

The Sun-Moon-Earth Solar-electric Power System to Enable Unlimited Human Prosperity

David R. Criswell

Cis-Lunar Inc., 16419 Havenpark Dr., Houston, Texas, 77059, U.S.A. (e-mail: drcriswell@comcast.com)

ABSTRACT

Earth and our Moon intercept tiny fractions of the high-quality power generated by the Sun. Earth's oceans and atmosphere, modified by the life of the growing biosphere, moderate the day-night swings of temperature to an average global temperature of 15°C (59°F). Our moderating biosphere enabled humans to evolve to where our industries now consume increasing parts of the ancient (i.e., fossil fuels, high-grade minerals, and others) and modern biosphere (i.e., atmospheric oxygen, clean water, and others) and are significantly degrading the modern atmosphere, oceans, and biosphere to provide us with thermal and electric power and other goods and services. Our ancient terrestrial resources cannot provide us sustainable economic growth and security. Natural sunlight on Earth cannot enable a growing economy. At Earth's surface, sunlight is unpredictably irregular and requires massive power collection, electric distribution, and power storage to provide somewhat reliable commercial electric power. In contrast, sunlight falls reliably onto the Moon, unimpeded by atmospheric clouds, rain, fog, and dust or life. Very low-mass solar-power collectors constructed on the Moon from lunar soils can convert the collected sunlight into beams of microwave photons that can be directed to receivers on Earth. These receivers can efficiently output low-cost commercial electric power. The beams dependably pass through all atmospheric conditions and can be provided night and day. Electric energy costs can decrease by a factor of 10 or more. This massless electric power enables a growing global economy that is sustainable and clean.

BIOSPHERIC POWER AND ITS LIMITS FOR THE PRODUCTION OF NET NEW WEALTH

The Earth continually intercepts approximately 175,000 terawatts (TW) of solar (s) power (1 TWs = 1×10^{12} W [solar]). However, just a fraction of this solar

power is captured every year by the biosphere in the form of carbon newly separated from atmospheric carbon dioxide (CO₂) and the newly created molecules of atmospheric oxygen. Each year, the trees, grasses, and grains of the biomass of the continents capture, in the form of new plant mass, approximately 60 terawatt

(thermal) years (TWt yr) or 0.03% of that primary solar energy. The oceans capture about the same amount as new plankton that is quickly consumed or lost in the ocean depths (Ehrlich and Roughgarden, 1987). In this chapter, the types of energy or power are noted by “s” for solar and “t” for thermal, as used above, and “e” for electric or microwave, and “m” for mechanical.

For the last 10 k.y., families on farms and their animals provided the muscle that converted the energy of biomass fuel into mechanically useful work such as harvesting crops. Useful work is the physical measure of force times distance or the equivalent energy exerted through thermal, chemical, electromagnetic, or other sources of work (Ayres et al, 2003). At the very best, humans and their animals converted less than 0.002% of the solar power illuminating Earth into useful work ($\sim 0.5 \times 120 \text{ TWt}/175,000 \text{ TWs}$). Their actual average conversion efficiency of total solar energy was far worse. Droughts, floods, severe and untimely cold, fires, and such further reduced the amount of captured energy. In addition, humans commonly degraded their immediate biosphere by overgrazing, overplanting, and clear-cutting their forests.

As a result, from the dawn of agriculture approximately 10 ka to the year 1800, per capita income worldwide was essentially stagnant at approximately US \$500/yr. However, around 1800, the per capita incomes of Western Europe and North America began to grow because machines that consumed fossil fuel delivered growing levels of useful work. By 1820, these per capita incomes averaged approximately US \$1200/yr (Maddison, 2001). During the 1800s, electromagnetism evolved from a scientific curiosity into tools that could, by the early 1900s, provide useful work more efficiently and at less total cost using electrical instead of thermal or mechanical systems.

By 1995, the one billion people within Western Europe, North America, their offshoots, and Japan achieved an income of approximately US \$20,000/yr per person. They generated the equivalent of approximately 7000 W of thermal power per person ($\sim 7 \text{ kWt/person}$) of primary thermal power. This power comes primarily from coal, oil, and natural gas, and the remainder from biomass, hydroelectric, and nonbreeder nuclear. In principle, the 1960s to early 1970s Western European standard of living could be maintained using approximately 6 kWt/person if the primary energy source is not the mass-intensive use of carbon fuels to extract energy from the chemically free oxygen molecules (O_2) of our atmosphere (Goeller and Weinberg, 1976). In contrast, five billion people in other nations achieved US \$3000/yr per person or less

and use approximately 1.4 kWt/person. Of these five billion people, several billion have little access to commercial thermal power and still depend primarily on biomass for fuel (Criswell, 1996).

THE CHALLENGES COMMERCIAL POWER SYSTEMS FACE WHEN SCALED UP TO ENABLE GLOBAL PROSPERITY

The World Energy Council (2000, p. 2) issued the following challenge (abbreviated). “...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, mostly in developing countries, without such access.” Key energy targets developed at the United Nations World Summit on Sustainable Development (United Nations, 2002, p. 16, item E) were to “diversify energy supply—and substantially increase the global share of renewable energy sources to increase its contribution to total energy supply.”

Rich and poor nations produce globally the equivalent of approximately 15 TWt of commercial thermal power. To accelerate their economic growth, the unit cost of energy supplied to the poor nations must be less than one-tenth of what is now paid by the rich nations. The population of Earth is anticipated to be approximately 10 billion people by 2050. To achieve global prosperity, the equivalent of approximately 60 TWt by 2050 must be provided, and this new power system must be supplied with 6000 TWt yr/century or more of new thermal energy thereafter. This new power must be sustainable and clean. Electric power is about three times more efficient than thermal power in the delivery of useful work. From 1980 to 2002, 1 TWt yr electric energy consumed in the United States was associated with generating approximately 26 trillion dollars of gross national product (GNP). During that same time frame, Western Europe and Japan achieved US \$42 trillion GNP/TWe yr whereas the developing nations achieved only US \$14 trillion/TWe yr.

