[Online Journal of Space Communication](https://ohioopen.library.ohio.edu/spacejournal)

Volume 9
Issue 16 *Solar Power Satellites (Winter 2010)*

Article 2

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Recommended Citation

Hsu, Feng () "Harnessing the Sun: Embarking on Humanity's Next Giant Leap," *Online Journal of Space Communication*: Vol. 9 : Iss. 16 , Article 2.
Available at: https://ohioopen.library.ohio.edu/spacejournal/vol9/iss16/2

Harnessing the Sun:
Embarking on Humanity's Next Giant Leap

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Abstract

It has become increasingly evident that facing and solving the multiple issues concerning energy is the single most pressing problem that we face as a species. In recent years, there has been extensive debate and media coverage about alternative energy, sustainable development and global climate change, but what has been missing (at least in the mainstream media) is the knowledge and point of view of scientists and engineers. From the scientists or engineers perspective, this paper discusses the prospects for mankind's technological capability and societal will in harnessing solar energy, and focuses on the issues of: 1) space based solar power (SBSP) development, and, 2) why it is imperative that we must harness the unparalleled power of the sun in a massive and unprecedented scale, which I believe will be humanity's next giant leap forward.

Solar Power from a Historic Perspective

Whether terrestrially based or space based, solar energy has not yet emerged as a significant solution in public discussions of global warming. Yet, among scientists and engineers and other visionaries, it is starting to be viewed as one of the most promising and viable ways to eventually remove human dependence on fossil fuels.

Nearly three years ago at the Foundation For the Future (FFF) International Energy Conference, my presentation was one of the few that took a look back at energy use in human history[1]. In this paper, I would like to offer a brief summary of the various stages mankind has passed through in our quest for energy, and how long they lasted. To understand and fully appreciate the profound idea that humankind has and can continue to harness sun's energy, it is imperative for us to learn from the history of our civilization and from the perspective of human evolution, especially from those societies in crisis over energy.

Previewing the history of human energy consumption and energy technologies, we can see that there were three such eras. In the early years of human presence on this planet, we relied on wood-generated energy, based on the burning of firewood, tree branches and the remains of agricultural harvests. Starting in the 1600s, our forefathers discovered the energy properties of coal, which taught us how to tap stored supplies of fossil fuels. Less than two hundred years later, about the middle of the 1800s, we found petroleum and learned to commercialize the use of oil and gas, which brought about our current industrial civilization. In the 20th century, society witnessed the dawn of electricity generation via hydro-power and atomic energy.

Today, demand for energy continues to soar, but we're rapidly using up our supplies of easily accessible fossil fuels. What is more, a profound environmental crisis has emerged as the result of our total reliance on energy sources based on those fuels.

In the 21st century, there is great uncertainty about world energy supplies. If you plot energy demand by year of human civilization on a terawatt scale, you will see the huge bump that occurred barely a hundred years ago (Figure 1). Before that, in the Stone Age, basically the cultivation of fire led to the emergence of agriculture, cooking, tool making, and all the early stages of human civilization. Now, after about 150 years of burning fossil fuels, the earth's 3 billion years' store of solar energy has been plundered.

In my view, mankind must now embark on the next era of sustainable energy consumption and re-supply. The most obvious source of which is the mighty energy resource of our sun. Adequately guide and using human creativity and innovation; the 21st century will become the next great leap forward in human civilization by taming solar energy, transforming our combustion world economy into a lasting solar-electric world economy.

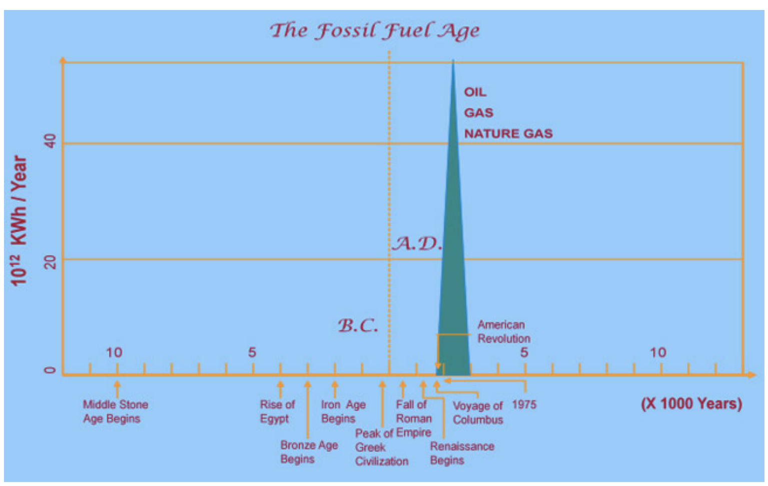

Figure 1. An approximation of fossil fuel age on the scale of human history. (click image for larger view)

