The Coming Age of Astroelectricity [1] [2]

By

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[1] This paper was prepared for the 26–30 June 2021 Space Renaissance International 3rd World Congress, Symposium 2 on Space Development, Session 2.5: Space Based Solar Power, Powering Civilian Space Development. This version of the paper is includes illustrations and has been reformatted for easier reading on tablets and computer screens.

[2] The 10-minute video version of this paper, presented at the conference, is available at: https://www.youtube.com/watch?v=5E-0NYnAaUA.

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Abstract

This paper defines a progressive engineering solution to the world's need to undertake an orderly transition to abundant clean energy by 2100 to eliminate net anthropogenic carbon dioxide emissions into the atmosphere and provide sufficient sustainable energy per capita to enable social and economic development while eradicating poverty worldwide. This paper begins by explaining the critical dependency of civilization on sufficient and affordable supplies of energy and the technologies to use this energy. The paper next examines the United Nations Framework Convention on Climate Change and the Paris Agreement to identify why these are now outdated and need to be replaced. The paper then proposes 2100 targets for the worldwide green energy required to achieve global sustainable development to a middle-class standard of living similar to that of the European Union. Next, the paper examines terrestrial sources of sustainable energy to quantitatively show why a substantial reliance on these sources is unlikely. The paper concludes by showing how space solar power-generated astroelectricity will enable the world to peacefully undertake its transition to abundant, sustainable energy.

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Introduction

Despite our dream to expand human civilization into space, a compelling argument on why this is needed has not yet been effectively made. (See Figure 1.) A century ago, Konstantin Tsiolkovsky foresaw the need for humanity to tap the immense resources of space to meet our growing terrestrial need for natural resources including energy. Achieving global sustainable energy security is now the world's primary challenge. However, the world has yet to embrace an effective path for providing sufficient sustainable energy per person to eradicate poverty, achieve true sustainable development, and enable a prosperous global middle-class standard of living. Space solar power-generated astroelectricity is the only practical path to achieve these goals. Building a global network of astroelectric systems at the scale needed to achieve global sustainable energy security is the compelling argument on why the permanent settlement of the central solar system must now be undertaken to begin the age of astroelectricity.

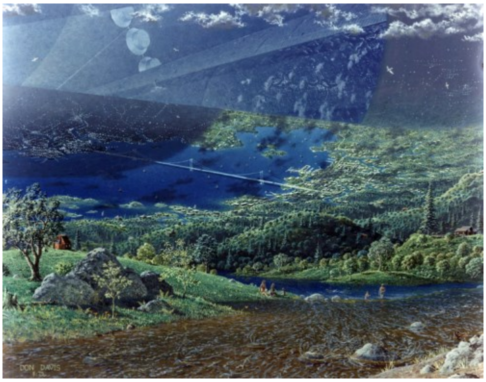

Figure 1: Notional human-built space colony. (Source: NASA.)

Understanding the essential role of energy in human culture

Striving to better understand human behavior, in 1943 Abraham Maslow organized the motivations for human behavior into three general groups: physiological needs, psychological needs, and self-fulfillment needs. These are often illustrated as a stacked pyramid with physiological needs at the bottom and self-fulfillment at the top. The physiological needs are those providing for a human's immediate survival: water, food (energy), shelter from the elements, and protection from threats. Maslow argued that meeting these physiological needs fundamentally drives human behavior.

Throughout hundreds of thousands of years of dramatically changing global climate conditions, our early ancestors survived by meeting their physiological needs, especially the need for food energy. For more than ten thousand generations, hunting and gathering food energy from the surrounding environment to avoid the persistent threat of starvation dominated their existence.

Towards the end of the last lengthy period of global glaciation, then still numbering only a few million, modern humans had migrated across all parts of the world except for Antarctica. As the climate warmed, at several locations around the world creative humans—instinctively seeking a better way of living—took advantage of the availability of suitable animals and plants to develop animal husbandry and farming to better secure their food supply.

Figure 2: Agricultural food energy. (Source: Licensed commercial image.)

While hominin culture had long embraced the key technologies of tool making and fire, the technological advance of agriculture enabled the fundamental cultural advancement referred to as civilization. Gradually, the hunting and gathering needed for survival was replaced by the agricultural production of food energy. (See Figure 2.) Consequently, permanent settlements were formed eventually enabling larger numbers of people to live together cooperatively as their food supply became more robust. Perhaps of greatest importance was that agriculture's increase in the food energy produced per unit of human effort enabled creative people to have the free time to invent further cultural advancements and undertake increased non-survival human efforts.

While the advantages of civilization were substantial, civilization became dependent on technology for meeting the physiological need for food energy. This growing dependency meant that as the population expanded, their ability to flee starvation due to famine by returning to hunting and gathering declined. Agricultural technology for producing most of the food energy became essential for civilization to endure.

Figure 3: Farming in Egypt along the Nile River, circa 1899, as it has been done for thousands of years. (Source: Library of Congress.)

