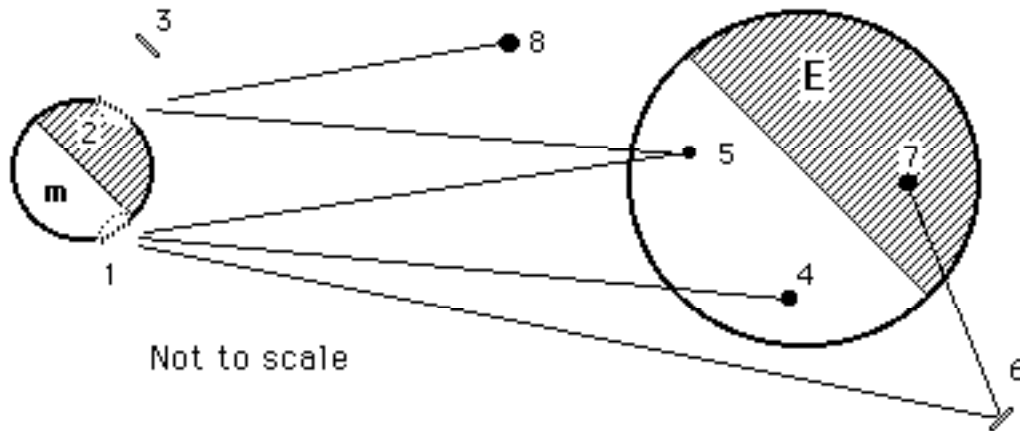


Figure 2 Components of the Lunar Power System

O'Neill [7] proposed that SPS be built of materials gathered on the moon and transported to space. Transport costs would be reduced. Design, production, and construction could be optimized for zero-gravity and vacuum. NASA funded studies on the production of Space Solar Power Satellites from lunar materials (LSPS). MIT examined the production and design of LSPS and factories for LSPS in geosynchronous orbit [11]. General Dynamics developed systems-level engineering and cost models for the production of one 10 GWe LSPS per year over a period of 30 years [8]. Both General Dynamics and MIT drew on previous studies at the Lunar and Planetary Institute that examined the feasibility of producing engineering materials from lunar resources [9,10].

General Dynamics formulated a system level infrastructure

model for the systematic analysis of three lunar production options. A NASA reference model for a 10 GWe SPS to be deployed from Earth established the performance requirements [12] and reference costs [13] for the LSPS. 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. The conclusion was that LSPS would be less expensive than SPS after production of 30 units totaling 300 GWe in capacity. LSPS would require progressively smaller transport of mass to space than SPS after the completion of the second LSPS.

The Lunar Power System (LPS) is shown in Figure 2. It consists of the power bases (1 & 2), orbital mirrors (3 & 6), and rectennas on Earth (4, 5 & 7) and in space (8). Space rectennas can have a low mass per unit of received power (< 1 Kg/Kw) and can enable high performance electric-rockets and rugged facilities. LPS would collect solar energy at one or more pairs of power bases (1 & 2, Figure 2) 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 rectennas on Earth (4 & 5, Figure 2) and in space (8) that convert the microwaves back to electrical power. Microwave reflectors (6) in mid-altitude, high-inclination

orbits about Earth can redirect microwave beams to rectennas that can not directly view the moon.

A microwave power beam would only be created, on request, to feed power to a designated rectenna. It would be shut off when the need for power ceased or the receiver rotated out of the line of sight to the beam. Beams would not be swept across the Earth from one rectenna to another.

Additional sunlight can be reflected by mirrors (3) in orbit about the moon to bases #1 and #2 during lunar night. 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 moon is a far better location for intrusive, large-area solar

collectors (SC) than is Earth. On the moon, 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 suited to the production and emplacement of large area and thin film, solid state devices [14,15];
- have far longer life because of the lack of air, water, and disturbances and by the use of lunar materials to shield against the space environment; 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 0.4 ton ($T=10^3$ 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. 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 circuit) transmitters [16] 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 "D" kilometers. The local subunits of this microwave phased array of sub-arrays is distributed over zones 1 & 2 in Figure 2. Zone length (D) = 30 km to 100 km and wavelength = $w = 10$ cm; $D/w > 10^6$. 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 ($=D*D/w$) 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 disturbances, and antenna construction requires only modest amounts of local materials considering the level of transmittable power.

The large and extremely rigid phased array antennas of LPS increase in pointing accuracy and decrease in stray power with increasing diameter and as the number of subarrays increases. A 100 km diameter antenna operating at 10 cm could have a bore sight accuracy the order of 10 meters at Earth using available microwave technology. If it were composed of 10^6 non-identical subarrays, the maximum stray power of its beams would be less than 10^{-6} of the intensity of the central beam.

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 no grating lobes. The stray power level should be very low and incoherent. LPS could probably operate economically at a lower power density (~ 1 milliwatt/cm²) than the leakage allowed under Federal Guidelines (5 mW/cm²) from microwave ovens used in homes. A beam intensity of 23 mW/cm², which produces little sensible heating in animals, will allow delivery of power at costs lower than those now associated with established hydroelectric dams.

