It's Always Sunny in Space

Why space-based solar power is a viable source of energy.

Rob Mahan

Advances in human civilization have always been fueled by the availability of excess energy in various forms. For the vast span of human history, energy from the Sun was converted to food and biomass by photosynthesis and expended in the forms of muscle power and fire. Energy from the Sun produced weather, and as a result, wind- and water power were eventually harnessed and converted into increased levels of societal organization.

When humans began to extract massive amounts of energy from plant-based fossil fuels—which originated millions of years ago, through photosynthesis driven by energy from the Sun—further technological complexity, economic surplus that freed increasing numbers from manual labor, and human population all exploded. Gasoline-powered, mass-produced automobiles represented freedom in the form of personal transportation. Electricity became an efficient way to deliver energy to homes and businesses, and eventually to power a global information network. Growth was good, and seemed unstoppable, at least to those with easy access to abundant energy.

More recently, science and rationality have led us to a stark realization. Year-over-year economic growth, driven by the ever-increasing consumption of finite natural resources to produce abundant energy and other goods, has proven unsustainable. Coupled with concerns about climate change resulting from the release of excessive carbon dioxide into the atmosphere, three broad future scenarios emerge:

- Continue the current, unsustainable trend of natural resource extraction, energy consumption, and economic growth, and let natural processes dictate the next era in human history.
- Based on current and past technologies, voluntarily and drastically reduce global energy consumption and revert much of humankind to the previous era of muscle, wind, and water power.
- Develop new technologies and find cleaner, renewable, or unlimited forms of abundant energy, while becoming better stewards of the finite natural resources that remain.

If the third scenario is the most appealing to you—as it is to me—and almost all forms of energy harnessed by humankind throughout history originated with energy from the Sun, doesn't it make sense to look directly to the source in our quest to find a clean, unlimited source of energy for all of humanity going forward?

What does "space-based solar power" mean?

Space-based solar power (SBSP) refers to the concept of collecting the Sun's energy in space and then transmitting it to Earth for use as a baseload renewable energy source. This involves putting solar panels in orbit around the Earth to continuously collect energy from the Sun. The energy is transferred to receiving antennas (rectennas) on Earth as microwave or laser beams, converted to electrical energy, and then sent to consumers through the existing power distribution grid. The goal of SBSP is to provide practically unlimited clean energy that is not subject to weather conditions or night-day cycles; energy that is available 24/7/365, anywhere on the planet.

Before we delve into the details and challenges around space-based solar power, let's take a brief step back in time to see how humanity got where we are today, and how we may soon be consuming the equivalent amount of energy in *150 billion barrels of oil every year*.

How much energy is globally consumed by humankind?

It took the first three million years of evolution for the world population to reach one billion of us. Over the past 220 years, fueled by advances in medicine, nutrition, and a massive glut of cheap energy from the worldwide fossil fuel industry, the world population has exploded to over eight billion humans. The United Nations estimates that the world population will expand to over ten billion by the year 2100.[1] In the developing economies of emerging nations, particularly in Asia, per capita energy consumption is increasing as people seek better lives for themselves and their families.

Driving—or driven by—economic and population growth, worldwide energy consumption also exploded over the past two centuries, and with it, energy-related carbon dioxide emissions. *The Enerdata World Energy & Climate Statistics* lists the 2021 global total energy consumption as 14,555 million tons of oil equivalent (Mtoe), or for comparison purposes, the equivalent of about 169,277 terawatt-hours (TWh) of electrical energy. For 2021, the global electricity generation is listed as 28,433 TWh of electrical energy, or about 16.8% of the global total energy consumption.[2]

A mid-range scenario presented in *the Enerdata Global Energy & Climate Outlook 2050* assumes policies that will lead to a global temperature rise between 2.0° C and 2.5° C and projects the 2050 global total energy consumption at 14,194 Mtoe. For comparison purposes, that is the equivalent of about 165,216 TWh of electrical energy. The 2050 projection for global electrical generation is listed as 51,891 TWh of electrical energy, or about 31.4% of the global total energy consumption. The increasing percentage of global total energy consumption represented by global electrical generation is driven by the continuing trend to convert more and more end-uses of energy away from fossil fuels and to electricity.[3]

In 2021, the U.S. Energy Information Administration (EIA) released the *International Energy Outlook,* which projects global energy consumption, electricity usage, and energy production trends through 2050.[4] Some of the key takeaways from this report include:

- By 2050, global energy consumption and energy-related carbon dioxide emissions will increase by nearly 50% compared to 2020, mostly as a result of population and economic growth in developing countries, particularly in Asia.
- Renewables will be the primary source for *new* electricity generation, but coal-fired generation will continue to be a significant part of the worldwide generation mix. Natural

gas, coal, and, increasingly, batteries will be used to complement intermittent renewable energy sources, helping to meet load demand and supporting grid reliability.
- Oil and natural gas production will continue to grow, mainly to support increasing energy consumption in developing Asian economies.