Around the same time as Maslow's first paper on human behavior, anthropologist Leslie A. White, from studies of ancient civilizations, identified the central importance of energy and technology for improving the culture—the standard of living—of ancient civilizations. White deduced that great ancient civilizations, such as Egypt, rose on the strength of their food production per unit of human effort. (See Figure 3.) He concluded that to continue to improve the standard of living, better technologies must be invented to produce and productively use more energy per person.

For thousands of years, up until about three hundred years ago, increasing agricultural productivity and related

Figure 4: 1600's painting of a water-powered gristmill. (Credit: Meindert Hobbema, Library of Congress.)

technology advance—such as water- and wind-powered grist mills—literally fueled the rise in the world's standard of living. (See Figure 4.) These improvements enabled more food energy to be produced per hour of work, enabling more discretionary work to be done to advance the standard of living.

In summary, what is thought of as civilization has endured because of the technological ability to produce sufficient food energy per person even as the population dramatically increased. Also, the standard of living has advanced more where the increased supply of food energy per person and the technologies using this energy have enabled greater discretionary effort to create and build what is thought of as cultural progress, e.g., Rome.

Steam power fundamentally altered the need for energy

Archaeological evidence suggests that hominins have used fire for survival—cooking and warmth—throughout most of their existence—perhaps, for more than a million years. While fire has also been used for key technological advances such as producing metal and cement for thousands of years, it was not until just three hundred years ago that the means of converting the thermal power of a fire into useful mechanical power was invented. At the end of the 1600s, a crude water pump was invented that used pressurized steam produced by boiling water as the motive force. A generation later, another inventor created a mechanical engine that converted the thermal energy of the steam into actual useful mechanical power. Finally, in the later 1700s, James Watt improved the steam engine into a commercially useful source of power that jump-started the industrial revolution.

Nearly eight centuries earlier, the ancient world's technologies of water- and wind-powered grist mills had finally expanded throughout Europe. In just an hour's time, a small village grist mill could grind sufficient grain to save hundreds of hours of the painful hand grinding required almost daily to produce sufficient flour for a family to make bread and porridge to meet most of their daily calorie (food energy) needs. As the Romans had done a millennium earlier, the mechanical power of watermills was also used to replace the human or animal effort required for, as examples, sawing timber, making leather, and forging metal. Watt's improved steam engine enabled the productivity improvements of watermills to be established wherever an affordable supply of fuel was available. Also, steam engines were not dependent on having sufficient rain or wind, making them useable year-round.

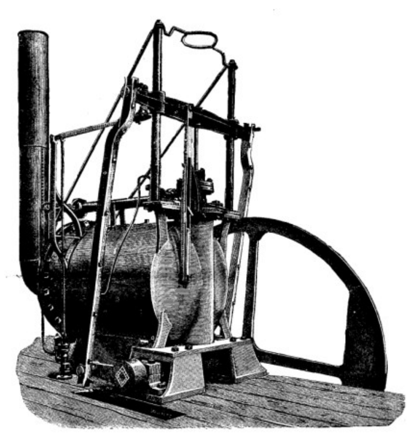

Figure 5: An early high-pressure steam engines developed by Richard Trevithick. (Source: 3 January 1885 supplement to the Scientific American.)

Steam power broadly enabled humans to be more productive, increasing the quantity and quality of the goods and services provided per hour of human effort. (See Figure 5.) As nations industrialized, meeting Maslow's physiological needs became more assured enabling the standard of living to improve even as the population grew. However, steam power, along with rapidly growing industries such as iron and steel production, substantially increased the demand for wood fuel. Soon local supplies of renewable wood fuel were exhausted. In need of a replacement, by the mid-1800s, coal became the world's primary industrial energy source.

The world's orderly transition to coal, followed by oil and natural gas, prevented an economic and social collapse due to industrial energy starvation. In large measure, fossil carbon fuels enabled and has so far sustained—literally, powered—the substantial growth and increasing prosperity of the middle class seen in both developed and developing nations. The world now gets about 85 percent of its industrial energy from fossil carbon fuels, with the demand increasing as developing nations seek equity in terms of their standard of living and general national industrial economic development.

The UNFC3 and Paris Agreement are outdated

Since the 1950s, the environmental movement has brought increased attention to the Industrial Age's impact on the environment. This movement resulted in the 1994 United Nations Convention on Climate Change (UNFC3) and its implementing protocol, the 2015 Paris Agreement. As explained below, these two guiding documents focusing on the economic development are now outdated and need to be replaced.

The UNFC3 treaty's "ultimate objective" is:

> *[S]tabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened* ***and to enable economic development to proceed in a sustainable manner.*** (Emphasis added)

While the UNFC3 ultimate objective implies that economic development should be undertaken "in a sustainable manner", Article 4, paragraph 7 clearly makes economic development and poverty eradication "the first and overriding priorities of the developing country Parties":

> *The extent to which developing country Parties will effectively implement their commitments under the Convention will depend on the effective implementation by developed country Parties of their commitments under the Convention related to financial resources and transfer of technology and* ***will take fully into account that economic and social development and poverty eradication are the first and overriding priorities of the developing country Parties.*** [4] (Emphasis added.)