The stray, incoherent power levels of the microwaves on Earth of a 20,000 GWe LPS may be less than the power per unit area thermally radiated by a human or the Earth itself. 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. This is a fundamental financial advantage over all other major power systems.

Two major factors must be considered in the use of lunar bases to supply electricity: 1. availability of continuous sunlight to the bases, and 2. the effect of lunar eclipses. 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, three days of power storage would be 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 actively oriented to reflect sunlight to the bases. Solar pressure, direct solar energy, or microwave beams can power the continuous reorientation.

Lunettas, a version of solar sails [17,18], 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 the economic model. The estimates assume the lunettas continuously illuminate the power stations. Continuous illumination requires a total area of all reflectors in orbit approximately equal to the area of all the power bases on the moon. The area in orbit will be divided over hundreds of separate lunettas.

A full eclipse of the moon has a duration of approximately 2 hours, is completely predictable, and occurs at the middle of the period when the moon is full. Orbital mirrors can reduce and even eliminate loss of power. At full moon the pairs of bases are generating twice their average power. This excess power could be stored in dedicated facilities on the moon buried high

temperature superconductors (HTSCs) derived from lunar materials) or on Earth. By 2050 the power storage on Earth associated with electric cars and peaking units (e.g., air-iron batteries, HTSCs in substations, pumped hydroelectric) distributed throughout the electric power network will likely have more than two hours of total storage capacity. The fleet of reflective mirrors in orbit about the moon can be sailed to higher orbits about the moon, in advance of the eclipse, and provide illumination during the total eclipse and the deeper portions of the partial eclipse. Several options can provide storage at the order of 15% additional costs [19].

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. However, continuous, load-following power is needed. That can be provided by means of microwave reflectors in orbit about Earth.

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. There will be approximately as many MMs as rectennas on Earth. MMs 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, under active control, to reflect a microwave beam from the moon to a rectenna on Earth. Several MMs can feed multiple power beams 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. Momentum control devices (momentum wheels or moment-of-inertia controllers) and gravity gradient tethers can also be used for attitude control. Power for drag make up and orientation can be tapped from the microwave power beam the MM is reflecting. The fine pointing of the reflected beam can be done electronically at the moon by shifting transmitters on and off along the periphery of the beam at its sources on the moon.

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. 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 the following section.

3. ENGINEERING AND FINANCIAL MODELS

An engineering model of the LPS has been developed for the amounts of materials that must be handled and the scales of equipment that must be provided to construct various sizes of LPS. That model has been exercised to determine the effects of variations in the engineering parameters. Table 1 lists the parameters considered to be most important for meeting the power profile shown in Figure 1. The values in Table 1 are

considered to be reasonable for the level of technology possible during the construction period beginning in 2000 and in light of sensitivity studies [20, 21, 22]. This analysis of the Lunar Power System uses results from previous studies. DoE and NASA spent over 30 M\$ of research devoted to SPS and the lunar-derived versions. The types of materials handling-operations to emplace a 20,000 GWe LPS are similar to those in Case D of the study by General Dynamics Corporation of the construction of Solar Power Satellites from lunar materials. Case D was scaled to the emplacement of 10 GWe of power every year over a 30 year period. General Dynamics estimated the total program costs to be 620 B\$ for Case D. The major cost drivers (*) and derived quantities (**) are indicated.

A second model was developed based on the GD results. The second model estimates, on a life-cycle basis, the mass of space equipment, supplies and components, number of people, and costs of R&D, transportation elements, and rectennas on Earth necessary for establishing a Lunar Power System of arbitrary size (20,21,22]. Table 2 presents the results for the parameters shown in Table 1. The top portion of Table 2 lists the engineering and manpower projections. The bottom portion lists costs. This example shows that the mature LPS is much less expensive than contemporary power systems both in capacity (\$/kW) and delivered energy (\$/kWh).

Previous studies on SPS and LPS have considered systems that provided the order of 300 GWe of power over a 30 year period. The full benefit of the R&D and initial installation of production were not fully realized. Table 2 and Figure 3 show the benefits of considering much larger capacity. The R&D for the lunar operations and the establishment of the transportation system and the initial lunar base, while expensive and long term, are a modest component of the overall expenditures. The dominant cost element becomes the construction of rectennas on Earth. This is extremely important in comparing the costs and risks of LPS versus SPS or any other large power system. The large, passive, and segmented transmitting apertures on the moon can provide many different beams of low power and each beam can be focused to a few hundred meters in diameter. Thus, rectennas on Earth can initially be small, the order of 10s MWe, and then grow smoothly in power output and diameter from that small level. Most of their growth can be paid for out of current cash flow. All other large power systems require a decade or more of upfront investment and do not return income until the project is complete. LPS may provide ways of decreasing the costs of rectennas specified in the SPS program.

