to the stars
ad Astra
THE MAGAZINE OF THE NATIONAL SPACE SOCIETY

SPECIAL REPORT

Space-Based Solar Power

Inexhaustible Energy From Orbit

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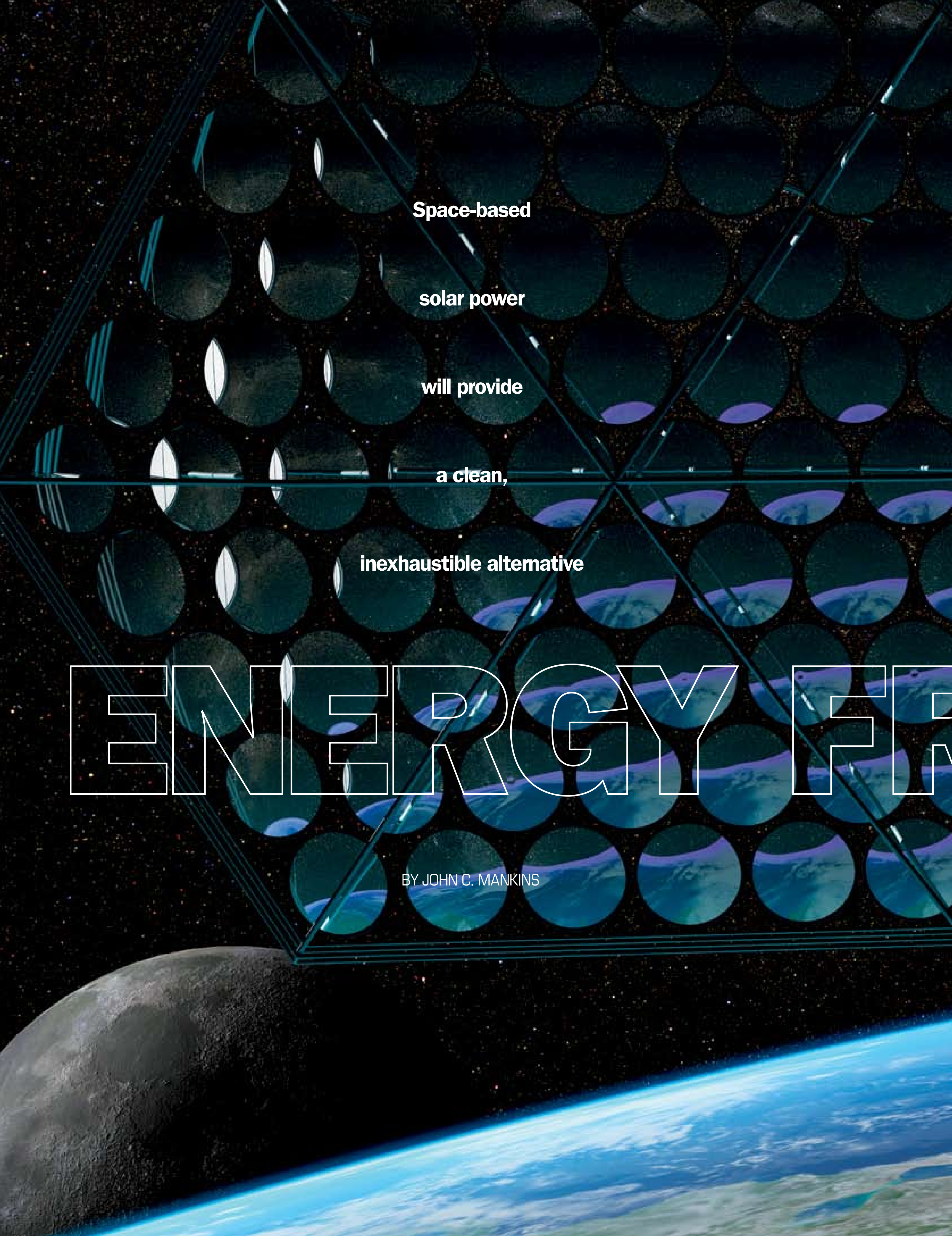
PHOTO: NASA

FEATURES

Energy from the sun is inexhaustible, as clearly underscored in this image taken aboard the Space Shuttle Endeavour. Long before Endeavour—in 1968—a mechanical engineer, Dr. Peter Glaser, envisioned a way to harness that energy for use on Earth with a concept now called Space-based Solar Power—a plan that was later studied in more detail by NASA and the U.S. Department of Energy. The general idea was that large satellites in geosynchronous orbit could capture solar power from the sun and transmit it to Earth—where it could be transferred through electrical grids to entire population centers. But in the late 1960s, the technology simply didn't exist to make it happen. Today, it does—as you'll see in our special report this issue from experts on this clean, renewable new energy source.

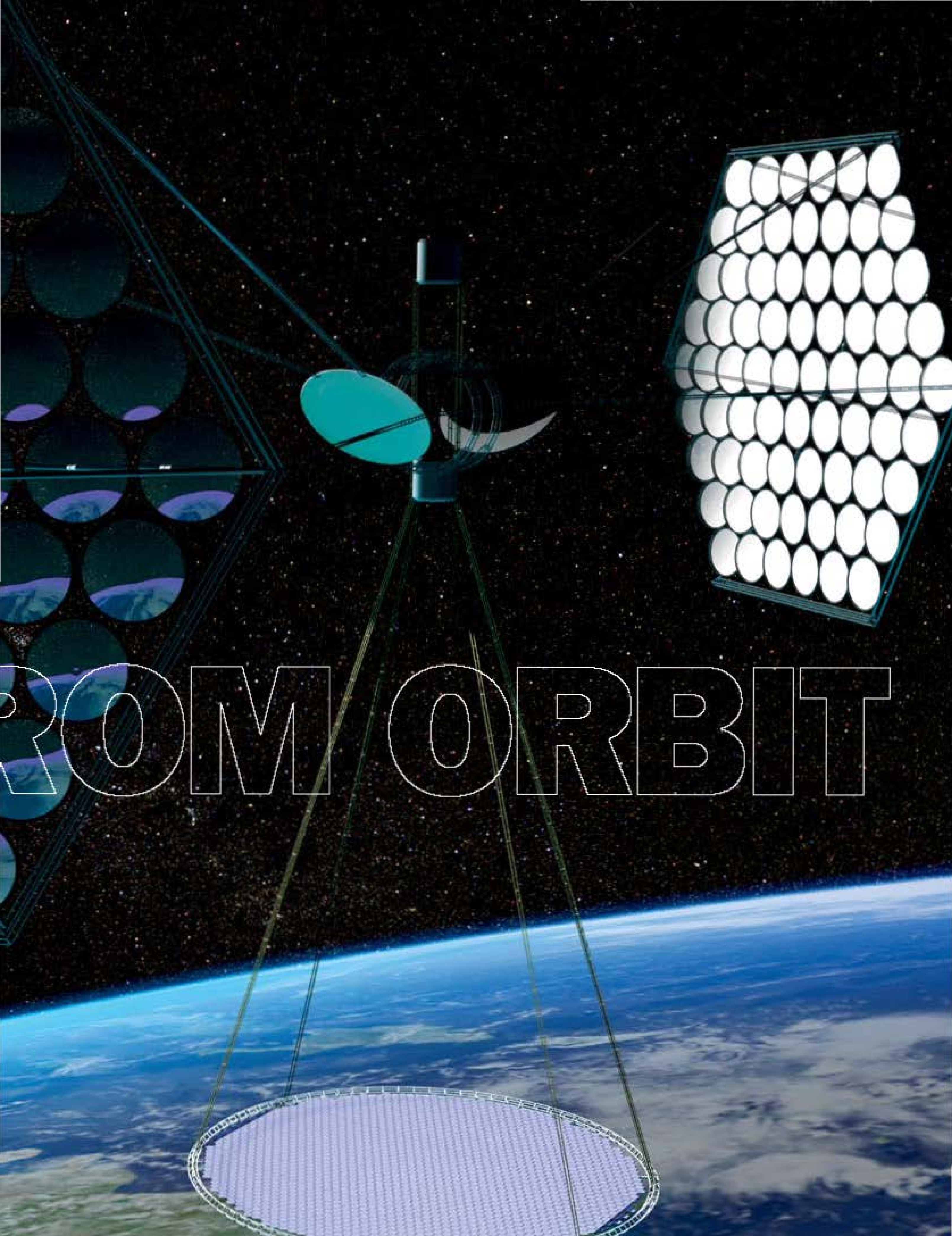
As Dr. Glaser says in an accompanying interview: "It's not just about Peter Glaser any longer. People all over the world know about solar power satellites. It's up to them to make it work for the whole world."



Space-based solar power will provide a clean, inexhaustible alternative

ENERGY FR

BY JOHN C. MANKINS


ROM ORBIT

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At an altitude of 22,240 miles above Earth, a great platform orbits, using vast, mirrored wings to collect a continuous torrent of sunlight always available in space. With few moving parts, the platform redirects and focuses this solar energy onto concentrating photovoltaic arrays—converting it into electrical power. In turn, the power is transmitted wirelessly—and with minimal losses—to highly-efficient receivers the size of airports on the ground.

It is a seamless, endless transfer: The platform constantly gathers more than 5,000 megawatts of sunlight and delivers more than 2,000 megawatts of clean, near-zero carbon electrical power to customers as needed anywhere within an area the size of a continent. It can be routed directly into the electrical grid as base-load power—and divided across a half dozen or more receivers to meet local peak power needs. It can be used as well to power the annual production of hundreds of millions of gallons of carbon-neutral synthetic fuels.