This clarification regarding developing country Parties means that their continued use, and likely increased future use, of fossil carbon fuels while continuing to emit greenhouse gases from fossil carbon fuels is acceptable so long as those countries are pursuing economic development and poverty eradication.

The Paris Agreement, in Article 4, paragraph 1, states:

> *In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible,* ***recognizing that peaking will take longer for developing country Parties,*** *and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of*

[4] UNFC3, Article 4, paragraph 7.

sustainable development and efforts to eradicate poverty. [5] (Emphasis added.)

As long as the *developing country Parties* have a stated goal of achieving sustainable development by the end of the century, unabated continued use of fossil carbon fuels is acceptable through at least mid-century, if not longer. Obviously, this is a different standard than that being applied to *developed country Parties* who have, ironically, already achieved a standard of living to which *developing country Parties* aspire to match.

A careful reading of the UNFC3 treaty and the Paris Agreement shows that they do not effectively protect against the long-term potential environmental harm from the use of fossil carbon fuels. Nor do they identify a technological path forward for our global civilization to continue to elevate the world's average standard of living through true sustainable economic development and poverty eradication. Hence, both the UNFC3 and the Paris Agreement are now outdated and should be replaced. **What is needed is a new treaty setting 2100 as the target for eliminating the combustion use of fossil carbon fuels while also defining a practicable technological path for achieving an increased per person supply of sustainable energy sufficient to enable a global middle-class standard of living.**

The primary justification of the need for a new treaty and protocol is the common-sense recognition that fossil carbon fuels are non-sustainable. The world's now elevated standard of living is substantially dependent on these fuels indicating that the collapse of civilization will ensue if a timely and orderly transition to globally available sustainable energy is not undertaken. Setting the year 2100 as the target for completion of this transition is consistent

[5] Paris Agreement, Article 4, paragraph 1.

with the vague language of Article 4, paragraph 1, of the Paris Agreement. A new implementing protocol would then establish a progressive engineering plan to undertake an orderly transition to sustainable energy—now referred to as green energy. Specifically, the plan would aim to provide an affordable per person green energy supply sufficient to enable worldwide economic development and the eradication of poverty—key goals of the UNFC3 and the Paris Agreement.

Preliminary planning for a progressive engineering transition to green energy

Establishing green energy targets for 2100

Fossil carbon fuels provide the mechanical power used to generate most of our electricity and the fuels used for manufacturing, transportation, and living. To replace these with green energy will involve a fundamental shift from combustible fossil fuels to sustainable energy systems that primarily produce electrical power directly, what is called green electricity. [6]

Common sense indicates that eradicating poverty requires an elevation of the standard of living to enable Maslow's physiological needs to be met. To achieve this, as White concluded, the world's average per person supply of affordable energy must be increased so that the additional goods and services needed can be provided. For this discussion, achieving a European middle-class standard of living will be set as the world standard of living target.

[6] While some renewable energy will be provided by renewable fuels such as wood, the vast majority will necessarily be supplied by green electricity. For this reason, in this top-level discussion, all needed green energy in 2100 is assumed to be in the form of green electricity.

To establish the green energy needed per person to enable a European middle-class standard of living, the energy consumption of the year 2018 is used for these estimates. The initial energy unit used for the following analysis is the barrel of oil equivalent or BOE. [7]

In 2018, the 28 European Union (EU) countries consumed the equivalent of 11.7 billion BOE of industrial energy from all sources. [8] With an estimated 2018 population of 513 million, the average EU per person energy use equaled 22.8 BOE. [9]

$$\frac{\text{11.7 billion BOE}}{\text{513 million people}} = \text{22.8 BOE per person}$$

Also in 2018, the entire world consumed the equivalent of 94 billion BOE of industrial energy. [10] The 2018 estimated world population was 7.5 billion. Thus, the world's 2018 average per person energy use was 12.5 BOE—55 percent of the EU value.

$$\frac{\text{94 billion BOE}}{\text{7.5 billion people}} = \text{12.5 BOE per person}$$

[7] A "barrel of oil equivalent" is a measure of the thermal energy released by the simple combustion of a carbon fuel. It originally represented the thermal energy, expressed in British thermal units (Btu), available from 42 U.S. gallons of crude oil. This size barrel was once adopted as a standard size for delivering oil. Now, instead of the average thermal energy of an actual barrel of oil, one BOE has been set equal to 5,800,000 Btu. The BOE unit is often used to report gross energy production or consumption. All forms of energy can be converted into an equivalent amount of BOE to enable annual total energy production or consumption to be reported.

[8] Eurostat available online, data table TEN00121

[9] The energy used on average per person includes both the energy used directly, such as for cooking, as well as the energy used to produce the products and provide the services used.

[10] BP Energy Outlook 2050: September 2020 available online.