Table 1 LPS Production & Operation Model

Major Parameters	Value
Rectennas (Construction & operations)*	
B\$/km ² or	0.2
B\$/GWe	0.8
Electric to microwave conver. eff.	0.9
Solar Cell Efficiency	0.1
Mass of orbital mirrors (T/Km ²)	3
Solar exposure per day*	1
Wavelength of power beam (cm)	10
Diffraction beam width Earth (Km)	0.2
Productivity factors	
Equip. work hours per 24 hours	23
Beneficiation equip.(T/T/Hr)*	0.1
Excavation equipment (T/T/Hr)*	0.01

Hot forming equip. (T/T/Hr)*	10	Scraping	2. 10 ⁸
Terrestrial components (T/MWe)	0.01	Beneficiation	1. 10 ⁹
Lunar microwave components (T/MWe)*	0.5	Others (glass, iron,...)	5. 10 ⁷
Habitat mass per person (T)	1	Equipment on Moon (T)	
Maintenance factor (MF)	0.5	Mining	12,000
Constant or minor adjustment		Processing	380,000
Free iron in soil (weight fraction)	0.001	Support & habitats	18,000
Weight fraction adhered glass	1	Space Facilities (T)	
Height of solar cell supports (m)	0.3	Low earth orbit	170,000
Thickness reflector frames(m)*	0.2	Low lunar orbit	12,000
Electric collection & output efficiency	0.9	Materials to Space (T/Yr)	
Assembly of macro-parts (T/T/Hr)	100	Moon to LEO	3.2 10 ⁵
Micro-parts production (T/T/Hr)	3000	Earth to moon	5.3 10 ⁴
Chemical refining (T/T/Hr)	100	People	
Electric mass driver (T/T/Hr)	50	Moon	4,400
System availability	0.99	Low lunar orbit	340
Rectenna collection efficiency*	0.98	Low earth orbit	400
Beam inten. rectenna (mW/cm ²)*	23	Cost projections	
Number of LPS bases (paired)	12	Total cost (B\$ 1990\$) (Maint. factor = .5)	18,200
Projected diameter of one base (KM)**	83.1	Rectenna costs (prod., main., repair)	15,900
Growth, costs, & sales		R&D, transportation, orbit, and moon	2,300
Accel. of growth rate (GWe/Yr/Yr)		Total energy return (GWe-Yrs)	9.6 10 ⁵
1st 10 Years	56	Total revenue, non-discounted (B\$)	841,418
Rate of steady production (GWe/Yr)	563	Non-discounted power costs (\$/kWh)	0.002
Period steady construction (Yrs)	30	Plant cost (\$/kW)	400
Final Installed capacity (GWe)	20,000	Earth mass (T) to moon per GWe-Yr	4.1
Costs multiplier (1990 - 2045)*	1.7	Energy payback (days)	5
Maintenance factor	0.5	excluding rectennas on Earth	
Price of electric power (\$/kWh)	0.1		
* Cost driver			
** Derived			

Total LPS expenditures are very large by contemporary standards. However, they would represent less than 0.2 % of world gross product between now and 2070, assuming a 4%/year growth rate, or 1% of cumulative United States GNP, assuming a 3.3%/yr growth rate. The United States now spends 10% of GNP on production of electric power [2]. LPS could free approximately 9% of GNP for other investments and expenditures.

The cost model projections are divided into five-year segments and the annual levels (B\$/yr) are presented in Figure 3 for four categories of expenditures: Transportation (Trnsp.), Lunar Base (LunB), Rectennas (RECTN), and Lunar Power System elements (LPS). Between 1990 and 1995 the expenditures (B\$/yr) for R&D are Trnsp. = 9, LunB = 4, RECTN = 0.1, and LPS = 10. Between 1995 and 2000 the test, engineering, and production of lunar elements is completed. Expenditures are Trnsp. = 54, LunB = 16, RECTN = 0.1, and LPS = 24. Equipment is deployed to Earth and lunar orbit and to the moon beginning in 2000. The 2000 to 2005 annual costs are projected to be Trnsp. = 41, LunB = 20, LPS = 20, and RECTN = 277. Pilot production of rectennas begin on Earth in 2000 at the rate of 56 GWe/year and grows to 563 GWe/Yr. Positive cash flow is possible during the 2000 to 2005 period at 0.1\$/kWh. Steady-state production begins in 2010 and is complete by 2040.

Table 2 Modeling Results

Item	Value
Engineering & Manpower Projections	
Materials mined (T/Yr)	

Three types of investors are anticipated: Government; consortia, and local organizations. Between 1990 and 2000 government programs would pay for the development and initiation of the transportation elements and the initial lunar base. Between 1990 and 1995 expenditures would be comparable to present government aerospace R&D. Between 1995 and 2000 expenditures would be approximately one-fifth of present annual expenditures on DoD and NASA. The lunar power program would maintain the present aerospace engineering teams of the United States during the 1990s and establish a vast new industry for the United States and allied groups.

