GLUC-2010-5745

ENABLING SUSTAINABLE & RAPIDLY GROWING GLOBAL WEALTH BY IMPLEMENTING THE LUNAR SOLAR POWER (LSP) SYSTEM

Dr. David R. Criswell
University of Houston, Houston, Texas (USA)
drcriswell@comcast.net

ABSTRACT

In 2008, Earth's commercial power systems provided ~225 watts of thermal power per person (225 Wt/person) to its 6.67 billon people. This totals to ~15 terawatts of thermal power (15 TWt = $15 \bullet 10^{12}$ Wt = 225 Wt/person • $6.67 \bullet 10^{10}$ people). However, they need the equivalent of 6,000 to 7,500 Wt/person of sustainable power for sustainable prosperity. So, by 2050 ten billion people will need ~75 terawatts of thermal power. Existing power systems are massive and move so much mass as mining wastes, coal, oil, natural gas, biomass, CO_2, ash and spent radionuclide's, water, air, and other forms that they disrupt and contaminate the biosphere locally and globally and consume 10% to 15% of the gross world product (40 T$ GWP by Y2000 in U.S. $). Both the International Panel on Climate Change and the commercially oriented World Energy Council repeatedly challenge world policy makers to enable a new sustainable global commercial power system that provides abundant and affordable electric power. Three Wt now generate ~1 We of electric power. By 2050 almost all power will be delivered electrically and 20-to-30 TWe can enable a prosperous world of 10 billion people (20 TWe = 2,000 We/person • $10 \bullet 10^9$ people).

The sun dependably illuminates our Moon with 13,000 TWs of solar power or ~650 times the 20 TWe needed by a prosperous Earth. The LSP System uses solar-powered bases built on the Moon to collect ≤1% of this sustainable power to dependably supply receivers on Earth with safe microwave power beams (≤ 230 We/m^2 or ≤ 20% the intensity of noon sunlight). The 20 TWe is output on Earth from ~100,000 km^2 of receivers and then into electric power grids all about the Earth without significant movement of mass within the biosphere. The LSP System can pay for its own growth after an investment of ~500 B$ ($500 \bullet 10^9$ $). Start-up, over 15 years, costs less than one year of the 2009 U.S. DoD budget.

Since 1980 Japan and Western Europe have produced ~42 T$ of gross domestic product (GDP) from 1 terawatt-year of electric energy (1 TWe-y). By 2050 a 20 TWe LSP System can enable a sustainable 840 T$ GWP (Y2050) or >84,000 $ GWP/person. Additional clean LSP electric energy can be used to extract all industrial carbon dioxide from Earth's atmosphere. A >10 T$ GL(lunar)P is possible within the 21st century.

GLOBAL WEALTH & ELECTRIC ENERGY

Both the International Panel on Climate Change and the commercially oriented World Energy Council have repeatedly challenged world policy makers to enable a new sustainable and affordable global commercial power system within the first part of this century (1, 2, 3). However, they and most government, private, and non-profit organizations tend to extrapolate the growth of commercial power from the capabilities of existing systems. They do not provide a systematic method by which to estimate the minimum commercial power needed to sustainably support Earth's growing human population independent of our biosphere and then use those projections to identify and implement the required power system(s).

Why is commercial electric power so important? Electricity, as opposed to chaotic thermal energy, is potentially the most effective source of useful work in final application. This is because an electric force vector, technology permitting, can be directed precisely, from the macro- to the atomic level, to deliver useful work, and thereby, clean new wealth and sustainable economic activity. Since commercial electric power was introduced in the 1880s an increasing fraction of primary thermal fuels (wood, coal, natural gas) and natural mechanical power (hydro, winds, tides, etc.) has been converted into electric power. In 2006 the averaged world electric power output was 1.3 TWe from fossil fuel, 0.3 TWe from fission, 0.33 from hydroelectric, and only 0.04 from geothermal, terrestrial solar, wind, wood, and waste (4).

From 1980 to 2002, Western Europe and Japan output ~4.80 $ GDP per kilowatt-electric hour of consumed electric energy (4.80 $ GDP/kWe-h or 42 T$ GDP/TWe-y). The United States and the world averaged ~2.95 $ GDP/kWe-h, and the Developing Nations only 1.56 $ GDP/kWe-h (5). This is why rapidly developing nations such as China make increasing production of electric energy and expanding their electric infrastructure among their highest national priorities.

Approximately 75 TWt is required to output 20 to 30 TWe (6-Chaps 2 & 9). By 2002, ~38% of all primary thermal energy in the U.S. was converted to electricity. The corresponding global trend implies a 100% electric world by the middle of this century. In 2000, ~ 40 T$ GWP/y was achieved. By providing the world 20 TWe of sustainable electric power and enabling the demonstrated Western European level of productivity, ~840 T$ GWP/y could be achieved.