While recognizing that there is substantial variation in energy use country-to-country in the EU because of the local climate and culture, the average EU per capita energy use of 22.8 BOE will be assumed to correspond to the energy needed for an EU middle-class standard of living. Therefore, for an assumed world population of 10 billion people in 2100, the total green energy needed annually will be around 228 billion BOE. This is 2.4 times the total energy used worldwide in 2018.

$$\text{10 billion people} \times \text{22.8 BOE per person} = \text{228 billion BOE per year}$$

$$\frac{\text{228 billion BOE}}{\text{94 billion BOE}} = 2.4$$

Producing this amount of energy in the form of sustainable energy is needed to enable the economic development needed to elevate the world's middle-class standard of living so that poverty is eradicated. The magnitude of the sustainable energy needed shows why setting 2100 as the target for the completion of the transition to sustainable energy is a reasonable year.

Converting 2100 energy targets into green electricity values

The word electricity can mean either electrical power or electrical energy. Electrical energy is simply the amount of total electrical power used during a period of time such as an hour.

The common units of electrical power for individual use are the watt (W) or the kilowatt (kW) equaling 1000 W. For perspective, a typical countertop microwave oven will use about 1000 W or 1 kW of power. If this operates for 1 hour, it will use 1 kilowatt-hour (kWh) of electrical energy.

The common unit of electrical power for national or global use is the gigawatt (GW) representing one billion W or one million kW. The Hoover Dam can generate 2 GW.

If this dam operates for 1 hour, it will produce 2 gigawatt-hours (GWh) of energy, enough to operate 2 million microwave ovens for that hour.

Industrial energy is consumed both as electricity and combustible fuels. In 2018, the EU generated 3,277,810 GWh. This equates to a consumption of 6,389 kWh per person.

$$\frac{3{,}277{,}810 \text{ GWh}}{513 \text{ million people}} \times \frac{1{,}000{,}000 \text{ kWh}}{1 \text{ GWh}} = 6{,}389 \text{ kWh per capita}$$

Assuming that this amount of electrical energy is entirely generated by fossil carbon fuels, this equates to 9.9 BOE of fuel used per person. [11]

$$6{,}389 \text{ kWh} \times 9{,}000 \frac{\text{Btu}}{\text{kWh}} \times \frac{1 \text{ BOE}}{5{,}800{,}000 \text{ Btu}} = 9.9 \text{ BOE}$$

$$22.8 \text{ BOE} - 9.9 \text{ BOE} = 12.9 \text{ BOE}$$

For the EU in 2018, this leaves a balance of 12.9 BOE of combustible fuels used directly or through the goods and services consumed. Thus, the 2018 average EU per capita energy use can be expressed as 6,389 kWh plus 12.9 BOE of combustible fuels. Of the 22.8 BOE total, 43 percent was used as electricity and 56 percent was used as combustible fuels. This will now be converted into the equivalent amount of green electricity.

For this preliminary planning estimate, the percentages of sustainable electricity and sustainable combustible fuel

[11] Based on U.S. Energy Information Administration data, each kWh of electricity generated using thermal energy is assumed to require an average of 9,000 Btu of thermal energy input. See: https://www.eia.gov/totalenergy/data/monthly/pdf/sec12_7.pdf.

will be set equal to that of 2018. [12] Further, each BOE of combustible fuel will initially be assumed to be provided by one BOE of hydrogen fuel produced using green electricity and electrolysis. To yield 1 BOE of hydrogen (HHV) in this manner, 2,161 kWh of green electricity is used in this analysis. [13] Hence, to produce 12.9 BOE of hydrogen would require 27,877 kWh.

$$12.9\ \text{BOE} \times 2{,}161\ \frac{\text{kWh}}{\text{BOE}} = 27{,}877\ \text{kWh}$$

For safety, convenience, global transport, and storage efficiency purposes, the green hydrogen is assumed to be further transformed at refineries into green carbon fuels. Using additional green electricity, the hydrogen will be combined with carbon dioxide extracted from the atmosphere and seawater to produce green natural gas and green liquid fuels, such as green diesel fuel and green jet fuel. Some researchers estimate that this will require about 25 percent more electricity. Thus, for this preliminary estimate, the total green electricity required per person to produce 12.9 BOE of green carbon fuels is estimated to be 34,846 kWh.

$$27{,}877\ \text{kWh} \times 1.25 = 34{,}846\ \text{kWh}$$

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[12] It is recognized that energy consumption is shifting more towards the direct use of electricity. However, it is too early to estimate the extent of this shift. Thus, the 2018 split of the energy consumed as electricity and the energy separately consumed as fuels is used in this preliminary analysis.

[13] The value of 2,161 kWh is the total electrical energy estimated by the author to produce 41.7 kg of gaseous hydrogen using advanced electrolyzers and compress this to 82.7 bar for pipeline transport to refineries where green carbon fuels will be produced. This quantity of hydrogen equates to one BOE of thermal energy at the higher heating value (HHV).

