Master Dissertation

Is Electricity production in space the future of green energy production?

Academic supervisor: DOS SANTOS PAULINO Victor

Master Aerospace Management Director: BENAROYA Christophe

Executive Summary

I choose the subject about Space Based Solar Power (SBSP), because it is a transversal topic which could lead to major changes for the future. In terms of economic and environmental issues, manufacturing, energy production, politics, geopolitics, geographical, military, social trends and so many other fields. The idea of having an easy, (almost) infinite and green electricity production is extremely exciting for me. I am thinking about it all day long and I hope you will learn and dream at least as I did during this project.

The idea is not new but today, we have all the levers, the answers and the technology readiness to be able to build a Space Based Solar Plant. How can we even imagine that tomorrow, we could abandon oil, coal and gas to infinite solar energy which will produce and send us electricity at day and night but also with bad weather conditions. It is the goal of the SBSP. It will give an answer to all the different issues we have today, it will make our world greener, it will reduce inequalities, and it will be flexible. We are the generation of the fast changes, this is one of the key to equilibrate the fast development of connected objects, progress of electricity consumption (objects, cars etc.) and one the major issue which is putting people against each other: pollution and climate change.

Through various articles, examples, interview, I will try to answer to this question and ensuing ones as is it really sustainable? How is it working? Will it be profitable and then realizable? What are the main blocking points? What are the main levers on this question? What recommendations could we give to achieve such an exciting project?

Technical feasibility as well as potential successful Business Model are addressed in this document, beginning of answers are given in order for the reader to build its own opinion and be able to analyse the different aspects, positive or negative, of the Space based solar power.

From scratch to the future, how this project will become reality or at least will affect and influence decisions in a near future and our way of producing energy. It is the time to change the energy producing model, the planet is waiting, and minds are ready to welcome the SBSP. Then, what are we waiting for?

In order to have a global overview, I have tried to vary types of sources that I used to have a fair and real view with the people for and against this project.

Acknowledgement

First, I would like to thank many of my colleagues at Airbus Defence and Space who helped me understand many technical aspects as well as their views and thoughts on the subject.

Secondly, I would like to thank the director of my master's in aerospace management; Mr. Christophe BENAROYA. In addition to his motivation and passion to transmit the love for aerospace sector, he has always been here for any help and question we could have and more than happy in sharing its knowledges.

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I will also gratefully thank Mr. Cornelius ZUND, my mentor during this academic year. He helped find and dig deep into my subject, explaining me how to be imbued in this subject and how to handle it.

I have a special thank for Mr. Yoann THUEUX, working at the innovation department at Airbus who kindly accepted to answer to my questions on the subject and bring me new and strong elements to support my work.

I will then thank all my comrades, which have been here and always keen to share their thoughts about my subject or help with any ideas they could have or articles they could have found. I will not forget this incredible year and experience in aerospace management with them.

Table of content

List of figures, tables, and appendices

Introduction

What's the biggest challenge of today's world? Each and every crisis related to anything is somewhere linked to this purpose. Covid crisis, Climate change, Ukraine's war to mention only recent crisis… All the recent events have shown a real issue in energy production /consumption /price. Furthermore, with more & more connected objects, IT environment or metaverse world, the needs in electricity will continue to grow fast. Even in our European territories that we thought were safe from electricity shortage, we have tremendous issues, we depend on other territories when energy production is at stake (Gas from Russia or North Africa, Oil from gulf countries…).

What's the solution? Produce more? And then pollute even more? Solar & wind powers have their own limits? First of all the price (even if is it now lower than nuclear power) but also space taken by plants. Nuclear is not polluting in itself but the waste recycling is a problem. Coal, Oil? To produce electricity that will powered electric cars? And continue to emit high quantities of carbon in the atmosphere. Gas? When the goal in our continent is to reduce our dependency from other countries. Hydrogen? When it is not always produced from green energies. Hydroelectricity? When our glaciers are melting and water is more and more needed to irrigate cultures and face rain scarcity. Energy is the key of today's & tomorrow's worlds.

What is then the ultimate solution? Consume less? When connected objects are becoming essential, when cars are more & more electric powered, when summers are hotter and winter colder.

It is one of the biggest threats but also one of the biggest challenges of our lifetime as about 80% of the energy produced comes from oil, coal and gas and only 1% from solar power.

Many countries are investing in future's solutions. One of the most promising is the nuclear fusion, the only and not least issue is the technology readiness level, and we are at the beginning of the trials. It will take a long time before being ready to produce mass energy. The issue is ongoing today, maybe we should look at some other technologies which are revolutionary in a way and feasible in the next decades.

Europe's goal is to be carbon neutral by 2050. Different levers are available to achieve it. But it will have to be absolutely green, feasible, affordable and achievable by 2050.

At the beginning of the 20th century, an idea, was born in Konstantin Tsiolkovsky's mind. Indeed, the Russian space pioneer wanted to take advantage of the sun's power in order to serve humanity. It is with this crazy idea that he invented the concept of space based solar plant. Because the idea was not feasible at that time with the technologies of the beginning of the last century, the idea was abandoned. But not completely abandoned. During the 60s/70s, some concepts (from NASA engineers) have been created… but again abandoned due mainly to lack of reliable technology readiness level and astronomic costs.
The subject is coming back on the stage cyclically and regularly, every time the technology is progressing and the world is facing strong issues. But it is the same for many different projects, many centuries ago, some people already thought building a tunnel under the English Channel. It is for many years a reality, why not the Space based solar power (SBSP)?

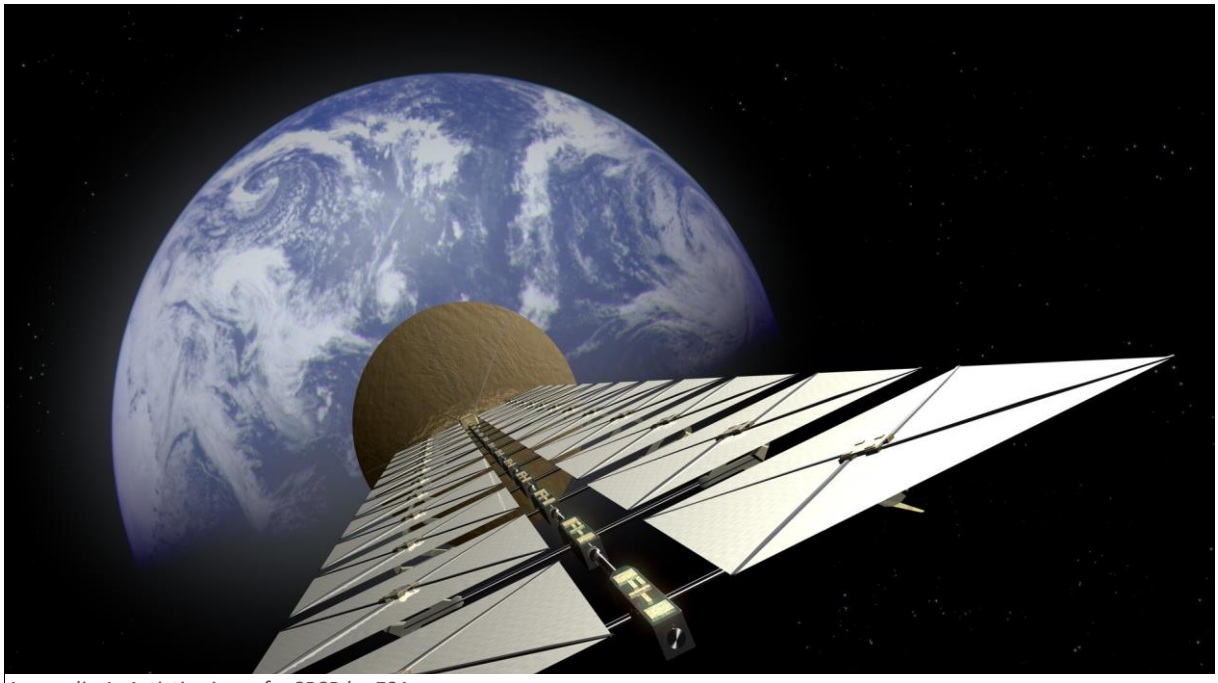
Today, with the technology improvements, many countries are betting again, and now concretely, on what we call a SBSP. We can quote the cases of China, the US, the UK, EU, and Japan who has even "written it into law as a national goal" (© physicsworld).