In an era when new energy options are urgently needed, space solar power is an inexhaustible solution—and the technologies now exist to make it a reality. The world cannot wait much longer. While the past century has been one of the most remarkable periods in human history, it has also been dominated by the use of fossil fuels. Yet, the accelerating global consumption of affordable and available energy sources will soon present fundamental challenges.

In less time than has passed since the founding of Jamestown, today's coal reserves will be forever gone. Also, most scientists agree that the use of fossil fuels is profoundly altering both local environments and the climate of the world itself. Capturing solar power from space-based platforms can solve this crisis. This is energy that is essentially carbon-free, endless and can be dispatched to best meet the dynamically changing requirements of populations separated by thousands of miles.

THE VISION OF SPACE SOLAR POWER

To be economically viable in a particular location on Earth, ground-based solar power must overcome three hurdles. First, it must be daytime. Second, the solar array must be able to see the sun. Finally, the sunlight must pass through the bulk of the atmosphere itself. The sky must be clear. Even on a seemingly clear day, high level clouds in the atmosphere may reduce the amount of sunlight that reaches the ground. Also various local obstacles such as mountains, buildings or trees may block incoming sunlight.

The longer the path traveled, the more sunlight is absorbed or scattered by the air so that less of it reaches the surface. Altogether, these factors reduce the average energy produced by a conventional ground-based solar array by as much as a factor of 75 to 80 percent. And ground solar arrays may be subjected to hours, days, or even weeks of cloud cover—periods when the array produces no energy at all.

By comparison, the sun shines continuously in space. And in space, sunlight carries about 35 percent more energy than sunlight attenuated by the air before it reaches the Earth's surface. No weather, no nighttime, no seasonal changes; space is an obvious place to collect energy for use on Earth.

The concept of space solar power first emerged in the late 1960s, invented by visionary Peter Glaser and then studied in some detail by the U.S. Department of Energy, and NASA in the mid-to-late 1970s. However, at that time neither the technology nor the market were ready for this transformational new energy option. Today, that has all changed.

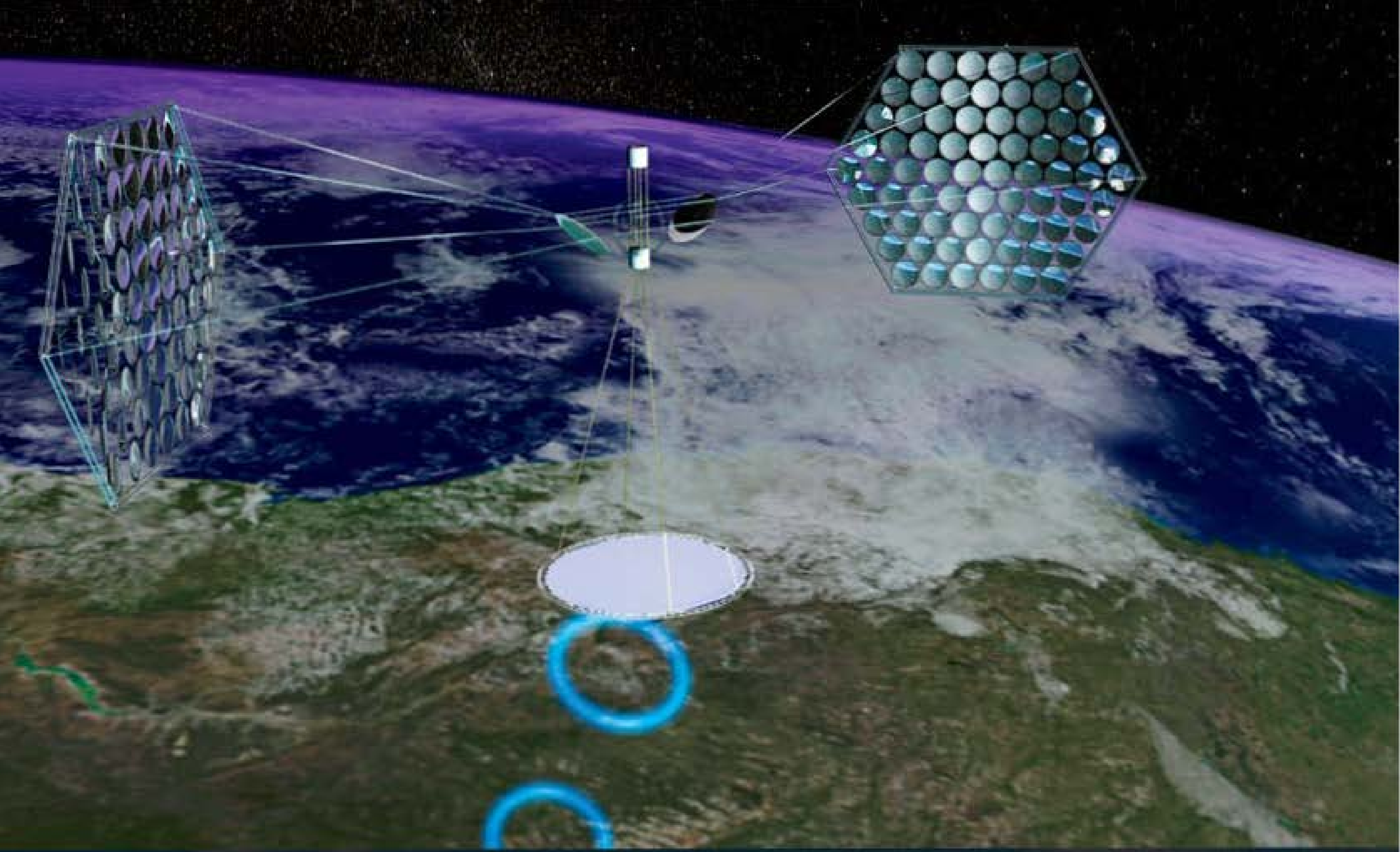
"There is practically no chance communications space satellites will be used to provide better telephone, telegraph, television, or radio service inside the United States."

—T. Craven, FCC Commissioner, in 1961 (the first commercial communications satellite went into service in 1965).

WHY WE NEED NEW ENERGY OPTIONS

Photographs of the sky over Beijing on a hot summer day—dark with particulates and unburned hydrocarbons dangerous to the young and the elderly—illustrate that the air pollution crisis that once plagued Los Angeles is not gone, but has only relocated. Similarly, making the

Located 22,240 miles above Earth, a solar power satellite uses mirrored panels to collect continuous energy from the sun. It then redirects the energy onto concentrating photovoltaic arrays, which convert it into electrical power. In turn, this energy is transmitted to the ground and can be routed into an electrical grid as base-load power and ultimately used to light up entire cities.



energy to run civilization releases enormous volumes of greenhouse gasses—over two pounds (one kg) of carbon dioxide for each kilowatt-hour (kwh) generated by coal. Global average temperatures and ocean surface temperatures are rising, along with insurance premiums for coastal areas—when insurance can be found at all.

At the same time, current space missions are narrowly constrained by a lack of energy for launch and use in space. More ambitious missions will never be realized without new, reliable, and less-expensive sources of energy. Even more, the potential emergence of new space industries such as space tourism and manufacturing in space depend on advances in space power systems just as much as they do on progress in space transportation.

New energy options are needed: sustainable energy for society, clean energy for the climate, and affordable and abundant energy for use in space. Space solar power is an option that can meet all of these needs.

HOW WOULD SPACE SOLAR POWER WORK?

"The concept is interesting and well-formed, but in order to earn better than a 'C', the idea must be feasible."

—Mid-1960s. A Yale University management professor in response to Fred Smith's paper proposing reliable overnight delivery service. (Smith went on to found Federal Express Corp.)

If collecting solar power in space is such a good idea, why isn't it already being done today? The simple answer: because it's hard! The platform itself offers major challenges. One challenge is to efficiently convert sunlight into electrical power, and in turn efficiently create an electrically (not mechanically) steered beam for transmission to a receiver on Earth. Another closely related platform challenge is to cost-effectively remove the remaining waste heat from the platform and its electronics so that it won't overheat and fail. The platform must meet these challenges while being as lightweight and inexpensive as possible. There are also a range of detailed issues involving pointing and control of the platform, and of designing platform systems for assembly, maintenance, and repair.

A major barrier to all space endeavors also applies to space solar power, and that is affordable access to space. This barrier is one of compelling importance. The problem of space access includes both low-cost and highly-reliable Earth-to-orbit transportation, and in-space transportation. (Fortunately, one of the key ingredients in overcoming this barrier is having a market that requires many flights. It's hard to imagine how air travel between continents would be affordable if the aircraft were used once or twice per year rather than once or twice per day!)

Advances that drive down the cost of space operations present significant hurdles, too. These hurdles involve a range of capabilities, most of which have never been demonstrated in space—but all of which are entirely taken for granted here on Earth. The kinds of capabilities in question include the highly-autonomous assembly of large structures, the deployment and integration of modular electronic systems, refueling, and repair and maintenance. (The key ingredient is to perform such operations without large numbers of operators and sustaining engineers on Earth—which drive the high cost of contemporary space operations.)

Environmental interactions pose another potential challenge. It is not yet understood how the space environment may affect the space solar power platform or how transmitting the energy may affect Earth's atmosphere.

The good news is that the basic physics of solar power satellites was resolved in the 1960s and 1970s, and that all of the challenges identified above can be overcome by engineering and economics.

A handful of the technical hurdles to space solar power stand out as particularly important: (1) highly efficient, high-temperature electronic devices; (2) delivering precise and safe wireless power transmission; (3) dramatically lowering the cost of the space systems and operations; and, (4) achieving low-cost access to space. And, all of these must be addressed in transformational new systems concepts.

