Solar Power via the Moon

FEATURE

by David R. Criswell

Prosperity for everyone on Earth by 2050 will require a sustainable source of electricity equivalent to 3 to 5 times the commercial power currently produced. Because of the low average incomes in developing countries, however, this energy must be provided at one-tenth the present total cost per kilowatt-hour. Solar-power stations constructed on the moon from common lunar materials could provide the clean, safe, low-cost commercial electric energy needed on Earth.

Microwave energy beams pass through rain, clouds, dust, and smoke

Currently, commercial energy production on Earth raises concerns about pollution, safety, reliability of supply, and cost. These concerns grow as the world's nations begin to expand existing systems to power a more prosperous world. Such growth could exhaust coal, oil, and natural gas reserves in less than a century, while the production and burning of these fossil fuels pollute the biosphere. Expanding nuclear fission power would require breeder reactors, but there is intense political resistance to that idea because of concerns about proliferation, nuclear contamination of the environment, and cost. Thousands of large commercial fusion reactors are highly unlikely to be built by 2050. Terrestrial renewable systems (hydroelectric, geothermal, ocean thermal, waves, and tides) cannot dependably provide adequate power. Using wind power would require capturing one-third of the power of the low-level winds over all the continents.

Although energy coming directly to Earth from the sun is renewable, weather makes the supply variable. Very advanced technologies, such as 30% efficient solar cells coupled with superconducting power transmission and storage, imply solar arrays that would occupy selected regions totaling 20% of the area of the United States. Studies funded by the World Energy Council project that terrestrial solar energy will provide less than 15% of the electric power needed for global prosperity by 2050.

Solar power from space

Two general concepts have been proposed for delivering solar power to Earth from space. In one, Peter Glaser of Arthur D. Little, Inc. (Cambridge, MA), proposed in 1968 that a huge satellite in geosynchronous orbit around Earth could dependably gather solar power in space. In the second concept, discussed here, solar power would be collected on the moon. In both ideas, many different beams of 12-cm wavelength microwaves would deliver power to receivers at sites located worldwide. Each receiver would supply commercial power to a given region. Such a receiver, called a rectenna, would consist of a large field of small rectifying antennas. A beam with a maximum intensity of less than 20% of noontime sunlight would deliver about 200 W to its local electric grid for every square meter of rectenna area. Unlike sunlight, microwaves pass through rain, clouds, dust, and smoke. In both scenarios, power can be supplied to the rectenna at night.

Several thousand individual rectennas strategically located around the globe, with a total area of 100,000 km^2, could continuously provide the 20 TW of electric power, or 2 kW per person, required for a prosperous world of 10 billion people in 2050. This surface area is 5% of the surface area that would be needed on Earth to generate 20 TW using the most advanced terrestrial solar-array technology of similar average capacity now envisioned. Rectennas are projected to cost approximately \$0.004/kWe•h, which is less than one-tenth of the current cost of most commercial electric energy. This new electric power would be provided without any significant use of Earth's resources.

The space-based technology poses little risk to human health. A person standing in the microwave beam would absorb about 2% of the incident power and feel slightly warmer. Nonetheless, the general population would be restricted from the industrially zoned beam area, and workers could be easily shielded. Such a beam does not pose a hazard to insects or birds flying through it. Microwave intensity under and horizontally beyond the rectenna will be far less than is permitted for continuous exposure of the general population.

Beams from a power base on the moon could be turned off in a few seconds or decreased in intensity to accommodate unusual conditions. However, the beams' frequency is the band used for industrial radio, which includes some portable phones, wireless connections to remote devices, and emergency-response radio systems. Interference generated at harmonics and subharmonics of the beam frequency would likely require reallocation of these systems to other segments of the radio spectrum.

Several types of solar-power satellites have been proposed. They are projected, over 30 years, to deliver approximately 10,000 kW•h of electric energy to Earth for each kilogram of mass in orbit around the planet. To sell electric energy at \$0.01/ kW•h, less than \$60 could be expended per kilogram to buy the components of the power satellites, ship them into space, assemble and maintain them, decommission the satellites, and finance all aspects of the space operations. To achieve this margin, launch and fabrication costs would have to be lowered by a factor of 10,000. Power prosperity would require a fleet of approximately 6,000 huge, solar-power satellites. The fleet would have more than 330,000 km^2 of solar arrays on-orbit and a mass exceeding 300 million tonnes.

By comparison, the satellite payloads and rocket bodies now in Earth geosynchronous orbit have a collective surface area of about 0.1 km^2. The mass launch rate for a fleet of power satellites would have to be 40,000 times that achieved during the Apollo era by both the United States and the Soviet Union. A many-decade development program would be required before commercial development could be considered.