Studies from different agencies around the globe (NASA, JAXA, ESA…) are dealing with this subject which could help us fighting against climate change, pollution …
We are perhaps closer than ever to a trial from China. Indeed, the country officially announced in 2020 its intention to build a space based solar plant and is probably the most advanced country today.

The idea is to get the maximum of sun's energy. "Every second, the sun gives off as much energy as 10 billion of nuclear bombs" according to © futurascience. In space, the energy is not stopped by the atmosphere and there is no day/night cycles. The production is increased up to 40% compared to solar energy production on earth (according to JAXA, Japanese Space Agency and ESA). Furthermore, to produce our electricity, we could only use sun power, in facts "0, 01% of the solar energy covers the earth needs" (© futurascience).

According to studies, research, interviews, we can ask ourselves the following questioning.

Is Electricity production in space the future of green energy production?



Appendix 1: Artistic view of a SBSP by ESA

1. Technical aspects

The solar energy is central in this subject, it plays an important role on everything that is living on earth… and further! Plants are growing thanks to the photosynthesis process. Earth is temperate thanks to the sunlight, life is possible thanks to the sun. It is an infinite (at our human scale at least) source of light, of heat, of power.

1.1 Let's take a step back with a bit of history in order to better understand our purpose.

The technology used is not new. For many centuries, we have found a way to use solar energy as a source of energy generation. Long time ago to cook food for example. More recently, with the work of the French physicist Alexandre Edmond Bequeret (in mid 1830s) we have discovered that we could produce electricity from the light. The technology was not mature enough to really produce energy but it helped understanding the way it is working. It is only at the beginning of the 20th century, with the discovery of photovoltaic cells, that we discovered how to use this solar power to produce electricity and/or boil water. The solar panel was born in the 1950s thanks to Bell laboratories and has grown in technology and utilization since then. The development and cost reduction of solar panels is tightly linked to space. First solar panels have been invented for space utilisation. It was a critical parameter, being able to produce its own energy in space and not bringing it directly from earth.
The space based solar plant is not a completely new idea. It has been imagined by Konstantin Tsiolkovsky a Russian space pioneer (at the beginning of the 20th century). During the 60s/70s, some concepts (from NASA engineers) have been created and then abandoned due mainly to lack of reliable technology readiness and astronomic costs.
The subject is coming back to the centre of interests regularly with the strong issues the world is facing.

Nowadays, studies from different agencies around the globe (NASA, JAXA, ESA…) are dealing with this subject which could help us fighting against climate change, pollution, energy dependency, resource and raw material depletion…
We are perhaps closer than ever to an essay from China (see part 3.6, page 18). Indeed, the country officially announced in 2020 its intention to build a space based solar plant. Maybe the space race is on again…

1.2 How a Space based solar plant is working?

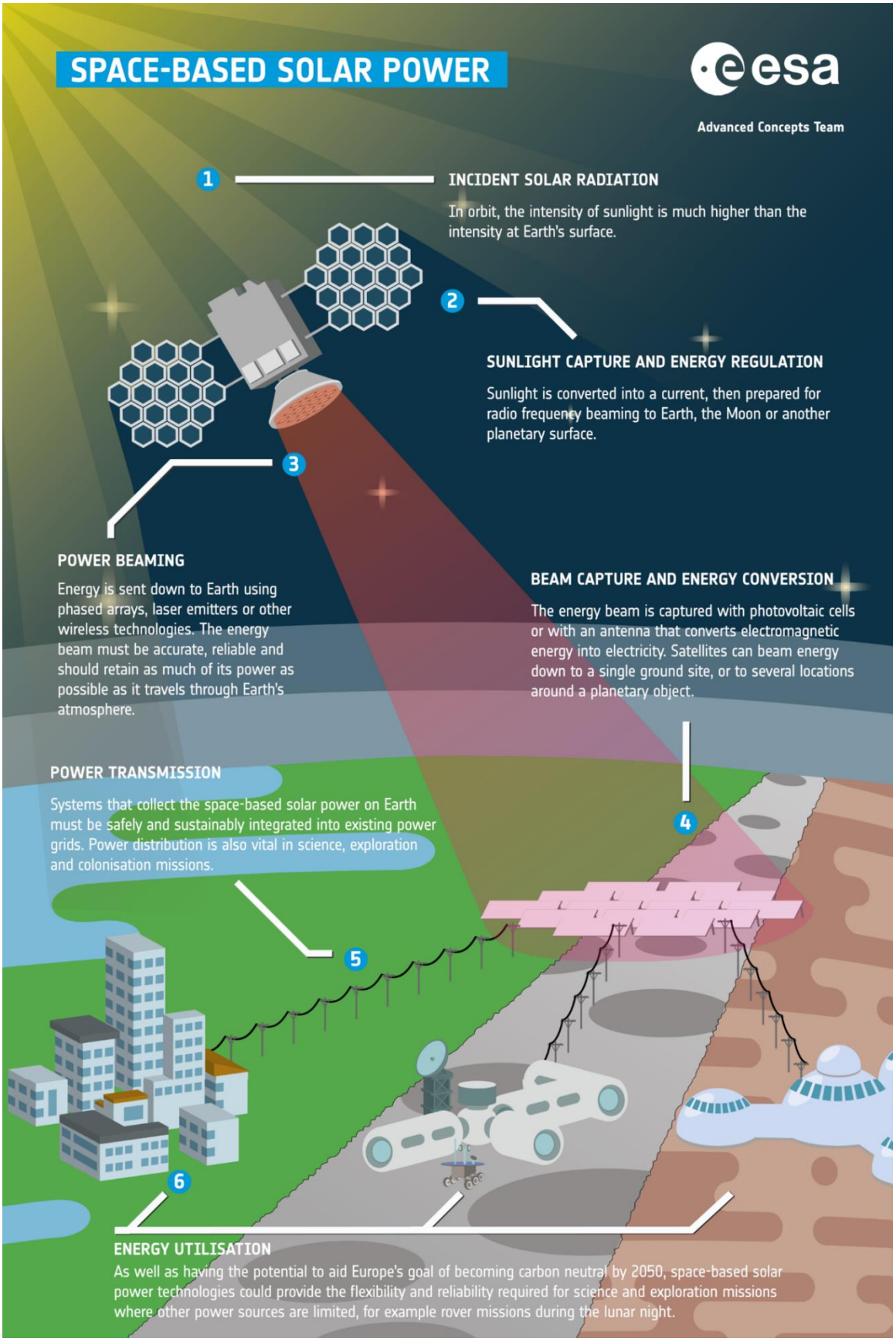
First of all, a huge station is sent and then assembled in geostationary orbit (GEO) at about 36 000 km from earth. This solar station, sent and then assembled in space (as for the International Space Station) thanks to several launches, is mainly equipped with photovoltaic panels and a transformer which converts electricity into a microwave beam (or laser beam following the technology used) to send it to a rectena (receiving antenna which converts electromagnetic energy into electricity) on earth ground. A major advantage of this technology is the flexibility, and the possibility to have different applications in space. You can send energy to a specific point equipped with a receiver. For instance, if a rover on Mars or a space station need energy, you can supply (refuel) it. The applicability could be either a specific place on earth or anywhere in the universe. This technology could incredibly accelerate exploration missions as well as our scientific knowledges.