Highly-Efficient Electronic Devices. The efficiency of individual devices determines the viability of the system—typically beginning with the solar array and ending with the receiver on Earth. There are several areas where excellent device-level efficiencies are important: first, within solar energy conversion systems; second, in the power management and distribution system that transports electrical energy from the solar energy conversion system to the wireless power transmission (WPT) system; and, third, in the devices of the WPT system itself. Fortunately, great progress has been achieved during the past 20 years in all of these areas.

Solar cell efficiencies have progressed from about 10 percent to 30 percent efficiency. Solid-state devices have advanced from efficiencies in the 20%–30% range in 1975 to 70%–80% today, operating best at low temperatures. Unfortunately, most space solar system designs require cells to withstand the high temperatures of concentrated sunlight. As a result, in order to reduce the mass of future high power SSP systems, at least some parts of the system must be modified to operate at higher than ambient temperatures.

Precisely-Controllable Wireless-Power Transmission. The size of the ground receiver is one key driver of the cost and expected resistance to market viability of SSP systems. There are a couple of ways that the size and cost of this part of the architecture can now be reduced. A simple equation describes the relationship between the size of the transmitter, the size of the receiver, and the frequency at which power is transmitted for a given distance between the transmitter and the receiver. Based on this equation, the baseline case may be defined: for a one-kilometer-diameter transmitter in geostationary Earth orbit, beaming power at a frequency of 2.45 GHz, a receiver on Earth must have a diameter of approximately 10 kilometers (neglecting effects of latitude). From this baseline, a number of variations may be considered.

To reduce the size of the transmitter, it might be useful to increase the transmission frequency. Unfortunately, frequency increase is limited in practical terms for several reasons. Available device efficiencies become lower with increasing frequency (affecting system economics).

Also, as frequency increases, the beam will be increasingly absorbed by atmospheric water vapor and particles. Alternatively, the diameter of the transmitter may be increased, but that requires more mass to be lifted into orbit.

Increasing the diameter of the transmitter would not affect device efficiencies—because frequencies would be unchanged, but it would increase the burden of rejecting waste heat from the platform. And, unless the power levels emitted by the transmitter were substantial, increasing diameter would lead to an increase in energy density at the ground that might prove unacceptable in most locations. One attractive solution to this problem could be to share the power from a single transmitter among several ground stations. This might be achieved either through the use of multiple pilot beams in a retro-directive-phased array system, or through the use of 'time-sharing' among several receivers (i.e., alternating the beam among them).

"Where a calculator on the ENIAC is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have only 1,000 vacuum tubes and weigh only 1.5 tons."

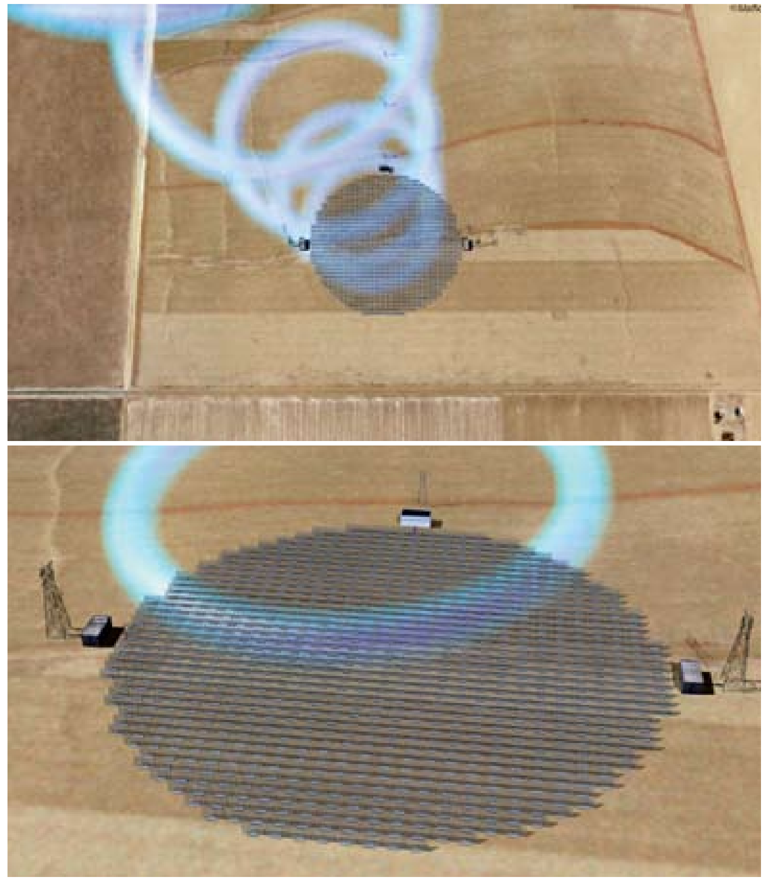
—Popular Mechanics, March 1949.

Lower-Cost Space Systems and Operations. The cost of space activities has several important components, including the cost of the hardware (initial and recurring), the cost of the people involved in operations and sustaining engineering, and the cost of launching the system (and its consumables) into space. As a result of these factors, a major spacecraft development project can cost many tens, if not hundreds, of millions of dollars. The International Space Station will have cost approximately $35 billion dollars in hardware, and perhaps that much again in launch costs by the time it is completed around 2010. (Fortunately, those costs have been spread across some 25 years and shared by 16 international partners.)

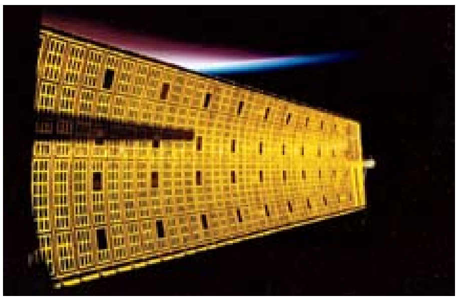
A new remarkable architectural concept called intelligent modular systems makes space solar power development more feasible than ever. The concept is a simple one: make very complex large systems by assembling a large number of smaller, intelligent, and modular systems. This extremely simple idea finds numerous parallels in nature: beehives, ant colonies, etc. This has only become feasible for space systems in the past decade or so.

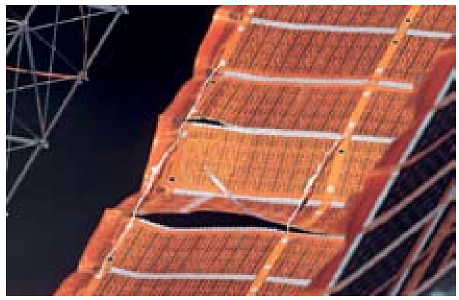
These "aggregate space systems" must involve modular architectures in which new system elements may be added, failed units removed and replaced, and configurations changed seamlessly and autonomously from local human intervention or ground-based remote control. In other words, future space solar power satellites will likely involve the concept of 'intelligent modular systems'—just as modern, ground-based commercial technologies do pervasively in the world around us. Also, these systems must involve large numbers of functionally-redundant, not too large systems elements—hence, making possible the automated, high-quality and low-cost mass production of the individual system elements that comprise the space solar power satellite. The architecture of future solar power satellites must more closely resemble a constellation of Global Positioning System satellites than it does the sophisticated, but scarcely-affordable engineering of the International Space Station.

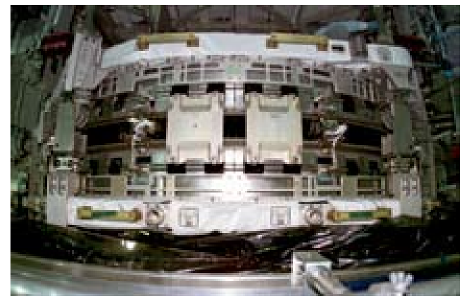
One of the most promising of future space solar power "systems-level concepts" is that of the "sandwich solar power satellite." In this case, incoming sunlight is redirected by large optical systems onto the back of an integrated platform structure that performs both the function of solar energy conversion and power beam generation. The elegance of the concept lies in its local management of power, and the exceedingly short distance (perhaps a few centimeters) for transporting electrical energy from solar array to wireless power. This approach has the potential to resolve many of the systems-level issues; particularly through extensive modularity that can enable autonomy, ease in-space assembly, and enable low-cost transportation.



Highly-efficient receivers as large as airports on the ground can receive more than 2,000 megawatts of near-zero carbon electrical power from orbiting solar satellites. Not only can the energy be transferred to electrical grids and delivered to population centers, it can also be used to power the annual production of hundreds of millions of carbon-neutral synthetic fuels. In effect, space-based solar power is a clean, efficient alternative to the use of dwindling amounts of fossil fuels.







ISS SOLAR POWER SYSTEM FACTS

The International Space Station's solar array wings were designed, built, and tested by Lockheed Martin in Sunnyvale, California.

Prior to launch, the solar cells are mounted on blankets and folded accordion-style into boxes measuring 20 inches (38 cm) high and 15 feet (4.6) in length. Each blanket is about two inches (five cm) thick while stored, and is certified for up to 82 months of storage without damage. The mast consists of interlocking battens which are stowed for launch inside a mast canister assembly designed, built, and tested by ATK-Able.

Once in orbit, EVA astronauts position the boxes and remove launch restraints. The central mast extends and pulls the blankets from their boxes. When fully deployed, a solar array wing (SAW) extends 115 feet (35 m), spans 38 feet (12 m) across, and extends out from an integrated equipment assembly (IEA) mounted on the truss. Once a second SAW is deployed in the opposite direction, the total wing span is over 240 feet (73 m).