GLOBAL POWER CHALLENGES

In 1976 H. E. Goeller and A. M. Weinberg provided a systematic method for estimating the commercial power needed by human civilization to allow it to live sustainably. They required the commercial power to be from a carbon-free source and adequate to:

- Obtain all major non-renewable material resources from their average crustal abundances and the ocean
- Recycle cleanly all goods and water
- Support sustainably all agricultural, industrial, residential, and transportation activities

Economic Independence from the Biosphere

They estimated that approximately ~7,500 watts of commercial thermal power per capita (=7.5 kWt/person) would be required. Ten billion people ($10 \cdot 10^9$) would require 75 TWt. A U.S.-style economy would require twice as much power per person (7, see page 688 column 1).

Electricity is the primary product of fossil and nuclear thermal power stations. A thermal power plant releases ~2/3rds of its input power as waste heat to the biosphere. Releasing the waste heat from a 75 TWt fleet of coal or nuclear plants presents major engineering and environmental challenges. Using river or ocean water on a once-through basis to remove the waste heat requires $\sim 3 \cdot 10^{13}$ tons/y. This approaches the $3.8 \cdot 10^{13}$ ton/y flow of all the world's rivers. Even the make-up water for use in cooling towers, at $\sim 1.3 \cdot 10^{12}$ tons/y, is enormous (wiki/cooling_tower_systems).

Biosphere-Dependent Fossil Fuel Power Systems

Goeller and Weinberg were strongly motivated to seek a carbon-free source of power knowing that a 75 TWt fleet of coal-fired power stations would consume the order of $1 \cdot 10^{11}$ tons/y of coal. However, they did not place that number in a context directly relevant to Earth's biosphere.

Burning fossil fuel actually yields useful energy by "mining" the net energy from the chemically free oxygen molecules of our modern atmosphere. Earth's chlorophyll-based plants generate approximately 100 TWt-y of net new combustible dry mass each year equally from the oceans (consumed quickly at sea) and land (primarily wood). The plants use solar power and photosynthesis to convert water and CO_2 into new plant life and also release $\sim 3 \cdot 10^{11}$ tons/y of new oxygen molecules (6-chap. 9, 8). A 75 TWt fleet of coal-fired power stations would consume over 70% of new oxygen in direct competition with all animal life. The fossil carbon power fleet would also output $3 \cdot 10^{11}$ tons/y of CO_2 or 15 times the output of all industrial CO_2 in 2004 (9).

Kerogen (i.e. - brown stuff) sediment and sedimentary rocks are the source of oil and natural gas and includes coal, oil shale, methane hydrates, and thousands of other types of carbon-rich remains of earlier biosphere/oxygen cycles. Geologists and mining engineers are increasingly adept at obtaining useful fuels from progressively lower grades of the $\sim 15 \cdot 10^{15}$ tons of kerogenic carbon (10). Since there are only $1 \cdot 10^{15}$ tons of oxygen in our modern atmosphere it is technically conceivable that an exponentially growing fossil fuel system could mine most of our atmospheric oxygen. Earth is a closed spacecraft. Its passengers must become aware of the biosphere's operational limits.

Nuclear Fission Reactors

Dr. Weinberg estimated that 15,000 five GWt reactors could supply the 75 TWt. Assuming a reactor lifetime of 30 years, 10 new reactors would be built every week as 10 old reactors are retired. For perspective, today 439 commercial reactors collectively output ~1 TWt.

A 75 TWt fleet of light water reactors would ingest ~4,200,000 tons/year of natural uranium and thus reduce fuel mass flow through the biosphere by a factor of 84,000 compared to coal. However, proven continental reserves of uranium would last less than 4 years. Uranium (^{238}U 99.28% & ^{235}U 0.72%) extracted from seawater would last ~1,000y. Uranium extracted with 100% efficiency would require processing $1.3 \cdot 10^{15}$ tons/y of seawater or 35 times the flow rate of all the rivers on Earth (11). The entire ocean would be filtered once over that thousand years. Ocean currents are driven by ~3 TWm of mechanical power supplied by Sun-Moon tides, surface winds, surface solar heating, and high latitude surface cooling. The pumping power to extract the uranium would exceed the natural mechanical power now driving the oceans. The vertical and horizontal thermal profiles of the ocean and ocean currents would be drastically changed (6 - chap. 9).

A light-water reactor burns ~1% of its uranium fuel. In principle, a breeder reactor can burn ~99% of uranium and thorium fuels and maintain a 75 TWt economy for many thousands of years Fission breeding reduces fuel and mining flows on land and sea by a factor of ~100, but still requires moving matter on scales comparable to the above natural matter flows of the biosphere. The breeder system also maintains an enormous inventory of plutonium that can be converted into nuclear weapons (6 - chap. 7, 11).

LUNAR SOLAR POWER (LSP) SYSTEM

A new sustainable commercial electric power generation system that does not damage the Earth's biosphere must meet these requirements:

1. Eliminate fuel gathering and transport and burning, ash disposal, oxygen consumption, CO_2 production, and their cost

2. Eliminate terrestrial power plants and ancillary facilities and their cost

3. Provide abundant electric energy that is independent of the biosphere and is affordable

A Lunar Solar Power System, built on the Moon from the common lunar materials, can meet these three requirements (6 - Chap. 9, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23).