Lunar solar collectors

Fortunately, in the Lunar Solar Power (LSP) System, an appropriate, natural satellite is available for commercial development. The surface of Earth's moon receives 13,000 TW of absolutely predictable solar power. The LSP System uses 10 to 20 pairs of bases—one of each pair on the eastern edge and the other on the western edge of the moon, as seen from Earth—to collect on the order of 1% of the solar power reaching the lunar surface. The collected sunlight is converted to many low-intensity beams of microwaves and directed to rectennas on Earth. Each rectenna converts the microwave power to electricity that is fed into the local electric grid. The system could easily deliver the 20 TW or more of electric power required by 10 billion people. Adequate knowledge of the moon and practical technologies have been available since the late 1970s to collect this power and beam it to Earth.

Successful Earth–moon power beams are already in use by the Arecibo planetary radar, operating from Puerto Rico. This radio telescope periodically images the moon for mapping and other scientific studies with a radar beam whose intensity in Earth's atmosphere is 10% of the maximum proposed for the LSP System.

Each lunar power base would be augmented by fields of solar converters located on the back side of the moon, 500 to 1,000 km beyond each visible edge and connected to the Earthward power bases by electric transmission lines. The moon receives sunlight continuously except during a full lunar eclipse, which occurs approximately once a year and lasts for less than three hours. Energy stored on Earth as hydrogen, synthetic gas, dammed water, and other forms could be released during a short eclipse.

Each lunar power base consists of tens of thousands of power plots (Figure 1) distributed in an elliptical area to form a fully segmented, phased-array radar that is solar-powered. Each demonstration power plot consists of four major subsystems. Solar cells collect sunlight, and buried electrical wires (not shown) carry the solar energy as electric power to microwave generators. These devices convert the solar electricity to microwaves of the correct phase and amplitude and then send the microwaves to screens that reflect microwave beams toward Earth.

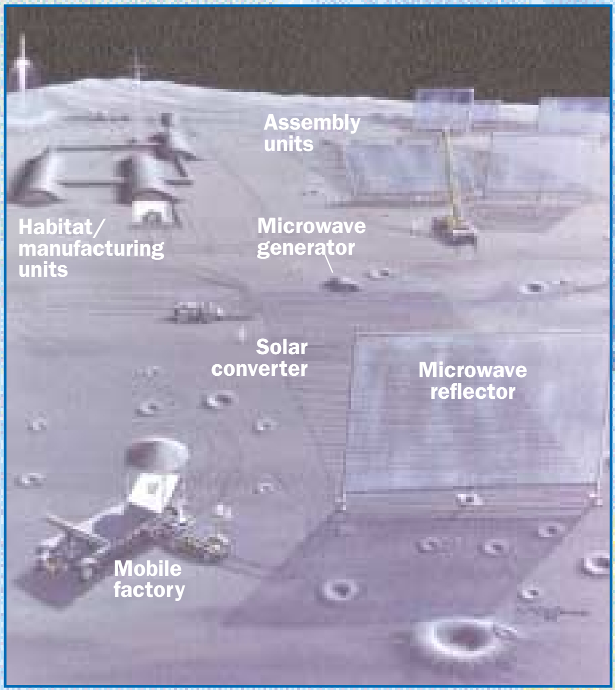


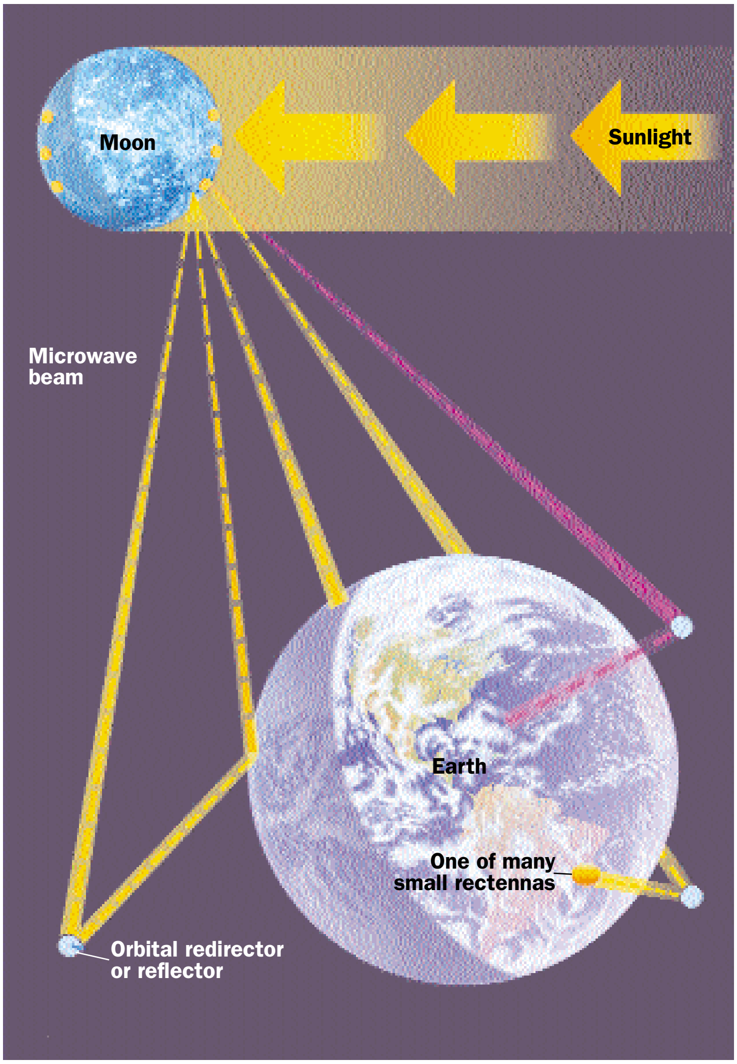
Figure 1. In this lunar power base, sunlight hits the solar converter, which transmits power via underground wires to a microwave generator, which in turn illuminates a microwave reflector. All such reflectors, when viewed from Earth, overlap to form a "lens" that can direct a narrow power beam toward Earth.