Each IEA is a cube measuring 16 feet (5 m) on a side and weighing nearly 16,850 pounds (7660 kg). It includes direct current converters, 12 batteries, battery chargers, control computers, and an ammonia cooling system to maintain electronic gear at the proper temperature. A single radiator panel extends 44 feet "down" from this unit.

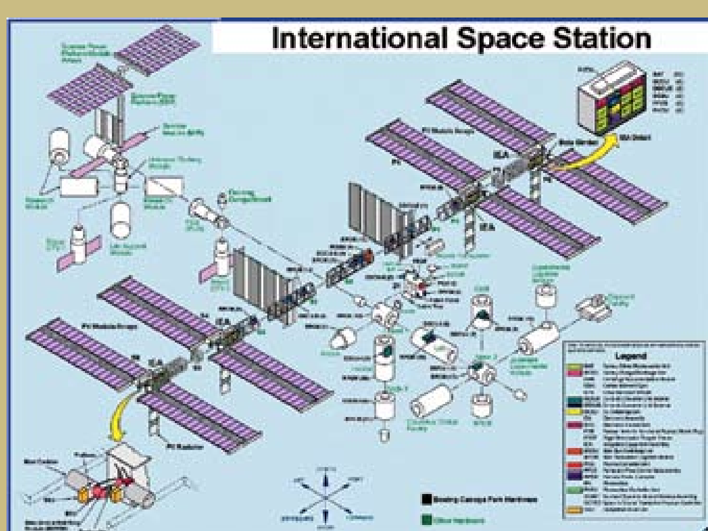
Two gimbals allow the arrays to rotate so that they face the sun and provide maximum power. The four beta gimbals tilt each pair of wings "side to side," and the two solar alpha rotary joints (SARJ) allow the starboard and port sets to spin 360 degrees around the truss. Each SARJ weighs 2,560 pounds (1160 kg).

One SAW weighs 2,423 pounds and has 32,800 solar cells that convert light into electricity. The cells, manufactured by Spectrolab and ASEC, are each three-inches (eight-cm) square and made from purified crystal ingots of silicon. The cells are assembled into 164 panels and 82 strings. The eight wings together cover an area of about 27,000 square feet (2,500 m^2)—more than half the area of an American football field.

Each pair of SAWs generates about 31 kw for a total output of about 124 kw when the station is complete—enough to meet the needs of 60 average homes (without air conditioning).

A space solar power satellite using the same technology as the ISS to produce one megawatt of power would need to be about eight times larger and massive than the station system.

—Marianne Dyson



Each pair of the ISS's solar array wings generates a total of 124 kilowatts, or the same amount of power needed for 60 average homes without air conditioning. The wings, when deployed in both directions, are more than 240 feet long.

PHOTOS: NASA

Lower-Cost Space Access. Space launch is a well-known and classic case of the "chicken-and-egg" problem, and one that has proven extremely hard to overcome. For many concepts, very low recurring costs per pound of payload can be achieved only with high launch rates (so that the cost of fixed initial investments and annual overhead costs can be spread across many launches). Achieving high launch rates depends upon the actual revenue-generating traffic to be carried, which depends significantly on earlier investments in space-utilizing enterprises (for example, investments related to in-space manufacturing capacity). And, as a result, increased investments in space-utilizing enterprises (government or commercial) will depend upon the prior existence of assured availability of reliable launch services at the lower prices.

So, in order to make space solar power possible, what has to be done about space transportation? In the case of conventional transportation infrastructures, low cost has always been achieved through reuse of vehicles and the deployment of general-purpose infrastructures that can be used many times by multiple customers, such as canals, railways, roads, and airports. It is hard to imagine how automobiles, aircraft, ships, or any other modern transportation system might somehow be produced so cheaply that the transport could somehow be "disposable" after each use. In order for space solar power systems to be economically viable, reusable Earth-to-orbit launchers will be essential.

In-space transportation advances are also needed. In-space transportation systems must be very fuel-efficient. Also, transport hardware costs must be dramatically reduced through the development of reusable, rather than expendable, systems. Finally, the personnel costs for the transport infrastructure must be drastically reduced: the system must be largely autonomous, involving neither "marching armies" of operators or maintenance engineers.

A MATTER OF SPECIAL CONCERN: OPERATING SAFETY

Assuring that a space solar power satellite can be operated safely—even in the face of operator error—is a critical requirement. There are several issues to consider: (1) assuring that the satellite's power beam is directed toward—and only toward—the desired target receiver; (2) delivering the beam energy precisely—without exceeding established radio frequency (RF) or light intensity limits outside a known receiver area; (3) establishing "fail-safe" methods and systems to minimize any risk to aircraft or spacecraft that might inadvertently approach the beam; (4) guaranteeing that under normal operations the power beam will not harm plants or animals near the receiver on the ground; and, finally (5) assuring that all other operations (including launch, manufacturing, etc.) are conducted in accordance with established industrial and government safety standards. Future efforts must assure that these and related issues are addressed effectively and transparently for energy from space to be accepted by the public.

HOW MUCH WOULD SPACE SOLAR POWER COST?

The economic goal of any new energy technology must be to deliver energy at prices that are competitive with existing and expected new providers. In the case of renewable energy, this goal has allowed for policy-driven "price adjustments" such as tax incentives or baseline price targets that may be set by government players interested in the development of a specific new technology. Such price adjustments have been commonplace in the development of renewable energy during the past several decades. In addition, price adjustments may be introduced for the purpose of achieving some other public good. For example, trading in carbon dioxide (CO_2) "credits" is a form of price adjustment, intended to reduce overall CO_2 emissions that are widely believed responsible for global climate change.

In the case of space solar power, what cost goals must be achieved in order for energy from space to compete with Earth-bound competitors?

Historically, manufactured spacecraft have been few in number, highly sophisticated in design and critical in operations. Examples include global communications satellites (as of 2007, the satellite radio industry in the U.S. was based on only two competing spacecraft), billion-dollar scientific probes in deep space (NASA's Cassini spacecraft to Saturn was a one-of-a-kind engineering marvel, as was the European Huygens probe it dropped on Titan), or a handful of military reconnaissance satellites that are essential to national security. Each of these space systems is a near-miracle, a uniquely-designed "Swiss watch" that must operate for years on a single winding. Most space systems developments are also highly expensive, prone to cost overruns during their implementation, and subject to sometimes lengthy schedule delays.

"Lee DeForest has said in many newspapers and over his signature that it would be possible to transmit the human voice across the Atlantic before many years. Based on these absurd and deliberately misleading statements, the misguided public . . . has been persuaded to purchase stock in his company..."

—a U.S. District Attorney, prosecuting American inventor Lee DeForest for selling stock "fraudulently" through the mail for his Radio Telephone Company, 1913.

Space solar power need not be impossibly cheap to compete. However, two high-level goals must be achieved. First, the mass of the system in space cannot be greater than about 3-6 kilograms (7-19 lbs.) for each kilowatt of energy delivered to the ground. Second, the cost for mass in space cannot be greater than about $3,000/kg ($1360/lb). I.e., the total installed cost of a space solar power system cannot be more than about $10,000 per kilowatt of power delivered on the ground. Remarkably, these cost goals now appear achievable using the technical approaches described previously.

Past space solar power concepts involved vast initial costs because of their dependence on huge, pre-positioned infrastructures. The new modular approaches (PCs and networks, rather than mainframes) hold the potential to transform not only the engineering of large space systems, but also

(Continued on page 59)

AN ENERGY PIONEER LOOKS BACK

An inspiring conversation with Dr. Peter Glaser BY WILLIAM LEDBETTER

At 84, Dr. Peter Glaser no longer travels the globe lecturing on the concept he first envisioned—the solar power satellite. From his home in Lexington, Massachusetts, Glaser seems perfectly at ease in knowing that others must now take his ideas forward into this century.

"I'm an old man now, and I don't travel much," he says. "All of my works and papers are in the collection at MIT. Besides, it's not just about Peter Glaser any longer. People all over the world know about solar power satellites. It's up to them to make it work for the whole world."

Considered the father of the space-based solar power concept, Glaser first went public with his research at the Intersociety Engineering Energy Conversion Conference in 1968—and followed that up with a landmark article for the journal *Science* in November of that same year. He received the first patent for solar power satellites in 1973. It was a defining moment in a career that had already contributed greatly to scientific research into solar power systems. His many accomplishments include a role as manager for the Apollo Laser Ranging Retroreflecter Array project, deployed on the Apollo 11, 14, and 15 missions.

Dr. Peter Glaser, 1990

I interviewed him by phone for *Ad Astra* in December 2007:

AD ASTRA: For most people under the age of 50, the possibility of building solar power satellites has always been with us, yet the system you proposed in 1968 was revolutionary. How did you come up with such a groundbreaking idea?

GLASER: I first considered the possibility while working on the Laser Ranging Retroreflecter Array project for the Apollo 11 moon mission. This is the device that measures the distance between the Earth and moon and is still being used. The more I learned about the moon and how much sunlight hits the moon's surface, the more intrigued I became with the idea that we could collect some of that energy and beam it back to Earth.

AD ASTRA: But you revealed your plan for building solar power satellites in 1968, before the Apollo 11 landing. What made you switch your focus from building collectors on the moon to satellites?

GLASER: It became apparent that in order to provide power to the Earth on a large scale, a network of satellites would be necessary. They would be more efficient and available 24 hours a day. I've described the whole process of how I developed the idea in a book that I published through Wiley Press called *Solar Power Satellites: A Space Energy System for Earth*.

AD ASTRA: You had the right idea, but evidently at the wrong time. When you first proposed the idea how was it accepted? Did many in the scientific community scoff and dismiss your plan?

