Quelle:
http://www.moonbase-italia.org/PAPERS/D1S2-MB Assessment/D2S2-06EnergySupport/D2S2-06EnergySupport.Criswell.pdf

World Energy Council 18th Congress, Buenos Aires, October 2001LUNAR SOLAR POWER SYSTEM: INDUSTRIAL RESEARCH, DEVELOPMENT, AND DEMONSTRATION*····DR. DAVID R. CRISWELL UNIVERSITY OF HOUSTON,

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Vorab, aus Wikipedia, Stichwort David C. Criswell

David R. Criswell, (July 17, 1941--September 10, 2019)[1] was the Director of the Institute for Space Systems Operations at the University of Houston. ISSO is the operational agent for the Houston Partnership for Space Exploration.

Criswell received a Bachelor of Science degree in 1963 (graduating cum laude) and a Master of Science degree in Physics in 1964 from the University of North Texas, in Denton, Texas. In 1968, he received a Doctorate degree in space physics and Astronomy from Rice University in Houston, Texas.[2]

He was an active member of the Power from Space Committee of the International Astronautical Federation and participated in IAF and United Nations Summits dealing with supplying energy to Earth. He also served on the Board of Governors of the National Space Society, a non-profit space advocacy organization in Washington, D.C.

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For over thirty years, Criswell was an advocate for obtaining solar power from the moon. He proposed the large-scale construction of solar collectors on the lunar surface, using local lunar materials. The solar energy would be converted to microwave energy and transmitted to Earth.[3]

Criswell envisioned that this energy source would spur an unprecedented amount of global economic growth (Gross World Product increasing by a factor of 10), while having a positive environmental impact (fossil fuel-burning power plants would be decommissioned). He pointed out that lunar-solar energy would not generate nuclear waste, and is not a finite resource (in the sense that fossil fuels are a finite resource).

He estimated that a 1 GigaWatt demo of the lunar-solar power generation system could be built over a 10-year period for approximately $60 billion in 1990 dollars.[4] (For comparison, the 1.65 GW Benban Solar Park in Egypt cost $4 billion in 2019; however, Benban's delivered power is 430 MW compared to the 1 GW demo delivers a full 1 GW.)

In short, Criswell believed that lunar-solar energy is the only viable option for generating the massive amounts of electrical power that would be needed to raise the standard of living in third-world nations to that of first-world nations.

He once said, from the University of Houston, that "We are already well beyond what the biosphere can provide. We have to go outside to get something else."

(Gelb markierte Hervorhebungen im Text durch L. H.; Tabellen werden bei Aufruf der bezeichneten Web-URL lesbarer angezeigt)

USA 1. WEC 2000 CHALLENGE [DÉFI DE WEC 2000] The World Energy Council Statement 2000 issues this Energy Challenge: “Slightly more than one billion people in the industrialized countries (about 20% of the world’s population) consume nearly 60% of the total energy supply whereas just under 5 billion people in developing countries consume the other 40% of the total energy supply” --- “The two billion poorest people ($1000 annual income per capita or less), a small but growing share of whom live in shanty towns with most still scattered in rural areas, use only 0.2 toe of energy [tonnes of oil equivalent of thermal energy] per capita annually whereas the billion richest people ($22000 annual income per capita or more) use nearly 25 times more at 5 toe per capita annually [5 toe/y-person ~ 6.7 kWt/person].” “Given this dramatically uneven distribution and the limited evidence of improvement in economic growth in many developing countries, WEC at the 17th World Congress in Houston in September 1998 concluded that the number one priority in sustainable energy development today for all decision-makers in all countries is to extend access to commercial energy services to the people who do not now have it and to those who will come into the world in the next two decades, largely in developing countries, without such access.” (WEC, 2000, p. 2) The challenge by WEC places several major constraints on this new power and energy. The new power must be clean. The new energy must be significantly less expensive than now. The Developed Nations expend approximately 10% of their gross product on all phases of commercial energy. The Developing Nations now have a per capita GDP of ~2,400 $/person-y. By analogy, if the Developing Nations spend ~10% of their GDP on all phases of providing 6.7 kWt/person, the new source of power must initially supply energy for ≤ 0.4 ¢/kWt-h. The new primary energy source and the new power system must be adequate for centuries and should have significant capacity for growth. Finally, due to the typically long development time of major industrial systems, it is likely that the new power system will utilize physical resources and technologies that are relatively well understood at this time. Can conventional energy resources and power systems be expanded to provide the new power? In the year 2000 the industrial and developing nations consumed the equivalent of ~14 TWt-y (terawatt-year) of thermal energy (T = $1 \bullet 10^{12}$). By the middle of the 21st century the world population is projected to be approximately 10 billion. To provide 10 billion people with 5 toe/person-y implies the global production of 67 TWt of commercial thermal power. For discussion, assume that world population stabilizes at 10 billion people. Over the 21st century the world will consume 5,400 TWt-y of thermal energy. Over an energy-rich 22nd century 10 billion people will consume 6,700 TWt-y. WEC studies estimate that coal has proven recoverable reserves of ~1,000 billion tonnes or 650 TWt-y of primary thermal energy. Proven coal reserves, as of the year 2000, would be consumed in 10 years by the WEC-power system. Ultimately recoverable coal and lignite is estimated to be ~ 3,900 tce (tonnes of coal equivalent) or 4,500 TWt-y. This is ~ 10 times the ultimately recoverable natural gas and conventional and unconventional oils (Trinnaman and Clark 1998). It is very expensive to establish conventional thermal (coal, nuclear) or terrestrial renewable systems that will output the equivalent of ~67 TWe of thermal power by 2050 and ~5,400 TWt-y of thermal energy by 2100. A coal-based power system is roughly estimated to cost the order of 2,500 T$ over the 21st century (Criswell 2001, 1998; Criswell and Thompson 1995). Gross world product per capita is now ~ 4,000 $/y-person. If per capita gross world product were to remain constant, the gross world product integrated over the 21st century would be ~3,600 T$. Thus, the life-cycle cost of the coal system approaches 75% of the integral gross world product. Energy costs are driven in part by the magnitude of commercial thermal power systems. It is important to grasp the physical magnitude of a commercial power industry that delivers 67 TWt. For simplicity assume that the new power will be provided exclusively by mining and burning coal. Providing 67 TWt requires the mining and combustion of 100 billion tonnes of coal each year. Figure I is a surface coal mine or strip mine in Texas (OSM 2001). Surface mining of coal, which will likely provide 70% or more of the coal, requires the removal and return of, very roughly, ten times the tonnage of overburden. Underground mining requires the displacement of rock approximately equal to the mass of the mined coal. A coal-prosperous world will likely require injection of the CO_2 and other combustion products into underground or deep-sea reservoirs. The entire mass-handling process, including transportation and ash removal and similar processes, will consume ~20% of the total energy content of the coal. Including the above immediately obvious factors implies that a 67 TWt world will extract and manipulate $2 \bullet 10^{12}$ tonnes/y of materials. If 10 billion people are provided the present United States level of power, 11 kWt/person, then 110 TWt global commercial power production is projected. Such a coal-fired economy would process ~$3.3 \bullet 10^{12}$ tonnes/y.