Since the 1960s, computer engineers have used electric systems to transfer increasing fractions of both unskilled and skilled labor into automated systems. Because of the greater economic effectiveness and intelligent feedback that is possible using electricity, a prosperous all-electric world of 2050 could be supported by approximately 2 kWe/person or, globally, approximately 20 TWe and approximately 2000 TWe yr of electric energy per century. Gross world product could

increase from approximately US \$45 trillion/yr today to the order of US \$800 trillion/yr or more by 2050. This implies a per capita world income of US \$80,000/yr or more. However, how can we energize a 20 TWe global power system?

POSSIBLE FUEL/OXYGEN, NUCLEAR, MECHANICAL, AND THERMAL OPTIONS

Coal is fossilized biomass, primarily trees, that was created by solar energy approximately 200 to 500 Ma (Foley, 1987) and during the Tertiary 55 to 65 Ma (Flores and Keighin, 1999). Burning a kilogram of coal releases approximately 8 kWt hr of thermal energy, or approximately 0.9 Wt of thermal power, if burned over 1 yr. The energy released today by the coal created in an ancient biosphere comes not from the coal but from the consumption of the chemically free molecular oxygen (O_2) of our modern biosphere. Burning approximately 10 kg (22 lbs) of coal a year releases as much potentially useful work or energy as a 50 kg (110 lbs) person can deliver as external work over the same year. Coal is projected to supply less than 4500 TWt yr of fossil energy. Oil and natural gas are projected to provide less than 1300 TWt yr of thermal energy (Clarke and Trinnaman, 1998). A prosperous world will consume in one century the fossil fuels that the ancient biosphere required 1,500,000 centuries to accumulate. Criswell (2002a, 2009, 2010) provides citations to the above and following observations.

Conventional nuclear reactors are limited by the total quantity of uranium and thorium that can be mined at a reasonable price. Breeder reactors can provide adequate power for centuries using uranium extracted from seawater. However, widespread adoption of this technology is limited by political concerns over proliferation, the potential for very long-term damage to regional and global environments, financial catastrophes from operator errors, inadequate power capacity by 2050, and the need to extract adequate uranium from enormous quantities of seawater. Large-scale commercial fusion is not anticipated to be available by 2050. See overviews by Hoffert et al. (2002) and Criswell (2002a, 2010) of the following topics.

The Earth releases approximately 35 to 45 TWt of geothermal power. It originates from the natural radioactive decay of uranium and thorium and the original in-fall energy of the gas, dust, and rocks that formed Earth. The outer 4 mi (7 km) of crust of Earth contains 1×10^7 TWt yr or less of geothermal energy. Obtaining less than 0.1 TWt of high-grade thermal power is readily doable at low cost. However, tapping far larger

quantities of geothermal heat requires deep wells, power-intensive recirculation of huge quantities of water laden with corrosive minerals, and the release into the environment of approximately 90% of the geothermal power as waste heat. The deep wells are costly to drill and maintain. Dependable recirculation of massive flows of water over the long term will not be demonstrated for many years. Moreover, a 20 TWe geothermal system would remove approximately 20,000 TWt yr of geothermal heat per century or approximately 0.2% per century of the total geothermal energy in the top 4 mi (7 km) of crust. The geologic and seismic consequences have not been examined (Criswell, 2002a). However, in 2009, Switzerland halted geothermal projects because of the local earthquakes induced near the drilling site. The developer closed a new geothermal project at the Geysers in northern California because of expenses just before the U.S. Department of Energy ordered the work to be halted (Glanz, 2009).

The ocean thermal energy conversion (OTEC) is proposed to extract the energy from the differences in temperature of the warm surface waters of the tropics and the cold deep waters. The OTEC is an inefficient and costly system that must mine huge quantities of the deep cold waters by pumping them to the surface. The deep cold waters take centuries to accumulate. Pumping cold waters to, or near, the surface can probably modify the weather globally as does La Niña. For extended discussions of the aforementioned power options, see Criswell (2001, 2002a), Hoffert et al. (2002), and Pimentel et al. (2002).

A significant fraction of the solar power that intersects Earth is available at the surface of Earth in several forms of renewable power. However, global hydroelectric (<5 TWm, mechanical), tides (≤ 0.07 TWm), and waves (1–10 TWm) are not adequate and are irregular (Criswell, 2002a).

Approximately 100 TWm of low-altitude wind power flows over the continents. Even at favorable sites, the wind power is irregular. Large and expensive systems are required to convert the wind energy into hydrogen or other forms for dependable storage and release. In addition, extracting significant fractions of the wind power over one continent can probably affect the climate of another continent (Lorenz, 2003).

LUNAR SOLAR-POWER SYSTEM

The Sun is the only reasonable source for 20 TWe of sustainable power. It continuously releases 390,000,000,000,000 TWs of solar power ($= 3.9 \times 10^{14}$