In total, the per person green electricity annual need per person in 2100 would be 41,235 kWh.

$$6{,}389\ \text{kWh} + 34{,}846\ \text{kWh} = 41{,}235\ \text{kWh}$$

For ease of understanding, this total annual energy value is converted into an equivalent continuous supply of green electrical power of about 4.7 kW.

$$\frac{41{,}235\ \text{kWh}}{365\frac{\text{days}}{\text{year}} \times 24\frac{\text{hours}}{\text{day}}} = 4.7\ \text{kW continuous}$$

Rounding this value up for this preliminary analysis, 5 kW becomes the per person target value for the world in 2100. For perspective, this is the electrical power required to operate five countertop microwave ovens continuously.

Estimating the total world green energy need in 2100

For 10 billion people in 2100, a continuous green electricity supply of 50,000 GW will be needed.

$$10\ \text{billion people} \times 5\ \frac{\text{kW}}{\text{person}} \times \frac{1\ \text{GW}}{1\ \text{million kW}}$$

$$= 50{,}000\ \text{GW continuous}$$

As mentioned previously, the Hoover Dam when operating at full output generates about 2 GW. **For perspective, to go green by 2100, a world of 10 billion people will need the green electricity generating capacity of 25,000 Hoover Dams operating continuously.** This is the magnitude of green electrical power generation needed to achieve the UNFC3 treaty and the Paris Agreement's goal of global <u>sustainable</u> economic development while eradicating poverty. **Obviously, those advocating for a rapid transition to green energy underestimate the challenge of producing the needed 50,000 GW of continuous green electrical power.**

In terms of total energy, nearly 438 million GWh of green electricity will be needed annually by 2100—more than 100 times the electrical energy generated in the EU in 2018. This further illustrates the magnitude of the challenge that engineers will need to address to enable the world to peacefully and equitably transition to sustainable energy. **Clearly, the magnitude of the increase in sustainable energy needed makes determining how best to achieve this goal an engineering responsibility, not a political responsibility.**

$$50{,}000\ \mathrm{GW} \times 365\ \frac{\mathrm{days}}{\mathrm{year}} \times 24\ \frac{\mathrm{hours}}{\mathrm{day}} = 438{,}000{,}000\ \mathrm{GWh}$$

Terrestrial sustainable energy sources alone cannot practically meet this need

The Earth's mean radius is 6,371,000 meters. The area facing the Sun is 127.5 trillion square meters. Of the 1,360 watts of sunlight shining on the Earth at the top of the atmosphere, about 35 percent is reflected immediately back into space. The remaining 65 percent is absorbed by the atmosphere, the ground, and the oceans. This solar power totals about 113 million GW.

$$127{,}516{,}117{,}977{,}447\ {\mathrm{m}^2}_{\mathrm{Earth}} \times 1{,}360\ \frac{\mathrm{W}}{\mathrm{m}^2} \times 0.65 \times \frac{1\ \mathrm{GW}}{1\ \mathrm{billion\ W}}$$

$$= 112{,}724{,}248\ \mathrm{GW}$$

In terms of raw power, this is over 2000 times the useful green electrical power needed by 2100. At first glance, this would appear to provide ample available renewable power from which the comparably meager needed 50,000 GW of green electrical power could be obtained. Unfortunately, this false impression leads many to conclude that sufficient sustainable energy transition solutions can be simply dictated politically—such as mandates to use wind power or ground solar power to replace fossil-generated electricity.

$$\frac{112{,}724{,}248\ \text{GW}}{50{,}000\ \text{GW}} = 2{,}254$$

Renewable energy sources that are unscalable

As estimated above, the needed growth in green electricity is substantial. To achieve this, terrestrial sources must be able to be substantially scaled up. Without further explanation, geothermal-electricity, biomass fuel such as wood, hydroelectricity, wave and tidal power, alcohol made from biomass, and algae-derived fuels are not significantly scalable. This leaves only wind power and ground solar power as the remaining terrestrial options.

Wind power cannot be practicably scaled up

The U.S. National Renewable Energy Laboratory estimates that commercial wind farms have an optimum installed nameplate generating capacity of around 0.0025 GW per square kilometer. With an assumed net capacity factor of 35 percent, each square kilometer of wind farms will yield 7.665 GWh per year.[14] To meet the needed 438 million GWh in 2100—disregarding the impact of the variability of wind power—57 million square kilometers of wind farms would be needed. For perspective, the land area of Africa is 30 million square kilometers. Obviously, a mandated substantial expansion of wind power is an impractical solution.

The capacity factor is the percentage of the total possible energy generated annually that is likely to actually be generated in a typical year.

$$0.0025\ \frac{\text{GW}}{\text{km}^2} \times 0.35 \times 365\,\frac{\text{days}}{\text{year}} \times 24\,\frac{\text{hours}}{\text{days}}$$

$$= 7.665\ \text{GWh per km}^2\ \text{per year}$$

$$\frac{438{,}000{,}000\ \text{GWh}}{7.665\,\frac{\text{GWh}}{\text{km}^2}} = 57{,}142{,}857\ \text{km}^2$$