GLASER: Yes, quite a few people laughed. They said the concept might be good, but that it was just too expensive. Of course, people back then thought that oil and gas were still so plentiful that we had hundreds of years before having to worry about running out. I suppose some people still believe that.

AD ASTRA: In light of the growing demand for dwindling hydrocarbons and the dangerous increases of greenhouse gases, do you think that the world is now primed to seriously consider space-based power systems?

GLASER: No, because people can still get gas for their cars too easily. Those in the top levels of science and government know what is coming, but the average man on the street will not care unless it impacts his wallet. That is the biggest problem. The basic approach is unchanged from my initial concept. We could have built this system 30 years ago. The technology just keeps getting better. The design and implementation is a small problem compared to the much larger obstacle of getting people to understand the potential benefits. Building such a system could provide cheap and limitless power for the entire planet, yet instead of trying to find a way to make it work, most people shrug it off as being too expensive or too difficult. Of course existing energy providers will fight, too. It only makes sense that coal and oil lobbies will continue to find plenty of reasons for our representatives in Congress to reject limitless energy from the sun.

Dr. Glaser, standing, in this archival image from *L5 News*.

AD ASTRA: Do you think the push to create space-based power systems should be spearheaded by the government or the private sector?

GLASER: Since it would be such a huge undertaking, I think it would be best accomplished at an international level, perhaps even managed by the United Nations. Each country could contribute their best effort, and then each country would reap the benefit of cheap and plentiful power from the sun. We could utilize the knowledge of all the nations that have been researching space-based solar power. If only one country has the satellites, the international community will worry that the technology will be misused. With every nation taking part in the planning, building, and operation of the system, there would be inherent transparency, oversight, and equality. There would be no secrets, and no country would be left in the dark.

On the other hand, if one nation decides to build the system, all hell may break loose. There would be distrust and a huge shift in the balance of power. Any nation with such a system would not only have an advantage in space, but they would have economic and military advantages on the ground as well. And there are many countries taking the idea of solar power from space much more seriously that we are in the United States. I would prefer to see a network of power satellites built by an international effort. ■

A LEGENDARY CAREER

A native of Czechoslovakia, Dr. Peter Glaser became a U.S. citizen in 1954 after receiving an M.S. degree from Columbia University in New York. He received a Ph.D. in 1955 in mechanical engineering and went to work for Arthur D. Little Inc., in Cambridge, Massachusetts, remaining there until his retirement as vice president in 1999. He has served on major committees for NASA and the National Academy of Sciences, and was president of the International Solar Energy Society. He was also the editor of the *Journal of Solar Energy* from 1971 to 1984.

Glaser received the Farrington Daniels Award from the International Solar Energy Society in 1983.

In 1993, the Peter Glaser Plenary Lecture was established in his honor by the International Astronautical Federation to be given at their annual congresses. He was inducted into the Space Technology Hall of Fame of the United States Space Foundation in 1996—and currently serves on the Board of Governors for the National Space Society.

William Ledbetter is past president of the NSS of North Texas, works in the aerospace/defense industry, and is a published science fiction writer. He lives near Dallas with his wife and two of his three children. Find out more at his Web site: www.williamledbetter.com.

RESOURCES

- Little, Inc. 1971. Method and Apparatus for Converting Solar Radiation to Electrical Power. U.S. Patent 3,781,647, filed July 26, 1971, and issued Dec. 25, 1973. Available online. http://www.freepatentsonline.com/3781647.html
- The Peter E. Glaser Papers (MC 569) are available for research in the MIT Institute Archives and Special Collections, Room 14N-118. http://libraries.mit.edu/archives/exhibits/glaser/

STRATEGIC IMPORTANCE

Solar power from space can help keep the peace on Earth

BY THE NATIONAL SPACE SECURITY OFFICE SPACE-BASED SOLAR POWER STUDY GROUP, A.K.A. "THE CABALLEROS"

It is rumored that shortly after the end of WWII, Professor Albert Einstein was asked what he now thought the greatest threat to mankind was. His prompt reply: "Exponential growth."

Like all species in a closed ecosystem, human civilization flourishes in times of new and plentiful resources and regresses in times of scarce supplies. Today, following more than a century of intense hydrocarbon use and six decades after Einstein's remark, the human population exceeds six billion with projections of nearly ten billion by 2050. Conventional hydrocarbon energy resource peaks are all expected to occur well before mid-century; and rising CO_2 levels may be unleashing an unprecedented global climate crisis.

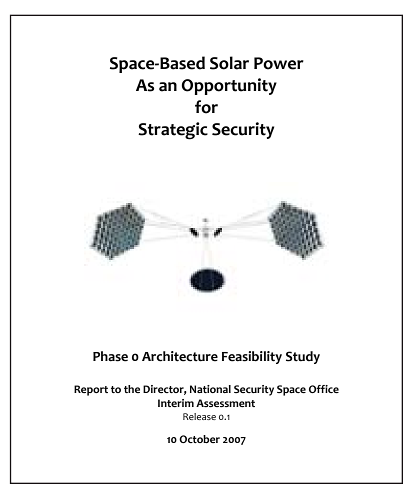
The 21st century is shaping up to be one of potential environment- and resource-driven conflict, and as the United States' ultimate guarantor of national security, the Department of Defense (DoD) is keenly aware of this future scenario. History teaches us that the application of sufficient energy and imagination to almost any problem ultimately leads to solutions for a better future. Ensuring abundant long-term energy security then becomes a fundamental pursuit of all societies.

Compared to Earth, the resources of space are infinite. In the Age of Exploration, Europe looked beyond the horizons of her surrounding oceans to solve a growing resource problem for a growing population. A similar time-distance problem separates human society today from the space resources needed to prevent its collapse and deliver the resources needed to support its ever-increasing levels of scale and complexity. While space already delivers ubiquitous telecommunication, global positioning, and surveillance commodities, these intangibles are higher-order services and not true life-sustaining resources. The first true resource delivered from space may very well be nearly limitless clean energy.

Enter the four-decade-old concept of space solar power (SSP). Originally invented in 1968 by Dr. Peter Glaser of Arthur D. Little, and last validated in 2003 by the National Academy of Sciences' National Research Council (NRC), SSP is a simple concept analogous to the hydroelectric dam as an energy-collection device. The traditional SSP architecture utilizes very large (kilometer-scale) photovoltaic arrays in geosynchronous Earth orbit (GEO) to convert a continuous stream of intense solar radiation into carbon-neutral electrical energy, which is then transmitted 24/7 through night and weather via microwave beams to collection rectennas on Earth's surface. In honor of its inventor, these space solar power satellites are sometimes fondly called, "Glasers." Total calculated end-to-end system efficiency for base-load power approaches 10 percent--remarkably high for any known natural or artificial energy production scheme. Variations on the basic concept include using solar dynamic versus photovoltaic collection systems, optical wavelength versus microwave power transmission, lunar versus orbital basing, and low-Earth orbit versus GEO architectures. Despite their differences, all systems share a common philosophy with the hydroelectric power model: invest in a high-capital infrastructure expense up front to then enable decades of clean, reliable, low-maintenance and low unit-cost energy collection, free from the volatile fuel expenses and vulnerabilities of conventional energy systems.

So why do we not have SSP satellites in orbit today when the NRC validated the concept as scientifically sound and on a healthy path toward technical feasibility as recently as five years ago? Over the course of 40 years the answer has always centered around "the business case" in the face of less-expensive competing conventional terrestrial energy sources. But that calculus is about to change.

The very real risks of climate change, energy nationalism and scarcity, unconstrained tech-


Space-Based Solar Power
As an Opportunity
for
Strategic Security

Phase 0 Architecture Feasibility Study

Report to the Director, National Security Space Office
Interim Assessment
Release 0.1

10 October 2007

nology explosion, and potential resource conflicts weigh heavily on the futurist minds of the action officers of the Air Force Future Concepts and Transformations Office and National Security Space Office (NSSO) "Dreamworks." These officers are charged with visualizing the world 25-or-more years from now, and informing and guiding Air Force and space strategy development. For a military that is fundamentally dependent on high-energy capabilities to protect its nation and the international commons for the good of all humanity, not only are the strategic risks associated with energy scarcity that lie ahead great, but so too are the operational and tactical vulnerabilities for the finest war-fighting and peacekeeping machine humans have ever known.

From Left: Col. Mike "Green Hornet" Hornitschek; Lt. Col. Paul "Plato" Damphousse; Lt. Col. Pete "Lips" Garretson; John "The Evil Dr" Mankins; Lt. Col. Mike Sires; Lt. Col. M.V. "Coyote" Smith; Mita Desai

It was from within this Air Force policy incubator and the NSSO that the spark to reexamine SSP as a strategic, operational, and tactical energy solution was struck. Beginning in the 1970s through 2001, the SSP was examined on multiple previous occasions by the Department of Energy (DOE) and NASA, but failed to find a champion in large part because SSP fell between organizational gaps (DOE does energy but not space, and NASA does space, not energy). On the other hand, because of its unique mission, DoD is the first government agency that will have to deal with the harsh realities of a coming energy peak. Self-developed, complex modern weapon systems spend two decades in pre-production and another five in operation—a 70-year life cycle that clearly places any new platforms (and our entire war-fighting doctrine) squarely on the backside of peak oil, and permanently in a hangar unless DoD can reinvent itself to remain relevant in an energy-scarce world. Therefore, DoD is in a position of greatest need for examining all alternate energy options. On a more tactical level, the very real high cost in dollars and lives lost to deliver large quantities of fuel and energy supporting operations in Iraq and Afghanistan has informed the military that energy logistics is a reality that begs for a paradigm change.