The sun dependably illuminates the Moon with 13,000 TWs of solar power. The LSP System, shown in Figure 1, consists of power bases, located on the east and west limb of the Moon as seen from the Earth (note spot on the left limb of Moon). The power bases convert sunlight to electricity and then into low-intensity beams of microwaves. The beams illuminate the power receivers (rectennas) on Earth that output commercial power to local and regional electric power grids. The lunar power bases need collect less than 1% of the solar power that the Moon intercepts to dependably provide rectennas on Earth with more than 20 TWe.

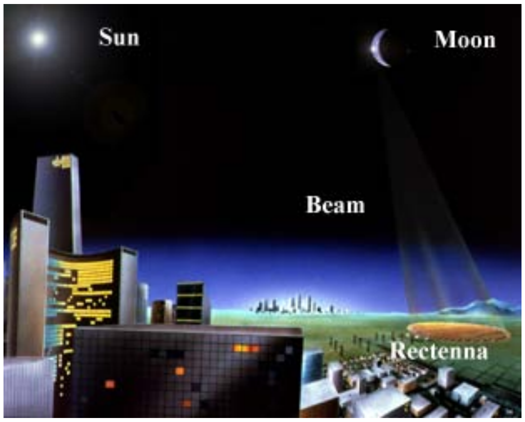

Figure 1: LSP System Viewed from Earth with a Power Beam from the Moon Feeding Microwave Power to a Power Receiver (Rectenna)

The power beams, as shown in Figure 2, are projected directly from the Moon to the rectennas that can view the Moon or by redirector satellites in orbit about Earth to rectennas that cannot view the Moon directly. The microwaves, ~10 cm to 13 cm in wavelength or ~3 to 2 GHz, dependably pass through all atmospheric conditions and provide electric power without movement of mass through the biosphere, without power plants, and power that is independent of the biosphere.

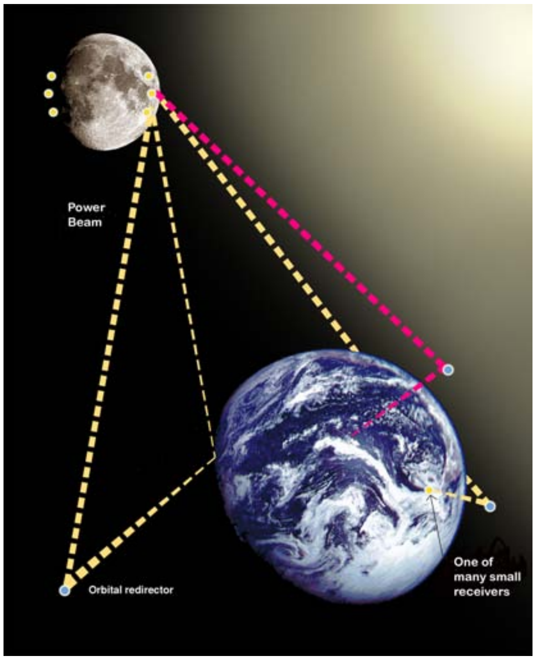

Figure 2: Sun–Moon–Earth Lunar Solar Power System

The rectennas are safely illuminated at a maximum of ~230 We/m^2 or ~20% of noon sunlight. They output ~200 We/m^2 and ~30 Wt/m^2 of waste heat. A rectenna can be ~90% transparent to sunlight. Areas under a rectenna can be whitened and reflect, averaged over a year, more solar power to space than the rectenna receives as microwaves. Thus, rectennas can be thermally neutral. Only 100,000 km^2 of rectennas would be required to dependably output 20 TWe of virtually massless pure electricity that does not contaminate the biosphere nor contribute directly or indirectly to global warming.

Rectennas would occupy much less area per unit power output than all other renewable systems. Stand-alone terrestrial solar and wind installations provide only 2 to 20 We/m^2 of delivered power because they are hostage to the biosphere, and therefore require vast power storage and transmission systems. These global terrestrial systems have the potential to create economic, political, environmental, and even military conflicts. A 20 TWe globally distributed array of terrestrial solar panels that feed global transmission lines and power storage facilities (45 days backup) would occupy over 2,000,000 km^2 as compared to the 100,000 km^2 for the LSP rectennas (6-Chap. 9, 14, 19).

Also, rectennas can be placed over productive agricultural and grasslands, deserts, shallow fisheries, contaminated areas, and industrial parks. Humans and other life can safely enter a beam and adsorb the equivalent of less than 0.4% of noontime sunlight. However, almost all life will be excluded from a beam by a perimeter fence about each rectenna. Microwave power will be blocked from the area under the rectenna by the rectenna's elements, and additional electrical screening can be added. The microwaves scattered by a 20 TWe LSP System into the general environment can be less intense than the light of a full Moon, which is far less than that associated with wireless phones.

In 2008 the U.S. average retail cost of electricity ranged from 0.056-to-0.29 $/kWe-h. The wholesale cost was ~50% of retail (EIA Electricity U.S. Data). LSP electricity can cost less than 0.001 $/kWe-h wholesale when LSP capacity exceeds 1 TWe. Using the electricity from its own rectennas, any region or nation can sustainably produce almost all its essential goods from local material resources and through recycling. The local rectennas can also power services. No nation will need to be dependent on other nations for fuel, clean water, agricultural chemicals, or other commodity items critical to its sustainable prosperity.