Ground solar power also cannot be practically scaled up

The U.S. National Renewable Energy Laboratory reports that the average installed nameplate power of solar farms is around 0.033 GW per square kilometer. With an assumed net capacity factor of 25 percent, each square kilometer of solar farms will yield 72.27 GWh per year. To meet the need for 438 million GWh in 2100, over 6 million square kilometers of solar farms would be needed. For perspective, this is nearly 80 percent of the land area of Australia. Obviously, a mandated substantial expansion of ground solar power is an impractical solution.

$$0.033\ \frac{\text{GW}}{\text{km}^2} \times 0.25 \times 365\,\frac{\text{days}}{\text{year}} \times 24\,\frac{\text{hours}}{\text{days}}$$

$$= 72.27\ \text{GWh per km}^2\ \text{per year}$$

$$\frac{438{,}000{,}000\ \text{GWh}}{72.27\,\frac{\text{GWh}}{\text{km}^2}} = 6.1\ \text{million km}^2$$

Expanding nuclear fission is both unwise and unlikely

Nuclear fission power plants use a controlled flux of free neutrons to induce the nuclei of certain radioisotopes to fission. As the nuclei fission, part of the original mass of each nucleus converts into energy—hence, the name nuclear energy. This energy turns into heat within a nuclear reactor. Circulating coolant water within the reactor extracts this heat which is then used to produce steam that drives turbine generators. Only three radioisotopes—U-235, U-233, and Pu-239—can be used as fuel for a nuclear reactor.

U-235 is a natural uranium isotope that exists in uranium ore. Of mined natural uranium, the U-235 isotope comprises only 0.72 percent. The rest of the mined natural uranium is the U-238 isotope which cannot be directly used as fuel. During the preparation of nuclear fuel, a process called enrichment increases the percentage of U-235 in the uranium to the 3–5 percent needed for use as reactor fuel.

In 2016, the World Nuclear Association estimated that a metric tonne of natural uranium will yield 44 GWh of electricity. A 1-GW nuclear power plant operating continuously will produce 8,760 GWh per year.

$$1\ \text{GW} \times 365\ \frac{\text{days}}{\text{year}} \times 24\ \frac{\text{hours}}{\text{day}} = 8{,}760\ \text{GWh per year}$$

This will require199 metric tonnes of natural uranium per 1-GW per plant-year.

$$\frac{8{,}760\ \text{GWh}}{44\ \frac{\text{GWh}}{\text{tonne U}}} = 199\ \text{tonnes U}$$

In terms of actual U-235 used, this equates to 1,433 kg per 1-GW plant-year.

$$199\ \text{tonnes U} \times 0.0072_{\text{U-235}} \times 1000\frac{\text{kg}}{\text{tonne}} = 1{,}433\ \text{kg U-235}$$

A new 1-GW nuclear power plant is expected to operate for 120 years. In its lifetime, this would require 23,880 tonnes of natural uranium.

$$199\ \frac{\text{tonnes U}}{\text{plant-year}} \times 120\ \text{years} = 23{,}880\ \text{tonnes U}$$

In 2016, the Nuclear Energy Agency and the International Atomic Energy Agency estimated that the total in situ natural uranium resource was optimistically

10.2 million tonnes. [15] If all of this could be recovered, this would meet the fuel needs of only 427 1-GW plants instead of the thousands needed. Obviously, there is insufficient natural uranium to use U-235 to fuel any substantial expansion of nuclear fission power generation.

$$\frac{\text{10.2 million tonnes}}{23{,}880\ \frac{\text{tonnes}}{\text{plant}}} = \text{427 1-GW plants}$$

Recognizing the inherent limitation of relying on U-235, nuclear fission power advocates propose approaches that would breed fuel. Breeding fuel involves bombarding certain elements with neutrons causing the elements to transmute into a different element. The two breeding alternatives are U-233 bred from thorium and plutonium Pu-239 bred from U-238. To replace U-235 with either U-233 or Pu-239 will require breeding roughly 1,400 kg each year for each 1-GW power plant. Like U-235, both U-233 and Pu-239 can be used to build nuclear weapons. [16] (See Figure 6.) About 10 kg is all that is required to make a nuclear weapon. Thus, all forms of breeding nuclear fuel for fission power plants create opportunities for nuclear weapon proliferation by rogue

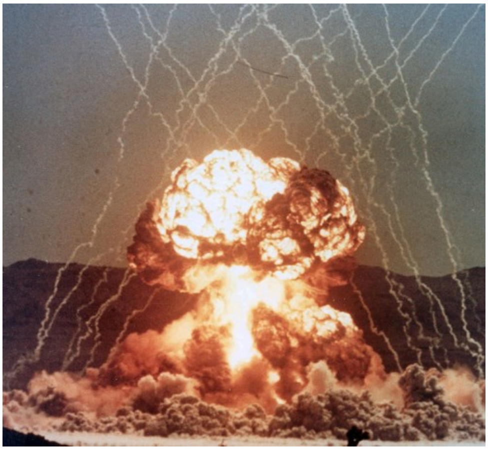

Figure 6: 1955 U.S. test of a nuclear weapon incorporating U-233. (Source: U.S. Government.)

[15] Uranium 2016: Resources, Production and Demand available online.