After concluding that most superficial observers of SSP casually and wrongly dismiss it either as science fiction or a complete economic infeasibility, a small group of motivated action officers from the Pentagon with science and technology, space, philosophy, operational, and strategy development backgrounds banded together (the self-anointed "Caballeros") with several long-time SSP experts on a voluntary mission to educate the un-informed about the amazing potential of this almost-forgotten energy idea. ⏩

WHY THE U.S. MILITARY IS NOT INTERESTED IN SOLAR POWER SATELLITES AS WEAPONS

When first confronted with the idea of gigawatts of coherent energy being beamed from a space-based solar power (SBSP) satellite, people immediately ask, "wouldn't that make a powerful weapon?" Depending on their bias that could either be a good thing: developing a disruptive capability to enhance U.S. power, or a bad thing: proliferating weapons to space. But the NSSO is not interested in space-based solar power as a weapon.

1. The DoD is not looking to SBSP for new armaments capabilities. Its motivation for studying SBSP is to identify sources of energy at a reasonable cost anywhere in the world, to shorten the logistics lines and huge amount of infrastructure needed to support military combat operations, and to prevent conflicts over energy as current sources become increasingly costly.

2. SBSP does not offer any capability as a weapon that does not already exist in much less-expensive options. For example, the nation already has working ICBMs with nuclear warheads should it choose to use them to destroy large enemy targets.

3. SBSP is not suitable for attacking ground targets. The peak intensity of the microwave beam that reaches the ground is less than a quarter of noon-sunlight; a worker could safely walk in the center of the beam.

The physics of microwave transmission and deliberate safe-design of the transmitting antenna act to prevent beam focusing above a pre-determined maximum intensity level. Additionally, by coupling the transmitting beam to a unique ground-based pilot signal, the beam can be designed to instantly diffuse should pilot signal lock ever be lost or disrupted.

4. SBSP would not be a precision weapon. Today's militaries are looking for more precise and lower collateral-damage weapons. At several kilometers across, the beam from geostationary Earth orbit is just too wide to shoot individual targets—even if the intensity were sufficient to cause harm.

5. SBSP is an anti-war capability. America can use the existing technical expertise in its military to catalyze an energy transformation that lessens the likelihood of conflict between great powers over energy scarcity, lessens the need to intervene in failed states which cannot afford required energy, helps the world climb from poverty to prevent the spawn of terrorism, and averts the potential costs and disaster responses from climate change.

Solving the long-term energy scarcity problem is too vital to the world's future to have it derailed by a misconception that space solar power might somehow be used as a weapon. That is why it is so important to educate people about this technology and to continue to conduct the research in an open environment.

–The NSSO SBSP Study Group,
a.k.a. The Caballeros

Because the NRC had already verified NASA's "Fresh Look Study" conclusion that SSP was not science fiction but instead just a very massive engineering challenge to solve, the Caballeros focused on how to demonstrate that SSP could in fact be economically feasible. While DOE and NASA had previously failed to close the SSP business case by examining energy as the only delivered revenue stream, DoD has a voracious demand for many different capabilities beyond just energy. These capabilities include command and control, persistent surveillance, operationally-responsive space access, space control, orbital debris removal, and in-space construction and maintenance of large structures. Recognizing that technical advances are occurring exponentially around the globe, and that history has shown time and again that deliberate and sustained innovation is the engine that drives true economic and political power, the "Eureka!" moment came with the realization that all of the previous business case analyses failed to include the economic and national security benefits of sure spin-off technologies and ancillary capabilities associated with deployment of a major SSP system. This list included not only the capabilities previously described, but also space infrastructure, low-cost reusable space access, orbital maneuver capabilities, broad-area space radar surveillance and telecommunication, and space-to-space and ground-to-ground power beaming. The ancillary benefit list was so remarkably large that it became nearly as important as the actual energy SSP could provide—no one in the DoD had ever viewed SSP through this lens before.

Eager to share their epiphany, the Caballeros set out to flesh out the SSP-DoD story by intensely researching military and dual-use energy applications for SSP. In addition to making large quantities of orbital power available for a long list of space applications, the most obvious use of SSP was for military base power. An average requirement of 5-15 MW of 24/7 baseload electricity could be delivered inside most base perimeters with a one km-wide or less rectenna—tremendously significant from a force-protection perspective for minimizing vulnerable external overland lines of fuel and power transportation.

Supporting the individual soldier came next. Today the average GI on the ground consumes the equivalent of one AA battery per hour to power his suite of electronic gear. Add to this the proliferation of other remote sensor and electronic equipment. The logistic supply requirement of this reality is enormous and could be significantly reduced by delivering low-intensity, wide-area broadcast power

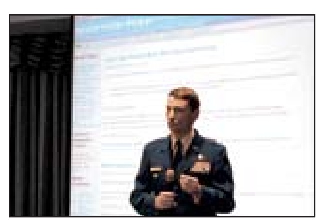
A FUNNY THING HAPPENED ON THE WAY TO THE SPACE-BASED SOLAR POWER REPORT

When someone in the media referred to us as "the Pentagon's space hippies" I had to laugh. Then again, our message was getting out. That's a good thing. You see, last year it was my pleasure to co-lead what I think was the cheapest and possibly the most influential space study ever done—well, that I've ever heard of anyway.

On October 10th last year (2007) the National Security Space Office (NSSO) presented a "Space-Based Solar Power Interim Assessment" with great fanfare at the National Press Club in Washington, D.C. The event was co-sponsored by the National Space Society who joined in announcing the formation of a new organization, the Space Solar Alliance for Future Energy (SSAFE), an alliance of thirteen well established space organizations, dedicated to "pursuing the recommendations of the SBSP study." Stories about space-based solar power appeared in print for weeks, and continue still. More importantly, countries around the globe took notice, as did a number of private entrepreneurs, and many are looking with fresh interest at the possibility of building space-based solar power systems of their own. How did this come to be?

In April, after Major General Jim Armor, then the Director of the NSSO (and my boss), received a very convincing briefing on the many reasons America should pursue space-based solar power by Colonel Mike "Green Hornet" Hornitschek, he came to me and said, "Coyote, I have no budget for this, but I want you to lead a six-month study on how to make space-based solar power a reality. This is just too important to America, its Allies, and the world. We all need clean energy for our security. You have six months. Brief me on your plan tomorrow."

Great. Solve the energy and environmental problems with zero funds. This was a Dilbert moment for me. Welcome to the Pentagon. The next day I met with the General. I explained that the only way I could imagine doing this was over the open internet in a Google Group or blog. He told me, "Coyote, nobody in the DoD has ever developed a future concept on the open Internet. This is risky, but this is just too important. Go ahead."


COYOTE SMITH, USAF

I figured I'd get a dozen or so scientists and engineers to participate in an access-controlled Google Group that I built. Boy was I wrong. Within a few weeks, I had just under 200 of America's top scientists, engineers, business people, lobbyists, lawyers, political staffers, academics, and entrepreneurs pouring their heart and soul into this project—for exactly the right price—free! I actually had to break the original site into five and create a totally public Web site with the help of the Space Frontier Foundation (http://spacesolarpower.wordpress.com/).

By the time the study ended in early September, before the conference hosted by the Air Force Academy's Eisenhower Center to brief the study findings, the total number of taxpayer dollars spent to study space-based solar power by the Pentagon was exactly…zero. True space advocates—many were members of the National Space Society and other fine space-focused organizations—gave their time and energy and demonstrated that there is a huge thirst for MORE SPACE not only in America, but also around this tiny globe. They made a huge difference!

—Col. "Coyote" Smith of the NSSO SBSP Study Group,
a.k.a. The Caballeros

over an entire area of operations. This same power could also be used to provide immediate relief in areas of humanitarian disaster or nation building.

Finally, utilizing both decades-old chemistry and recently discovered technologies from U.S. national labs, SSP energy can be used as raw feedstock for the production of any carbon-neutral synthetic fuel ranging from basic hydrogen to long-chain hydrocarbon jet fuel. This is significant and potentially the most exciting of all applications because today the DoD is the largest single consumer of petroleum in the U.S.

Now with a story and briefing in hand, the Caballeros hit the pavement. Starting first inside the Pentagon, the message was ultimately delivered to numerous senior Air Force and DoD leaders, the Defense Science Board, the OSD Energy Security Integrated Process Team, DOE and Department of Commerce representatives, the President's Office of Science and Technology Policy, various Washington think tanks, and numerous commercial companies. Sometimes solo, and sometimes as a group, the sum total of the Caballeros' experiences quickly taught them that once explained in the proper context, the SSP concept resonated quickly and exponentially with their audiences. Positive response was virtually universal. The most important resonance may have occurred on March 6, 2007, when three members briefed General James Armor, then Director of the National Security Space Office. Recognizing the simultaneous national, economic, energy, and space security benefits associated with the new energy regime that SSP offered, Gen. Armor directed the immediate collection of additional information normally associated with a formal architecture study and called for maximum broadcast of the SSP idea to all audiences under the full imprimatur of his office.

Buoyed by the NSSO Director's support, the Caballeros eagerly turned to execute his guidance, but quickly discovered that normal DoD budget process lead times would prevent any funded study activity for at least a year—a year the SSP momentum would not tolerate. Ultimately partnering with Charles Miller and the Space Frontier Foundation, the NSSO Dreamworks Office quickly found a solution by establishing separate invitation-only and public access web pages as a virtual architecture study to collect current opinions, assessments, and technical information on SSP. The results were overwhelming. Within only a few months, over 170 international SSP experts were engaged in a first-ever continuous on-line dialogue addressing all the major aspects of the concept. The conversation could no longer be contained to cyberspace, and in September 2007, the U.S. Air Force Academy Eisenhower Center for Space Defense Studies sponsored a two-day workshop to discuss and debate the conclusions forming on the web pages. The consensus was clear: study findings were ready to be published.