Power bases on the Moon will be constructed from the local lunar materials (24, 25, 26, 27). Figure 3 illustrates a few demonstration power plots located within one of the LSP power bases. Mobile (#4, #5) and fixed (#6) factories, shops, and habitats are transported from the Earth to the Moon. These fixed and mobile factories then make the LSP power bases from the local lunar materials. The factories produce hundreds to thousands of times their own mass in products. Production on the Moon ultimately averages down the cost of transportation from the Earth to the Moon to a reasonable cost per unit of power-base component.

After transport from Earth to the Moon of the initial mobile and fixed factories and habitats, lunar industrial materials can also be used on the Moon to manufacture a large fraction of the additional production units. This process is called *bootstrapping*. Using bootstrapping, detailed systems engineering models reveal that

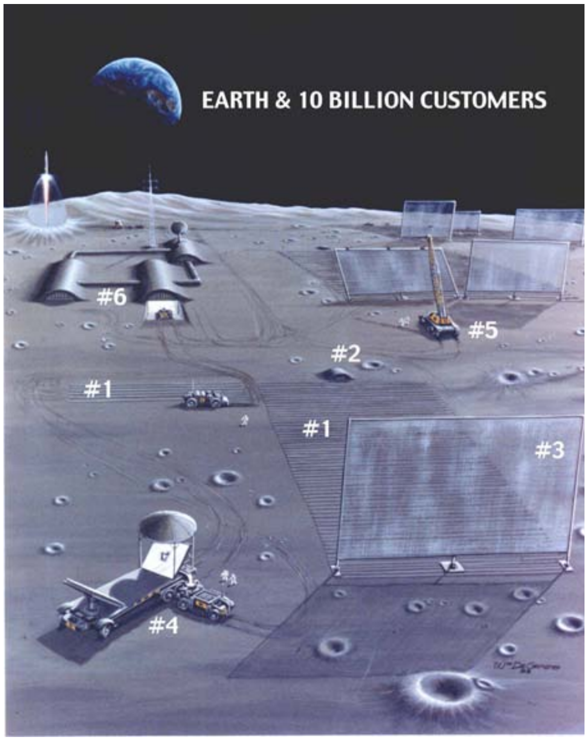

FIGURE 3: LSP Demo Base: Multiple Power Plots (Arrays of Solar Converters #1, Microwave Transmitter #2, and Microwave Reflector #3), Set of Mobile Factories (#4) & Assembly Units (#5), and Habitat/Manufacturing Facility (#6)

one kilogram of materials from Earth enables delivery of ~140,000,000 kWe-h of electric energy to Earth. By comparison, natural uranium burned once in a light-water reactor delivers ~80,000 kWe-h. Burning one kilogram of oil with the oxygen of Earth's atmosphere provides only ~12 kWe-h.

TERRESTRIAL GLOBAL POWER SYSTEMS' MASS EFFECTIVENESS

As shown in Table 1, conventional solar, hydroelectric, fossil, and nuclear power systems not only process enormous flows of mass through the biosphere but are themselves extremely massive per unit of delivered electric energy (tons/TWe-y) and are relatively short lived. Therefore, they are expensive to construct and maintain, environmentally intrusive, and output expensive electric energy (6-Chap. 9, 14, 19, 28, 29).

The U.S. DoE examined a stand-alone terrestrial solar power installation that consisted of 16.5% efficiency solar cells operating under 18-to-1 solar concentrators (Table 1: *1.*). They assumed 2 hours of battery power storage each day. The total mass of the PV arrays, batteries, supporting structure, and foundations were calculated. The system required $\sim 2 \bullet 10^{8}$ tons of equipment to output 1 TWe-y of energy. This system takes over 20 years to pay back the energy needed to construct it. As noted earlier, stand-alone terrestrial solar and wind power systems must be scaled up in area and electrical capacity, provided with global power lines, months-long power storage, and be very carefully managed to output dependable power. Even then a large volcano, dust storms, and other events within the biosphere or political-sphere can disrupt the power for an indefinite time.

Grand Coulee Dam has a mass of ~20,000,000 tons and an average output of 0.0023 TWe (*2.*). Over the next 100 years it could output 0.23 TWe-y. This implies $\sim 9 \bullet 10^{8}$ tons of equipment to output ~1 TWe-y. Up-river silting, political objections, and major floods and seismic events limits a dam's useful life. Global hydroelectric resources are projected to supply ≤1 TWe of averaged power (30).

Nuclear-fission light-water reactors have massive foundations, containment vessels, and facilities and are only 50% more mass efficient than Grand Coulee (*3.*). They pay back their construction and maintenance energy in 1.3 years. But, like coal, they consume the non-renewable uranium. The considerable mass of short and long-term nuclear waste storage facilities is not included.

A coal-fired power plant, including the mining equipment and unit trains, requires only 25% the operating mass of a light-water reactor (*4.*). However, it consumes half the mass of Grand Coulee every year in coal for the same averaged power output. A 20 TWe world would consume ~6,600 Grand Coulees of coal per year. This includes the additional coal burned for mining, transport, and ash management – but not for CO_2 sequestration.