[16] The United States produced U-233 and included U-233 in a nuclear weapon test on 15 April 1955. Pu-239 was produced during World War II and has been used in nuclear weapons ever since.

nations. Hence, using U-233- or Pu-239-fueled nuclear power plants to provide sustainable energy is very unwise. Relying on nuclear fuel breeding to substantially expand nuclear fission power is unlikely.

The age of astroelectricity has arrived

World political leaders have agreed that achieving worldwide economic development and the eradication of poverty should be "the first and overriding priorities" of developing nations. Further, they have emphasized that this should be done as soon as is practicable in a sustainable manner which, by common sense, undertakes an orderly transition to sustainable energy.

The preceding analysis indicates that to achieve these priorities, terrestrial sustainable energy sources are significantly inadequate given the large and growing population and the desired global middle-class standard of living. Anthropologist Leslie White, drawing on his observations of the growth and decline of past civilizations, concluded:

> *No culture (civilization) can develop beyond the limits of its energy resources ….* [17]

Nearly a century ago, space philosopher Konstantin Eduardovich Tsiolkovsky foresaw the coming need for humanity to utilize the immense natural extraterrestrial resources of the solar system to continue to grow and prosper. Clearly, our civilization has now reached this key nexus where an extraterrestrial energy resource must be tapped if continued growth is to be achieved and cultural collapse is to be avoided.

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[17] Leslie A. White, The Evolution of Culture: The Development of Civilization to the Fall of Rome, McGraw-Hill, 1959, p. 368.

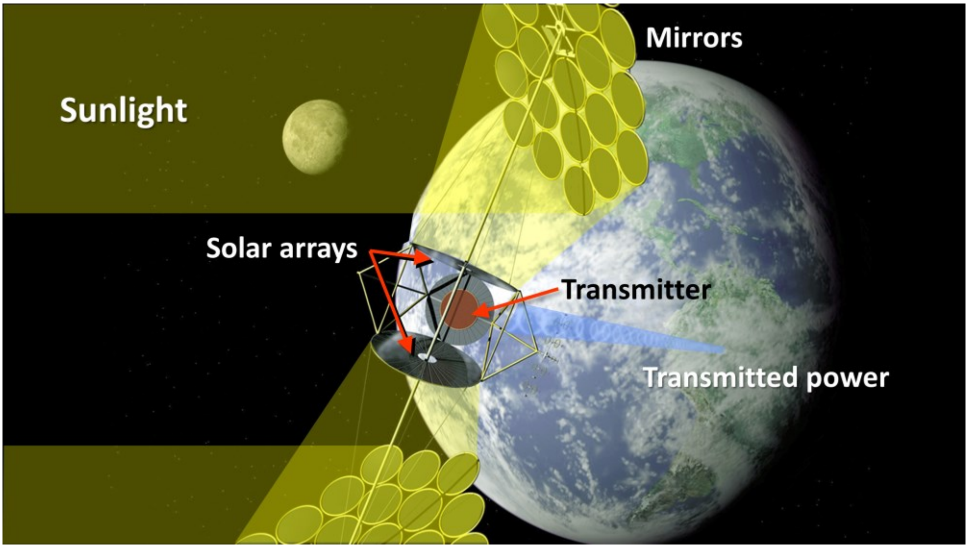

Figure 7: Operation of a GEO space solar power platform. (Original illustration source: NASA. Modified image credit: J. M. Snead.)

A half-century ago, Peter Glaser invented space solar power-generated astroelectricity. What Glaser recognized was that while the space surrounding the Earth appears devoid of anything, it is actually constantly filled with substantial solar energy that cannot directly be seen. Glaser conceived large space platforms that would collect sunlight, turn this into green electricity, and transmit this power to ground receiving stations, called astroelectric plants, where it emerges as astroelectricity. (See Figure 7.) When combined with terrestrial nuclear and renewable energy sources, producing astroelectricity is how we can undertake an orderly worldwide transition to abundant sustainable energy.

The number of astroelectric plants needed

Based on Glaser's patent, NASA and the U.S. Department of Energy undertook a substantial study of space solar power in the late 1970s and early 1980s. A baseline system design was developed that would deliver 5 GW of astroelectricity—equivalent to five 1-GW nuclear power plants. This electrical power would be almost continuously dispatchable. [18]

For this preliminary planning estimate, 20 percent of the 50,000 GW of green electrical power needed in 2100 will be assumed to come from terrestrial sources. [19] This means that terrestrial sustainable energy sources will supply the equivalent of 10,000 GW of continuous green electrical power while the remaining 40,000 GW will be supplied by astroelectricity. With each astroelectric plant supplying 5 GW, 8,000 GEO space solar power platforms and the same number of astroelectricity plants will be needed. At 8,000 locations around the world, a dispatchable power supply equal to 2.5 Hoover Dams will be built to enable global sustainable development.

$$\frac{40{,}000\ \mathrm{GW}_{\mathrm{astroelectricity}}}{5\,\frac{\mathrm{GW}}{\mathrm{plant}}} = 8{,}000\ \text{5-GW astroelectric plants}$$

Land area needed for the astroelectric plants

In NASA's baseline design, an astroelectric plant built at 35 degrees latitude would require 164 square kilometers of land for the receiving antenna array and a safety

[18] At local midnight for the week before and after the spring and fall equinoxes, the GEO space solar power platform will enter the Earth's shadow. This will last for around one hour. For the remainder of the year, the platform is always in sunshine, generating sustainable energy. During this short time, hydrogen-fueled gas turbine generators will meet dispatchable electrical power needs.