It is useful to place the fossil fuels industry into a broader context. Coal, oil, natural gases, oil shale, and speculative resources such as natural gas hydrates are the decay products of ancient plants. These fuels are fossilized sunlight or indirect stores of solar power. Over 100 million years was required for the Earth to accumulate its merger inventory of fossil fuels. Today, if the annual production of new trees and grasses were burned over a year, they would release less than 50 TWt-y of primary thermal energy. The biomass of Earth contains only ~ 230 TWt-y of primary thermal energy. Table I lists 25 options for obtaining the equivalent of 60 TWt of commercial power. It appears that 24 of the power options cannot enable an energy-prosperous 21st century (Criswell 1998a, 2001). It is estimated that an expansion of the existing Mixed power system in Row 1 (a combination of coal, oil, natural gas, biomass, nuclear, hydroelectric, and miscellaneous renewables) can only provide ≤3,200 TWt-y of commercial energy due to economic and environmental constraints and a maximum output by 2050 of <11 TWe. The mixed, coal (Row 4), and conventional fission (Row 16) systems would exhaust their estimated fuels early in the 22nd century. As previously noted, bio-resources (Row 2) and peat (Row #3) are not applicable (NA) due to their small total store of energy and small replacement rate. To meet the energy challenge posed by WEC 2000 requires low-cost, dependable, and direct access to solar power. The sun, Figure II, is the dominant source of power and energy for Earth. The jet aircraft leaving the exhaust trail across the sun is propelled by fossilized solar energy. The jet is 15 kilometers from the photographer (Albrich 2000). For scale, the small dot just above the jet aircraft is the planet Mercury. Mercury is 39% of the distance from the center of the sun to Earth (Albrich 2000). Mercury is 4,800 km in diameter or approximately the width of the United States of America. Earth is ~150 million kilometers from the center of the Sun. The sun outputs $3.9 \bullet 10^{14}$ TWs of solar power. The sun is powered by the nuclear fusion of hydrogen into helium and heavier elements. Four input hydrogen nuclei have slightly more mass than the resultant helium nucleus. The lost mass (dm) is converted into an increment of energy (dE) as specified by $dE = dm \bullet c^2$, where $c = 3 \bullet 10^8$ m/sec is the speed of light. The sun now converts $dm/dt =$ 140,000 billion tonnes/year of matter into energy ($=1.4 \bullet 10^{14}$ tonnes/y). Refer again to Figures 1 and 2. This coal-prosperous world that provides 6.7 kWt/person will manipulate materials within the biosphere at 2.3% of the rate at which the entire sun fuses hydrogen into the heavier elements. The sun delivers ~177,000 TWs of solar power to the disk of Earth. It is reasonable to attempt to capture that power at the surface of Earth. Unfortunately, the terrestrial renewable systems listed in Table I, such as wind (Row 13) and solar (Rows 14, 15), are "not stand-alone" (NSA) and must be supplemented by other power systems of similar capacity. This drives up the cost of the delivered energy by a factor of 5 or more. Also, very large-scale renewable systems can directly affect the biosphere by changing the natural flows of power, water, and wind and by modifying the reflective/radiative properties of large areas of the Earth. Fission breeder reactors appear to be unacceptable politically and very expensive. Net energy output from controlled nuclear fusion remains to be demonstrated (Rows 19 – 21). Figure I. Surface Coal Mine

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POWER SYSTEM OPTION (Note: 3 Wt ~ 1 We in utility) Resource TWt-y 2050 Output TW electric Pollution Vs Now Vs ¢/kWe-h
1. Mixed (Case 2A) ≤ 3,200 11 (~33TWt) Large >
2. Bio-resources (in #1) < 230 <0.2 More >
3. Peat < 60 ~0 More >
4. Coal (in #1) < 4,500 < 4 Large >
5. Oil & gas (in #1) < 1,300 < 8 Large >
6. Natural gas hydrates TBD >10,000 TBD Large Likely > Not Stand Alone @ 20 TWe: #2, 3, 7, 10, 11, 12, 13, 14, 15
7. Hydroelectric (in #1) < 14 < 1.6 Low >
8. Salinity Gradient to Sea ~ 1,700 < 0.3 TBD Likely>>
9. Salinity Gradient to Brine ~ 24,000 < 0.3 TBD Likely>>
10. Tides 0 < 0.02 Low >
11. Ocean Thermal ~ 200,000 < 0.1 Large >>
12. Geothermal (in #1) ~9,000,000 < 0.5 Low >
13. Wind (not stand alone) (in #1) 0 < 6 Low >
14. Terrestrial Thermal Solar 0 < 3 TBD >>
15. Terrestrial Solar PV (in #1) 0 < 3 TBD >> 1
6. Fission (no breeder) (in #1) < 430 < 1.5 Large >
17. Fission (breed 238U/T) < 33,000 In #16 Large >
18. Fission (breed ocean U) ~ 6,000,000 In #16 Large >
19. Fusion (D-T/:U-Th) < $6 \cdot 10^{9}$In #16 Large Likely > 20. Fusion (D-T) >> $1 \cdot 10^{9}$0 likely More Likely >
21. Fusion (D-He3 Lunar) ?~100 to 10^{5}0 likely More Likely >
22. GEO Solar Power Satellites 0 < 1 Low >>
23. LEO Solar Power Satellites 0 <0.1 Low >>
24. SPS beyond GEO (NTM) 0 < 1 Reduce Likely ≥
25. Lunar Solar Power System 0 ≥ 20 Reduce Likely ≤Table I. Global Power System Options for 2050

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The conventional global commercial power industry, expanded to supply 67 TWt, must manipulate solar-fusion scale quantities of atoms and molecules within the biosphere but only extract a few tens of millionths of an electron volt of usable energy per manipulated atom. All this effort inside the biosphere of Earth simply to obtain a very modest 67 TWt boggles the mind. There must be a practical alternative. After all, the sun manipulates 30 times that mass per year to produce 390,000,000,000,000 TWs of solar power. Over the next ~5 billion years of stable operation the sun will release ~2,000,000,000,000,000,000,000,000 TW-y of energy (~$2 \cdot 10^{24}$ TWs-y). 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. If a significant fraction can be delivered to Earth at a low cost, the new power requested by the World Energy Council can be supplied to all the people on Earth for many centuries.