The LSP System rectennas on Earth use ≤15% of the mass on Earth of a comparable coal plant (*5.*). The rectennas (Figure 1) receive the power as an inward flow of massless photons. The

	Power System	System Lifetime (y)	Tons per TWe-y	Electric Energy Payback (y)
1.	Terrestrial PV(16%, 18•Sun, 2hr batteries)~	30	190,000,000	>20
2.	Hydroelectric (G. Coulee, 2.3 GWe Avg.)	100	91,600,000	0.7
3.	Light-Water Reactor	30	40,100,000	1.3
4.	Coal plant with mining and unit trains	30	10,000,000	1.3
5.	LSP Earth Rectennas (concrete supports)	30 (build-up)+50	1,500,000	0.33
6.	LSP Earth Rectennas (electronics and wiring)	30 (build-up)+50	15,000	0.02
7.	LSP (1980s tech., Moon & LLO components)	30 (build-up)+50	1,200,000	99% direct solar
8.	LSP (1980s tech.) (equipment from Earth)	30 (build-up)+50	300	0.1

Table 1: Large Power Systems - Lifetimes, Mass Efficiency (Tons/TWe-y), Electric Energy Payback Time (y)

electrical and electronic components add only ~15,000 tons/TWe-y (6.). Better rectenna design can greatly reduce the mass of support structures.

The LSP System differs from all terrestrial power systems in its effects on the Earth. The reservoirs behind hydroelectric dams, farming for biomass, and large solar arrays change Earth reflectance, usually decreasing it and increasing the waste solar power that flows into the biosphere. A 20 TWe collection of wind farms will have to capture ~10% of the wind power that flows at low altitude over the continents. They can potentially modify global wind patterns. Coal and other fossil fuel plants emit CO_2. The fossil fueled CO_2 added since the start of the industrial revolution converts an additional 1% of the 174,000 TWs of solar power that Earth intercepts into extra heat (~170 TWt) that then re-circulates within the biosphere, heats it, and contributes to global warming (6-Chaps 1, 2 & 9).

LSP System capacity can be increased at a faster rate to provide an extra 13 TWe of clean, massless electricity to Earth. The additional clean electric energy, ~ 650 TWe-y, can be used to remove the 1,900 Gtons of industrially produced CO_2 in the oceans and atmosphere and convert it into inert carbonate rock.

RETURNS FROM THE LSP INVESTMENT

The LSP components built on the airless and mechanically quiet Moon can be very thin and therefore very low mass per unit of collected solar energy. Concentrated sunlight is the primary energy source to make glasses for the photovoltaics (#1), microwave reflectors (#2), microwave generators (#3) and other components in Figure 3 from the lunar soils. Solar electric energy is a small fraction of the input energy. Solar electric power is produced from the simple arrays placed directly on the lunar surface (#1's in Figure 3). The solar power is collected in each of the many small power plots distributed within a larger power base. The thousands of individual sub-beams generated from the power plots are then combined in free space above the power base into massless microwave power beams directed toward Earth. Thus, the power components on the Moon have only 0.6% of the mass per unit of energy delivered to Earth of a terrestrial photovoltaic array with only 2 hours of battery power storage (Table 1 - *7.* & *1.*).

Less than 300 tons of consumables and machinery are required to build the components to send back to Earth 1 TWe-y of clean energy (Table 1 - *8.*). This highly efficient use of mass is one key to the projected low cost of solar electric energy from the Moon and the short time to pay back the energy invested to install a unit of power capacity. The tons/TWe-y of the lunar components can be reduced by another factor of 10 in the transition from 1980s to 2020s operating and production technology (16).

Restricting the initial lunar and space expenditures to 0.001 $/kWe-h of returned energy implies that up to 140,000 $/kg can be expended on the lunar demonstrations and space operations. The demonstration LSP System, with its industrial-scale manufacture of low-cost commodity goods, such as structures and life-support chemicals, and new lunar services, especially electric power, will enable safe living on the Moon.

A 20 TWe LSP System will require major investments in machines, supplies, and people on the Moon and for the transportation systems between the Earth and the Moon. The LSP demonstration can be deployed with operationally robust derivatives of the Space Transportation System, new expendable launch vehicles, and lunar facilities and systems derived from the operational International Space Station. The LSP System production phase will provide the motivation, operational scale, and financial resources to significantly reduce transportation costs.

Table 2 (6.) gives the approximate life-cycle cost of an LSP System that delivers, without the need for power storage, 20 TWe of load-following power to Earth and 1,500 TWe-y of energy between 2015 and 2100. The construction and maintenance of rectennas on Earth is 87% of the life-cycle cost. This estimate assumes 1980s levels of operating and production technologies on the Moon. All labor and initial production machinery is brought from Earth. Financing of the construction phase at 3%/y real interest for 30 years, ~34 T$, is the largest single expense.