On October 10 2007, a Phase "0" Interim Feasibility Report was delivered to the NSSO Director. The summer-long discussion also produced a completely unexpected consequence: on the same day as the feasibility study release, 13 disparate space advocacy groups, including the National Space Society, announced the formation of the Space Solar Alliance For Future Energy (SSAFE) to promote the SSP idea to the American public, policy makers, and industry.

From the humble beginnings of simply examining a left-for-dead, decades-old idea in the context of the new 21st century strategic environment, a groundswell of public, private, commercial, and international interest in space solar power has emerged. The next step in creating this capability is building support for incremental demonstrations to prove the technical feasibility that in turn should validate the business cases and open a floodgate of government and private investment to build both the carrying trade and the SSP satellites themselves. Ultimately, in a grand security strategy context, SSP is a concept that quickly sells itself. The mission then is simple: make everyone understand SSP, and then let the good side of exponential growth take over from there. ■

WHY SBSP VERSUS SSP?

One of the more amusing anecdotes of constructing the Phase 0 SBSP Architecture Study is the influence of modern information technology systems on our language. Many people familiar with the concept of space solar power (SSP), or solar power satellites (SPS) wondered where and why after 40 years of consistency, the Pentagon would decide to rechristen it "space-based solar power," or SBSP.

If one is trading many e-mails, typing space solar power gets tedious. So like any good military organization, abbreviations become the language of choice. But in the early stages, one of the core study members had a firewall that would kick-back or "disappear" any e-mail with "SSP" in it. Apparently some monetary, provocative, or medical scam had used the acronym, and it was thus blocked by a spam filter. Despite pleadings to allow these official e-mails, the IT powers-that-be would not relent. Therefore the recipient begged for a re-title of "SSP" to "SBSP" so the e-mails could get through. So, a four-decade history of common nomenclature was replaced because of IT inflexibility, or alternately, because of some illicit spammer that had an alternate definition of SSP. As Paul Harvey would say, "Now you know the rest of the story."

—The NSSO SBSP Study Group,
a.k.a. The Caballeros


COL. MIKE HORNITSCHEK

"The Caballeros" include Col. Mike Hornitschek, USAF; Col. (select) Coyote Smith, USAF; Lt. Col. Pete Garretson, USAF, and Lt. Col. Paul Damphousse, USMC.

The views expressed in each of these articles are those of the authors alone and do not reflect any official DoD, USAF, or USMC policy or positions.

A NEW COALITION

NSS announces the Space Solar Alliance for Future Energy at the National Press Club BY ARTHUR SMITH

WASHINGTON—The National Space Society—joined by Apollo 11 astronaut Buzz Aldrin and military and civilian energy experts at the National Press Club—announced the formation of a major advocacy group to promote space-based solar power in November.

The new Space Solar Alliance for Future Energy brings together 13 leading non-profit research and space advocacy groups. Underscoring the need for the new coalition was the release of a landmark new report which was presented to the U.S. Department of Defense's National Security Space Office (NSSO) on the viability of space-based solar power (SPSP) as a solution to the world's energy crisis.

"As the United States makes the decision now to answer the energy challenges of the next 50 years, space-based solar power must be a part of the answer," NSS Senior Vice President Mark Hopkins told reporters at the October 10 news conference. The SBSP study "charts the path forward. While the technical challenges are real, significant investment now can build Space Solar Power into the ultimate energy source: clean, green, renewable, and capable of providing the vast amounts of power that the world will need."

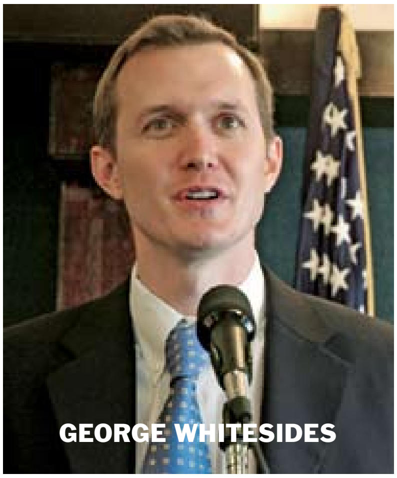
NSS Executive Director George Whitesides said, in opening remarks: "This is a big issue—the future of energy for the planet."

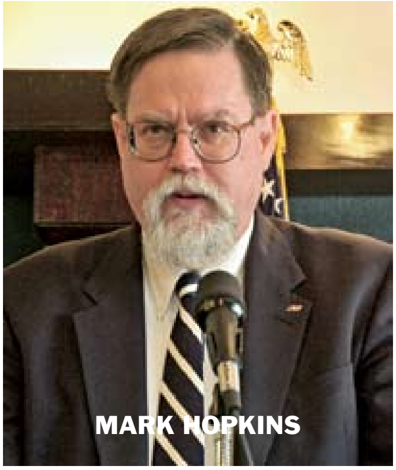
Joining Whitesides and Hopkins at the news conference were space-based solar power experts from across the nation. Among the highlights:

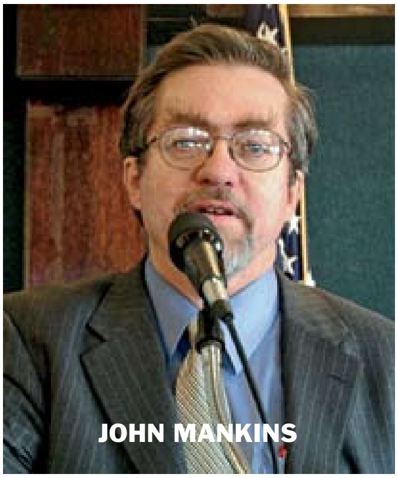
—**Former NASA scientist John Mankins**, now president of the Space Power Association and Artemis Management Solutions, told reporters that the world's population is on its way to 8 or 9 billion in this century, driving a tremendous growth in the demand for affordable and abundant energy. "Energy supplies are falling behind energy demand, and that leads to higher prices," he said.

In the coming century, restraining carbon emission levels to 2 times pre-industrial revolution levels, will require finding 40 terawatts of carbon-neutral or "green" energy—and that is two or three times the amount of energy that is used today. "That's a tremendous challenge," Mankins said. But, he noted, unless nations do ambitious things, they are unlikely to retain an edge in science and technology, in educational systems, government agencies, and in their industrial base.

—**USMC Lt. Col. Paul Damphousse**, NSSO's chief engineer, presented the findings of the study on behalf of Air Force Col. M.V. "Coyote" Smith who led the study but was unable to attend the briefing.


GEORGE WHITESIDES


MARK HOPKINS


JOHN MANKINS

ALL PHOTOS: BRUCE JANELE

The overarching conclusions, Damphousse noted, were that "SBSP does present a strategic opportunity for the United States in the 21st Century" by potentially advancing the nation's security, capability, and freedom of action. Importantly, the study did not identify any technical show stoppers, but "the business case does not close yet," he said, adding that "demonstrations are the key." The report advocates a government-led proof-of-concept program, starting in small incremental steps and leading to a large-scale demonstrator.

—**Charles Miller**, (above, far right) a director of the Space Frontier Foundation (SFF) who led the public/private part of the study, said the SFF fully endorses the recommendations in the report—and believes that the U.S. government should start a new national initiative in this area.

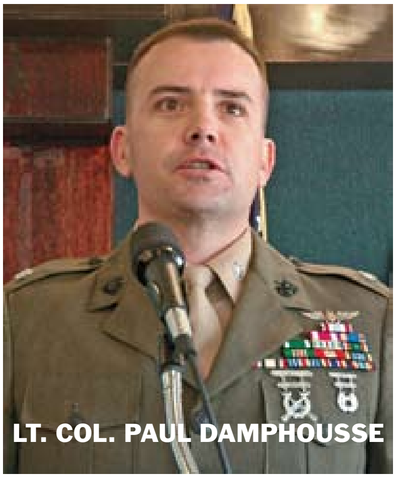
—**Apollo 11 astronaut Buzz Aldrin** closed the meeting with a short video from Apollo 11 as an example, he said, of "what can be done with a challenge."

Space-based solar power, Aldrin said, won't be "one small step" but will take decades to meet the energy challenges facing the world.

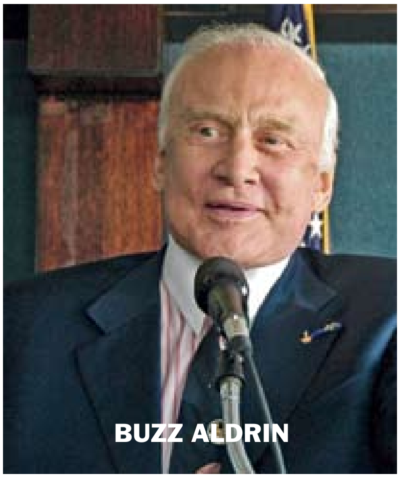
"As a responsible society, I think it is really our duty to make the investments, and to make them today—not to wait until the nation needs to catch up again," he said. "The technical developments needed for space-based solar power will open up the space frontier."

Reporters participating in the news conference included CNN's **Miles O'Brien** and others from Aviation Week, Space News, the Los Angeles Times, and National Public Radio.