A national or international consortium could be formed to develop, procure, and implement the elements for LPS production and do the RDT&E for rectennas. After the year 2000 this consortium would conduct all off-Earth operations. Between 2000 and 2005 it would begin receiving a net positive revenue from the sale of power on Earth.

Rectennas could be constructed, operated, and paid for by private groups, cooperatives, and countries as appropriate.

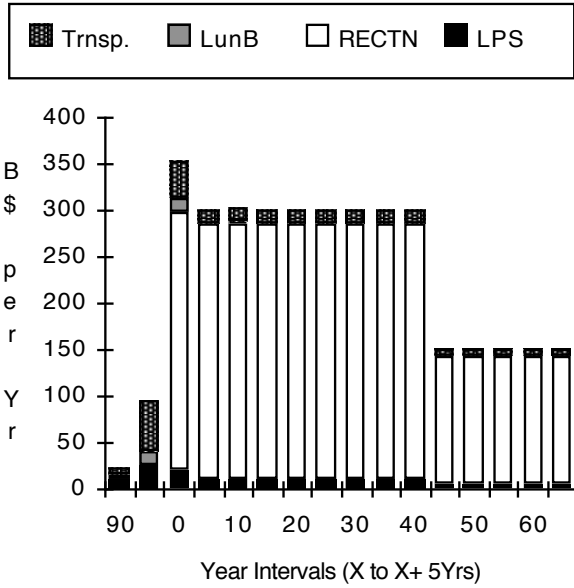


Figure 3 LPS Expenditures

Virtually all the costs of rectenna production would be covered by current cash flow.

The General Dynamics study estimated the expenditures for research and development (R&D), production, and maintenance of all elements of the LSPS and the production system in 1977\$. Costs of goods and services have increased since 1977 by a factor of 1.7. We can assume that costs for the types of goods and services assumed in the General Dynamics study will vary similarly between 1990 and 2040. Therefore, in the costing model all expenditures between 1990 and 2040 can be multiplied by a cost multiplier (CM). The results of the point model in Table 2 assumed CM = 1.7.

CM was also varied between 0.1 and 50 to see how the profitability of LPS depends on costs between 1990 and 2040. This dependence was calculated in terms of internal rate of return (IRR). IRR is the interest rate that equates the present value of the expected future receipts to the cost of the investment outlay [24]. Alternatively, the IRR is the interest rate that must be received if the expenditures were invested in a bank and the same net return was received.

Figure 4 shows the results in terms of Internal Rate of Return (IRR) versus the cost multiplier (CM). Figure 4 contains the results of six surveys of IRR. In the top set it was assumed that power is sold at 0.25\$/kWh and in the bottom set power is sold at 0.1 \$/kWh. At each price level the IRR was calculated over three periods of time. They are from 1990 to 2010, to 2040, and to 2070.

The results of these calculations are startling. The rates of return are far higher than any major investment opportunity available today. Even if the costs of LPS were ten times higher than presented in Table 2, the IRR would be close to 20% per year. It is inevitable that the costs of all other power systems will rise in the next century and push the price of their power above 0.25\$/kWh even without accounting for environmental costs and hidden taxes. LPS would be extremely robust financially at

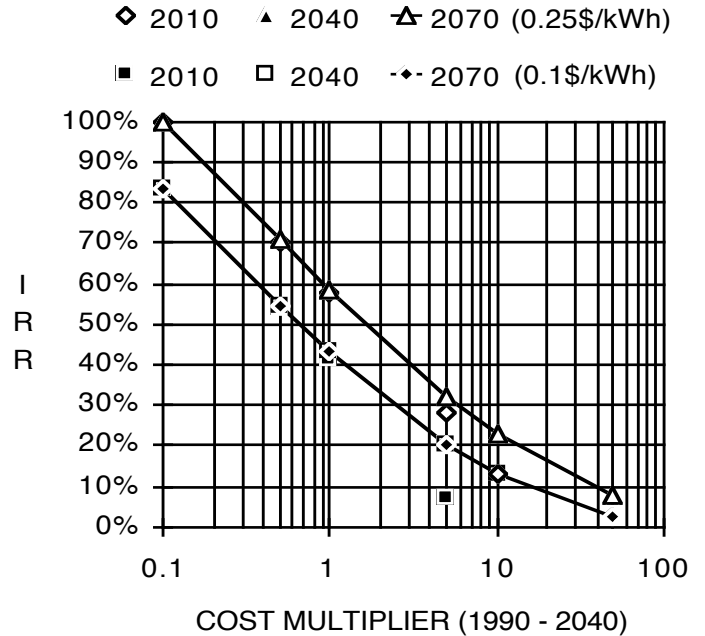


Figure 4 Internal Rate of Return vs Cost

0.25\$/kWh. There would be a long-term net return even with a factor of 50 increase in costs. LPS would be profitable in the first decade of operation against cost increases up to a factor of 10.