If 90% of the lunar manufacturing system is made from lunar materials and the rectennas on Earth employ screen-like reflectors to concentrate the incoming microwaves, the cost drops by a factor of 10 (Table 2: 7.). Again, the single major expense is interest, 3.2 T$ (7. minus 8.), on funds borrowed to conduct the construction phase. However, most of the LSP and rectenna construction can be a pay-as-you-go process. Rectennas can begin to efficiently output power after their diameter exceeds a few hundred meters.

An LSP demonstration project can likely break even by the time it sells ~0.5 TWe-y of energy on Earth at 0.1 $/kWe-h. Total cost to this point is projected to be ~0.5 T$ measured in 2003$ (Table 2: 9.). After breakeven, lunar construction could be financed from energy sales. Private and government bonds can be sold and the funds used to accelerate the growth of power bases and rectennas, thereby accelerating the growth of GWP. The projected unit costs of LSP electricity, averaged over the 1,500 TWe-y, are 0.005 $/kWe-h (Table 2: 6.), to 0.0005 $/kWe-h (7.), to 0.0003 $/kWe-h (8.). Several versions of the LSP System have been analyzed over a range of 0.1• to 10• times the reference industrial productivity on the Moon, and all are profitable (16, 19).

Consider the implications of the LSP System for China. A prosperous China of 1.3 billion people requires at least 2,600 GWe. This would enable a sustainable 110 T$ GDP/y or 84,000 $ GDP/y-person by mid-century. The 15,000 km^2 of rectennas required would be 0.16% of the land area of China and 0.015% of its land, lakes, and estuaries. For scale, the Three Gorges Dam is projected to output an annually averaged power of ~11.41 GWe. Its reservoir surface area will be ~1,045 km^2. (wiki/Three_Gorges_Dam). An equal area of rectennas would output ~209 GWe of load following power. Use of the Three Gorges Dam can be optimized for water management and transportation. An LSP-powered China would be prosperous, and would not have to mine coal nor compete with all other nations for fuel and mineral resources.

Implementing the LSP System will generate the following major resources on the Moon, in cis-lunar space, and on Earth:

- > 5,000 tons of general lunar manufacturing systems @ 10 years
- > 500,000 tons of lunar production machinery @ 15 years
- Large-scale transport between the Earth and the Moon
- 1,000s of people on the Moon and many thousands more tele-workers on Earth
- Multiple bases along and across the limbs of the Moon as seen from Earth
- Megawatts to terawatts of electric and beamed power @ 5 years to 2050 (Earth to cis-lunar space and Moon, Moon to cis-lunar space and Earth)

Approximately a decade into full-scale installation of the LSP System, a small fraction of the production facilities and people can be redirected to grow a generalized economy using local lunar materials. Assume that after the demonstration phase is complete the capacity of the LSP System is expanded by 0.3% and this extra capacity increases at 5%/y. The extra energy is directed to generating net new wealth on the Moon and in cis-lunar space.

Approximately 0.01 TWe would be available to generate ~0.4 T$/y of new *Gross Lunar Product* (GLP) 5 years into LSP construction. By year 40, when Earth is provided 20 TWe, the lunar economy receives 0.26 TWe and achieves ~11 T$/y GLP (Table 2: #16). After year 40, most of the LSP production facilities can be redirected to economic development of the Moon and human development of our Solar System.

21st CENTURY POWER TOOLS

The power tools of the 20th Century were power stations (hydroelectric, coal, natural gas, oil, nuclear fission), local and long-distance electric transmission systems, electric motors, electric trains, and the thousands of other electric devices and electronic systems used to enable exponential economic growth since 1880 (13).

The new power tools for the 21st Century are:

- Sun – the primary power source
- Lunar solar power bases
- Large aperture radar facilities within the LSP bases
- Power beams
- Beam-redirectors/rectennas in space and on the Earth and Moon
- Beam powered transports (ion, and others)
- Rationalized industrial production facilities on the Earth, the Moon, and other Moon-like bodies

Given adequate funding and focus, within 5 to 8 years microwave power beams can be sent from stations on Earth to recycling ion-drive tugs that carry cargo from low-orbit about Earth to low-orbit about the Moon (31). High-tonnage cis-lunar transport cost can be reduced to the order of 10s $/kg. Low-cost commercial-scale power can be beamed to lunar bases and immediately enable the industrial-scale operations appropriate to the rapid growth of the LSP System.

Industrial-scale lunar power and lunar development can enable these additional benefits:

- Provide ~300,000 km^2 of radio telescope collection area (LSP reflectors front & back areas)
- Locate, track, and characterize all comets and asteroids and directly deflect those sufficiently large to threaten Earth
- Enable radio, optical, x-ray, and gamma ray