In solving humanity's energy problems we must learn from our ancestors. Taming the natural forces of the sun will be much like our ancestors' early efforts to harness the power of wild fire. We must use common sense, as they did, developing the tools and technologies that address the needs of our time. The Romans used flaming oil containers to destroy the Saracen fleet in 670. In the same century, the Japanese were digging wells to a depth approaching 900 feet with picks and shovels in search of oil. By 1100, the Chinese had reached depths of more than 3,000 feet in search of energy. This happened centuries before the West had sunk its first commercial well in 1859 in Titusville, Pennsylvania. With all such human creativities in the past, the searching for energy has been driven by our combustion world economy, which focused primarily on what's beneath the surface of our planet - the secondary energy resources which originated from the power of our sun. Now it's time for mankind to lift their heads and start focusing our profound creativity in harnessing the sun and making our way into the energy technology frontiers in the sky.

Solar Energy - The Ultimate Answer to Anthropogenic Climate Change

The evidence of global warming is alarming. The potential for a catastrophic climate change scenario is dire. Until recently, I worked at Goddard Space Flight Center, a NASA research center in the forefront of space and earth science research. This Center is engaged in monitoring and analyzing climate changes on a global scale. I received first hand scientific information and data relating to global warming issues, including the latest dynamics of ice cap melting and changes that occurred on either pole of our planet. I had the chance to discuss this research with my Goddard colleagues, who are world leading experts on the subject.

I now have no doubt global temperatures are rising, and that global warming is a serious problem confronting all of humanity. No matter whether these trends are due to human interference or to the cosmic cycling of our solar system, there are two basic facts that are crystal clear: a) there is overwhelming scientific evidence showing positive correlations between the level of CO2 concentrations in the earth's atmosphere with respect to the historical fluctuations of global temperature changes; and b) the overwhelming majority of the world's scientific community is in agreement about the risks of a potential catastrophic global climate change. That is, if we humans continue to ignore this problem and do nothing, if we continue dumping huge quantities of greenhouse gases into earth's biosphere, humanity will be at dire risk.

As a technical and technology risk assessment expert, I could show with confidence that we face orders of magnitude more risk doing nothing to curb our fossil-based energy addictions than we will in making a fundamental shift in our energy supply. This is because the risks of a catastrophic anthropogenic climate change can be potentially the extinction of human species, a risk that is simply too high for us to take any chances. Of course, there will be economic consequences to all societies when we restrict the burning of fossil fuels in an effort to abate "global warming." What we are talking about are options and choices between risks. All human activities involve risk taking; we cannot avoid risks but only make trade-offs, hopefully choosing wisely. In this case, there has to be a risk-based probabilistic thought process when it comes to adopting national or international policies in dealing with global warming and energy issues.

As the measure of risk is a product of "likelihood" and "consequence," when consequence or risk of a potential human extinction (due to catastrophic climate change) is to be compared with the potential consequence or risk of loss of jobs or slowing the growth of economy (due to restriction of fossil-based energy consumption), I believe the choice is clear. My view is that by making a paradigm shift in the world's energy supply over time through extensive R&D, technology innovations and increased production of renewable energy, we will create countless new careers and jobs and end up triggering the next level of economic development, the kind of pollution free industrial revolution mankind has never before seen.

The aggravation and acceleration of a potential anthropogenic catastrophic global climate change, in my opinion, is the number one risk incurred from our combustion-based world economy. At the International Energy Conference in Seattle, I showed three pairs of satellite images as evidence that the earth glaciers are disappearing at an alarming rate.[2] Whether this warming trend can be reversed by human intervention is not clear, but this uncertainty in risk reduction doesn't justify the human inactions in adapting policies and countermeasures on renewable energy development for a sustainable world economy, and for curbing the likelihood of any risk event of anthropogenic catastrophic climate changes. What is imperative is that we start to do something in a significant way that has a chance to make a difference.