Hospitable environment

Unlike Earth, the surface of the moon is compatible with the construction of extremely large areas of thin solar collectors and their dependable operation over many decades. No oxygen, water, atmospheric chemicals, or life is present to attack and degrade thin solar collectors. No wind, rain, ice, fog, sleet, hail, driven dust, or volcanic ash will coat and mechanically degrade them. Moonquakes and meteor impacts produce only tens of nanometers of ground motion. Micrometeors erode thin solar collectors less than 1 mm every 1 million years.

To produce the lunar components, a few people and a

Ian Worpole



Ian Worpole

Figure 2. A "lens" at a base on one side of the moon (or at a linked base on the other side, if sunlight dictates) directs a microwave beam to a relay satellite or directly to a field of rectifying antennas (a rectenna) on Earth.

small quantity of production machinery, components, and supplies must be transported to the moon. The production machinery constructs the lunar power bases primarily from materials that are widely available on the moon. Bulk soil and separated soil fractions can be melted by concentrated sunlight and formed into thin glass sheets and fibers or sintered into rods, tubes, bricks, and more complex components. Silicon, aluminum, and iron can be chemically extracted from lunar soil for fabrication of solar cells. Trace elements can be brought from Earth for doping solar cells. It is estimated that a kilogram of materials transported from Earth to the moon would result in the delivery of 200 times as much electric energy to Earth as a kilogram of a solar-power satellite.

However, the power-per-kilogram ratio can be further increased because the requisite production machinery can be designed so that 90% or more is made on the moon from lunar materials. This further reduces the total mass that must be ferried from Earth and, hence, reduces the up-front cost of transportation. In this case, 1 kg of facilities and components sent to the moon will return approximately 1,400 times as much energy to Earth as 1 kg of a solar-power satellite deployed from Earth.

Earth hangs permanently in the sky just above the lunar horizon. As seen from Earth, the microwave reflectors of all the power plots of a power base appear to overlap and form an antenna 30 to 100 km in diameter. A lunar power base can efficiently deliver power to a rectenna as small as 400 m in diameter that outputs 25 MW of electric power. Larger rectennas will output proportionally more power. Note that 30 km is the maximum operational diameter of the Very Large Array (VLA) for radio astronomy, which is located 80 km west of Socorro, New Mexico. The VLA has operated automatically for more than 15 years and has routinely achieved 10 times the phasing accuracy required at the 12-cm wavelength by the LSP System.

If the cost of the lunar activities—including the design and building of a delivery system—is restricted to \$0.001/kWe•h, then as much as \$140,000/kg can be invested in establishing and operating the LSP facilities and components. An LSP demonstration system could begin delivering commercial power within 10 years of program start-up. The cost and rate of growth of the LSP System are limited only by how clever we are in applying our industrial skills, not by the cost of transporting materials to the moon.

Rectennas located on Earth between 60º N and 60º S can receive power directly from the moon approximately 8 hours a day. Power could be received anywhere on Earth via a fleet of relay satellites in high-inclination, eccentric orbits around Earth (Figure 2). A given relay satellite receives a power beam from the moon and retransmits multiple beams to several rectennas on Earth required by an alternative operation. This enables the region around each rectenna to receive power 24 hours a day. The relay satellites would require less than 1% of the surface area needed by a fleet of solar-power satellites in orbit around Earth. Synthetic-aperture radars, such as those flown on the Space Shuttle, have demonstrated the feasibility of multibeam transmission of pulsed power directed to Earth from orbit.

The LSP System is a reasonable alternative to supply Earth's needs for commercial energy without the undesirable characteristics of current options. The system collects sunlight on the moon's surface, converts it to usable energy, and beams the energy to receivers on Earth. The system can be built on the moon from lunar materials and operated on the moon and on Earth using existing technologies. More-advanced production and operating technologies than those described here will significantly reduce up-front and production costs. The energy beamed to Earth is clean, safe, and reliable, and its source—the sun—is virtually inexhaustible.

Further reading

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B I O G R A P H Y

Physicist David R. Criswell is director of the University of Houston's Institute for Space Systems Operations in Houston, Texas (dcriswell@houston.rr.com).