By any account, the total amount of energy consumed by humankind *every year* is staggering and difficult to comprehend. If the U.S. EIA projection of a 50% increase in global energy consumption by 2050 proves correct, the approximate number of barrels of oil equivalent (boe) consumed by humankind *every year* will be:

14,555 Mtoe x 150% x 6.849e+6 boe / Mtoe =

149,537,669,738
barrels of oil equivalent per year

It is beyond the scope of this article to illustrate how much CO2 would be released by burning 150 billion barrels of oil every year. Suffice it to say—it would be a lot.

How much energy is available to us from the Sun?

The Sun radiates about 174,000 terawatts (TW) of power to the Earth's cross-sectional area, of which about 134,000 TW reach the surface, the rest being absorbed or reflected by the Earth's atmosphere. Therefore, over the course of a year, the Earth receives 1,173,840,000 TWh of energy from the Sun.[5] As mentioned above, in 2021, the total global energy consumption was the equivalent of about 169,277 TWh of electrical energy, so *there is about 7,000 times more energy available from the Sun than humankind currently consumes*.

Since the Sun is only about halfway through its estimated ten-billion-year lifespan, in practical terms, we can say that energy from the Sun is unlimited. Ironically, we can also say that since energy from the Sun has always powered photosynthesis, the chemical energy that is released when burning calories, biomass, and fossil fuels came from the Sun. And finally, since wind is created by uneven heating of the Earth's atmosphere by solar radiation and by the planet's revolution around the Sun, wind energy originated as energy from the Sun, as well.

So why not just use enough solar panels on Earth?

A little-known fact about all electricity distribution systems, i.e., "the grid," is that 100% of the time, the electricity supply (generation) has to be balanced with the electricity demand (load), because electrical energy cannot be stored in power lines or other parts of the grid. In other words, all electricity that is generated must be used by a load (a light bulb, an air conditioning condenser, an electric vehicle charging station, etc.) almost instantaneously. If total generation exceeds total load at any given time, automatic safety controls either shut down the overloaded grid or divert the excess electrical energy to other grids.

Distribution grid operators know that the electricity demand, or load, varies with the time of day and with the seasons of the year. When the load begins to exceed the supply, if additional supply is not brought online, either partial (brownouts) or complete (blackout) shutdowns occur; conversely, when the load diminishes, the amount of supply must be reduced to keep the grid in balance. Grid operators also know that the load on their grid never drops below a certain baseline level, also known as the "base load."

Electrical power generation falls into two broad categories:

- Intermittent Power: generation levels change quickly and uncontrollably with varying conditions, such as night/day cycles, weather, and atmospheric variability by season and by region. Most renewable energy sources, such as terrestrial solar power and wind power, fall into this category.
- Baseload Power: generation is slower to come online but can be maintained at a constant level with the consumption of a fuel. Coal-fired power plants, natural gas-fired power plants, and nuclear power plants fall into this category.

Without massive, expensive storage capacity (pumped hydro, compressed gas, mechanical, chemical, thermal, etc.), intermittent generation must be supplemented with baseload generation to assure that demand can be met and grid balance can be maintained at all times.

This brings us back to the question: *Why not just use enough solar panels on Earth*? The answer lies in the differences between terrestrial (earth-based) solar power and space-based solar power.

Terrestrial Solar Power	**Space-based Solar Power**
It's Always Darkest Before the Dawn Output varies from zero to peak with the night/day cycle.	*It's Always Sunny in Space* In geosynchronous orbit, solar panels are in full sun nearly 100% of the time, so there is no output variability.[6]
Output varies uncontrollably with weather and other changing atmospheric conditions.	Peak output is continuous 24/7/365.
Total output varies with global location, e.g., latitude and annual weather conditions vary greatly between Scandinavia and the Saharan Desert.	Total output is constant, independent of location in geosynchronous orbit, and can be as much as eight times more than an equivalent installation of terrestrial solar photovoltaics.
Ideal terrestrial locations are not always near population (demand) centers, and transmission losses limit the practical distance power can be moved over power lines.	Power can be transmitted to receiving antennas nearly anywhere on the surface of the planet for final distribution over local grids.
Intermittent terrestrial solar power without energy storage requires supplemental fossil-fuel or nuclear power generation. Subject to	Available, clean energy from the Sun is also non-renewable ... but for all practical intents, it is *unlimited*.