Solar energy is captured in space thanks to the photovoltaic cells on a huge production station (some kilometres wide). Then, the produced electricity will have to be converted into microwaves or laser in order to be transferred to receivers on earth ground. The two different technologies which could work have their advantages and inconvenient.

- The first one (and the most promising one) is microwave beaming to earth.
  After being converted into micro wave, energy is transferred to earth and can pass through clouds and rainfall. Moreover, it is safer than the laser because the density is lower. Following studies from ex-NASA astrophysicist John Mankins, microwave technology for Space Based Solar Station is not dangerous because of the wavelength is long (about 12cm), and then does not affect DNA, and is not carcinogenic.

- The second technology developed is the laser beaming to earth.
  The electricity is converted into a laser transferred to earth. Unlike the microwaves, the lasers cannot pass through clouds and are susceptible to atmospheric disturbances. Furthermore, lasers are dangerous for human eyes, then, rules and safety requirements will have to be implemented to avoid injuries. The advantage of using laser technology is that the tool is compact and can fit within a small transformer and transmitter.

These technologies are not science-fiction but already a reality. In 2015, the Japanese space agency (JAXA), performed energy transfer (1.8 kilowatts) via microwaves over 50 meters. More recently, in April 2022, US Navy researchers succeeded by performing electricity transfer of 1.6 kilowatts into direct current electricity. The European are also betting on this technology. On the 27th of September 2022, a team from Airbus performed the same exercise and I had the chance to have a talk with the leader of this project. (See part 3.3)
However we still cannot completely assess the adverse effects of this technology for example on human health, aircrafts in flights, electronic objects…



Appendix 2: Drawing from the advanced concepts team of the European Space Agency (ESA)

This drawing is well explaining the concept, how it works and what could be the concrete benefits of this technology. We can see the SBSP, the energy beam to earth. And the different applications possible, on Earth, the Moon, Mars or other celestial bodies.

2. Advantages and drawbacks of the SBSP

2.1 This technology has many advantages.

The main issue in our today's world is the green side of each subject. We have to preserve our planet. It is everywhere, in everyone's mind. As energy production is the main polluter, it has to adapt, fast, and at all prices. This new way of producing electricity could replace huge polluting industries and raw materials as oil, coal and gas.

Another big issue encountered on earth is for solar panels. Indeed, at night they don't produce anything, the energy production is not continuous. The capacity of production is available only during the day and electricity is not easily storable! (Even if progress are made in the storage capacities and efficiency). The loss in production is heavy, even more when we know that maintenance is done for a period in which the plant produced a bit more than half of its capacities. The second phenomenon preventing the technology to work at its maximum is the atmosphere. Indeed, the atmosphere is stopping and reflecting the solar beams before touching earth ground. Thanks to the SBSP, the production will be continuous and not be affected by the weather conditions.

The third issue we could tackle is the space taken by ground solar plants earth ground. It clearly takes a lot of space which is not used for agriculture or let for natural reserve (and not installed on building's roofs). The space based solar plant is not taking a square meter on ground except for receiving antennas (which could be installed above the sea for example).

The fourth advantage of the SBSP compared to its twin on earth is the risk limitation/mitigation. A photovoltaic plant on earth is subject to climatic disasters (fires, floods, hail, storms, tornados…) but also human malevolence. Due to the changing weather or difficult climatic conditions in some areas (polluted area, tropical weather, extreme temperatures…) the panels' usury can be very fast and the production would decrease years after years. The only risk that could be taken into account for the SBSP is the risk of collision in space.

It will also take its part to reduce inequalities (countries with no oil, no sun or no infrastructures could use a SBSP) in theory, because every country will not be able to invest in such a project.

This new space plant could resolve all these issues. And as Chris Rodenbeck, a scientist from the US Naval Research Laboratory, said it is green! "It's the only form of green, renewable energy with the potential to provide continuous, baseline electrical power". By producing almost 24/7 and by capturing integrally sunbeams, the solar space plant could produce a lot more than the same station on ground. According to ESA (European space agency) the sunlight is 11 times more intense in space than on the European territory.

Very good | Good | Average | Bad

Advantages / disadvantages of a Space based solar plant				
	Space based solar plant 83%	Index	*Earth based solar plant 71%*	Index
Energy Production	Continue energy production 24/7 +40% compared to earth ground plants	10	Produce at 15% of its max capacity © greenmatch + No production at night and very limited when cloudy or polluted areas -> reliability issue	5
Environment	Environmental friendly (- launch to space) Renewable/infinite energy	8	Environmental friendly Renewable/infinite energy but can distract ecosystems if placed in landscape	8
Land surface utilisation	Take no space on ground (apart from ground antennas/rectenas)	10	Take lot of space on ground compared to its energy production	3
Energy dependency	Energy sovereignty	10	Energy sovereignty	10
Maintenance	Limited maintenance needed but inaccessible if any issue	7	Limited maintenance needed	9
Price	Price to launch in space	5	Price to install + site security costs in operation	7
Technology	Technology readiness level	7	Technology readiness level	9
Risk	Risk of collision in space (almost negligible at GEO orbit)	9	Fragile -> Risk of climatic disasters (fires, floods, hail, thunderstorms, tornados etc) Risk of human malevolence	6
Usury	Normal usury but subject to radiations	8	Accelerated usury due to climatic conditions (especially in tropical weathers or locations with extreme temperatures)	7
Flexibility	Energy is not yet storable but could be sent to different locations on earth or in space following the needs	9	Energy is not yet storable and is limited to supply close locations or be injected in the energy mix	7

Appendix 3: Table representing the plus and minus of a Spaced based solar power and Earth based solar power. Table based on my own research.

2.2 But has also some inconvenient

The biggest one is the cost issue. The cost of building the elements (millions of solar cells) and the cost to launch them in orbit (several launches needed, with currently not reusable space shuttles). Nowadays, the cost to launch 1 kg of payload in orbit is in average 10 000$. However, the price to launch payload in space has dropped drastically for the last 20 years thanks to companies from "New Space" as Musk's Space X, Bezos's Blue Origin etc. These companies spend huge amounts of money in R&D in order to be the most competitive. NASA have also "price reduction to access to space" as one of their main goal. Their objective is to reduce the cost to reach space to hundreds of dollars per kg by 2045 and dozens of dollars per kg by 2060.

The price will then continue to drop during the coming years but is still a brake to the development: the project seems to be too expensive to be competitive (see next part on Costs).

One of another major inconvenient is also the technological challenge to put and assemble an enormous station in orbit. It is feasible, it has been shown with the different space stations but still challenging, it is difficult to achieve and we do not know about the reliability of the system. The parts will have to be launch on a specific orbit, then space robots would probably be needed to assemble the station in GEO orbit.

The technology readiness level is another blocking point. To send energy from space to earth receivers, we must control the overall process. From electricity transformation to microwave or laser; for the transfer to earth using receivers and for the re-transformation in electricity. Everything has to ben planned, every issue that could be encountered must be taken into account. If a miss or an issue is affecting the project, the losses could be huge in terms of cost, image and confidence within the technology. The yield has also to be sufficient, the SBSP will have to be sustainable economically speaking. If the production is lower than planned it could be either difficult to finance the cost, the return on investment will not be sufficient. The project (or next projects) will not be viable and the SBSP projects could be abandoned.