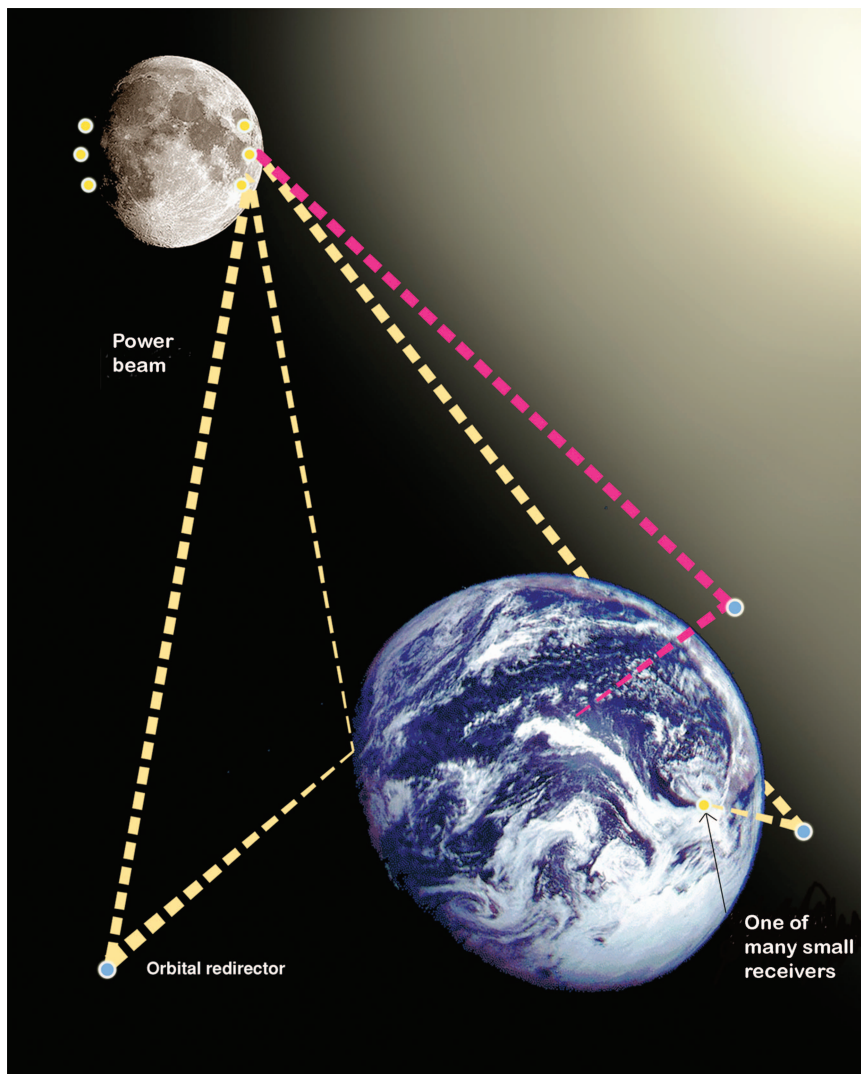


FIGURE 1. Artist's concept of beaming power directly to Earth and via beam redirectors in orbit about the Earth).

TWs) and will release approximately 2×10^{24} TWs yr of solar energy over the next approximately 5 b.y. as it slowly increases in power output before its nova stage. The long-standing problem is how to dependably and affordably collect that power and cost-effectively deliver it to customers.

The National Aeronautics and Space Administration, the U.S. Department of Energy (U.S. DOE), and the National Science Foundation have expended approximately US \$75 million examining the P. E. Glaser concept for deploying space solar-power satellites in geosynchronous orbit about Earth. The studies argue that the satellite concept is feasible in principle. However, they project very high costs for the energy that is delivered to Earth, even with devices of high efficiencies (National Research Council, 1981; Criswell and Waldron, 1993).

Fortunately, the Moon exists. The Moon dependably receives 13,000 TWs of solar power. A lunar solar-power (LSP) system can collect a few percent of this

power and beam it to receivers on Earth for world-wide distribution. Figure 1 (not to scale) provides an overview of such an LSP system. The yellow circles on the opposite sides of the Moon are three pairs of LSP bases. The same face of the Moon always faces Earth. Thus, each base always faces Earth. Each pair of power bases, augmented by fields of solar collectors just across the edge of the Moon, continually and dependably would collect solar power over the course of the lunar day-night cycle of approximately 709 hr. Solar power arrays near the poles of the Moon might, in very restricted areas, capture solar energy over the entire month. However, the total of the potential areas is far too small to provide significant commercial power to Earth.

A power base, represented by one of the yellow disks in Figure 1, is 20 to 60 mi (30–100 km) in apparent diameter as seen from Earth. A power base converts the solar electricity, as available, into many beams of microwaves. A given beam then is created by all the



FIGURE 2. Artist concept of a rectenna that is tens of meters above farmland and adjacent factories and near a city (courtesy of U.S. Department of Energy, National Aeronautics and Space Administration artist concept, 1980).

power plots within the power base and is directed to a field of rectifying antennas, collectively termed a rectenna (Figure 2), on Earth during the approximately 8 hr the rectenna could effectively view the Moon.

The optimal beams are approximately 12 cm (~ 5 in.) in wavelength (~ 2.5 GHz). Unlike sunlight, because of the chemical composition of the atmosphere of Earth, microwaves of this wavelength pass through clouds, rain, fog, and dust with little absorption. The beams, 20% or less of the intensity of noontime sunlight, would dependably deliver power to rectennas on Earth that are several hundred meters or more in diameter. Each rectenna would convert 85% or more of the microwave power it received into electricity and provide the net new electricity to local and regional power grids. The rectennas can have an average output of approximately 200 MWe/km². Many thousands of rectennas, totaling approximately 40,000 mi² (100,000 km²) in area, are required on Earth to output 20 TWe to customers on Earth.

Power beams are sent also to relatively compact redirector satellites in orbit around Earth (Figure 1). These satellites redirect beams to rectennas that cannot view the Moon. Most of these satellites would likely be in eccentric and high-inclination orbits about Earth. At the high part of its orbit, a satellite looks directly down on rectennas in the midlatitude regions of Earth, where most people live. The beams are constantly formed, shut off, and reformed as Earth, the Moon, and satellites move with respect to one another. The intensity or diameter of a given beam is decreased as local power needs about its rectenna decreases.

HOW A POWER BASE IS BUILT AND THE SCHEDULE AND COST

Figure 3 illustrates a small segment of a power base that could be located on and just across the horizon of the Moon as seen in photograph 1. Low unit costs of LSP energy would be achieved by making the solar arrays (1), microwave transmitters (2), and microwave subreflectors (3) primarily out of the common lunar dust (Criswell, 2000, 2001, 2002a, b).