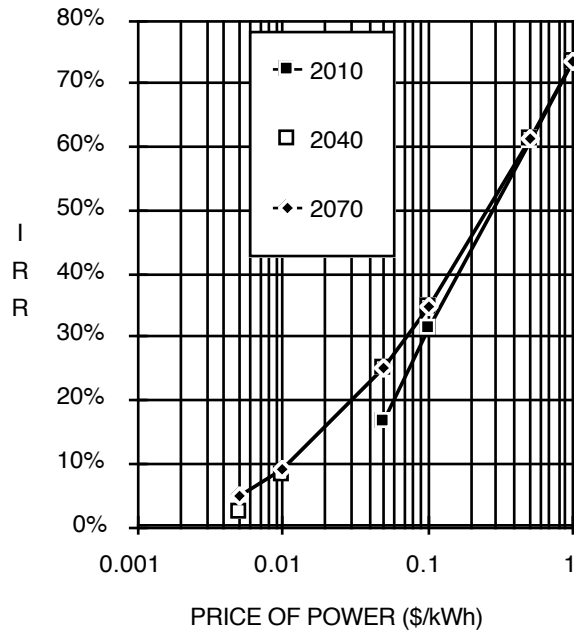


Figure 5 Internal Rate of Return vs Price of Power for Cost Multiplier (1990-2045) = 1.7

Remember from Figure 3 that most of the cost of LPS is associated with the construction of rectennas on Earth. LPS may permit the use of longer wavelength microwaves and therefore make use of rectennas that do not require high mechanical accuracy. This might make rectennas considerably

less expensive than assumed in Table 1. The Cost Multiplier might be less than 1 and therefore allow extremely high rates of return and also provide for very large growth in the costs of the lunar and space systems.

Figure 5 shows the dependence of IRR on the price of power for the same three intervals from 1990 to the three specified end dates. IRR exceeds 18% per year for all three intervals if power sells for more than 0.05 \$/kWh. Long-term returns occur for prices greater than 0.005 \$/kWh. The effect of the cost of maintenance on all elements of the system between 2040 and 2070 was also examined. The nominal maintenance factor (MF) was taken to be 0.5 for the calculations in Table 2 and Figures 3, 4, and 5. This corresponds to rebuilding half the complete system between 2040 and 2070. MF has virtually no effect on IRR for values between 0 (no maintenance required) and MF = 100.

The LPS is extremely robust economically in the face of cost growth during construction and maintenance. It offers significant rates of return under a wide range of conditions for the assumed engineering, operational, and price parameters. Advances in technology can sharply decrease expenditures during all phases of the LPS program [22]. LPS can enable a vast increase in space activities that would allow exploration of space at a level far greater than planned by NASA under the Moon–Mars Initiative [41].

4. GLOBAL POWER SYSTEMS AND THEIR LIMITS

Large-scale power systems are long-term commitments (30 to 100 years). The fuel supplies, manufacturing and maintenance support, generators, power storage, and distribution systems must all be built and sustained. The waste products must be dealt with and waste heat allowed for. At this time most analyses of power needs and supplies tend to extrapolate from current practices and resources. For reference, we note that in 1976 the United States consumed 2,600 GW by burning carbon and hydrocarbon fuels (93.5%), fissioning uranium in nuclear plants (2.6%), running rain water through hydroelectric dams (3.8%), and tapping geothermal (0.1%) sources in 1980. America spends approximately 10% of GNP, 500 B\$/Yr, to build, maintain, and fuel its 500 GWe power system. By extension, a 20,000 GWe world system would require an expenditure the order of 20,000 B\$ per year. However, extending present techniques will deplete conventional sources of energy by 2100.

Table 3 summarizes critical characteristics of major options to fill the power profile of Figure 1. Column 2 indicates the fuel that would be used over the seventy year period. Column 3 indicates the scale of machinery to produce and maintain the power plants and provide the fuel. Column 5 shows the total tonnage of equipment needed to produce a GWe-Yr of power. The higher the numbers in column 5, the more effort is required to build and maintain the system and the greater the opportunity for environmental modification of the biosphere of Earth.

Hydroelectric power is our cleanest form of power. The worldwide installed capacity is 2,200 GWe. However, the maximum capacity, at an undependable 50% capacity factor for all sources >5 MWe, is only 9,700 GWe [4]. Notice in line one the enormous quantity of water that must flow through 100-meter-high dams to supply 20,000 GWe. Thus hydroelectric can not support a 20,000 GWe world. However, hydroelectric could be used to provide very large scale peaking and backup power

from many hours to months. There would be less interference with the uses of water for agriculture, domestic supplies, and recreation.