	ECONOMIC ACTIVITY OR VALUE	**T$/y**	**T$**
1.	Gross World Product (GWP) (@ 2000 in 2002$s, 6.03 billion people)	+40.3	
2.	Sum GWP (@ 6,840 $/y-person, 2000-2100; 10 billion in 2050)		+6,050
3.	Coal-fueled system Cost (1,500 TWe-y & 3%/y for 30 y, 2000$s)		-1,700
4.	Terrestrial Solar Power Cost (*1,500 TWe-y; 1 day of thermal storage)		-1,400
5.	Terrestrial PV Cost (*; 45 days•6.6 TWe storage output) or GEO Solar Power Satellites from Earth or Moon (*; 40 TWe for load following)		-10,000
6.	LSP (ref.-1980s) Cost (1,500 TWe-y; Rectennas 87%)		-72
7.	LSP (Bootstrapped) Cost (1,500 TWe-y; Reflector Rectennas 77%)		-6.9
8.	Engineering Cost of #7 (1,500 TWe-y; @ 0%/y interest)		-3.7
9.	LSP Demo breakeven (2003$) (@ 0.1 $/kWe-h		-0.5
10.	E&P (Global Oil and Natural Gas @ 2003) for ~1.6 TWe equiv.	-0.2	
11.	U.S. Corporate Liquidity (2003)		+4.7
12.	Annual profits selling 20 TWe (@ 1¢/kWe-h)	+1.6	
13.	GWP (10 billion people @ 2050 with 20 TWe)	+830	
14.	GWP (@ 2100 with 20 TWe)	+1,200	
15.	Sum of GWP with LSP (2000 – 2100: 1,500 TWe-y of LSP energy)		+66,000
16.	Gross Lunar Product (GLP) {0.3% energy @ 40 years, 5%/y growth}	+11	
17.	GLP funded R&D (2050) {3.3% of GLP}	+0.36	

Table 2: Major Cash Flows (T$/y = $1 \cdot 10^{12}$ $/y), Energy Cost (-T$), and Positive Liquidity (+T$) and Summed Gross World Product (+T$)

telescope networks distributed about the Moon to continuously monitor our Earth, sun, solar system, and universe

- Extract all industrial carbon dioxide from Earth's atmosphere by 2100

MOVING FORWARD TO 2050

Sustainable, clean, dependable, and abundant electric power can, by 2050, enable the steady increase of sustainable wealth on Earth by a factor of 10 to ~84,000 $GWP/person-y. Energy, like agriculture has done, can decrease from ~15% of GWP today to ~1% of GWP and thus liberate considerable global economic activity for other uses. Over the 21st Century the LSP System can increase cumulative GWP, after energy expenditures, by ~60,000 T$ (Table 2: #15 – #8 – #2). The LSP System will provide humanity a significant increase in sustainable profits and wealth with literally unlimited opportunities for growth (32, 33).

Development of the Moon and industrial-scale exploration of the solar system requires the development of known lunar resources and a skilled population on the Moon, in cis-lunar space, and on Earth. These newly useful resources will generate growing off-Earth profits and net new wealth that indexes humankind's growing independence from the ancient limited resources of its birthplace.

REFERENCES

1. Climate Change 2007: Synthesis Report, 73 pp. (especially note Section 6) http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf
2. World Energy Council (2000, page 2) Energy for Tomorrow's World – Acting Now!, 175pp., Atalink Projects Ltd, London.
3. WEC Statement 2009 Building the new World Energy Order, 4pp., http://www.worldenergy.org/documents/wec_statement_2009.pdf
4. Energy Information Agency, Table 8.9 Electricity End Use, 1949-2008, (2008) http://www.eia.doe.gov/emeu/aer/txt/ptb0809.html
5. Criswell, D. R. (2009) Lunar Solar Power for the Human Race to Sustainable Prosperity, 31pp. (manuscript)
6. Watts, R. G. (editor) (2002) "Innovative Energy Strategies to CO_2 Stabilization" Cambridge University Press http://www.cambridge.org/uk/catalogue/catalogue.asp?isbn=9780521807258
7. Goeller, H. E. and Weinberg, A. M. (1976) The age of substitutability, Science, 191, 683-689.
8. http://en.wikipedia.org/wiki/Oxygen_cycle
9. http://en.wikipedia.org/wiki/File:Global_Carbon_Emission_by_Type_to_Y2004.png
10. Falkowsi, P., and R. J. Scholes, E. Boyle, J. Canadell, D. Canadeld, J. Elser, N. Gruber, K. Hibbard, P. Hogberg, S. Linder, F. T. Mackenzie, B. Moore III, T. Pedersen, Y. Rosenthal, S. Seitzinger, V. Smetacek, W. Steffen) (2002, 13 October) The Global Carbon Cycle: A test of our knowledge of Earth as a System, Science, p. 293, Vol. 290 (Table 1)
11. Hoffert,M. I. and Ken Caldeira, Gregory Benford, David R. Criswell, Christopher Green, Howard Herzog, Atul K. Jain, Haroon S. Kheshgi, Klaus S. Lackner, John S. Lewis, H. Douglas Lightfoot, Wallace Manheimer, John C. Mankins, Michael E. Mauel, L. John Perkins, Michael E. Schlesinger, Tyler Volk, Tom M. L. Wigley (2002, November 1.) Advanced technology paths to global climate stability: energy for a greenhouse planet, Science vol. 298, 981 – 987.
12. Criswell, D. R. (2004) Lunar-Solar Power System, Encyclopedia of Energy (Cutler J. Cleveland, Editor-in-Chief), vol. 3 (Gl–Ma), 677 – 689, Elsevier Academic Press
13. Criswell, D. R. (2003 December/2004 January) Lunar Solar Power: Reaching for the Moon?, IEEE POTENTIALS, 20 – 25 [Request copy from author that corrects printer's errors.]
14. Criswell, D. R. (2002) Characteristics of Commercial Power Systems to Support a Prosperous Global Economy, Acta Astronautica, Vol. 51, No. 1–9, pp. 173–179.
15. Criswell, D.R. (2002, April/May) Solar power via the Moon, The Industrial Physicist, 12-15. See letters to the editor and Reprise in June/July, August/September, and October/November issues or at http://www.tipmagazine.com
16. Criswell, D. R. (2001, October) Lunar Solar Power System: Industrial Research, Development, and Demonstration, [Discussion Sessions; Division 1: World