Mobile installation units are transported from Earth to the Moon. These mobile installation units, items 4, 5, and 6 in Figure 3, produce hundreds to thousands of times their own mass in LSP components. This means that the cost of LSP components is not dominated by Earth-to-Moon transportation costs. Maintenance and repair of the mobile installation units is conducted in facility 7 (Figure 3). The Apollo program lunar landers (Figure 4), the six Apollo Lunar Surface Experiments Packages, and space suits and rovers were tested on Earth inside large vacuum chambers before being shipped to the Moon. In a similar manner, the mobile installation units and facilities will be developed and tested on Earth. Moreover, production equipment can be demonstrated in facilities attached to the International Space Station. Personnel on Earth will direct most of the manufacturing and operations on the Moon.

Estimates are published of the mass of equipment, number of people, and cost needed to demonstrate the LSP concept. They are derived from studies funded by the National Aeronautics and Space Administration and the U.S. DOE of the construction

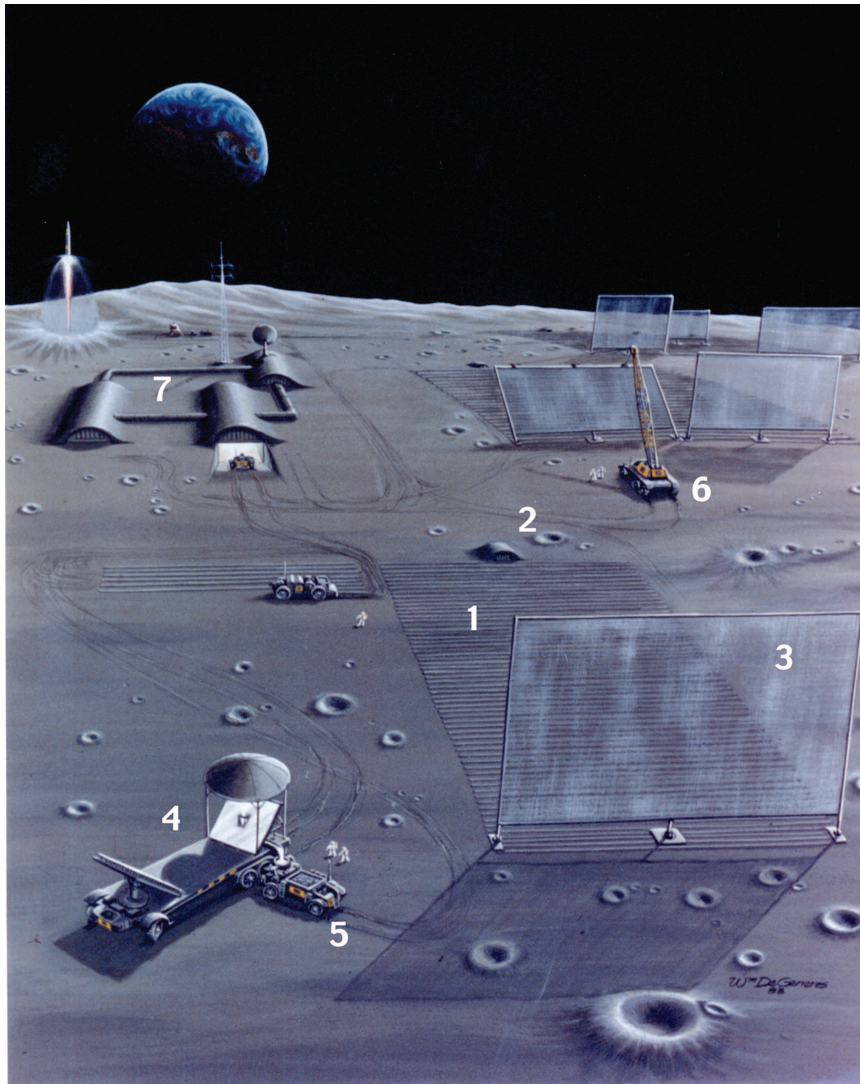


FIGURE 3. Lunar solar-power demonstration base. One demonstration power plot is depicted in the right-hand foreground of the figure. This power plot consists of four basic elements. Solar arrays that convert the solar power into electricity (1) are observed, shown here as north-south-aligned rows of photovoltaics. This electric power is collected by a buried network of wires, not shown, and delivered to a microwave transmitter under the protective mound of lunar soil (2) at the anti-Earthward end of its power plot. The microwaves are of wavelength “w.” The plot’s subbeam is reflected by microwave subreflector (3) toward Earth.

of solar power satellites in orbit about Earth from both terrestrial and lunar materials. Assuming the same operating technologies, it is 50 times less costly, per unit of power capacity, to build LSP on the Moon than to deploy solar power satellites from Earth.

The LSP models assume 10 yr for research and development and deployment of the initial production equipment to the Moon and another 10 yr to build up a P_{demo} of commercially significant electric power delivered to Earth. If $P_{\text{demo}} = 100$ GWe, then 300 people and 22,000 tons of equipment would be required on the Moon. Over the 10 yr demonstration period, additional supplies and components will be transported from Earth. The demonstration base would cost approximately US \$400 billion in 2004 dollars and return approximately US \$600 billion for electric power sold at US \$0.1/kWe hr. Energy costs will drop abruptly as LSP capacity increases.

Based on 1980s technologies, the LSP bases would occupy approximately 25% of the lunar surface (the

solar cells would occupy 2.5% of the total base area) and deliver 20 TWe of useful power to Earth. For the projected 2020s technology, power bases that deliver 20 TWe of useful power to Earth would occupy less than 0.2% of the lunar surface (see tables 2 and 3 of Criswell, 2001).