Safety is central in the project, people are already scared about the potential consequences of a problem with the laser or the microwave transmission technologies from space to earth. We can also raise the security level that it has to maintain. System hacking could have disastrous potential consequences. It has to be safe and secure and this would probably help to choose the best technology to transfer energy.

Finally, maintenance will be very complex. It is not (at least nowadays) possible to imagine that every month, we will send a spacecraft to maintain the station or replace defective parts either by human beings or robots. The costs here again would be astronomic. We have to ensure that if a system is failing, it does not affect the entire SBSP. Satellites today can last for 25-30 years while still functioning well without any maintaining action, by only using soft maintenance actions.

3.Which Business Model?

3.1 High costs

What could be the Business Model? As we have seen previously, this technology is very expensive, if we add the price of the production, the launch, the installation in space and the maintenance, we can reach an astronomic price. It is today too high to be competitive.

Let us take the example of British households who are paying today under £2 per watt. With the technology we are analysing, it is approximately £154. About 77 times higher!

Then, how can we even imagine that the SBSP could one day be sustainable and competitive? Can we bet on green, continuous energy at all costs?

The costs are high because of the cost of the launch, cost of different components and the cost of infrastructures on ground. If we compare the high costs of launching the panels to space with electricity generated, today it is not profitable and not balanced. Panels are too heavy (cost per kg to launch in space) compared to the power in watt generated. If we add all these costs, it is about 100 times higher than the balance to be profitable (according to Frazer-Nash Consultancy report ordered by the UK).

Fortunately, the price is not the only driver in a project and could be turned to our advantage.

Let's analyse a famous business model with a concrete case used some years ago.

3.2 Example of performant BM

We will analyse the situation factually and by taking a simple, effective and well known model. The Tesla motors case.

Our space plant BM could be as Tesla did at the beginning. Tesla was selling very efficient electric cars and very expensive about 100 000 $ and even a Roadster at 200 000 $. It was only oriented to catch wealthy people. Then, some years after, they could sell a smaller car at a smaller price affordable to more people. With the high prices and margins made with the first expensive cars, they could finance the next generation. This business model is also used by Elon Musk's company Starlink right now. To be able to have internet connectivity from Starlink network, you must pay about 500-600$ at the beginning and a subscription of about 100$ each month. It is huge, the majority of people pays ten times less and are not interested in Starlink but for some specific applications (streaming, online gaming, maritime applications…) and certain people it makes sense.

This business model idea could be easily replicated with the space station. At the beginning, the price could be tremendous. Single households are not ready to pay electricity 10 times more than today. But some other organisations would be interested. What about very remote scientific bases in Antarctica. Maybe the price to sell energy in here will be comparable to the price they are paying today to send generators and oil throughout the white continent. It would be at least far simpler than bringing all needed material in there. Why not also transferring energy to the war scenes we are engaged in. For example in the desert. Camps are electrified by generators and then with oil. As these regions are often really unstable, even dangerous, wouldn't it be better to beam energy directly to the base camp instead of risking life's crossing risky areas to

bring oil? Militaries would be up to pay more their energy and maybe not much more as we can easily imagine that the price of energy transported through thousands of kilometres should be expensive. The third option presented by Karen Jones (senior project leader at Aerospace Corporation, USA) is the help in catastrophies. Natural disasters happen often poor areas where electricity is not everywhere and/or the connections may be destroyed. With this technology, only a receptor is needed and hospitals or refugees camps could be supplied to help saving people. States could pay for this or helping organisations, or even with funds and donations helping saving lifes. Thanks to this idea, the relief chain could be improved and reconstruction accelerated.

Then, after using space energy production for specific areas, the technology would mature, the application could be extended to more and more areas of application… Ecology concerns are raising and this technology is going in the right direction. And the cost will drop down. It is already the case for ground photovoltaic plant where the development has been promoted thanks to the governments subsidies. Now the model has found its own balance as the volume of installation has increased, leading increase in manufactory components allowing cost scaling. Furthermore, the evolution of the minds in the future will stick to this idea/project, if it works. If the first demo is making its proof, the electricity companies as well as individuals would want to use energy coming from SBSP. Having a green energy without fluctuation is still the dream today but it is coming slowly and would maybe find its efficiency in this project.

This energy, compared to the terrestrial one is not affected by prices fluctuations (according to JAXA) as we can be affected by today, ecology, wars, disasters, supply shortages. Russian gas, oil Brent, coal are fluctuating a lot following the geopolitical issues.

3.3 Extremely high potential

Despite its cost, technical and technological issues, it has a tremendous potential. Advenit Makaya, an ESA engineer explained that “The potential of this concept which is contributing to a sustainable and long-term energy production is very high” Indeed, for Europe which is not geographically rich in terms of natural and non-renewable resources, it could be a great opportunity to escape energy dependency from Asia or Africa. Moreover green energy, what we, European people are looking and waiting for today on the continent.

She added, “it would not only generate clean energy, but would also be very flexible: it could be integrated into power grids on Earth, but also used for exploration missions”. European Space Agency is as many other actors more than interested in this concept.

Airbus is going even further by thinking to apply the technology to power satellites, aircraft and even drones. Planes in flight could be fuelled with electricity produced by the space solar farm. Aircraft could fly further, gain in lightness and could even send back energy to earth or other transportation means if it receives more energy than needed.

It has the goal to help fighting against pollution but also improve aviation sector image toward new generations which are more and more aware of the climate issues and could be tempted to stick with ideologies such as “shame of taking plane” for example.

Recently, as we could have seen in the media, Airbus launched studies about what they call “solar power beaming”. The idea was to work on a very promising project to produce energy

in space and sending back to earth, similar to SBSP. I had the chance to have a talk with Yoann Thueux who is both passionate and in charge of the project.

For now, the team is small but many volunteers who are interested in the subject work to improve, give ideas and advices, and share their different skills in order to help and contribute to the success of the idea.

Today, the European company is following its own path but it is not excluded that in some years Airbus could allocate a consequent budget and sign strategical partnerships either with private companies or public bodies in order to strengthen its capabilities.

In September 2022, the company presented a demonstrator to show that microwave transmission for electricity is feasible. The demonstration of 2,4 kw over 36 meters was a success and the teams are already working on the future of the project. As the goal is to transmit electricity from space to earth, they have to climb a bit to try to transmit electricity from planes to the ground. The ultimate goal is a 2000-metre diameter structure in geostationary orbit, but the first prototypes would be at a smaller scale, for example 20x20 metres.

For Yoann, the question of the technology used is made. Lasers are too dangerous (the energetic density needed to transfer to earth is too high) and inefficient with clouds and atmosphere. Moreover, they could be hacked and weaponised by malevolent groups or persons. If all the energy is focusing one point, it could be extremely damageable to human integrity. With microwave technology, fortunately, it is not possible.

What is then the best place for the solar power station? GEO? LEO? For Low Earth Orbit, the problem is that the station is too close from earth to point to large spectrum, it has to perform difficult movements to point specific places and is in the shadow of the planet. For GEO, these issues are already solved and the loss of energy is almost negligible.

The goal is to create a virtuous circle. This solar station could serve to create green hydrogen thanks to electrolysers for example (indeed today, most of the hydrogen produced is made using non-renewable energies). The liquid hydrogen used to launch rockets is not green, we could use the SBSP to produce green hydrogen for space applications, to be able to launch other space based stations. Green hydrogen for space applications would be technically and economically possible for the next years.