Terrestrial Solar Power (TSP), both direct (photovoltaics) and indirect (ocean thermal) may eventually provide competitive power during sunny conditions in cooperation with other systems that work at night and during unexpected periods of high demand. However, because of the inevitable occurrence of indeterminately long periods of bad weather in a given locale, any TSP must be oversized to send extra energy to tremendously expensive dedicated storage units. Expensive provisions must also be made for distribution of a large fraction of the TSP output around the planet on a regular basis by means of transmission lines, synthetic fuels, or microwaves [3]. TSP will require the same scale of manufacturing as hydroelectric systems and a much higher level of maintenance activity. It seems likely that some useful level of TSP might be integrated economically with rectennas in an SPS or LPS system.

Indirect terrestrial solar power systems such as ocean current generators would slow the ocean currents (25,000 GW) [3]. Ocean thermal conversion (OTC) systems would quickly mine out the deep cold waters of the oceans. OTC uses a much larger flow of cold water from the deep ocean to produce a kWh of power than does a 100 m high hydroelectric dam. The oceans have a mass of only $1.4 \cdot 10^{18}$ tons [25, 26]. A 20,000 GWe OTC system would deplete these deep waters. The systems of production to build and maintain the units in row 1 are also very large and requires several years to pay back the energy of construction and operation. LPS has approximately a five-day energy payback period for lunar operations.

Could nuclear power, line 2, be the answer? In 1985 250 GWe was produced in 374 plants, 0.66 GWe average capacity, by burning 40,000 tons of U^{238} . Society had to face the multi-thousand year storage of an additional $1,000 \text{ m}^3$ of high-level waste and the start of decommissioning of the earliest and smallest reactors [27]. Most likely the decommissioned reactors will be entombed in concrete at ground level for several thousand years. The power cycle in Figure 1 would require a vast increase in the size and scale of operations of the nuclear industry. There are many troubling problems. Without reprocessing and at the present burning efficiency of uranium ($0.006 \text{ GWe-Yr/Ton } U^{238}$) nearly 10^8 tons of U^{238} would be required. This is the order of the U^{238} supply estimated to be available from continental sources at 500\$/Kg [27]. Fuel costs will rise to the point that reprocessing and breeding are required. Reprocessing would add additional expense to the fuel cycle. Without reprocessing, the plutonium inventory would build to greater than $1.5 \cdot 10^5$ Tons which has the potential for conversion into over 300,000 nuclear warheads [28]. Reprocessing will lead to transport of concentrated plutonium. Protection of nuclear fuel and wastes at the part-per-million level would be required to prevent state or private terrorists from building nuclear bombs.

Approximately $2 \cdot 10^6 \text{ m}^3$ of high-level waste will be produced over the Figure 1 life-cycle. Beginning in 2040, 3GW reactors will be decommissioned at the rate of 100 to 200 per year and entombed for thousands of years. The wastes and entombed reactors can be targets for terrorist bent on duplicating Chernobyl for their own purposes. Deep burial of wastes and construction of reactors deep underground could minimize the impact of accidents and terrorist actions but would raise greater

concerns about ground water contamination than now exists in the United States over comparatively trivial quantities of waste and contaminated reactors.

Table 3 Masses & Energy Output of 20,000 GW Power Systems Over 70 Years

TERRESTRIAL SYSTEMS	Fuel(70 Yrs) (T)	Equip & Plant(T)	Tot Energy (GWe-Yrs)	Specific Mass (T/GWe-Yr)
1. Hydro & TSP (without storage)	9 10 ¹⁶	8 10 ¹⁰	9 10 ⁵	900,000
2. Nuclear fission	6 10 ⁷	2 10 ¹⁰	6 10 ⁵	30,000
3. Coal Plants, Mines, & Trains	3 10 ¹²	6 10 ⁹	6 10 ⁵	10,000
4. Rectenna Pedestals (SPS & LPS)	-	4 10 ⁹	--	4,000
(Electronic elements*2)	-	2 10 ⁷	--	20
SPACE SYSTEMS	First Year Equip. (T)	Total Equip. (T)	Total Energy (GWe-Yr)	Specific Mass (T/GWe-Yr)
(Mass shipped from Earth)				
5. SPS made on Earth (10 T/MWe)	2 10 ⁶	3 10 ⁸	6 10 ⁵	500
6. LSPS from lunar materials	2 10 ⁷	5 10 ⁷	6 10 ⁵	80
7. LPS	3 10⁴	3 10⁶	8 10⁵	3

There are major objections to both concentrating and dispersing such a huge number of reactors. Historically, there have been two major accidents with power reactors over 2,400 GWe-Yrs of production [27]. If safety were increased by a factor of 100, then a Chernobyl-class accident could be expected every 10 to 20 years.

A crude estimate indicates that the present 250 GWe nuclear power industry has increased the level of background radiation by 1/500 over the past 30 years [27]. At this rate, a 20,000 GWe industry would increase the background radiation by 50% by 2070. Finally, there are fundamental financial considerations. Private investors face 6 to 20-year-long delays before profits are forthcoming from nuclear power plants. Interest expenses can dominate program costs.