The cost of electric energy can fall to a fraction of a cent per kilowatt electric hour. By comparison, in 2003, the global exploration and production of oil cost approximately US \$130 billion (United States). Total global-energy-related expenditures are 10 to 15% of the gross world product.

GENERALIZED LUNAR INDUSTRIES AND BOOTSTRAPPING

The components of the LSP system shown in Figure 3 are produced from the common silicate materials of the lunar soils and rocks. Solar collectors



FIGURE 4. Earth, Moon, and Apollo 11 lunar module (1969 AS11-44-6643; the image is courtesy of the Earth Sciences and Image Analysis Laboratory, National Aeronautics and Space Administration Johnson Space Center.

(1) and wiring, microwave transmitters (2), and reflectors (3) are commodity products produced in large volume at low unit cost. Heiken et al. (1991) provide an introduction to the hundreds of thousands of pages of research on the Moon, its soils, and environment. In March of every year, articles presented at the Lunar and Planetary Science Conference near Houston reveal hundreds of new findings. The 2010 Lunar and Planetary Science Conference attracted more than 1700 new articles. The meetings of the American Geophysical Union and other professional societies also contribute to the ongoing flood of new findings.

Iron, aluminum, other metals, industrial glasses, ceramics, and process chemicals can be extracted from the lunar soils to manufacture a large fraction of the mobile installation units (4, 5, and 6) and facilities (7) shown in Figure 3. The facilities (7) can be augmented in size and capability to accommodate additional manufacturing. This process is commonly called bootstrapping. Bootstrapping enables the exponential growth of LSP power bases on the Moon. As shown in Figure 5, the pink blocks near the top represent complete sets of mobile installation units such as those shown in Figure 3. Mobile installation set 1 begins producing power plots (yellow blocks at the bottom part) at a steady rate. Once

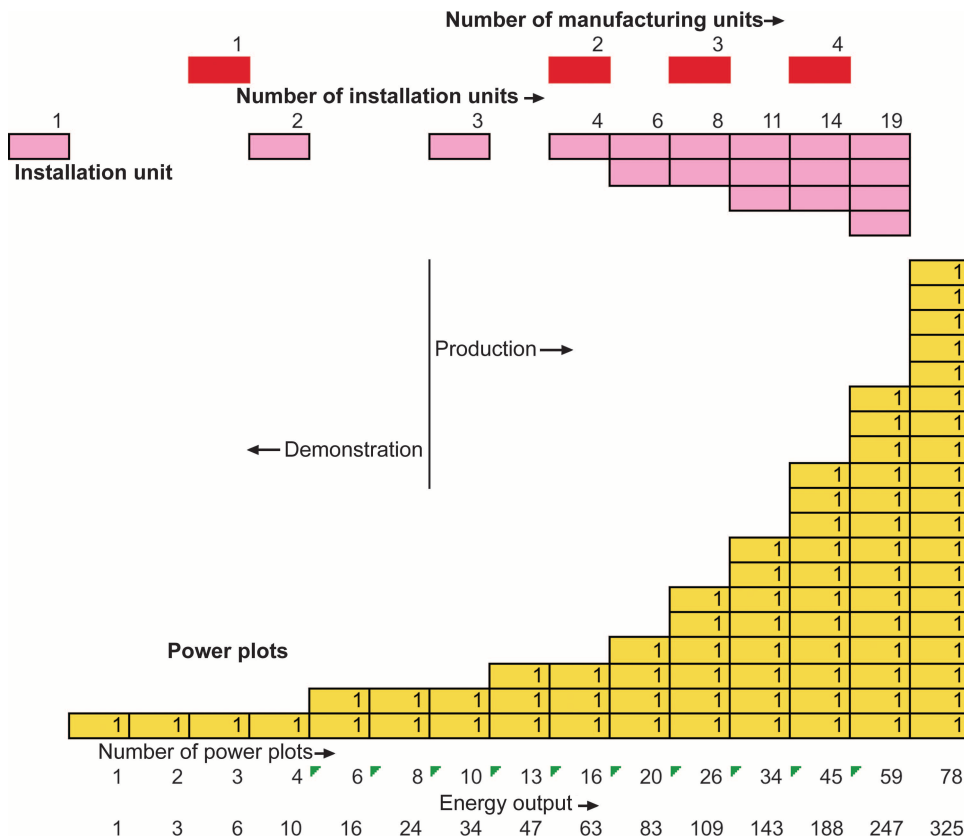


FIGURE 5. Exponential growth of power plots using bootstrapping manufacturing facilities construct from the local lunar materials 90% or more of the installation units that emplace the power plots (modified from Criswell, 2002a).



FIGURE 6. Photograph of the phased array radar AN/FPS-85 at Eglin Air Force Base in Florida, U.S.A. The transmitter is the smaller six-story-high structure on the left that supports 5134 transmitting units. The nine-story unit on the right supports 4660 receiving units. Photo taken April 6, 2011, by the author during an authorized visit to the installation.

established, each power plot continues to convert solar power into electric power. After four units of time, the first bootstrapping manufacturing facility (red block) is deployed to the Moon. It then manufactures 90% of mobile installation unit 2 from lunar materials. Thereafter, mobile installation units 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.

How small a bootstrapping facility can engineers achieve? This is a challenging, but reasonable, question. The design and operation of bootstrapping facilities and mobile factories are interlinked with the design of the power plots and the lunar materials and environment. Our ability to operate activities on the Moon from virtual control centers on Earth and the level of automation that can be achieved on the Moon are relevant. Most, if not all, of the machinery and activities can be developed and demonstrated on Earth (Freitas and Gilbreath, 1982; Criswell, 2001).

POWER BEAMING IS THE APPLICATION OF INDUSTRIAL-SCALE PHASED ARRAY RADAR TECHNOLOGY

Electromagnetism is one of the four fundamental forces of nature. Electromagnetism has increased the efficiency, intelligence, and output of useful work.