2. LUNAR SOLAR POWER SYSTEM

The Lunar Solar Power (LSP) System was presented to the 17th World Energy Congress (Criswell 1998). Figure III illustrates the essential features of the LSP System: Sun, Moon, microwave power beam from a power base on the Moon, and a microwave receiver (i.e. rectenna) on Earth. The LSP System uses bases on opposing limbs of the Moon. The Moon bases receive sunlight, convert it to electricity, and then convert the electric power into microwave power beams. Each base transmits multiple microwave power beams directly to the rectennas on Earth when the rectennas can view the Moon. Power beams are not esoteric. The Arecibo Radio Telescope in Porte Rico routinely beams microwaves from the Earth to the Moon. The beam intensity is approximately 20 W/m$_2$ going upward through the atmosphere. This is 10% of the maximum intensity, ≤ 230 W/m$_2$, proposed for transmission of commercial power (Criswell, 2000, 1998). Each of the bases on the Earthward side of the Moon is augmented by fields of photoconverters just across the far side of the Moon from Earth. Power lines connect the Earthward base and the extra arrays of photoconverters on the far side of the Moon. One or the other of the two bases in a pair will receive sunlight over the course of a lunar month. Thus, one or the other of the bases in a pair can beam power toward Earth over the entire cycle of the lunar day and night. The rectennas on Earth are simply specialized types of centimeter-size TV antennas and electric rectifiers. A rectenna is illustrated in the lower right of Figure III. A rectenna converts the microwave beam it receives into electricity and outputs the pollution-free power to local electric distribution systems and regional grids. Long-distance power lines are not necessary. Rectennas are the major cost element of the reference version of the LSP System. Unlike for Earth, the lunar sky is always clear. There are no obscurations due to an atmosphere, clouds, smoke from fires, dust, volcanic ash, or biological/chemical smog. The power beam from the Moon passes through the atmosphere, clouds, fog, snow, smog, smoke, and normal rain with a percent or less of attenuation. An extremely heavy, ≥ 25 cm/hour, rain will attenuate the beam by ~30%. This level of rain is very rare in most regions and lasts only a few tens of minutes. The intensity can be increased to maintain the electric output of the rectenna. A rectenna, that receives a load-following power beam of ≤230 W/m$_2$ will, over the course of a year, output approximately 180 We/m$_2$ of electric power. The rectenna will output this power whether it is located in a desert, the tropics, or in the polar regions. In comparison, a stand-alone solar array on Earth outputs much less average power per unit of area. A stand-alone solar array is one that feeds power directly to a grid and also to a storage system so that power can be provided during the night or when the sky is obscured. A stand-alone solar array on Earth will have an averaged output of <3 W/m$_2$ if it uses 1980s technology and < 20 W/m$_2$ using advanced technologies. The solar array on Earth is a captive of the biosphere, season, and weather. The power output of the rectenna is independent of these limitations. Rectennas on Earth can only view the Moon and receive power approximately 8 hours each day. Earth-orbiting satellites can redirect beams to rectennas that cannot view the Moon and thus enable load-following power to rectennas located anywhere on Earth (Criswell, 2000). Rectennas on Earth and the lunar transmitters can be sized to permit the use of Earth-orbiting redirectors that are 200 m to 1,000 m in diameter. Redirector satellites can be reflectors. Alternatively, a relay satellite can receive a power beam from the Moon. The relay satellite then retransmits several new beams to different rectennas on Earth. Unmanned and manned spacecraft have demonstrated the transmission of beams, with commercial-level intensity in low Earth orbit.Demonstration-scale reflectors and retransmission technologies have been and are now operating in space. The preferred power beam is formed of microwaves of ~12 cm

Figure III. Sun, Moon, Beam, and Rectenna wavelength, or ~2.45 GHz. This frequency of microwave travels with negligible attenuation through the atmosphere and the atmosphere's variable loads of water vapor, clouds, rain, dust, ash, and smoke. Also, microwaves in this general frequency range can be converted into alternating electric currents at efficiencies in excess of 85%. Other frequencies can be used. However, they will experience greater atmospheric attenuation. Power beams will be 1 to 20 times more intense than recommended for continuous exposure by the general population. The tightly focused beams will be directed to rectennas that are industrially zoned to exclude the general population. Microwave intensity under the rectenna will be reduced to far less than is permitted by continuous exposure of the general population. The beam power is absorbed by the rectenna and can be further reduced by secondary electrical shielding. A few hundred meters beyond a beam, the intensity will be far below that permitted for continuous exposure of the general population. Low-intensity beams do not pose a hazard to insects or birds (Osepchuk, 1998; Kolata, 2001). Humans flying through the beams in aircraft will be shielded by the metal skin of the aircraft, or by electrically conducting paint on composite aircraft. Of course aircraft can simply fly around the beams. Beams can be turned off in a few seconds or decreased in intensity to accommodate unusual conditions. Earth can be supplied with 20 TWe by several thousand rectennas whose individual areas total to ~10•10^4 km^2. Existing thermal and electric power systems, to deliver 14TWt or the equivalent of 4.7 TWe, utilize far larger total areas. In many cases, such as strip-mined land or power line right-of-ways, the energy production degrades the land for several years to decades and/or precludes multiple uses. Rectennas could be placed over such land. Individual rectennas can, if the community desires, be located relatively close to major power users and thus minimize the need for long-distance power transmission lines. Individual rectennas can be as small as ~0.5 km in diameter and output ~40 MWe. Relatively small rectannas can be placed over agricultural land and industrially zoned facilities thus enabling multiple uses of the same land. Rectennas can be as large in area as necessary to produce larger electric power output. The world economy is gradually converting from thermal to electric power. At the present rate of change electricity will provide almost all end-user power by 2050. The reason is that 1 We of electric power is increasingly providing the goods and services previously provided by 3 Wt of thermal power. Thus, 20 TWe of electric power can provide the goods and services now supplied by 60 TWt of thermal power. This is why the third column in Table 1 is referenced to 20 TWe. Also, electricity can provide new types of goods and services – for example, computers and telecommunications, that cannot be powered directly by thermal energy. The LSP System can provide this electric energy without the use of significant terrestrial resources. 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. It is projected that the LSP System, using known technologies, can achieve the order of 10% efficiency in the transformation of solar power at the Moon into commercial electric power delivered on Earth. The delivery of 20 TWe of electric (e) power to Earth at 10% overall efficiency implies that the power bases on the Moon capture energy from the fusion of 71 tonnes/y of hydrogen within the sun. This 71 tonnes of lost solar mass replaces the many hundreds of billions of tonnes of coal, oil, natural gas, and biomass that would otherwise be consumed after 2050. It replaces the hundreds of billions of tons of wind and flowing fresh water that would otherwise be diverted from their natural courses. Unlike fossil, nuclear, or terrestrial renewable power systems, the LSP System would require very little continuous processing of mass on Earth to receive and distribute the electric power. The fundamental waste product of lunar solar power on Earth is waste heat. This waste heat is eventually converted into infrared photons and radiated back to space.