Nuclear fusion of deuterium (D) and tritium (T) has been a goal of the United State, Europe, the USSR, and Japan for over 40 years. Progress is very slow, expensive, and unsteady. Political support is wavering in the United States for the traditional approach based on magnetic confinement of a D-T plasma. Even if net energy production is achieved in this century, it is generally anticipated that practically engineered power plants would not be possible until 2050 [29]. Critical problems include providing an inner wall to contain the vacuum conditions of the plasma and extracting energy from neutrons over a substantial period of plant operation. Also, D-T plants will generate an inventory of radionuclides that will pose radiation hazards qualitatively similar to those of fission plants [30, 31].

He3 obtained from the moon may offer another new option for supplying power to Earth [31]. There are no major reserves of He3 on Earth. D-He³ will fuse, under ideal conditions, to release He⁴, a proton, and 18.7 Gw-Yrs of energy per ton of He³. The fusion products would be charged so the power could be extracted by direct conversion to electricity at very high efficiency. Under non-ideal but expected conditions, neutrons will be produced at 1% the level of D-T reactions. This reduction in neutron fluence makes it reasonable to expect that the inner wall of a D-He³ reactor can last the life of the reactor. However the inner wall of the reaction chamber and associated components will be highly

radioactive.

He³ is present in the surface soils of the moon at the level of 1 - 15 ppb by weight. Large mining units would be placed on the

moon that use solar thermal energy to

extract the trace quantities of He³. A useful engineering figure of merit is the number of Figure 1 power cycles the lunar He³ could support. The greater the number of power cycles the more attractive the resource. The number of power cycles given in Table 4 are the product of the average depth of the resource, soil density (3 T/m³), He³ concentration, conversion efficiency of mass to power, and extraction efficiency and all divided by the life-cycle output of the planetary power system (960,000 GWe-Yrs).

Table 4. He3 Power Cycles

	Nominal	High	Low
Depth(m)	3	10	1
[He3]wt. Fraction	8E-09	1.5E-08	5E-09
Extraction Effic.	0.5	0.8	0.1
Conversion Effic.	0.5	0.9	0.3
# Power Cycles	13	240	0.3

Continuing basic and engineering research is needed over the next 30 to 50 years to show that the D-He3 cycle, which has 10 times the ignition temperature of D-T, is obtainable. At this time, the demonstrated conversion efficiency is zero. Extensive surveys of lunar soils are needed to prove the He³ reserves. Earth-based research and lunar in-situ demonstrations are needed before large-scale mining can begin.

The burning of carbon is the dominant source of power for both the developed and developing nations. Table 3 shows why carbon is still the fuel of choice. It is relatively portable and can be gathered and burned in power systems that are relatively low in engineered mass. Note the *Equipment and plant mass* and *specific mass* per unit of produced energy in the right hand column for carbon are small compared to hydroelectric dams, TSP, or nuclear plants. The carbon burning industry can be "relatively" small per unit of delivered energy and highly efficient as long as it does not have to shoulder the full environmental costs of the processes and waste products. The power profile of Figure 1 would consume half the estimated reserves of coal [1, 27] and result in full depletion by 2110.

During that period world society would face escalating prices. World industry would lose efficient access to concentrations of carbon for use in synthetic materials with a far greater added-value. The concentration of atmospheric carbon dioxide would increase by a factor of 7 or more [32, 40].

SPS, LSPS, and LPS would bring power to Earth by means of microwave beams directed into rectennas. The rectennas designed for SPS were optimized to operate at 10 cm wavelength. Line 4 of Table 3 assumes the rectenna supports are concrete. The antenna elements and associated electronics are low mass and are highly efficient in converting microwaves to electric power (>95%). There is little waste heat at the reception area. Rectennas can be very simple structures compared to hydroelectric, nuclear, or coal plants. As can be seen from column 5, a rectenna can output 2 to 300 times more energy than the other options, per unit of engineered mass. The ground under the rectenna is potentially available for other uses such as agriculture, solar collectors, or even low-quality mirrors that would reflect sufficient sunlight back into space to maintain the Earth in energy balance with the incoming beam of microwaves. This study assumes the microwave intensity is 23 milliwatts per cm² at the rectenna. This is approximately 20% of the power density of sunlight at high noon.

The United States currently allocates 50,000 km² of land to the generation and distribution of 500 GWe of electric power [24]. This corresponds to 1 mW/cm². LPS power could come into the United States at one-fifth the power density associated with an allowed leakage of power from microwave ovens. The cost of LPS power is inversely proportional to the power density in the beam and the cost per unit area of the rectenna.

SPS, LSPS, and LPS require extensive operations in space. Originally, SPS was to be deployed from Earth. However, some of the original proponents consider that launching the order of 5,000,000 tons/year of materials into space may be environmentally objectionable. As mentioned earlier, the moon is now seen as a source of materials for the construction of LSPS in space [23]. Table 3 gives the scale of machinery, parts, and consumables associated with deploying the reference SPS from Earth and the reference LSPS from the moon [8]. These numbers might be reduced by a factor of 3 by using more advanced technologies than considered reasonable in the late 1970s. Transporting LSPS materials into space from the moon adds costs. Additional production steps are required in space compared to building LPS.