How can we extend the application of electromagnetic tools beyond Earth and create new supplies of useful work? The answer is power without wires provided from the Moon.

Power beaming is not exotic. It is simply a form of radar. Almost all radars operate at high gain. This simply means that they focus their radiated power into a narrow beam. Large phased array radars have been in constant operation since the 1960s by the United States, Britain, the Soviet Union, and other nations to detect and track ballistic and tactical missiles, spacecraft and space debris, and aircraft. The largest military phased array radar is the AN/FSP-85 Phased Array Space Surveillance Radar at Eglin Air Force Base in Florida (Figure 6) in the United States. The AN/FPS-85 has operated non-stop since 1968. It is a pulsed radar (5% duty cycle) with a maximum pulse power intensity of approximately $25,000 \text{ W/m}^2$. Its average power intensity at its near-field–far-field boundary is approximately 130 W/m^2 or approximately 50% of that recommended for commercial power beaming. During the last 40 years, it has beamed the equivalent of approximately 100,000 bbl of oil to space. It, and the dozens of other military phased arrays, meets the power density and wavelength regulations imposed by the U.S. Environmental Protection Agency on the long-term exposure to microwaves outside the limits of the sites. Osepchuk (2002) discusses the environmental and safety concerns of the microwave beaming of power from space solar-power satellites. Waldron and Criswell (1993) present the significant advantages of beaming power from far larger antennas on the Moon. The AN/FPS-85 radar was refurbished in the late 1990s, while in full operation, to mostly solid-state

amplifiers. It has proved to be so reliable that its local maintenance shop was closed. In 1975, the Jet Propulsion Laboratory (JPL) Goldstone 85 ft (26 m)-diameter dish beamed power across 1 mi (1.6 km) to a planar array of rectennas that output 30 kWe. This early rectenna converted approximately 82% of the incident microwave power into electricity.

Power beaming is essentially an industrial-strength planetary radar. The longest range radar of Earth is the 1000-ft (305-m)-diameter reflector near Arecibo, Puerto Rico. Operating at a 5 in. (12.6 cm) wavelength, it produced the delay-Doppler image of the South Pole of the Moon in Figure 7. The Arecibo beam passes through the lower atmosphere of Earth at approximately 20 W/m^2 or approximately 10% of the intensity proposed for the beaming of commercial power from the Moon to Earth.

Phasing a widely dispersed array of transmitters or receivers is not a fundamental problem. The very large array (VLA), shown in Figure 8, 30 mi (50 km) west of Socorro, New Mexico, consists of 27 large, individual parabolic dishes (National Radio Astronomy Observatory, 2003). These dishes ride on three sets of railroad tracks that form a “Y” across the high desert. The individual dishes can be positioned along the three tracks to simulate a distributed array that is 21 mi (33 km) in diameter. The time base at each dish is accurate to less than 0.4 in. (<1 cm) of wavelength in the range of 2 GHz. This accuracy is necessary for real-time correlation, or phasing, of the signals from the 27 receivers. The absolute timing, or phasing for a given look direction, has been maintained automatically for weeks at a time over the past 30 years while the dishes track celestial objects over the entire sky. The VLA can image the surface of the Moon under near-field conditions. Since 2003, the VLA timing and data col-

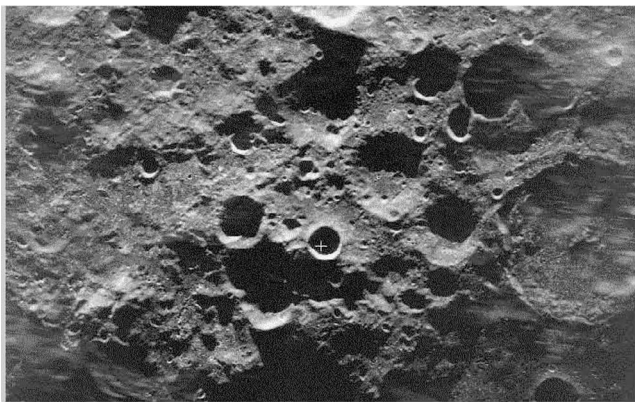


FIGURE 7. Arecibo radar image of the lunar South Pole (modified from Margot et al., 1999).



FIGURE 8. View of the very large array looking south (image courtesy of National Radio Astronomy Observatory/AUI, 2003; photo by Dave Finley).

lection system has been upgraded from microwave conduits to fiber optics and its data capabilities increased by over a factor of 100.

Phased array radars use segmented transmitters that are commonly located next to one another in a plane. However, individual apertures can be positioned about curved surfaces and even away from one another. Extremely large, but low mass per unit area, transmitting apertures, with acceptable efficiency, could be built on the Moon at acceptable cost using common lunar materials (Figure 3). This is possible because the Moon has no atmosphere, has one-sixth the gravity of Earth, and is mechanically stable, and the relatively simple transmitting apertures would always face toward Earth. The LSP system does not handle large power flows on the Moon. Instead, the thousands of relatively small power plots combine their subbeams into industrial-strength microwave beams in the open space above the lunar surface.

Early in the development of the LSP system, its beams could be directed to space tugs equipped with low mass rectennas and ion drives that require little reaction mass. Brown (1992), who first demonstrated microwave power beaming, estimated that the cost of transport between low Earth orbit and low lunar orbit could decrease to a few dollars a kilogram.

ENVIRONMENTALLY FRIENDLY ENGINEERED POWER PHOTONS AND WORKING ELECTRONS

Beamed power can be designed to be environmentally neutral. Beamed power need not introduce net heat into the biosphere. The rectenna outputs

pure electricity that is directly consumed as useful work. Almost all of the now-consumed useful energy is radiated back to space as long-wavelength infrared. The 15% or less waste heat released to the environment by the rectennas can be more than offset by painting some of the area under the rectenna white and reflecting an equal flow of sunlight back to space.