Solar Power - The Best Renewable Energy Source for the Future

Now mankind faces an energy crossroad. As a species, we have basically two directions in our quest for energy: 1) either we look for energy based on cosmic-based, open and unlimited original resources, which means everything comes from the stars, from the sun, or 2) we continue to rely on earth-based, local and confined secondary energy resources. There is no secret that every single bit of energy on this planet comes from the sun. In my view, we have a small window of opportunity over the next couple of decades. Either we're going to go down or we're going to go up as a species. The direction we follow largely depends upon how we approach our energy challenge.

Learning how to harness our sun for solutions to our energy problems will not be unlike our ancestors harnessing the wild fire. I believe it will lead to an inevitable leapfrog in the process of human evolution. Bill Michael, a University of Chicago professor, wrote "Use of fire illustrates that human evolution is a gradual process; modern humans did not emerge overnight in a 'big bang' of development, but rather slowly adapted from their primitive origins. The use of fire by humans throughout time to overcome environmental forces is a fundamental and defining aspect of human nature."[3]

Before we reach that tipping point of negative sustainability, there is still time for humankind to tame the natural forces of the sun and harness it for the well-being and survival of our species. The best place, of course, for a nuclear fusion reactor is about 149E6 km (149 x 106 km) away. This one happens to be free of charge and we can count on it being around for a long time. The sun's energy only takes 8 minutes to arrive on earth and leaves no radioactive waste (and it is terrorist proof). Our sun puts out about 3.8E11TWh of energy per hour. Our planet receives about 174,000 terawatt each second. Every minute, earth's surface gets more solar power than we human beings can use in a whole year.

We must learn how to bypass the solar-to-fossil inefficiency. About 4.6 billion years ago, the earth was just formed, and it was 3.5 billion years ago that there was the first sign of life. Not until 1.5 billion years ago was there multicell biology; real life started just about 500 million years ago. The dinosaur lived about 150 million years ago and went extinct. Human beings have lived maybe a few hundred thousand years. You can see that it took about 3.5 billion years and rare geologic events to sequester hydrocarbons and build up hydrogen in the atmosphere. If you do a little calculation, you will find that using direct solar energy is about 1,200,000,000,000 times more efficient than using a secondary solar energy, such as oil. Why not go directly to the well of the sun?

Solar Energy vs. Other Forms of Renewable Sources

We must set priorities and choose wisely. Within the next 30 years, we're going to have an explosive increase in demand for new sources of fuel. According to recent U.S. Department of Energy data, all renewable sources of energy including biomass, hydropower, geothermal, wind and solar represent only about 6 percent of total U.S. energy production in the US. Nonrenewable energies, namely fossil fuels, represent the other 94 percent.

To see solar energy as the best option for our future, we have to set comprehensive criteria for energy priorities. This seems to be a major challenge for us. We need to define criteria, and they must be quantifiable and measurable. First, energy has to be at low cost, to be affordable for all human beings. Next, it should be inexhaustible in terms of livable planetary lifetimes. Also, it must cause no harm to the environment, ecosystem or to human lives. And it must be readily available and accessible around the globe. It has to be in a usable form, decentralized, scalable and manageable. There must be low risk of potential misuse; it must not be convertible to a weapon of mass destruction.

Such requirements have to be achievable. The energy options pursued must satisfy basic needs and goals of humanity, help improve quality of life, retain human values and facilitate global collaboration. Goals must include expanding human presence and survivability within our solar system, to be achievable through citizen participation and organized demonstrations of creativity. They have to be consistent with the elevation of human culture and the advancement of civilization. When you evaluate renewable energy sources against these requirements and criteria, it is not hard to understand why solar power is the most viable for sustainable human development.

Our nonrenewable oil/gas fuels will be depleted in another 40 to 60 years; coal will be depleted in about 300 to 500 years. Some people estimate our reserves in coal to last a thousand years; but that doesn't really matter since the global environment far before that time will likely have suffered catastrophic changes. The mining of nuclear fission material will be depleted in about 50 years. Nuclear power based on this material has major issues with waste deposit, and the risks of proliferation and misuse are high. Nuclear had 40 years of opportunity and did little to help the world solve its strategic energy problem.