[19] It may be technically feasible to combine photovoltaic solar panels with the astroelectricity receiving antenna elements. If possible, the entire area of each astroelectric plant would also be a solar farm. This alone may pro-vide the assumed 20 percent of the needed energy provided by ground sources.

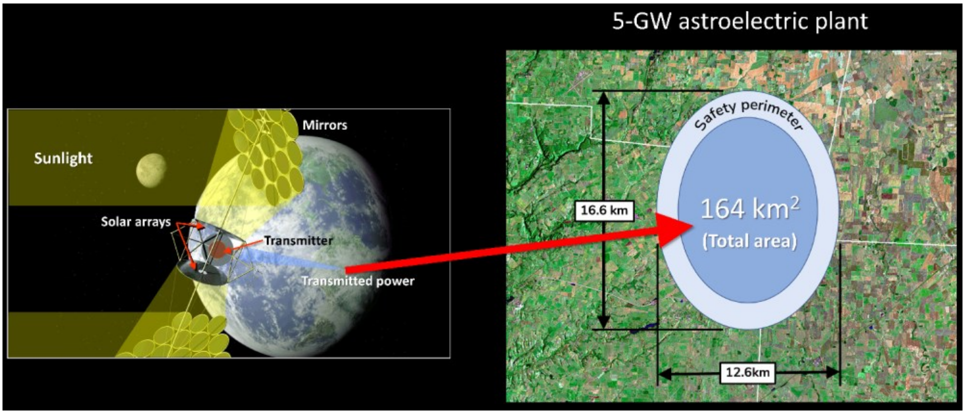

Figure 8: Illustration of an astroelectric plant. (Credit: J. M. Snead.)

perimeter.[20] (See Figure 8.) In total, about 1.3 million square kilometers of land would be needed—far less than any combination of terrestrial alternatives. Recall that an all-wind solution will require nearly 60 million square kilometers and an all-ground solar solution would need over 6 million square kilometers.

$$\text{8,000 5-GW astroelectric plants} \times 164 \frac{\text{km}^2}{\text{plant}} = 1{,}312{,}000\ \text{km}^2$$

Conclusion

For tens of thousands of years, humans have migrated to find more of the natural resources needed for a better life. For our human civilization to continue to thrive and complete its industrial development that began 300 years ago, humans will migrate into space this century to undertake the spacefaring industrial revolution needed to build thousands of space solar power platforms. This will

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An astroelectric plant located on the equator with its GEO platform directly overhead would be circular with a diameter of about 12.6 kilometers. When the plant is located off the equator, it becomes elliptical in shape due to the transmission not arriving perpendicular to the ground.

require exploring the Moon and the asteroids, mining these for the needed raw materials, building immense space habitats and lunar settlements for people to live in safely and comfortably, establishing an astrologistics infrastructure throughout the central solar system, and building and operating the space solar power platforms. It is likely that several million people will be living and working in space by 2100 when the world has peacefully transitioned to sustainable energy, poverty has been eradicated, and the Age of Astroelectricity will be fully underway.

Of course, undertaking this transition to astroelectricity depends entirely on the world's political leaders recognizing that our civilization is at the practicable limits of what the Earth alone can supply in terms of the green energy needed per person to achieve the desired global middle-class standard of living. The only truly progressive path forward is to abandon the UNFC3 treaty/Paris Agreement and forge a new treaty directing the implementation of a progressive engineering plan to complete the world's transition to green energy by 2100 using primarily astroelectricity. This needs to be the world's first and overriding priority and becomes the compelling reason for humanity to truly become spacefaring and permanently settle the central solar system. We simply have no other alternative if civilization is to peacefully and prosperously survive this century!

About the Author

James Michael Snead is an aerospace Professional Engineer in the United States, an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and a past chair of the AIAA's Space Logistics Technical Committee. He is the founder and president of the Spacefaring Institute LLC which is focused on space solar power-generated astroelectricity and the astrologistics infrastructure necessary to enable the spacefaring industrial revolution that will build space solar power energy systems. Mike Snead has been involved in space development since the mid-1980s when he supported the U.S. Air Force Transatmospheric Vehicle (TAV) studies, the National Aerospace Plane program, and the Delta Clipper Experimental (DC-X) project. In 2007, after retiring from civilian employment with the Air Force, he began to study the need for (and politics associated with) undertaking space solar power. He has published numerous papers and articles on various aspects of manned spaceflight and energy beginning in the late 1980s. His technical papers are located at: mikesnead.com. His blog is at: spacefaringamerica.com.