The 20 TWe of power beams do not introduce CO₂, methane, or any other greenhouse gases into the atmosphere as do burning fossil fuels. Likewise, the LSP beams do not accumulate or release radioactive elements; disturb the flow of rivers, ocean currents, and tides, or air; or require the harvesting of biomass.

The relatively simple rectennas can be placed over deserts, shallow bays, industrial centers, or contaminated land. Rectennas placed over agricultural land, as depicted in Figure 2, can prolong the growing season and, as needed, release extra waste heat to protect against freezes. Net new LSP energy can be used to remediate damage to the environment and nurture the biosphere back to preindustrial conditions. Lunar solar-power energy can decouple humanity from dependence on the power, mass, and life flows of the biosphere.

WHY COLLECT SOLAR POWER ON THE MOON INSTEAD OF ON EARTH?

Because the Earth-Moon system follows an elliptical orbit around the Sun, depending on the time of year, the Sun provides approximately 1320 to 1430 Ws/m² at the distance from the Sun of the orbits of the Earth and the Moon. Why is it impractical and too costly to simply gather solar power on Earth? Note the clouds in the atmosphere of Earth in Figures 1, 2, 4, and 8. The atmosphere of Earth and clouds reflect solar power back to space, absorb it, and block it from reaching the surface of Earth. Dust, smoke, and ash from large fires, volcanoes, and windstorms can do the same on a continental scale. The length of daylight changes with the seasons. Solar power at any point on the surface of Earth is unpredictably irregular and captive to changes in regional and global climate.

Today, it is technically challenging for a stand-alone solar array on Earth to output a useful average of 3 We/m² ground area. Stand alone means that the array is not connected to a backup grid and is the only supply of dependable power to a large region. Power storage, conversion systems, and long-distance transmission lines are required, which significantly decrease the effective output of solar cells or concentrators and increase expense. Twenty terawatts of electric power

would require approximately 7×10^6 km² of collector area. This is approximately 5% of the landmass of all the continents and 70 or more times the 40,000 mi² (100,000 km²) of the area required for the rectennas (Criswell, 2002a).

Low-cost electric power requires thin films of relatively low cost and very long life to concentrate and/or collect the diffuse solar power. Our atmosphere of Earth contains natural and industrial contaminants, organisms, and wind that attack thin films, dirty their surfaces, degrade them, and destroy them.

The Moon is different, containing no atmosphere nor life. Thin films, made from the local lunar dust, can operate dependably for decades. The surface layers of the Moon are extremely quiet. Moonquakes and the impacts of even large, but very rare, meteors are a few tens of nanometers in amplitude. Micro-meteorites erode surface materials at 1 mm/m.y. or less (Heiken et al., 1991). Moreover, the Moon is outside the regions of the magnetosphere of Earth, which contain intense radiation.

The LSP system is able to avoid the hazards and inefficiencies of gathering diffuse sunlight on Earth. It can economically gather diffuse solar power and convert it into streams of electromagnetic waves that are designed to dependably and safely deliver power efficiency to inexpensive receivers (rectennas) on Earth when that power is needed.

THE MOON: THE LARGEST PROSPECT OF THE ENERGY INDUSTRY

It is unlikely in the 1800s that Carl August von Steinheil imagined storage batteries powering the Apollo 16 rover (Figure 9). James Clerk Maxwell

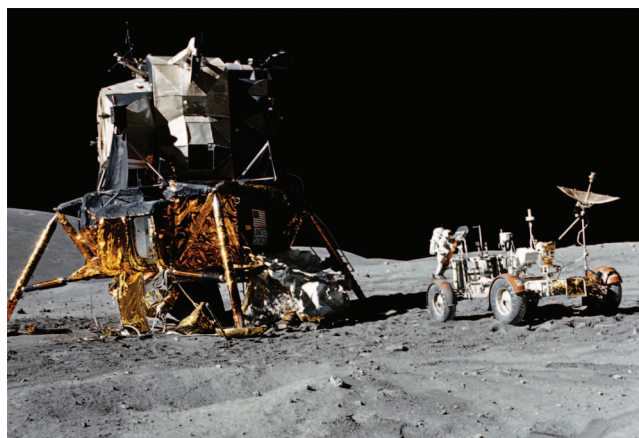


FIGURE 9. Apollo lander, rover, and John Young on the surface of the Moon (photo AS16-107-17436, courtesy of National Aeronautics and Space Administration).

certainly did not imagine live television from the Moon or the International Space Station. However, that and more have happened.

Even today, most of us do not seem to realize that the Moon was explored sufficiently for use 40 years ago, if the United States had stayed. It is necessary for us to live on an Earth where nine out of ten people are impoverished. We can use the Moon to provide us an enormous flow of net new, useful work. We can move from depleting the Earth and the biosphere to sustaining, nurturing, and protecting them.

Significant increases in the cost of oil lead to recessions in the developed nations (Leonhardt, 2003). In contrast, the economic tide created by dependable LSP power can steadily raise all boats. Economic growth of the wealthy nations would accelerate because they finance both the LSP system and the growing consumer economies of the other nations. Poor nations could afford to expend approximately 10% of their per capita gross domestic product, approximately US \$300/person, to purchase approximately 2 kWe/person in power to build sustainable economies. For the first time in its existence, the human race could gather affordable net new work from beyond the biosphere and build sustainable net new wealth of enormous scale.