The Moon, Figure IV, dependably receives 13,000 TWs of solar power. Figure IV depicts twenty power bases, ten on each limb or visible-edge of this full Moon. They are adequate to provide 20 TWe of electric power to Earth. The bases can be unobservable to the naked eye. Much more power could be provided. The Moon turns once on its axis every 28 days with respect to the sun. Fourteen days after the view in Figure IV the opposite side of the Moon will be illuminated. Additional fields of solar converters located approximately 500 kilometers across the limb Moon from each base in Figure IV will receive full sunlight. These cross-limb bases of solar converters can be connected by power lines to the bases on the Earthward side of the Moon. Approximately once a year the Moon will be totally eclipsed by the Earth for up to 3 hours. Lunar eclipses are completely predictable. Unlike the situation for terrestrial renewable power systems, it is possible to precisely plan for the amount of additional LSP energy that must be provided to Earth for use during a lunar eclipse. Continuous power can be provided on Earth by storing solar-derived energy on the Moon and transmitting it to Earth during the eclipse. Predicable amounts of energy can also be stored on Earth and released during the short lunar eclipse. Eclipse-power can be produced on Earth from conventional systems such as natural-gas-fired turbines. Because the turbines would operate at full capacity for only a few hours each year the natural or synthetic gas would last for many centuries and produce negligible pollution. Finally, mirrors, similar to proposed solar sails, could be placed in orbits high above the Moon and reflect solar power to the bases during the eclipse. Such mirrors eliminate the need for expensive power storage. The orbital mirrors can increase the sunlight on the power bases over the entire lunar month and thereby increase power output. 3. LSP DEMONSTRATION BASE Figure V illustrates a demonstration power base. A power base is a fully segmented, multi-beam, phased array radar powered by solar energy. This demonstration power base consists of tens to hundreds of thousands of independent power plots. A power plot is depicted in the middle to lower right portion of Figure V. Each power plot emits multiple sub-beams. A power plot consists of four elements. There are arrays of solar converters [#1], shown here as north-south aligned rows of photovoltaics. Solar electric power is collected by a buried network of wires and delivered to the microwave transmitters. Power plots can utilize many different types of solar converters and many different types of electric-to-microwave converters. In this example the microwave transmitters [#3] are buried under the mound of lunar soil at the Earthward end of the power plot. Each transmitter illuminates the microwave reflector [#2] located at the anti-Earthward end of its power plot.

Figure IV. Ten Pairs of LSP Bases

Figure V. LSP Demo Base: Multiple Power Plots [Arrays of Solar Converters #1, Microwave Reflector #2; and Microwave Transmitter #3], Set of Mobile Factory [#4] & Assembly Units [#5], and Habitat/Manufacturing Facility [#6] [Base De SEL Demo: Traçages Multiples De Puissance [Matrices solares de convertidores # 1, Réflecteur À micro-ondes # 2; et l'émetteur de micro-onde # 3], a placé de l'usine mobile [# 4] et des unités d'Assemblée [# 5], et du service de Habitat/Manufacturing [# 6]]

All the reflectors [#2] in a power base overlap, when viewed from Earth, to form a filled lens that can direct very narrow and well-defined power beams toward Earth. The Earth is fixed in the sky above the power base. Large microwave lenses, depicted by the circles in Figure