debate as to the time frame, both fossil and nuclear fuels are finite, non-renewable natural resources with environmental impacts.	
Land use and local plants and animals are impacted by the installation of vast solar farms.	In space, land use has no meaning, and the available area of the geosynchronous orbit sphere is vast.
The Bottom Line	
Terrestrial solar power, without supplemental fossil-fuel or nuclear power generation or hugely expensive and potentially harmful energy storage technologies, must remain the intermittent electrical power generation source.	Space-based solar power is, by definition, a baseload power source that does not require fossil-fuel supplementation or energy storage, and it does not emit CO_2 or other potentially harmful byproducts.

Should we abandon terrestrial solar power altogether?

Heavens, no! An all-of-the-above approach to meeting global energy needs is a rational course of action, as long as it is coupled with ongoing research, development, and deployment of superior solutions. The cost of terrestrial solar has come down over the past couple of decades, solar photovoltaic efficiencies continue to improve, and the U.S. government recently increased the federal tax credit for homeowner-owned solar generation back up to 30% of the total installed system cost, extending the tax credit for the next decade. Although the mix will continue to be adjusted, all existing forms of energy generation represent a bridge solution, until a truly clean, unlimited baseload power source can be brought online and scaled up to meet the global energy consumption demand.

What are the key components of space-based solar power, and what are the challenges?

The key components of space-based solar power are:

- Collectors in geosynchronous orbit, about 22,000 miles away from Earth.
- Wireless power transmission in the form of microwaves at a frequency not impeded by clouds, storms, etc.
- Stations with large receiving antennas that convert the microwave power to alternating current (AC) electricity.
- Connections to the existing electrical grid for distribution to regional consumers.

Unlike other proposed energy generation solutions, SBSP does not require any fundamental scientific breakthroughs to make it a reality. However, major challenges do exist in the technical, financial, and political realms. The U.S. four-year election cycle is a major challenge to implementing any long-term project that requires critical thinking and consistent commitment. Space law must be established to define the rules for staking claims to orbital slots, as well as harvesting resources on the Moon or in space.

Space is a hostile environment to humans. Advancements in the areas of robotics and automation can increase safety and reliability, as robots can operate in hazardous environments and perform repetitive tasks with high precision. Once developed, these new technologies could play a critical role in the development, deployment, and ongoing maintenance and repair of space-based solar power systems.

Are there any active space-based solar power projects currently being conducted?

Virtually unknown to the public at large, several countries[7, 8, 9] have recognized the potential of space-based solar power and are currently undertaking research, development, and demonstration projects. Some of the ongoing SBSP projects from around the world that major news channels have not yet reported on include the U.S. Naval Research Laboratory Photovoltaic Radio-frequency Antenna Module (PRAM)[10] as well as Solar Space Technologies Pty Ltd (SST),[11, 12] which aims to deliver a solar power satellite into geostationary orbit to supply energy to the Australian grid by 2027. China aims for a space-based solar power test by 2028, with advanced planning in phases from 2030 through 2050.[13]

Will a rational analysis of the existing model of never-ending economic growth based on the ever-increasing extraction of finite natural resources lead us to corresponding ways of thinking? Will the environmental impacts of burning billions of tons of fossil fuels every year lead us to new, clean, and unlimited sources of abundant energy? For the sake of the generations of humankind to come, I truly hope so.

Abstract
Advances in civilization are driven by the availability of excess energy. As the human population has exploded over the past two centuries, the global consumption of energy has also drastically expanded. But the current economic model is unsustainable without the development of a clean, unlimited source of energy. Space-based solar power (SBSP) can directly access the power of the Sun, and has the potential to be that clean, unlimited baseload power source of energy for the entire planet.

Author Bio
Rob Mahan is a retired mechanical engineer who spent most of his career in the automotive and aerospace industries. The 2007 National Security Space Office Interim Assessment, "Space-Based Solar Power As an Opportunity for Strategic Security" rekindled his interest in space-based solar power and its long-term potential to become the unlimited clean energy source for the planet. He maintains the website *Citizens for Space Based Solar Power* with the goal of bringing information about this potentially game-changing technology.

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