Energy Market Challenges; 1.2.2 Hydroelectricity, Nuclear Energy and New Renewables] 17pp., 18th World Energy Congress, Buenos Aires, Argentina. (available from author).

17. Criswell, D.R. (2000) Lunar Solar Power System: Review of the technology base of an operational LSP System, Acta Astronautica, Vol. 46, No. 8, 531 – 540, Elsevier Sciences Ltd.
18. R. D. Waldron and D. R. Criswell (1998) Costs of space power and rectennas on Earth, IAF-98-R.4.03, (1998), 5p., International Astronautical Congress
19. Criswell, D.R and Russell, R.G. (1996) Data envelopment anaylsis of space and terrestrially-based large scale commercial power systems for Earth: A prototype analysis of their relative economic advantages, Solar Energy, Vol. 56, N. 1, 119-131, Elsevier Science Ltd.
20. Waldron, R.D. and Criswell, D.R. (1993) (September) Summary of Characteristics of Beamed Power Radiation Patterns and Side Lobe Residual Power Levels for Lunar Power System, Acta Astronautica Vol. 29 (10/11):765-769. Pergamon Press Ltd
21. Criswell D. R. and Waldron, R. D. (1993) International Lunar Base and Lunar-based Power System to Supply Earth with Electric Power, Acta Astronautica, Vol. 29, No. 6, pp. 469-480. Pergamon Press Ltd. Presented at 42nd Congress of the International Astronautical Federation, October 5-11, 1991 (Montreal, Canada). 15pp. Paper #IAA-91-699.
22. D. R. Criswell and R. D. Waldron (1990, August) Lunar System to Supply Solar Electric Power to Earth, Proceedings of the 25th Intersociety Energy Conversion Engineering Conf., Vol.1, #900279, Aerospace Space Power Systems", 61-71, Reno, NV
23. Criswell, D. R. and Waldron R. D. (1991, April). Results of Analyses of a Lunar-based Power System to Supply Earth with 20,000 GW of Electric Power, Proceedings of SPS 91 Power from Space: the Second International Symposium, page a3.6, 186-193. Paris, France.
24. R. D. Waldron, R. D. and D. R. Criswell (1980) Materials Processing in Space, Space Industrialization (Ed. B. O'Leary), Vol. I, Ch. 5, 98 – 130, CRC Press
25. D. R. Criswell, and R. D. Waldron (1980) Lunar Utilization, Space Industrialization (Ed. B. O'Leary), Vol. II, Ch. 1, (1980), 1 – 53, CRC
26. Waldron, R. D. and Criswell, D. R. (1983) Concept of the Lunar Solar Power System, Space Solar Power Reviews, Vol. 5, 53 – 75.
27. R. D. Waldron, T. E. Erstfeld, and D. R. Criswell (1979, February 12) The role of chemical engineering in space manufacturing, CHEMICAL ENGINEERING, 81 – 94, McGraw Hill, NY [Note table VI]
    Translated into Chinese. 1979 American Industrial Report, (September) Issue No. 37: 26-43. (in #63.)
28. Cirillo, R.R., Cho, B.S., Monarch, M.R., and Levine, E.P. (1980, April) Comparative analysis of net energy balance of satellie power systems and other energy systems, DOE/ER-0056, Argonne National Laboratory, 136pp.
29. Criswell, D.R. (1991, 27 – 30 August) Terrestrial and space power systems: Life-cycle energy considerations, SPS91: POWER FROM SPACE, A1.2, 71 – 81, SEE & ISF, Paris/Gif-sur-Yvette
30. Hydropower and the World's Energy Future (2000) http://www.ieahydro.org/reports/Hydrofut.pdf
31. Brown, W. C. (1992, July) A Transportronic Solution to the Problem of Interorbital Transportation, NASA CR-191152, 168p.
32. Criswell, D. R. (1985) Solar System Industrialization: Implications for Interstellar Migration. In Interstellar Migration and the Human Experience, eds. B.R. Finney and E.M. Jones, 50-87. 354pp, Univ. Calif Press.
    Noted in June 1986 "Book Reviews," by P. Morrison. Scientific American. pp.28-29
33. Criswell, D. R. 1985. Cis-lunar Industrialization and Higher Human Options, Space Solar Power Rev. 5: 5-38.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge comments on early drafts by Prof. Robert G. Watts of Tulane Un. (Department of Mechanical Engineering, Retired) and by my clear minded determined editor Paula R. Criswell.