IV, are practical because the same face of the Moon always faces Earth. Thus, the many small reflectors shown in Figure V can be arranged in an area on the limb of the moon so that, when viewed from Earth, they appear to form a single large aperture as depicted in Figure IV. The Moon has no atmosphere and is mechanically stable. There are no moonquakes. Thus it is reasonable to construct the large lens from many small units. Individually controllable sub-beams illuminate each small reflector. The sub-beams are correlated to combine coherently on their way toward Earth, to form one power beam. In the mature power base there can be hundreds to a few thousand sets of correlated microwave transmitters illuminating each reflector. This arrangement of multiple reflectors will likely include additional sub-reflectors or lenses in front of each main reflector. To achieve low unit cost of energy, the lunar portions of the LSP System are made primarily of lunar-derived components. Factories, fixed [#6] and mobile [#4, #5], are transported from the Earth to the Moon. High output of LSP components on the Moon greatly reduces the impact of high transportation costs of the factories from the Earth to the Moon. On the Moon the factories produce 100s to 1,000s of times their own mass in LSP components. Table II characterizes LSP Demonstration Bases (Criswell and Waldron 1993). It is assumed that ten years is required to plan the Base and establish it on the Moon. Three sizes of Base are modeled. The absolute costs are less important than the trend of cost versus the total power put in place after ten years of operations. The smallest base, see column #1, installs 1 GWe of power that is delivered to Earth (= 1•10^9 We). A total cost of 60 B$ is predicted as measured in 1990 U.S. dollars. Cost of the LSP production equipment is 12 B$ (=1.a + 1.b). The base is estimated to have a mass of 2,300 tonnes and requires 30 people on the Moon. Electricity sold on Earth at 0.1$/kWe-h generates 4.4 B$ of revenue. Notice the largest base (Column #3). It is scaled to install 100 GWe received on Earth. Overall cost increases by a factor of 4 but sales of electric power increase by a factor of 100. The largest base pays for itself. Cost of LSP production equipment, the mobile units in Figure VII, increases by only a factor of two. The production process will continue after the ten year demonstration. Thus, cost of the delivered energy will continue to decrease. Given the existing world space program, the demonstration base could be established in less than ten years and the production process could be accelerated. Costs of Demonstration Lunar Bases #1 #2 #3 GWe installed over 10 Years 1 10 100 GWe-Yrs of energy 5 50 500 Gross Revenue (B$) (@0.1$/kWe-H) 4.4 44 438 Net Revenue (B$) -56 -47 195 Total Costs (B$) (sum 1+2+3) 60 91 243 1. R&D (B$) (sum a+b+c+d) 42 51 86 a. LPS Hardward (B$)11 11 11 b. Construction System (B$)1 3 11 c. FACILITIES & EQUIPMENT (B$) 5 10 30 d. TRANSPORT (B$) 26 27 35 2. Space & Ops (B$) 17 34 103 3. Rectenna (B$) 0.6 6 55 $/kWe-H 1.4 0.2 0.06 Moon (tonnes) 2,300 6,200 22,000 Space (tonnes) 970 2,700 9,700 People (moon, LLO, & LEO) 30 85 300 Table II. Cost (1990$) of LSP Demonstration Base [Coût (1990$) de base de démonstration de SEL] 4. SCALE AND COST FOR 20 TWe LSP SYSTEM Establishing and maintaining a 20 TWe LSP System is a far larger activity than the LSP Demo Base. Table III gives the key technology and operating assumptions that scale the size of a 20 TWe LSP System (Criswell 1995, Criswell and Waldron 1991). Two sets of assumptions are presented. The first is for an LSP System that could have been initiated in the 1980s if the United States had stayed on the Moon during the 1970s. Both models assume the use of mirrors in orbit about the Moon to illuminate the power bases. This eliminates the need for fields of solar collectors on the far side of the Moon and for power storage during an eclipse. A 1980s-era LSP System would occupy approximately 15% of the surface area of the Moon. Eighty per cent of the area would be the empty area between the solar arrays. Using solar collectors on the far side of the Moon and eliminating the solar mirrors in orbit about the Moon increases the area of the 1980s-style bases to ~25% of the lunar surface. Assuming 2020s operating technology, all demonstrated by advanced systems as of today, reduces the area occupied by the LSP System to 0.16% of the lunar surface. The bold figures indicate the major changes. Advanced LSP bases are completely covered by solar collectors with 35% efficiency of conversion of solar into electrical power.

PARAMETERS SYMBOL BASELINE ADVANCED 1980S ~2020S Scale Factors Total rectenna output at Earth (GWe) Po 20,000 20,000 Construction time (yr) Tc 30 30 Equipment work hours per 24 hours Tw 23 23 Number of power bases (pairs) Npb 12 12 Beam intensity at rectenna center (mW/cm^2) Fb 23 23 Beam wavelength (cm) Lb 10 10 Beam diffraction diameter at Earth (km) Bd 0.2 0.2 Energy Conversion of Sunlight to Solar Cell Output Solar power in free space (W/m^2) Psun 1,370 1,370 Illumination of one cell (geometry) Ng 0.32 0.32 LO mirrors (none = 1, full illum. = Pi) Nm 3.14 3.14 Fill factor (cell ground area/base area) Nf 0.20 1.00 Solar cell efficiency Nsc 0.1 0.35 Ng*Nm*Nf*Nsc*Ntl/Np = = E1 0.64% 35.00% Solar Cell to Rectenna Output Electric power collection effic. (I^{2}R) Npc 0.94 0.99 DC power conditioning (short storage) Npcm 0.96 0.99 Electric to microwave conver. eff.(tubes) Nmw 0.85 0.95Lunar reflector efficiency Nsr 0.98 0.99 Fraction of power into one beam Nbf 0.80 0.90Fraction of one beam toward rectenna Nb 0.95 0.95 Reflector (satellite) efficiency Nsat 0.98 0.98Earth atmospheric transmission Na 0.98 0.98 Antenna efficiency Nrec 0.89 0.98Microwave power conditioning Npce 0.88 0.98Electric grid connection effic. Ng 0.97 0.98 Average system availability Navail 0.95 0.99 Npc*Npcm*********Ng*Navaf = l= E2 39.60% 70.53% Areal Conversion. Eff.(E1*E2 =) E4 0.25% 24.68% Average electric output (W) at Earth per m^2 of lunar base (Psun*E4 =) Pe 3.45 338.18 Conversion eff./unit of active cells = E4/Nf 1.26% 24.68% Area Bases/Area Moon Ab 15.26% 0.16% Table III. Functional Parameters and System-Level Efficiency (1980s and 2020s) 4.1. All Production Equipment Supplied from the Earth Table IV provides estimates of the tonnage of equipment and number of people that must be deployed from Earth over 70 years to produce a set of lunar power bases with 20 TWe of capacity as received at Earth (Criswell 1998a). The system modeling begins by estimating the mass of power plot components, shown in Figure V, required to provide a unit of power capacity on Earth. The mass of photoconverters, buried wires, microwave generators, microwave reflectors, and components and consumables imported from Earth are estimated. The productivity of these types of machinery, their consumables and replacements, and the energy inputs to the various types of equipment were taken from the literature on similar terrestrial operations. Also, the late-1970s studies by General Dynamics-Convair and MIT on the production of components for space solar power satellites from lunar materials were used. The rate of production of the LSP components and the production facilities were calculated for a ten-year ramp-up period and thirty years of full-scale production. At the end of 40 years the 20 TWe LSP System is in place. The system model includes the additional equipment and materials needed to maintain all the bases and rebuild 50% of the power collectors and transmitters between 2050 and 2070.