We did not talk about the decommissioning of the former stations neither. It has a substantial cost which has to be taken into account in the overall budget. Today, there is no space law about the waste in space. It will have to be placed on a cemetery orbit or deorbited in the earth atmosphere (no de-orbiting planned if in GEO because it would use too much fuel). It will be necessary to invent a structure infinitely reusable and plan the potential integration of new and future technologies in it.

By 2035, we should have a small scale working power station in space for example for specific applications such as scientific bases in Antarctica (continent which is on darkness 6 months of the year) It will be the time to test the technology and show to everyone that it is reliable and safe. The goal, amongst many others, is to have by 2045’s a solar space station in lunar orbit to provide electricity to Moon bases.

It is only a concept but we can see a keen interest as more and more private and public actors are launching projects on the subject.

3.4 Funds & donations

A promising financing program would be from partnerships but also from funds and donations. Indeed, sponsors could really be interested in this green SBSP. Furthermore, it is good for the image to help such projects.

For example a billionaires couple named Bren gave more than 100 million $ in 2013 for this specific project to the California Institute of Technology (Caltech). The project's first test to launch the first prototypes should happen at the beginning of the year 2023.

3.5 UK consultancy example

We can take the example of the United Kingdom. Indeed, the country's solar electricity production is limited due to its geographical location and the lack of space as being an island. Nowadays, European states are facing strong energy production issues because of the war and complex geopolitical context with huge tensions. The UK recently launched studies to assess the feasibility of a space solar plant with the objective of supplying UK territory with infinite and renewable energy and being, energy production speaking, self-sufficient.

The UK government asked for a report from Frazer-Nash consultancy which has been published in September 2021. The report clearly mentioned and concluded that the Space Based Solar Power is technically feasible and economically competitive. This cost-benefit analysis has been awarded by the European Space Agency on the 10th March 2022 as well as a parallel analysis from Roland Berger consultancy. The objective was to evaluate the business case for SBSP applied to Europe.

As the budget to initiate the project is tremendous, the report is analysing the different sources to raise money. The government could contribute as well as private investors to finance the project and be able to wait because of the slow ROI.

The report evaluated the cost of a SBSP for the UK about £17 billion. The technical characteristics would be 1.7km diameter for the station in orbit (with a weight of 2 000 tonnes) to deliver 2GW (about 2.6 % of the UK's generation capacity which is quite big. The problem is on the ground with receivers taking about 6.7 km by 13 km on land. The idea, considering that the UK is an island with limited space is to place it offshore.

Fortunately, the environmental, geopolitical, and economical contexts play in favor of this project. Indeed, the cost to launch in space has never been as low as today, the goal of many western countries is to be carbon neutral by 2050s. They could then be ambitious and invest huge amount of public budgets in these types of projects.

This report is also addressing the issue of the time. The time we will have to wait before it become reality and produces mass electricity. What do we do between now and the next 20-30 years before the SBSP could produce energy? We could bet on new ways of living using green hydrogen for example or batteries to store energy and use it when we need the most. Store it within electric cars batteries for instance.

3.6 Already on track: the example of China

China is probably the most advanced country in the space plant launch. The country is planning to launch by 2028 a first station prototype being able to produce 10 kilowatts at low earth orbit to test the transmission technology and adjust for the future one. By 2035, they plan to launch a more powerful space solar power station at a geosynchronous orbit producing 10 megawatts for military and civilians' purposes. By 2050 and the potential progress in technology such as for solar cells, the output would be 2 gigawatts and be commercially viable.

The Western countries and particularly United States and looking at this project as a new space race where the US are far behind (a similar project has been abandoned 20 years ago by NASA). They are shared between what to do. Following China and spend a lot of money to build a SBSP or let them do and see if it is working. When we know that the SBSP will cost several billions $, it is not an easy point and it is more a political question.

3.7 What about the USA and Europe?

The US

In this new space race the US are very discrete these last years but they are still working on the subject. The Air Force Research Laboratory, has launched a demonstrating project to test the transformation of solar energy into radiofrequency in 2021. The concept is not beaming energy anywhere but the goal is to adapt and improve the technology used. The report has shown that it is feasible and demonstrated favorably that it could work.

The secret project was launched thanks to a military space plane called X-37B robotic space plane and spent more than 300 days in Earth Orbit. The US plan to launch other projects such as SPIRRAL in the following years.

Europe:

ESA is also involved in research projects about the SBSP but they have not today the necessary funds to launch a true prototyping working project. A small company called Emeraude (which is building and managing photovoltaic plants on ground) performed a successful trial some weeks ago to test power beaming prototype for space applications… It could be a potential company to follow for the next years.

Recommendations

Then, what recommendation could we give to achieve the goal of one day having a working SBSP.

1. First of all the SBSP will have to be giant: about 2 square kilometres. Then, the number of solar cells would be huge. This is why it would be interesting to implement mass cells production. The goal is being able to produce a lot of cells to complete the 2km2 of the station but also to achieve economies of scale. Parts of the already existing factories or new factories could be dedicated to the production of these photovoltaic cells.
   Thanks to the evolution and improvement of the technology in the following years, the solar cells would be more efficient and lighter. Moreover, we could use the same process as we are now using to produce mass cars batteries for electric cars or microchips for connected objects. Implementing big factories is the key to achieve such program.

2. The second recommendation would be the implementation of strategic partnerships. Indeed, the astronomic cost of the project is not viable for a small state on its own. Countries could decide to bring together their strengths in terms of research, financing, politics, regulations in order to build a SBSP. International organizations such as European Union, Mercosur (the South American common market associating Argentina, Brazil, Paraguay and Uruguay (Venezuela membership has been suspended) and other associated states) or others could lead this project by bringing together the different member states.
   The partnerships could be performed by space agencies, many programmes are already common between NASA, ESA, Roscosmos, JAXA etc. Space agencies have a strong culture of intercultural teams and projects. Moreover, they have the knowledge about making spacecraft and technical capabilities to conceive the SBSP.
   Private companies could also be part of this incredible adventure. They often have strong financing capabilities and are eager to take more risks than public bodies. We can imagine many different configurations of partnerships between these three types of actors. Private/public partnerships, Private-private etc.

3. The third recommendation would be regulation. We can consider two different types of regulations which could be applied.
   Regulation on space. Nowadays, except the regulation about space or celestial bodies' ownership, and weapons in space, we have no space law. If space is not regulated for private stakeholders (SBSP but also, manned flights, satellites constellations…) they will profit from absence of sanctions. It could be an important issue and it is necessary to anticipate this case.
   The second regulation could be applicable to "big profits oil companies" for example. Encouraging them to invest in green R&D and in projects as the SBSP. Many of these companies have the investment capacities to spend money in it. With regulations indicating them the way to follow to benefits from these capacities, they could be more than interested in these projects and a major part of the feasibility of such a project. It is an investment toward the future. Oil stocks will be "sold out" in some decades. They have to diversify their activities and before constraining them, it could be interesting to

educate them on the subject. It is more or less already the case with the "rights to pollute". Less you pollute, less you pay. Less you produce energy from oil, and more from green sources, more it will benefits for you in the future.

4. The fourth recommendation is the creation of a virtuous circle, thanks to the SBSP. Indeed, the goal is to be green. The fuel of rockets to launch the SBSP is not green. We could create a model when having the first SBSP producing electricity, beaming it on earth to produce green hydrogen (thanks to electrolysers) we could then use this hydrogen to power launchers. It is a great example of virtuous circle applied to our concept. And it could work quite easily.