Hydro power is renewable but such an energy source is limited and unstable. Liquid biomass competes for land with food production. Hydrogen (fuel cell), a form of energy storage rather than a source of energy, carries certain risks in storage and transport. Wind, geothermal and tidal solutions tend to also be unstable, intermittent and costly. Solar energy, on the other hand, basically doesn't matter whether it is surface or space-based; it has some limitations, but one of them is not harm to human beings.v

The Prospects for Solar Energy Development from Space

Why solar energy from space? Is it technologically feasible? Is it commercially viable? My answer is positively and absolutely yes. One of the reasons that less than one percent of the world's energy currently comes from the sun is due to high photovoltaic cell costs and PV inefficiencies in converting sunlight into electricity. Based on existing technology, a field of solar panels the size of the state of Vermont will be needed to power the electricity needs of the whole U.S. And to satisfy world consumption will require some one percent of the land used for agriculture worldwide. Hopefully this will change when breakthroughs are made in conversion efficiency of PV cells and in the cost of producing them, along with more affordable and higher capacity batteries.

Roughly 7 to 20 times less energy can be harvested per square meter on earth than in space, depending on location. Likely, this is a principal reason why Space Solar Power has been under consideration for over 40 years. Actually, as early as 1890, inventor of wireless communication Nikola Tesla wrote about the means for broadcasting electrical power without wires. Tesla later addressed the American Institute of Electrical Engineers to discuss his attempts to demonstrate long-distance wireless power transmission over the surface of the earth. He said, "Throughout space there is energy. If static, then our hopes are in vain; if kinetic - and this we know it is for certain - then it is a mere question of time when men will succeed in attaching their machinery to the very wheel work of nature."[4] Dr. Peter Glaser first developed the concept of continuous power generation from space in 1968[5]. His basic idea was that satellites in geosynchronous orbit would be used to collect energy from the sun. The solar energy would be converted to direct current by solar cells; the direct current would in turn be used to power microwave generators in the gigahertz frequency range. The generators feed a highly directive satellite-borne antenna, which beamed the energy to earth. On the ground, a rectifying antenna (rectenna) converted the microwave energy to direct current, which, after suitable processing, was to be fed into the terrestrial power grid.

A typical Solar Power Satellite unit - with a solar panel area of about 10 square km, a transmitting antenna of about 2 km in diameter, and a rectenna about 4 km in diameter - could yield more than1 GW electric power, roughly equivalent to the productive capability of a large scale unit of a nuclear power station. Two critical aspects that have motivated research into SPS systems are: 1) the lack of attenuation of the solar flux by the earth's atmosphere, and 2) the twenty-four-hour availability of the energy, except around midnight during the predictable periods of equinox.

The Technological and Commercial Viability of SPS

Among the key technologies of Solar Power Satellites are microwave generation and transmission techniques, wave propagation, antennas and measurement calibration and wave control techniques. These radio science issues cover a broad range, including the technical aspects of microwave power generation and transmission, the effects on humans and potential interference with communications, remote sensing and radio-astronomy observations.

Is SPS a viable option? Yes, in my opinion, it can and should be a major source of base-load electricity generation powering the needs of our future. SPS satisfies each of the key criteria except for cost based on current space launch and propulsion technology. We all know that the expense of lifting and maneuvering material into space orbit is a major issue for future energy production in space. The development of autonomous robotic technology for on-orbit assembly of large solar PV (or solar thermal) structures along with the needed system safety and reliability assurance for excessively large and complex orbital structures are also challenges. Nevertheless, no breakthrough technologies or any theoretical obstacles need to be overcome for a solar power satellite demonstration project to be carried out.

Our society has repeatedly overlooked (or dismissed) the potential of space based solar power. The U.S. government funded an SPS study totaling about 20 million dollars in the late 1970s at the height of the early oil crisis, and then practically abandoned this project with nearly zero dollars spent up to the present day. A government funded SPS demonstration project is overdue. Ralph Nansen, a friend of mine, who was the former project manager of the Apollo program at Boeing and who later managed the DOE-NASA funded SSP proof of concept study in the late 1970s, detailed the Boeing study in his excellent 1995 book Sun Power: The

Global Solution for the Coming Energy Crisis[6]. In 2009, he authored another book entitled Energy Crisis: Solution From Space[7]. I highly recommend the reading of each of these two books for those interested in this topic. Of course, Dr. Peter Glaser's 1968 book and other papers[8] are superb reading on this topic as well.