10• LSP REF. LSP REF. Boot 90% TONNES OF LUNAR EQUIPMENT Micro-manufacturing 3,205,323 250,605 24,361 Hot Forming 1,031,271 103,127 10,313 Beneficiation 321,229 32,123 3,212 Habitats, shops, mobile units 75,057 23,341 22,085 Chemical Refining 246,945 24,941 2,469 Gather & eject to orbit 43,185 4,383 438 Excavation 83,115 831 80 Cold Assembly 2,776 278 28 TOTAL (tons) 5,012,039 442,630 62,915 NUMBER OF PEOPLE Moon 55,915 4,717 436 Lunar Orbit 4,986 468 59 Earth Orbit 5,010 443 63 COST OF EQUIPMENT & PEOPLE (77$) FOR 20 TWe &

1,000 TWe-y to Earth 19.5 T$ 1.75 T$ 0.26 T$ ENERGY ENGINEERING COST ($/kWe-h) Reference Rectenna (7.9 T$) 0.0106 0.0037 0.0037 Reflective Rectenna (0.82 T$) 0.0078 0.001 0.0004 Table IV. Life Cycle Cost for Heavy LSP, Reference LSP, and Bootstrapped LSP Column 3 of Table IV shows that over the 70 year life-cycle the manufacturing of solar converters and similar products requires approximately 57% of the equipment mass or ~250,000 tonnes. Habitats, shops, and other support facilities require approximately 23,000 tonnes of equipment to support 4,700 people. People cannot work on the surface of the Moon for long periods due to solar and cosmic radiation. All surface operations are automated and/or controlled by people in habitats, shown in the left side of Figure V. People are protected by at least three meters of lunar soil. Lunar employees will support equipment maintenance and repair, logistics, remote operations/monitoring, and life support. The engineering cost is presented in 1977 US dollars. For simplicity, Table IV does not include financing cost. See Criswell and Waldron (1990, 1991) for a discussion of internal rate of return. The engineering cost of all lunar and space related activities, including launch and manufacturing on Earth, is 1.75 T$ (1 T = 1•10$_{12}$). NASA and DOE, in the late 1970s, estimated the cost of building the rectennas on Earth. Those studies were used to calculate the engineering cost of 20 TWe of rectennas at 7.9 T$. Notice that rectenna construction and operation is five times greater than the cost of all the lunar-related operations. The 20 TWe LSP System will deliver 1,000 TWe-y of energy over the life cycle of 70 years at an average cost of 0.0037 $/kWe-h (0.37 ¢/kWe-h). The power bases can be maintained indefinitely at far lower cost than is required to develop and construct them. On Earth, rectennas that utilize reflective concentrators will reduce the number of expensive rectifiers and also be less subject to mechanical loads from wind, rain, and ice. Reflector rectennas might reduce the rectenna cost to 0.8 T$ and the engineering cost of energy to 0.001 $/kWe-h (0.2 ¢/kWe-h). Over time the cost of LSP energy should decrease. The results in Table IV assume the cost of launch from Earth to orbit is 470 $/kg. Again, this cost is in 1977 US$. Increasing the cost of Earth-to-orbit transportation to 5,000 $/kg significantly increases the up-front cost of building LSP REF. Life-cycle engineering cost increases to ~5.2 T$. However, the life-cycle engineering cost of LSP REF energy increases by only ~20% (Criswell 1995). The LSP systems model assumes the extensive use of lunar-derived propellants for the transport of people and high-priority cargo between Earth orbit, Lunar Orbit, and the surface of the Moon. Solar electric propulsion is used for the transport of cargo from Earth orbit to Lunar orbit. Less productive manufacturing equipment, column one of Table IV, with lower output will increase the size and cost of the lunar and space operations. The second column in Table III assumes that all the production machinery must be ten times more massive than for LSP REF (the fourth column) to achieve the same output of LSP components. Total tonnage of production machinery on the Moon increases by a factor of 11 to 5 million tons. Engineering life-cycle cost increases to 19.5 T$ over the 70 years. However, the engineering cost of the electric power on Earth increases by only a factor of three, to 0.0106 $/kWe-h, for the Reference Rectenna. In the 1970s NASA and DOE studied the deployment of large solar power satellites (SPS) from Earth to geosynchronous orbit. These extensive studies projected that a 0.01 TWe SPS would have a mass, including supplies and repairs over 30 years, of ~150,000 tons. This implies that 150,000 tonnes of SPS mass deployed from Earth could provide 0.3 TWe-y of energy or a specific energy output of 500,000 tonnes/TWe-y. Recent studies indicate slightly higher specific mass for several different types of SPS (Feingold et al. 1997). The LSP REF System provides 1,000 TWe-y of energy for 443,000 tons over 70 years or a specific energy output of 442 tonnes/TWe-y. For delivery of energy to Earth the LSP REF is projected to be ~1,000 times more efficient in its use of mass deployed from Earth than an SPS. The 10•LSP REF System has a specific energy output of 5,000 tonnes/TWe-y and is thus still ~100 times more efficient in the delivery of power to Earth per tonne of machines, people, and supplies deployed from Earth than is an SPS. 4.2 Manufacturing Production Equipment Iron, aluminum, industrial glasses, ceramics, other metals, and process chemicals are extracted from the lunar soils to make the components of the LSP System depicted in Figure V. These lunar industrial materials can also be used on the Moon to manufacture a large fraction of the mobile factories [#4, #5], shops [#6], and habitats [#6] shown in Figure V. This process is often called "bootstrapping." Within our terrestrial economy it is simply called "local manufacturing." Of course, the production machinery in Figure V must be designed for optimal use of parts manufactured on the Moon. The bootstrapping equipment and operations will be fully refined during the demonstration phase. The last column of Table IV assumes that 90% of the mass of production equipment is "booted" from lunar materials. The model is adjusted for the additional people needed to conduct the extra level of manufacturing. The model is also adjusted for a higher level of support from Earth in the form of remote monitoring and tele-operation. Only 63,000 tonnes is shipped to the Moon over the period of seventy years and yet it enables the delivery of 1,000 TWe-y to Earth at a specific energy of 63 tonnes/TWe-y. Engineering cost, in 1977 US $, of electric energy could decrease to 0.0004 $/kWe-h (or 0.04 ¢/kWe-h). Refer to Criswell (1998a) for additional details. Bootstrapping significantly decreases mass of facilities in orbit about the Earth and the Moon and the number of people. Sixty-three people work at the support station in orbit about Earth. This is only 10 times the number of people planned to be on the International Space Station in 2005. Bootstrapping enables the exponential growth of the LSP power bases on the Moon. Refer to Figure VI. Each cross-hatched block near the top represent a complete set of mobile factories such as shown in Figure V. Mobile Factory set #1 begins producing power plots, the clear blocks at the bottom, at a steady rate. Once established, each power plot continues to convert solar power into electric power. After four units of time, the first Bootstrapping facility is deployed to the Moon. It then manufactures 90% of Mobile Factory #2 from lunar materials. Thereafter, Mobile Factories #1 and #2 produce two new power plots every unit of time. Power capacity and energy output grow exponentially. Bootstrapping facilities are brought to the Moon until sufficient manufacturing capacity is established on the Moon to provide 20 TWe by 2050. Once full-scale production of power is achieved, many of the Bootstrapping facilities can be directed to providing a wider range of new lunar goods and enabling new services. 5. GLOBAL AEROSPACE CAPABILITIES It is now technically and operationally reasonable to consider LSP demonstrations and, soon thereafter, large scale commodity production of power from the Moon. Figure VII reminds us that, using the crude technologies of the 1960s, the United States sent 12 people to the Moon (Apollo 11, 12, 14, 15, 16, and 17), 9 more to orbit about the Moon (Apollo 8, 11, 12, 14–17), and three about the Moon (Apollo 13). They all returned safely to Earth. The Lunar Rover shown in Figure VII was designed, developed, tested, and delivered to the Moon in only 33 months. Like the Lunar Rover, all the production and bootstrapping processes depicted in Figure V can be developed and demonstrated on Earth to a very high level of operational fidelity. The Apollo- and Soviet-era lunar programs and the worldwide Post-Apollo lunar research program, of well over 1 billion dollars of peer reviewed research, provide the essential knowledge of the common lunar resources. On-going lunar research has now mapped the major mineral and chemical composition of the entire surface of the Moon.