5. The fifth recommendation would be to take into account life ending of the satellites and the SBSP. The decommissioning of the solar station will be an issue at the end of its operational life. And it will cost a lot. Two solutions to be taken into account from the beginning of the project.
   We could consider that thanks to the technology improvement we would be able to create a platform and a system that could evolve thanks to the new technologies that are coming to the market. Indeed, after 30 years of operation, the system, which was very new and performant, will be outmoded. It will then be necessary to plan possible updates for the future or changing in the system already at the birth of the SBSP.
   The second possibility (if the first one is too complex or if there is any issue) is the decommissioning of the Space power station. For example, by sending it to a utilized orbit (sort of satellites cemetery) in order to preserve other working satellites in the area.
   The other possibility for decommissioning is to deorbit it by entering the atmosphere. It is a possibility to consider even if, knowing the size of the SBSP, it would be complex and not all the station would be disintegrated by entering the atmosphere (idea of deorbiting it above the Nemo point in the Pacific Ocean like MIR Space Station for instance).

6. The sixth recommendation is about the business model we want to implement to be sustainable with a positive ROI. The idea, as explained with the Tesla case would be to launch a first SBSP for specific and expensive issues at the beginning (Scientific missions in isolated places, military purposes, disasters etc.) and then deploy it to "everyone" afterwards. Cost of launch will be reduced in some years due to hard price competition. Technology will evolve, the solar panels will be more productive and the ROI for the first applications will be positive in order to finance the next concept. Even if it is very difficult to predict as many different indicators could evolve, the return on investment could be positive. This SBSP would be complementary to the green energy plants we already have today on ground.

7. The last recommendation is to educate people. They need to know that such projects exist, they need to give their ideas to help improve the SBSP. Everyone has to play a role in this global challenge.

Conclusion

By analysing our SBSP venture, we have found an exciting project which was born decades ago but is still questioning today and more we advance in time, more we evolve in technology, more we reduce launch to space costs, closer we get to see a working Space base solar power.

Many obstacles remain on the way before achieving the goal. Huge cost, technology readiness, need of big on ground infrastructure, components manufacturing etc. The main roadblock is the price the households and companies are willing to pay for this green energy, but some say (© Financial Times) it will be in the future 3 to 4 cents the watt, then, less expensive than what we're paying today.

It is a solid project for a green and continuous electricity production. It is also very flexible, and what we look for in our today's life is flexibility. If you have too much energy production, you can point it to another region or sell it to another country. If you need energy for military purposes in a foreign country, you can use the SBSP, instead of trying to bring electricity and fuel to remote lands. Instead of risking life at an already huge cost. Although after natural disasters, if a hospital has no more electricity, for space exploration missions, lunar space station etc. It is for some experts, complementary with what we have on earth today already producing energy.

As the project is a real challenge, it could also bring a lot technologically speaking. For space exploration missions, it is a big step forward, the question of fuelling or refuelling while performing tasks in space or exploring the universe is not an issue anymore. We could introduce here technical specificities which could be used in other domains. Science and medicine for example are closely related, many experiences have been made in space. It has millions of applications and will for sure help us live better and greener on our planet but also anywhere we want to go.

It will be a turning point in space exploitation, energy production and technology achievement. After the industrial revolution at the end of the 18th century, the internet revolution at the end of the last century, it could be the next revolution…

Self-assessment

This experience brought me deep in my thoughts. I asked myself so many questions about how to handle such a wide subject. Will it be real in some years, difficult to imagine but I hope to see it producing electricity one day. It could be a major step to overcome our environmental issues.

Through the readings, the academic articles, interviews, videos, I learned many technical as well as business oriented concepts on a subject which fascinates me. This subject was at the same time wide and very precise, abstract, and concrete, historic and very actual.

At the beginning I thought that I would have some difficulties to find interesting documents on the subject (many academic articles and figures were not up to date as the technology is evolving very fast). But by searching more specifically, I could find many interesting articles which were differing from the main purpose to bring other concepts or other technical ideas (for example an academic article about the security of the systems which was not addressed in most of documents or a precise way of assembling space station on GEO orbit). I have learned a lot thanks to numerous documents that I read and the ideas are not all written in this essay, I had to make choices. These choices were difficult to do. I had to think following my question and what elements would be important or necessary to answer to it while still giving all the aspects for the reader to build its own opinion. As the SBSP is still a non-existing project, only a concept for now, the work to find tangible figures and correct predictions was hard but interesting as I am very curious, passionate buy the subject and analytical in my work. I was always keen to take more information, listen to radio podcasts and speak with people either to have their thoughts on the question or to explain them why it would be a great invention and a huge help for many of our today's issues.

I choose this project because it was close to my values, it has not really been so difficult for me to be entirely invested in this work. Indeed, most of the people of my generation (myself included) feel concerned about environmental issues, and in our domain, we must show that space and aerospace in general are polluting but are bringing a lot more than that. We find new ways of producing, to discover, to connect people, to preserve our world. Yes, it pollutes, yes it has to reinvent itself every day to find new solutions but if we have access to images showing wildfires, typhoons, destruction of rainforest, turtles' migration, Co2 rate in the sea, disasters, it is thanks to space. If we are connected with the entire world today it is thanks to space. It is our everyday life and we do not even know it. I want to place myself as an ambassador of space applications for my generation, to show them that our impact is at the end a lot more positive than negative, that the space applications are infinite and we have much more to discover, to explore and to improve. The Space based solar power is the greatest example of this potential success.

References

Academic article about laser transmission of SBSP: (2020)
https://www.tandfonline.com/doi/full/10.1080/20909977.2020.1815497
Author: Yasser A. Abdel-Hadi.

Airbus article about power beaming to earth: (2022)
https://www.airbus.com/en/newsroom/news/2022-09-solar-power-beams-a-step-towards-cleaner-energy
Authors: Communication team Airbus with Jean-Dominique Coste and Yoann Thueux

Academic article about process-based life cycle sustainability assessment of the space-based solar power concept: (2020)
https://strathprints.strath.ac.uk/74277/
Authors: Wilson, Andrew Ross and Vasile, Massimiliano and Oqab, Haroon B. and Dietrich, George B.

Unclassified document from US Army War College about technical, economic, and operational assessment of a Space-based Solar Power: (2015)
https://apps.dtic.mil/sti/pdfs/ADA616385.pdf
Author: Jeffrey L. Caton

Academic article about the security implications of space-based solar power: (2012)
https://journals.sagepub.com/doi/full/10.1177/0096340211433005
Author: Leet W. Wood

Academic article about in-orbit assembly mission for the Space Solar Power Station: (2016)
https://www.sciencedirect.com/science/article/abs/pii/S0094576516301734
Authors: ZhengAi Cheng, Xinbin Hou, Xinghua Zhang, Lu Zhou, Jifeng Guo, Chunlin Song.

Academic article from the University of Maryland about Space Solar Power: “An Idea Whose Time Will Never Come?” (2004) https://drum.lib.umd.edu/handle/1903/3992
Author: Fetter, Steve

Press article from the site “The Conversation” about the benefits it could bring and how it is working:https://theconversation.com/a-solar-power-station-in-space-heres-how-it-would-work-and-the-benefits-it-could-bring-179344

Press article from the site Greenmatch: https://www.greenmatch.co.uk/blog/2020/02/space-based-solar-power

Internet site about the potential efficiency of a SBSP for UK: https://spaceenergyinitiative.org.uk/uk-to-launch-first-power-station-in-space-limitless-green-energy-to-slash-foreign-ties/

Press article about Chinese SBSP project from a British point of view: (2022)
https://news.sky.com/story/china-brings-forward-launch-of-solar-power-plant-space-station-that-would-beam-energy-back-to-earth-12629255

Press article about the Chinese Space station from an American point of view: (2019) https://www.cnbc.com/2019/03/15/china-plans-a-solar-power-play-in-space-that-nasa-abandoned-long-ago.html

Academic technical article about the thermal design, analysis and comparison of three concepts of space solar power satellite: (2017) https://www.sciencedirect.com/science/article/abs/pii/S0094576516310013
Authors : Chen Yang et al.