What I really want to point out here is that we can solve the cost issue and make Solar Power Satellites a commercially viable energy option. We can do this through human creativity and innovation on both technological and economic fronts. Yes, current launch costs are critical constraints. However, in addition to continuing our quest for low cost RLV (reusable launch vehicle) technologies, there are business models for overcoming these issues.

Several such models have been studied and are now being pursued by some American private aerospace entrepreneurial companies, such as the SE (Space Energy Group) and the SIG (Space Island Group) based in Switzerland and California. The SE approach is based on systematic development of solar technologies for terrestrial and for space environment applications. The company expects to rely on extensive terrestrial solar technology development as the stepping stone, focusing on the space-grade thin film PV technology innovations for launch cost reductions. The SIG idea is to modify and utilize legacy components of the Space Shuttle, turning the huge volumes of the external Shuttle tanks into a commercial asset for the space-based research and orbital tourism industry. Increased demand in space tourism will certainly bring about higher launch rates, which should drive down space transportation costs. Who would have thought that ordinary people could afford air travel just a few decades after the Wright brothers had succeeded in flying their first aircraft?

We must advocate solar energy as a sustainability strategy for the future of humanity. That is the way to pursue Solar Power Satellites. We should not, nor do we need to, restrict our vision by choosing between terrestrial and space-based solar. The dream of SPS can be realized much sooner by getting behind the use of terrestrial solar energy and the development of pertinent solar technology on a global scale. Development of nanoparticle ultra high efficiency, low weight, low cost PV cells, along with higher capacity and lower cost energy storage systems, will also benefit SPS development. Our ultimate goal is to tame the "very wheelworks of nature" and harness the energy of the sun. It's not important whether we achieve this goal via SPS or through terrestrial solar approaches, or whatever technological approaches may be created for large scale and affordable use of solar energy.

Nanotech based PV solar cell materials are now being produced more cheaply and are reaching over 50% efficiency. Revolutionary developments are occurring in battery technologies. It is possible that one day we will not need to launch huge PV satellite structures into space to satisfy base-load electricity consumption for the entire planet, except of course for power supply in space environments. It is instructive to observe the 30% annual growth of the solar energy industry even without government policy support in such nations as the U.S. and Russia. Imagine the day when we are no longer dependent on gas and oil when our houses are built with cheap and highly efficient solar cell material installed in the roof and in siding, and parking lots in shopping malls and office buildings are equipped with solar powered charging plug-ins for electric cars.

Achieving Energy from Space - A Roadmap Ahead

I believe that the future hope for a viable Solar Power Satellite system lies in the collaborative efforts of private, entrepreneurial space businesses and venture capital investment, undertaken as a global scale commercial enterprise. Quite frankly, as a former employee of one of the great space agencies of the world, I am pessimistic about getting the necessary government support for any SBSP project. I was disappointed, even surprised, to see no mention about energy and economic development from the United States' vision for the future of its space endeavors.[9]

There are visionaries in the world who do see the significance of space exploration and humanity's connection to space for future energy development. One such visionary is the recently retired president of India, Dr. Kalam Abdul. President Abdul had the great vision and courage to speak publicly on the prospects for space solar power while addressing a symposium on "The Future of Space Exploration" organized by Boston University[10]. Kalam Abdul believes that inter-disciplinary research on space will enable new innovations at the intersection of multiple areas of science and engineering. The former president said, "Civilization will run out of fossil fuels in this century. Solar energy is clean and inexhaustible. However, solar flux on earth is available for just 6-8 hours every day whereas incident radiation on a space solar power station would be 24 hrs every day. What better vision can there be for the future of space exploration, than participating in a global mission for perennial supply of renewable energy from space?"

Government policy and regulatory support will be crucial to success, as will the funding of R&D and related technology demonstrations. U.S. government support for space solar during the 1980s was negligible. NASA initiated its "A Fresh Look" studies in the mid-1990's. Subsequently, the U.S. Department of Energy abstained from any involvement. During this time, the Japanese government and industry became interested in the SPS concept. The Japanese updated the reference system design developed in the System Definition Studies of the late 1970's, conducted some limited testing and proposed a low orbit 10 megawatt demonstration satellite. So far, their effort has been curtailed by their economic problems and by their lack of manned space capability. SPS Interest by other nations has persisted, but only at low levels of activity.