OF BOOTSTRAPPING FACILITIES-> 1 2 3 4 # MOBILE FACTORY SETS -> 1 2 3 4 6 8 11 14 19 MOBILE FACTORY SET 1 1 PRODUCTION---> 1 1 1 1 1 1 <--- DEMONSTRATIONS 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 POWER PLOTS 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 # POWER PLOTS-> 1 2 3 4 6 8 10 13 16 20 26 34 45 59 77 ENERGY OUTPUT--> 1 3 6 10 16 24 34 47 63 83 109 143 188 247 324 Figure VI. Exponential Growth of Power Plots and Energy Output The International Space Station, Figure VIII, forcefully reminds us that most of the major industrial nations now cooperate to explore and exploit the resources of space. The International Space Station is a long-term cooperative program of the United States, the European Space Agency and several of its member states, Japan, Russia, Canada, Brazil, and others. The International Space Station, though still under construction, is now operational. It can be seen at selected times on clear evenings and mornings as the brightest star in the sky. Log into the NASA-JSC web site for sighting opportunities organized by major cities or by longitude and latitude.
http://spaceflight.nasa.gov/realdata/sightings/index.html

The International Space Station program provides the international level of cooperation, technology, and operating systems that enable a quick return to the Moon. A permanent international lunar base can be established to conduct industrial research and development and foster economic development of the Moon. In addition, nations and private companies now have far more space launch capacity than is needed to establish and support a major lunar base. An international lunar base for industrial research and development can be established within the existing cash flow of the major civilian space programs as spending on the construction of the International Space Station decreases. Finally, automation and remote operations are a normal component of terrestrial industry. This is especially true of mining and oil/gas extraction companies. Major off-shore platforms use and advance most of the critical capabilities, such as underwater robotics and complex operations and logistics, that will be employed on the Moon and in space to build and maintain the Lunar Solar power bases. Much of the human work on the Moon can be adapted for tele-operation and supervisory control from Earth. Now is the time to establish the next international space program – an international base on the Moon to demonstrate the production and operation of the Lunar Solar Power System.

6. LSP SYSTEM FINDINGS AND RECOMMENDATIONS The Lunar Solar Power System has been recommended for serious consideration by national and international panels and aerospace working groups. Several are referenced in Criswell (1988). The United States National Science Foundation and the National Aeronautics and Space Administration co-hosted a workshop on the construction of space- and lunar-based solar power systems (Bekey et al. 2000). In particular, the group found that solar electric power from facilities on the Moon can benefit the economy of Earth. Lunar manufacturing is possible. The arguments for the Lunar Solar Power System are compelling. Of course, independent verification is needed. The fabrication of solar cells on lunar simulates in a vacuum is demonstrated (Ignatiev et al. 2000). It is anticipated that cells manufactured in the lunar environment will, at large scale production, be less expensive than cells manufactured for use on Earth. Fabrication and assembly of lunar-derived components

into a Lunar Solar Power System is possible. The production systems will be advanced, compared to those now used on Earth, but development pathways can be seen. It is reasonable to expand production capacity on the Moon through the use of lunar materials. Findings 1. Solar-electric commercial power provided to Earth from space or lunar-based facilities can benefit the economy of Earth. (Recommendations 1, 5) 2. Lunar manufacturing is possible. In some cases lunar manufacturing may be superior to manufacturing on Earth because the primary products are better suited to the lunar environment and resources. Essentially all materials and energy needed to produce solar power systems on the Moon and systems to beam the power to Earth are available on the Moon. (Recommendations 2, 3, 4, 5, 9) 3. Machines and components deployed from Earth can be used to make power components from lunar resources, producing much greater installed power than can be obtained from an equal mass of power equipment deployed from Earth. (Recommendations 2, 3, 4, 6, 7)

Figure VII. Moon, Astronaut, and Rover 4.