Academic technical article about a new design project for space solar power station: (2015) https://www.sciencedirect.com/science/article/abs/pii/S0094576515300680
Authors: Yang Yang et al.

Press article from the Sydney Morning Herald about Chinese space station: (2019) https://www.smh.com.au/world/asia/plans-for-first-chinese-solar-power-station-in-space-revealed-20190214-p50xtg.html

Book "The Case for Space Solar Power"; Author: John Mankins (Virginia Edition Publishing, 2014)

Financial Times video on SBSP (2021) https://www.youtube.com/watch?v=oBlOb2z26Do

Article about different projects launched by countries about SBSP: (2013) https://www.acteurdurable.org/energie-solaire-spatiale-avec-ferme-solaire-en-orbite/

Article about history of SBSP: (undated) https://www.ecosources.org/centrale-solaire-spatiale

Academic article about Space solar power satellite for the Moon and Mars mission to show other applications than Earth ground: (2022) https://www.sciencedirect.com/science/article/abs/pii/S2468896721001026
Authors: Aditya Baraskar et al.

Article about the American project of testing different technologies in earth orbit: (2021) https://www.space.com/x-37b-space-plane-solar-power-beaming
Author Leonard David

Article about donations given to the California institute of technology dedicated to the SBSP: (2021) https://www.caltech.edu/about/news/caltech-announces-breakthrough-100-million-gift-to-fund-space-based-solar-power-project

Article about billionaires donations for Caltech to fund SBSP: (2021) https://spectrum.ieee.org/solar-power-from-space-caltechs-100-million-gambit

Podcast of Rémy André SudRadio, Tuesday 11th October about SBSP and power beaming trials from Emeraude company.

Academic article about space base solar power written in 1992, with the key issues and challenges of that time: (1992) https://ieeexplore.ieee.org/abstract/document/141356
Author: Arthur D. Little

Academic article about Flexible Solar Cell Arrays for Increased Space Power, comparing it with newer documents, showing well evolution of the technology of solar cells power between the 60's and nowadays: (1967) https://ieeexplore.ieee.org/abstract/document/5408720/authors
Author: Kenneth A. Ray

Academic article about space energy, utilization, development, exploitation and how to use SBSP for space missions: (2021) https://www.sciencedirect.com/science/article/abs/pii/S0306261921003810
Authors: Tao Zhang et al.

About the author

My name is Arthur MADELINE, I am a French student of 23 years studying at the master's in aerospace management at Toulouse Business School. This master in quite wide and oriented toward the aviation and space businesses.

I have always been passionate by aviation, space, and defence sectors and this master was a great opportunity for me to learn and strengthen my skills in the domain I would like to work in. Indeed, I was born in Montpellier, and I moved to Toulouse to be able to learn and work in aviation. I had the chance to perform my Bachelor at Toulouse Business School and choose the specialisation in Aviation management for the third year at ENAC (French civil aviation school).

I also had the opportunity to learn in internships in this sector.

My first experience was an internship as community manager at Thales Alenia Space in 2019 where I learnt how to perform benchmarking, articles writing and seen how a major space actor was communicating, internally and externally. I had the opportunity and the autonomy to post on social media, to help in organizing events or trade shows, but also relations with the press. This experience brought me lot of confidence, I could work in cross cultural teams, be autonomous in my work and post on social networks by myself due to the confidence granted by my tutor.

My second working experience was at Safran in Paris in 2020. I was not in any way close to the final product, but I was accompanying associations which could became financed by the Safran foundation. I was in charge of helping the associations preparing their application dossier and explaining their goals and actions for the company council.

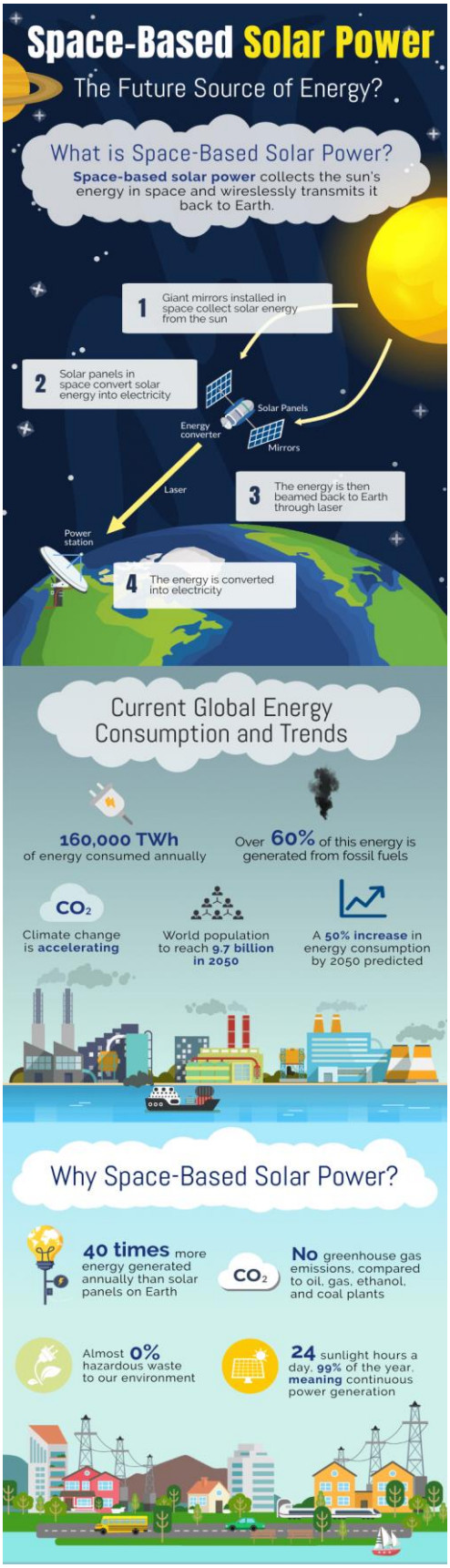
This subject speaks a lot to me because I am the Vice-President of an association which supports children and families facing children suffering from serious illnesses such as cancers. In the goal to help them as well as the research, we organize events in order to collect funds.

I am also an active volunteer at the French red cross, working either as paramedic for events or disasters and as group leader for social actions (meeting homeless people in the streets of Toulouse at night in order to help them, talk with them, give them food and orient them toward right associations following their case).

From April of 2022, I am in internship at Airbus Defence & Space at the quality department. I belong to two different teams. One more related to projects and process modelisation and the Business management system (tool where all the internal and not technical documents of the company are stored). The other team is more related to technical quality, performing risk analysis (I was in charge of the risk analysis improvement for the ground support equipment for space applications).

In the future of my professional life, I would like to work in strategy for major aviation or space companies. I have the different skills in rigor, curiosity, and analysis but I still need to improve them. To reach my goals, I will have to gain experience in different strategic domains to be able to have a global overview of the sector, the market and different stakeholders. It is by building experience in this domain that I would feel legitimate to access to Strategy jobs.