The overwhelming initial cost of development and deployment has remained the primary obstacle. As noted, number one on the list of cost barriers is the cost of space transportation. Solar power satellites are only economically feasible if there is low cost space transport. For SPS to be successful, we need an organized consortium consisting of private businesses, venture capitalists from major international partners, along with government support of R&D and technology demonstrations by industrial nations. We need this concerted effort to bring down associated risks in safety, reliability and technology maturity. The Comsat model for the successful launching and commercialization of communications satellite industry should be a viable approach for Solar Power Satellite implementation.

An "Apollo Project" for Space Solar Power

An major effort led by the U.S. - similar to the 1960s Apollo Project to put a man on the moon - with broad participation from the international community may be what is needed to create, implement and operate a commercial scale SPS system. Please remember, an inherent feature of Solar Power Satellites is their location in earth orbit outside the borders of any individual nation. Their energy will be delivered back to the earth by way of wireless power transmission. WPT applications must be compatible with other uses of the radio frequency spectrum in the affected orbital space. SPS infrastructures must also be launched and delivered into space. International involvement of governments is mandatory for coordinating global treaties and agreements, frequency assignments, satellite locations, space traffic control and other features of space operations to prevent international confrontations.

It is imperative that a multi-governmental organization or entity be put in place. For the U.S. - or any single nation - to implement a full-scale SPS project alone will be extremely difficult, if not inconceivable, due to the many political, regulatory and technological reasons stated. However, it is equally important that there be a lead nation providing the necessary leadership in such a complex and interdependent international effort. The various project elements involving multiple government and industry partnerships must be clearly defined. The United States is a logical leader in this area because of the breadth of its technology infrastructure and capability, as well as the magnitude of financial resources available in its industry and financial community. Building, launching and operating a system of Solar Power Satellites in space orbit is going to be a technology and engineering endeavor requiring great human effort and ingenuity. If we can go to the Moon and achieve the splitting of atoms, we can also overcome the inefficiency problems of solar-electric conversion, and we can achieve affordable access to space. We can make Solar Power Satellites a cost competitive source of energy for all of humanity.

SPS component technologies will also enable human economic expansion and settlement into space, which is important for the permanent survival of our species. To this end, a "vertical expansion of humanity" into our solar system in the new millennium can be every bit as important as the "horizontal expansion" achieved by our ancestors beginning in the 1400s. Indeed, SPS will provide a natural platform for promoting human collaboration in an area that has the potential to make a real difference in smoothing out global economy imbalances due to gross disparities in energy resources, thereby preventing inevitable confrontations. SPS can be also a major steppingstone in transforming our current combustion world economy into a sustainable and clean world economy that is solar-electric powered.

Looking Forward to a Brighter Future

Mankind must now start looking to the sun for its ever increasing energy needs, and to solve its environmental crisis, I think of "harnessing of the sun" as the 3rd giant leap in the process of human evolution. The first giant leap was when human beings came down from the trees and started to use fire, which brought tool making, agriculture and ancient civilization. Then human beings invented internal combustion engines and discovered electricity, which allowed mankind its 2nd giant leap forward, bringing modern industrialization. Now we're running into profound energy and environmental crises. Mankind must now make more intelligent and creative use of alternative energy sources. The next giant leap for our civilization will be to achieve a new, more sustainable solar-electric civilization, built on a direct and inexhaustible and energy source from the stars.

Can mankind achieve the next giant leap into the solar-electric civilization? The past can be our guide. We have shown ourselves capable of such space achievements as the Manhattan and Apollo projects. We can make it happen - but not if we fail to educate and mobilize the public and politicians around the globe. The key changes and support needed are less technical and economic than social and political aspects[11]. Indeed, it's a policy issue, and it is encouraging to see that the government of Japan has taken a lead position to support the SBSP development[12]. When it comes down to a space race or war, we can achieve nearly anything. But can we rally the public and politicians for peace and sustainable human development? Can we promote the Solar Power Satellites idea for what it will be: a Manhattan project for peace?

Dr. Robert Goddard liked to say, "It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow." I would like to conclude this paper with what I said at the end of my talk at the Seattle energy conference, "As intelligent creatures rooted in the cosmic origin, humanity was meant to survive and spread its presence all over the universe by milking the energy of the stars."

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