If lunar materials can also be used to fabricate part of the production equipment, even greater leverage can be obtained. The complete fabrication of production equipment from lunar materials can lead to a state of near self-replication, or bootstrapping, and very rapid growth of installed power transmission capacity on the Moon. (Recommendations 4, 5, 9) 5. The Lunar Solar Power System concepts presented by Dr. David R. Criswell and Dr. Robert D. Waldron are compelling but require independent validation. (Recommendations 1, 5, 8) 6. Building solar cells on the Moon, as described by Dr. A. Ignative, should be inherently less costly than on the Earth. On Earth the deposition/implantation processes must be operated within vacuum systems that are expensive to build, operate, and maintain. The terrestrial cells must be made to resist degradation by air, water, and other chemical and biological agents. Terrestrial cells must be mechanically rugged. In comparison, the cost of lunar solar arrays are reduced by producing the solar converters in the lunar vacuum. Sunlight can be used directly for evaporation of constituents. The solar converters and structural components are very much reduced in mass through such options as depositing solar cells directly on the lunar surface. (Recommendations 2, 6, 7, 8) 7. Lunar production systems can be teleoperated/supervised from Earth. As materials extraction, fabrication, and assembly processes become more complex, the autonomous robotic systems should provide greater efficiencies. Both teleoperated and robotic systems require development for all phases of the lunar and space operations. (Recommendations 3, 7, 9) 8. A certain level of robotic cooperation is needed in production and operation of the Lunar Solar Power System. The required level of robotic intelligence that is needed has not been determined but developmental pathways can be seen. (Recommendations 3, 7, 9) 9. The expansion of productive capacity on the Moon, denoted as self-replication or bootstrapping, derives from human expertise and information supplied from Earth to the productive machines on the Moon. In this manner the lunar manufacturing can leverage the skills and resources of terrestrial industry and attract terrestrial manufacturing companies to the development of space/lunar power and other systems. (Recommendations 4, 5, 9) The workshop developed nine recommendations for the evaluation and demonstration of the LSP System. The recommendations include very rough estimates of the investments and time required for the key tasks. Many can be done in parallel. This minimizes the time required to establish a growing Lunar Solar Power System. Recommendations 1. Independently verify the Lunar Solar Power System designs as proposed by Dr. David R. Criswell and Dr. Robert D. Waldron. (Findings 1, 5) Evaluation 5 M$ 1 year 2. Demonstrate on Earth the viability of making useful solar conversion systems from simulated lunar materials and test the systems. Demonstrate at least two different solar conversion systems that offer lower cost than terrestrial systems. Demonstrate key "unit processes" such as excavation and hauling, extraction of raw materials (Si, Fe, TiO_2, etc.), materials and logistics, solar array production, test and verification, and repair and removal. (Findings 2, 6) Laboratory Demonstrations 10 M$, 2 years Prototype Production 50 M$ 4 years Figure VIII. International Space Station [Internationale Station spatiale]

3.. Demonstrate on Earth the production, primarily from simulated lunar materials, of the following functional elements of a power plots of the Lunar Solar Power System: systems to collect solar electric power; conversion of the solar electric power to microwaves (at least two approaches); phasing of the microwave sub-beams to form multiple independently controlled beams; and, forming large synthetic apertures by passive and/or active reflectors. Unit processes to be demonstrated include: production of glass and ceramic components; production of solar-to-electric components; fabrication of structures; production of microwave sources; production of microwave-reflective meshes; and, teleoperated and robotic production, assembly, and emplacement. Demonstrate the emplacement and operation of the forgoing components and system. (Findings 2, 3, 7, 8) Laboratory Demonstrations 20 M$ 3 years Prototype Production 100 M$ 5 years 4. Identify key unit processes, if any, that must be demonstrated under conditions of lunar-gravity and/or lunar-vacuum. Demonstrate these particular unit processes early on in orbit about Earth using unmanned satellites, the Shuttle, and/or International Space Station. Identify unit processes, if any, that must be demonstrated on lunar materials available from the Apollo collection or that must be done on the Moon. (Findings 2, 3, 4, 9) On-orbit Demonstrations TBD 3 years Apollo lunar sampels TBD 2 years On the Moon TBD see recomm's #8 and #9 5. Develop life-cycle models for the development and operation of the Lunar Solar Power System. Make the models available and refine the models. Consider all aspects of the life-cycle (ex. design, demonstrations, prototype implementation, economic and environmental effects and benefits, organizing, financing, governing, full-scale construction, maintenance, and removal). Examine worldwide science and technology activities for practices, devices, and systems applicable to Lunar Solar Power System demonstrations, operations, and implementation. (Findings 1, 4, 5, 9) On-going Program 3 M$ 8 years 6. Test representative products, assemblies, components, and systems at the prototype and pre-production levels. There will be considerable phasing and overlap of research, development, and demonstration projects and programs. (Findings 2, 3, 6) Prototype 100 M$ 6 years Pre-production 500 M$ 6 years 7. Conduct three to four competitive demonstrations of full scale production units within sealed environments on Earth (vacuum and inert atmospheres). For example, deploy complete sets of mobile production/assembly units via a C-130 size cargo aircraft to remote desert sites. From a remote control site direct the production/assembly units to enter large pressure-supported plastic domes. Each dome is transparent, filled with an inert atmosphere, and the floor is covered with simulated lunar soils and rocks. Use solar power that enters the dome during the day to power the production/assembly units. These units manufacture the major components and assemble and maintain representative "power plots" of Lunar Solar Power System. The power plots constructed in the domes are phased together to direct beams to local receivers, receivers in space, and receivers (signal-level) on the Moon. (Findings 2, 3, 6, 7, 8) Demonstration 2 B$ 4 years 8. Land three to five "Surveyor-class" unmanned spacecraft on the Moon. The landers carry microwave transmitters that are operated together to direct signal-level beams to research receivers on Earth. The landers demonstrate the Moon as a stable platform for the transmission of narrow beams to Earth and to receivers in orbit about Earth. The landers also support a wide range of tests of solar cells and other components for the Lunar Solar Power System. (2, 5, 6) Landers 1 B$ 5 years 9. Seek innovative methods of reducing the mass of production equipment and supplies/consumables that must be transported from the Earth to the Moon to build the Lunar Solar Power System and support logistics between the Moon and Earth. Evaluate production systems (e.g. power, chemical reactors, mobility systems including excavation and hauling) designed for being constructed on the Moon primarily from lunar materials. Aggressively explore and demonstrate the feasibility of "starting kits" and boot-strapping of production equipment from lunar materials. (Findings 4, 8, 9) Design and Demo Explorations 50 M$/year 5 years Demonstration (Earth and Moon) 500 M$/year 7 years

The World Energy Council challenges us to provide 10 billion people by 2050 with ~67 TWt of low cost and clean commercial power by 2050 (WEC 2000). This is equivalent to 20 – 30 TWe of electric power. This power rich world of 10 billion people will require ≥7,000 TWt-y per century, or 2,000 – 3,000 TWe-y, of commercial energy. These levels of power and energy are far beyond what can be supplied by conventional power systems. The sun is the only reasonable power source for a prosperous world. It contains adequate fuel, is a functioning fusion reactor that does not have to be built and operated, and it retains its own ashes. The challenge is to build the transducer that can extract this power and deliver it to consumers on Earth at a reasonable cost. The Moon receives 13,000 TWs of dependable solar power. The Lunar Solar Power System, built on the Moon, is the transducer. It can deliver net new power to consumers on Earth that is independent of the biosphere and clean. The Developing Nations can afford LSP electricity. LSP electricity can accelerate the economic growth of all nations. Net new LSP electric power enables all nations to produce and recycle their goods and consumables independent of the biosphere. Transportation and services can be powered without consuming or affecting the biosphere. The WEC–2000 challenge can be achieved by 2050.

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