Also on hand was **Air Force Maj. Gen. James Armor**, past president of NSSO. ■



LT. COL. PAUL DAMPHOUSSE



BUZZ ALDRIN

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SPACE FRONTIER FOUNDATION:
http://space-frontier.org
Margo Deckard,
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SPACE STUDIES INSTITUTE:
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Lee Valentine,
Executive Vice President

SPACE ENTERPRISE COUNCIL:
www.uschamber.com/space
David Logsdon, Executive Director

AEROSPACE TECHNOLOGY WORKING GROUP:
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Ken Cox

MARSHALL INSTITUTE:
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Jeff Kueter, President

MOON SOCIETY:
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Peter Kokh, President

PROSPACE:
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Loretta Hidalgo Whitesides, President

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SPACEWARD FOUNDATION:
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SHARESPACE FOUNDATION:
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Lisa Cannon

AIAA SPACE COLONIZATION TECHNICAL COMMITTEE:
http://www.aiaa.org/portal/index.cfm?GetComm=195&tc=tc
Klaus Heiss, Chairman

ON THE MOON

Lunar material will be an important asset in the construction and launch of solar power satellites

BY AL GLOBUS

While it has been suggested that in the long term, space solar power (SSP) can provide all the clean, renewable energy Earth could possibly need (and then some), there has been less discussion on the most economic way to produce that power. If we want to build two or three solar power satellites, one obvious approach is to manufacture the parts on the ground, launch them into orbit, and assemble them there, just like the International Space Station. But a few power satellites won't solve our energy or greenhouse gas problems. We'll need more.

To generate all the energy used on Earth today (about 15 terawatts) would require roughly 400 solar power satellites 10 kilometers across. Assuming advanced, lightweight space solar power technology, this will require at least 100,000 launches to bring all the materials up from Earth. But even 400 satellites won't be enough. Billions of people today have totally inadequate energy supplies—and the population is growing. Providing everyone with reasonable quantities of energy might take five to ten times more than we produce today. To supply this energy from solar power satellites requires a staggering launch rate. There are two major issues with a very high launch rate.

The cost issue is obvious: the cheapest launches today run thousands of dollars per kilogram to low Earth orbit (LEO), and we need to get the materials all the way to geosynchronous Earth orbit (GEO), which is significantly more expensive. The cost of launch goes up very quickly with the change in velocity, which is measured in meters per second (m/s). For each increase in velocity, additional fuel is needed, and even more fuel to lift the additional fuel, and heavier structures to hold the increased fuel, and even more fuel to lift the heavier structures … you get the idea. In any case, the velocity change from the ground to LEO is 8,600 m/s, but to GEO it's 12,400 m/s. Paul Werbos (see references on page 36) estimates that launch costs must come down to somewhere in the neighborhood of $450/kg for SSP to deliver energy near current prices (5-10 cents/kw-h). Fortunately, a high launch rate drives prices down, just as the mass-produced Ford Model-T was far cheaper than the previous generations of automobiles.

The environmental impact of these launches is also a concern. Today there are few launches and, therefore, they have little effect on the atmosphere. What will happen when hundreds of thousands of rockets are dumping exhaust, even clean exhaust, into the upper atmosphere? If the vehicles are reusable, which we expect, they will use atmospheric drag to come down. The heat generated will create a number of chemical reactions in the upper atmosphere. What will be the effect? We don't know. There's reason to believe the problems won't be severe, but the studies conducted so far are inadequate.

SOLUTION: LUNAR MATERIALS

Both the cost and environmental impact of launches can be massively reduced long-term through the use of lunar materials. In that scenario, only the facilities to mine the moon and convert these materials into solar power satellites need be launched from Earth. It's the difference between launching a car factory, which is large, versus the millions of cars it produces, which is a lot bigger.

SSP satellites can be made largely of silicon and metals: silicon to convert sunlight to energy, and metals for structure, mirrors, and the antenna. The Apollo program proved conclusively that the moon contains large quantities of both. Launch from the moon requires far less energy than launch from Earth, because the moon is much smaller and therefore exerts a much weaker gravitational pull. Also, geosynchronous orbit is 12,400 m/s from the Earth's surface, but only 4,600 m/s from the surface of the moon. Of course, launch from the moon would also have no effect on the Earth's atmosphere.

The Stanford/NASA summer studies (see references on page 36) closely examined electromagnetic launch of materials from the moon, which requires no fuel, only energy. This system, called a mass driver, could deliver millions of tons of material per year to orbit. A mass driver works using electromagnetic forces to provide rapid acceleration, similar to the initial startup of some roller coasters. On the moon magnetic buckets full of lunar materials ride an electromagnetic wave generated by structures installed on the lunar surface. At just the right point, the buckets release their payload and return for reuse. The payload is sent into space at very high speed with no fuel cost or terrestrial environmental impact.

Lunar materials must be converted into satellite components, a difficult materials processing and manufacturing problem in an unfamiliar, unique environment. Some of the work, such as mining, must be conducted on the lunar surface. Other work, such as assembly and test of solar power satellites must be conducted in orbit. The rest of the work, materi-

The environmental impact of these launches is also a concern. Today there are few launches and, therefore, they have little effect on the atmosphere.

ILLUSTRATION: WARREN TURNER, 2007

als processing and component manufacture, will be divided optimally between these locations. To minimize the mass launched from the moon, we may want to process the materials to eliminate the bits not needed in orbit. Because lunar dust is small, sharp, and difficult to deal with, we may also wish to fuse the material to avoid launching lunar dust to the orbital work site. Conversion of the processed materials into satellite components might best be done in orbit since bulk materials can take a great deal of shaking and acceleration on launch, but more complex components often cannot.

Lunar and orbital SSP operations may require only a small staff because many of the operations may be automated or remotely controlled from Earth, like unmanned aircraft, undersea robots, and most of today's spacecraft. Although there is a communications delay of about three seconds for the roundtrip to the moon and back, preliminary experiments suggest that operators can easily accommodate this delay for at least some tasks (see references). It is clear that research and testing of remote operations and automation on the moon and in orbit would help reduce the risk and cost of future SSP operations.

While SSP development has many, many problems, they are the kinds of problems we can solve. Although there is a lot of work to be done, there is a real pot of gold at the end of the rainbow: all the clean renewable energy we could possibly want. Importantly, no other energy option offers the quantity and environmental advantages of SSP from lunar materials. The vast majority of the work is done on the moon and in orbit, thousands of kilometers from the Earth's biosphere.

If we were to decide today to vigorously pursue SSP built from lunar materials, what should we do? While that is a complex question, here's a start:

- Build a series of increasingly capable SSP systems, starting with something small and working up to a fully-operational satellite and ground system.

- Use the International Space Station (ISS) to develop the necessary in-orbit processing, manufacturing and assembly technology.

- Use NASA's lunar base to develop the necessary mining and processing technology and infrastructure.

- Develop less-expensive launch vehicles through research, funding prizes, granting private developers' access to unique government facilities, and guaranteeing government markets.

- Develop simulators to conduct research on teleoperated and automated lunar and orbital mining, processing, manufacturing and assembly.

- Develop closed-loop life support—recycling air and water, reclaiming waste, and growing food—on the ground and on the ISS to reduce launch requirements.

- Conduct a major research effort to determine the impact of high launch rates on the Earth's atmosphere.

Besides creating a lasting and clean energy source, building SSP from lunar materials will develop lunar mining, in-space materials processing, launch vehicles, closed-life-support systems, and large satellite construction—much of what we need to create communities beyond Earth. SSP, particularly built from lunar materials, would be a huge step towards realizing the NSS Vision. ■

Al Globus has studied and advocated space settlement for 30 years. He has published articles on space settlement design, lunar teleoperation with communication delays, nanotechnology for space development, and on many computer science topics. His views and publications on space settlement may be found at space.alglobus.net.

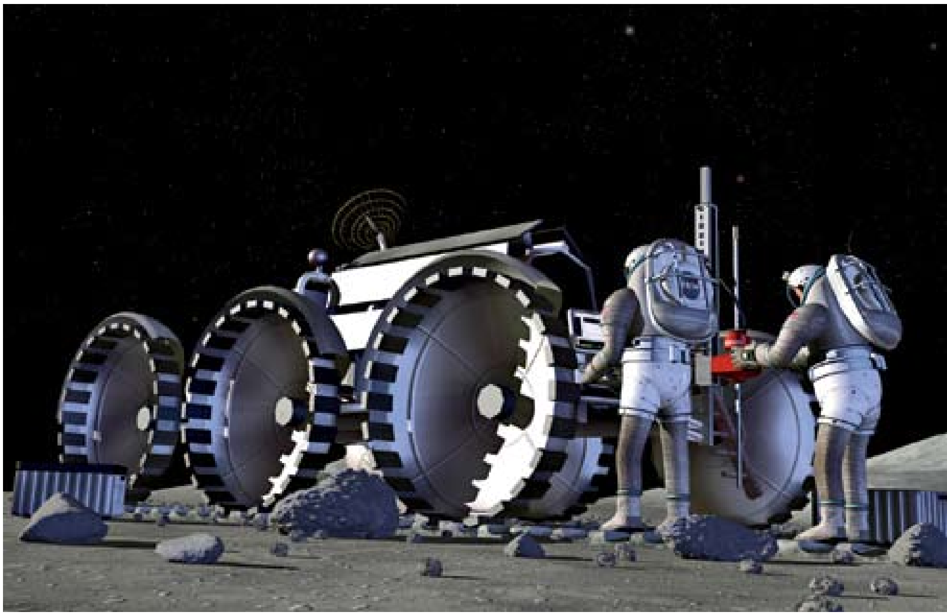

ILLUSTRATION: NASA

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