Appendices



Appendix 4: Plan of the SBSP, its applications and its characteristics

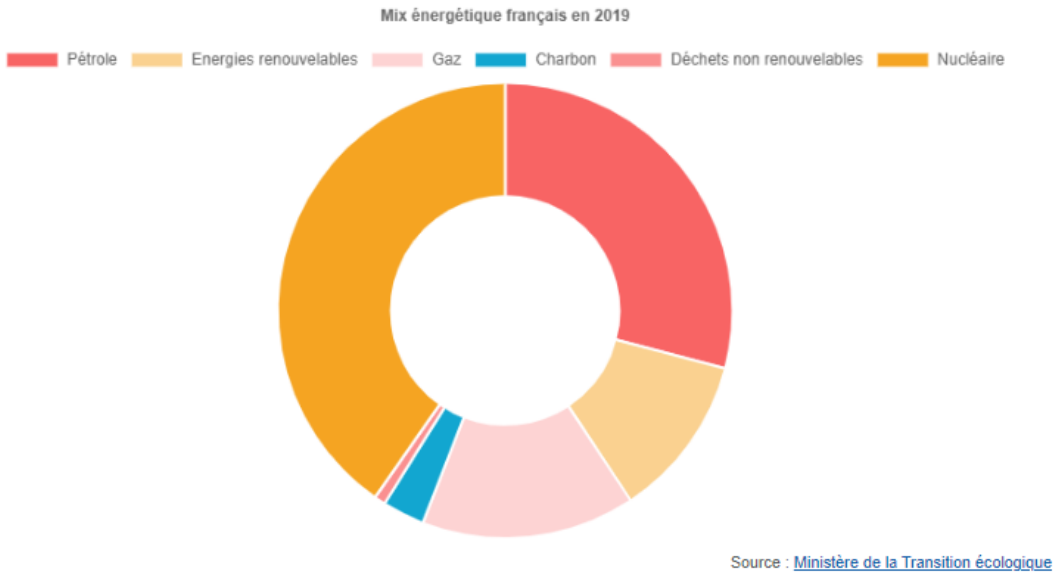


Figure 5: Energy mix France 2019

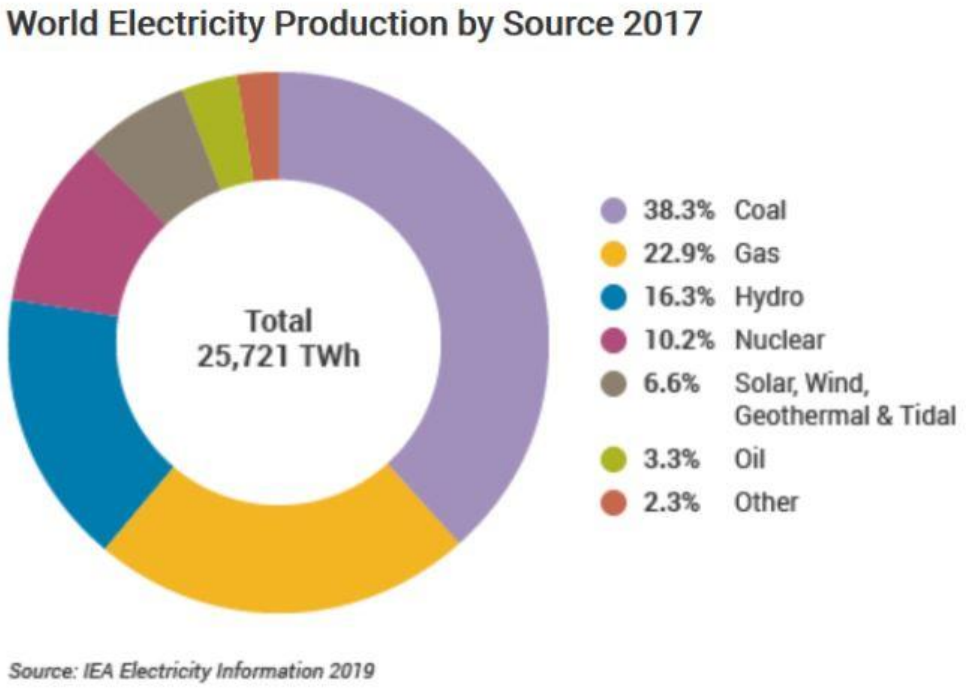


Figure 6: World electricity production 2017

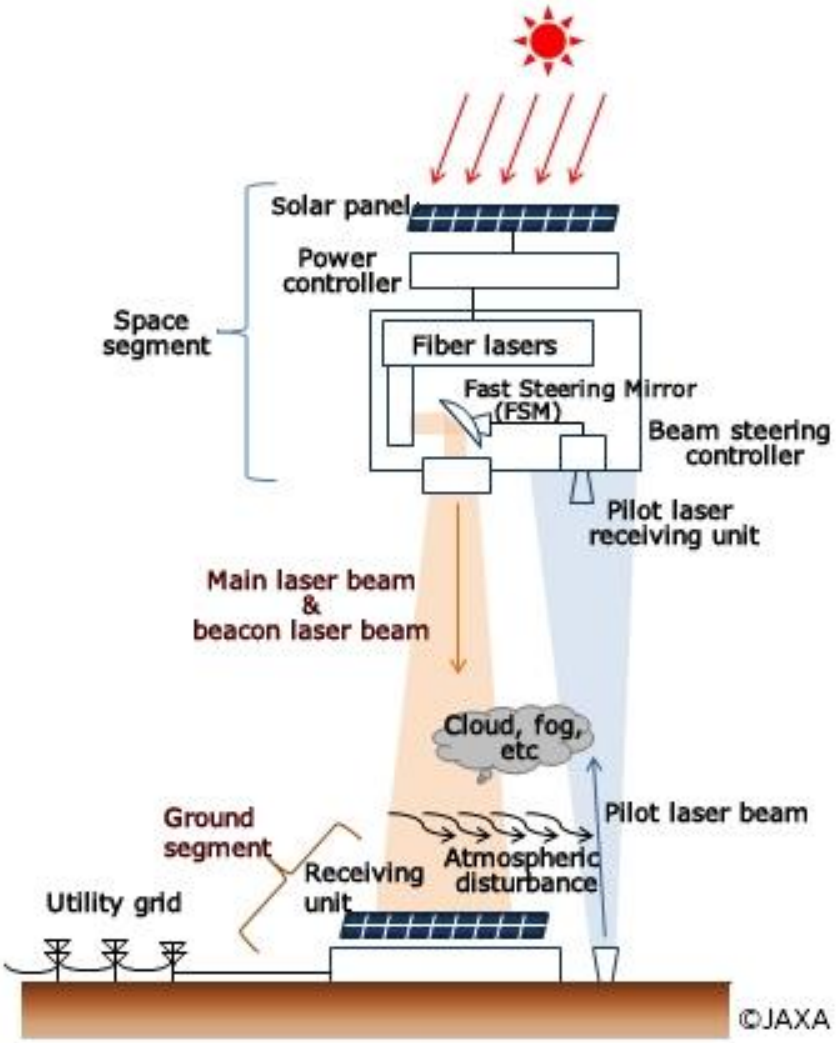


Figure 7: How a SBSP is working by the Japanese Space Agency

Source d'énergie	Énergie	Émissions de CO2 (kgCO2e/kWh)
Énergie nucléaire 	Électricité (centrale nucléaire)	0,006
Énergie renouvelable 	Électricité (centrale hydraulique)	0,006
	Électricité (éolien terrestre)	0,0141
	Électricité (éolien en mer)	0,0156
	Bioéthanol	0,144
	Biométhane	0,0163
	Bois granulé	0,027
	Bois bûches	0,032
	Électricité (photovoltaïque)	0,0439
	Électricité (géothermie)	0,045
Énergie fossile 	Gaz naturel	0,243
	Propane	0,27
	Butane	0,273
	Fioul domestique	0,314
	Électricité (centrale gaz)	0,418
	Électricité (centrale fioul)	0,73
	Électricité (centrale charbon)	1,06

Source : Base Carbone de l'ADEME (Agence de la Transition écologique)

Figure 8: Energy sources classification from the less polluting to the most polluting