REFERENCES CITED

- Ayres, R. U., L. W. Ayres, and B. Ware, 2003, Energy, power and work in the U.S. economy, 1900–1998: *The International Journal*, v. 28, no. 3, p. 219–273.
- Brown, W. C., 1992, A transportronic solution to the problem of interorbital transportation: *National Aeronautics and Space Administration CR-191152/pt-7452*, 178 p.
- Clarke, A., and J. Trinnaman, 1998, *Survey of energy resources*: London, World Energy Council, 337 p.
- Criswell, D. R., 1996, Lunar-solar power system: Need, concept, pay-offs, challenges: *Institute of Electrical and Electronics Engineers Potentials*, v. 15, no. 2, p. 4–7.
- Criswell, D. R., 2000, Lunar solar power system: Review of the technology base of an operational LSP system: *Acta Astronautica*, v. 46, no. 8, p. 531–540.
- Criswell, D. R., 2001, Lunar solar power system: Industrial research, development, and demonstration: 18th World Energy Congress, Buenos Aires, Argentina, p. 17.
- Criswell, D. R., 2002a, Energy prosperity within the 21st century and beyond: Options and the unique roles of the Sun and the Moon, in R. Watts, ed., *Innovative energy strategies for CO₂ stabilization*: Cambridge, Cambridge University Press, p. 345–410.
- Criswell, D. R., 2002b, Solar power via the Moon: *The Industrial Physicist*, v. 8, no. 2, p. 12–15: <http://www.tipmagazine.com> (accessed April–May 2002).
- Criswell, D. R., 2009, Lunar solar power (LSP) system: Practical means to power sustainable prosperity (abs.): *X-Energy Minerals in the Solar System: Resources of the 21st Century*, Denver, Colorado, AAPG 600724, p. 16: [http://www.docstoc.com/docs/20161411/Lunar-Solar-Power-\(LSP\)-System-Practical-Means-to-Power](http://www.docstoc.com/docs/20161411/Lunar-Solar-Power-(LSP)-System-Practical-Means-to-Power) (accessed June 9, 2009).
- Criswell, D. R., 2010, Enabling sustainable and rapidly growing global wealth by implementing the lunar solar power (LSP) system: *Global Lunar Utilization Conference 2010-5745*, Beijing, China, American Institute of Aeronautics and Astronautics, 10 p.
- Criswell, D. R. and R. D. Waldron, 1993, International lunar base and lunar-based power system to supply Earth with electric power: *Acta Astronautica*, v. 29, no. 6, p. 469–480.
- Ehrlich, P. R., and J. Roughgarden, 1987, *The science of ecology*: New York, Macmillan, p. 524–525.
- Flores, R. M., and C. W. Keighin, 1999, A summary of Tertiary coal resources of the Wind River Basin, Wyoming, in 1999 resource assessment of selected Tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region, U.S. Geological Survey Professional Paper 1625-A, p. SW-1–SW-18.
- Foley, G., 1987, *The energy question*: London, Penguin Books, 304 p.
- Freitas, R. A., and W. P. Gilbreath, eds., 1982, *Advanced automation for space missions*: Washington, D.C., U.S. Government Printing Office, National Aeronautics and Space Administration SP-2255, 393 p.
- Glanz, J., 2009, Drilling ordeals said to delay geothermal project: *The New York Times*, August 19, 1 p.: <http://www.nytimes.com/2009/08/20/us/20alta.html> (accessed June 24, 2012).
- Goeller, H. E., and A. M. Weinberg, 1976, The age of substitutability: *Science*, v. 191, p. 683–689, doi:10.1126/science.191.4228.683.
- Heiken, G. H., D. T. Vaniman, and B. M. French, 1991, *LUNAR sourcebook: A user's guide to the Moon*: Cambridge, Cambridge University Press, 736 p.
- Hoffert, M., et al., 2002, Advanced technology paths to global climate stability: Energy for a greenhouse planet: *Science*, v. 298, p. 981–987, doi:10.1126/science.1072357.
- Leonhardt, D., 2003, Jump in price of oil puts new strains on economy: *The New York Times*, March 2, 2003, <http://www.nytimes.com/2003/03/02/business/jump-in-price-of-oil-puts-new-strains-on-economy.html?scp=2&sq=2%20March%202003&st=nyt&pagewanted=1> (accessed December 7, 2011).
- Lorenz, R., 2003, Full steam ahead: Probably: *Science*, v. 299, p. 837–838, doi:10.1126/science.1081280.
- Maddison, A., 2001, *The world economy: A millennia perspective*: Organization of Economic Cooperation and Development Paris, 383 p.: <http://www.theworldeconomy.org> (accessed May 30, 2010).

- Margot, J. L., D. B. Campbell, R. R. Jurgens, and M. A. Slade, 1999, Topography of the lunar poles from radar interferometry: A survey of cold trap locations: *Science*, v. 284, p. 1658–1660, doi:10.1126/science.284.5420.1658.
- National Radio Astronomy Observatory, 2003: <http://www.aoc.nrao.edu/intro/vlapix/looksouth.jpg> (accessed November 27, 2011).
- National Research Council, 1981, *Electric power from orbit: A critique of a satellite solar power system*: Washington, D.C., National Academy Press, 185 p.
- Osepchuk, J. M., 2002, How safe are microwaves and solar power from space?: *IEEE Microwave Magazine*, December 2002, p. 58–64.
- Pimentel, D., M. Herz, M. Glickstein, R. A. Zimmerman, K. Becker, J. Evans, B. Hussain, R. Sarsfeld, A. Grosfeld, and T. Seidel, 2002, *Renewable energy: Current and potential issues*: BioScience, v. 52, no. 12, p. 1111–1120, doi:10.1641/0006-3568(2002)052[1111:RECAPI]2.0.CO;2.
- United Nations, 2002, *Report of the World Summit on Sustainable Development*: <http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N02/636/93/PDF/N0263693.pdf?OpenElement> (accessed December 7, 2011).
- Waldron, R. D., and D. R. Criswell, 1993, Summary of characteristics of beamed power radiation patterns and side lobe residual power levels for lunar power system: *Acta Astronautica*, v. 29, p. 765–769.
- World Energy Council, 2000, *Energy for tomorrow's world: Acting now!*: London, AtalinkProjects Ltd., 175 p.