SPS and LSPS are optimally suited for operation in geosynchronous orbit about the Earth. Assuming that the Earth is supplied with power by SPS units with an average delivered power of 100 GWe then 200 units would be required. The units would be the order of 50 km by 20 km on a side. They would be concentrated along the portions of the geostationary arc associated with the continents of the northern hemisphere and sparsely placed over the Pacific Ocean. Along longitudes associated with dense human population they might be separated by less than 10 times their longest dimension. Closely spaced units would be prone to shadowing each other during equinox passage twice a year.

LSPS and SPS could direct power to rectennas on Earth within only a limited range of latitude and longitude. The satellites serving a region on Earth would have to be oversized to meet peak power demands of that region and to provide backup across three time zones during periods when all the

satellites serving one time zone are eclipsed by Earth. Most power from space will go to rectennas at mid to high latitudes. These rectennas will have to be oversized by a factor of approximately two to three for SPS and LSPS compared to LPS. The rectenna costs in Figure 3 could be increased by a factor of two to three for SPS and LSPS compared to LPS.

LSPS and SPS units would be extremely sensitive to collisions with even low-velocity orbital debris and would be potential sources of enormous quantities of debris. Collisions between these satellites might make space flight from Earth impossible for many years. There are fundamental advantages to solar power satellites that are constantly directed at the sun. Designing SPS and LSPS units for operations in other than geosynchronous orbit should be considered.

LPS does not have the mechanical directness of SPS. LPS needs orbital reflectors about the moon and microwave reflectors about the Earth. However, the space components are very low mass per unit of power they handle. LPS requires the smallest amount of equipment and final materials of any of the power systems, as can be seen from line 7 of Table 3. Engineers would not have built the large hydroelectric dams if it had been necessary to excavate the catchment areas and river valleys first. The water and geography were gifts of nature that engineers have used to elevate mankind materially through the twentieth century. The moon provides the solid state equivalent for the twenty-first century. It is there, correctly positioned, composed of the proper materials, and lacking the environment of Earth that is so damaging to thin-film solid-state devices.

It is now widely agreed that alternative energy sources must be developed. However, few individuals appreciate the magnitude of the challenges to enabling a prosperous world by supplying 2 kWe/person of clean, dependable, and reasonably priced power. The problem is still viewed as amenable to widely discussed "conventional" approaches [33] or viewed in a regional frame with no reference to fundamental global issues [34]. Societies must presumably take a long view. They must question the wisdom of investing in large systems that operate at relatively low conversion efficiency (30 -50%) and that require

- competitive access to decreasing fuel supplies;
- essentially permanent entombment of increasing quantities of highly dangerous wastes;
- creating enormous quantities of relatively high grade nuclear materials;
- dispersal of environment modifying wastes such as CO₂ irretrievably throughout the biosphere, and
- introducing heat loads comparable to the rate of transport of heat between the northern and southern hemispheres (10⁶ GW) [42].

As is often the case, the solution can come from stepping outside the context of the problem. In this case, the need is to look beyond the confines of Earth and to the energy resources of the sun and the already known natural resources of the moon. Development of LPS can not only supply clean energy to Earth but can provide the stable and long term operations between Earth and space that will enable the permanent movement of mankind beyond the planet.

5. LPS SUMMARY

Why is the LPS so attractive as a large-scale power system? 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 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 and begin to produce net revenue at a small size. 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.

6. PACE OF DEVELOPMENT

LPS can be developed expeditiously [35, 36, 37, 38, 39]. 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. The LPS design can be improved. More extensive and refined financial and engineering analyses are required 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 described in Table 2 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.

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Lunar Power System to Supply Electric Power to Earth
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Solar power industries located off the Earth have essentially unlimited growth potential. The challenge is to build a commercial system that can extract a tiny portion of the immense solar power and deliver the energy to customers on Earth at a reasonable price. The answer is the Moon. The disk of the Moon dependably receives 13,000 TWs of solar power. As opposed to conventional power systems, the Lunar Solar Power System supplies net new power to Earth. Net new electricity can be used to power the production and recycling of goods and the provision of services. Net new electricity can be used to restore the biosphere. Solar Cell to Rectenna Output Electric power collection effic. The Earth receives solar energy in the form of light and heat. But in today's world, the words 'power' and 'energy' are leaned more towards 'electricity'. This article explains how electricity is harvested from the solar energy and how it is utilized. How solar power works? Photovoltaics directly convert solar energy into electricity. They work on the principle of the photovoltaic effect. When certain materials are exposed to light, they absorb photons and release free electrons. This phenomenon is called as the photoelectric effect. Solar panels or modules are designed to supply electric power at a certain voltage (say 12v), but the current they produce is directly dependent on the incident light. As of now it is clear that photovoltaic modules produce DC electricity.