Switzerland: An Astrostrom Startup Nation?

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2.5 Space-Based Solar Power, Powering Civilian Space Development
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ABSTRACT

By ratifying the Paris Agreement on Climate Change, Switzerland has committed to become CO2 neutral by the year 2050. The 2011 Fukushima reactor disaster has pushed the Swiss government to progressively retreat from nuclear power. These two simultaneous goals will bring the country to face an Energy Dilemma which is described in the first part of this paper. To meet its 2050 goals, several energy reduction measures and policies are being implemented as well as increasing support for inland renewable energy production. An analysis of Switzerland's current energy options shows that, regardless of such measures, available renewable energy options such as hydroelectric, wind and solar photovoltaic, while useful and necessary, cannot be sufficiently scaled to replace both nuclear power and carbon fossil fuel energy sources by the year 2050. This will result in major economic and societal consequences for the country if sufficient clean energy resources cannot be secured. The second part of the paper introduces the Space Energy Option - the concept of harvesting energy in space -- Astrostrom -- to address Switzerland's energy dilemma. To demonstrate its economic feasibility, a cost comparison between a Solar Power Satellite (SPS) and a nuclear power station of comparable capacity was made using a simple Levelized Cost of Electricity (LCOE) calculation by making a comparison of the Engineering, Procurement and Construction (EPC) costs of both systems. Then the price per kWh delivered by SPS is compared with the current price of solar power in Switzerland to determine a profitability scenario. The analysis indicates that Switzerland could not only provide sufficient CO2 neutral energy to meet its 2050 policy goals, but potentially could also achieve energy independence that is both sustainable and profitable.

Energy Measurements

A gigawatt (GW) is a unit of power equal to one billion watts. A terawatt (TW) is a unit of power equal to one trillion watts. A gigawatt hour (GWh) is a measure of energy. One GWh is the electrical energy consumption rate equivalent to a billion watts consumed in one hour. One TWh is the electrical energy consumption rate equivalent to a trillion watts consumed in one hour. One GWh is equivalent to 3,600 gigajoules = 3.6 terajoules (TJ). One GWh = 3,600,000,000,000 Joules. One TWh is equivalent to 3,600 terajoules = 3.6 Petajoules (PJ). One TWh = 3,600,000,000,000,000 Joules.

PAPER

1 Part 1: The Swiss Energy Dilemma

To meet its obligations to the Paris Agreement on Climate Change, in 2019 the Federal Council resolved that, as of 2050, Switzerland is to reduce its net greenhouse gas emissions to zero. In the wake of the Fukushima reactor disaster in 2011, the Swiss Federal Council and Parliament decided that Switzerland is to withdraw from the use of nuclear energy. [1]

The Swiss government estimates that Switzerland's population will increase by approximately 20% from its current 8.5 million to about 10 million by the year 2050. [2] Without massive changes to society and infrastructure, one could assume that energy consumption would also increase by at least 20% in this period rising from 27 GW to 33 GW [a]. In terms of energy, a 20% increase would translate into 289 TWh to be provided each year

[a] 33 GW * 24 * 365 ÷ 1,000 = 289 TWh

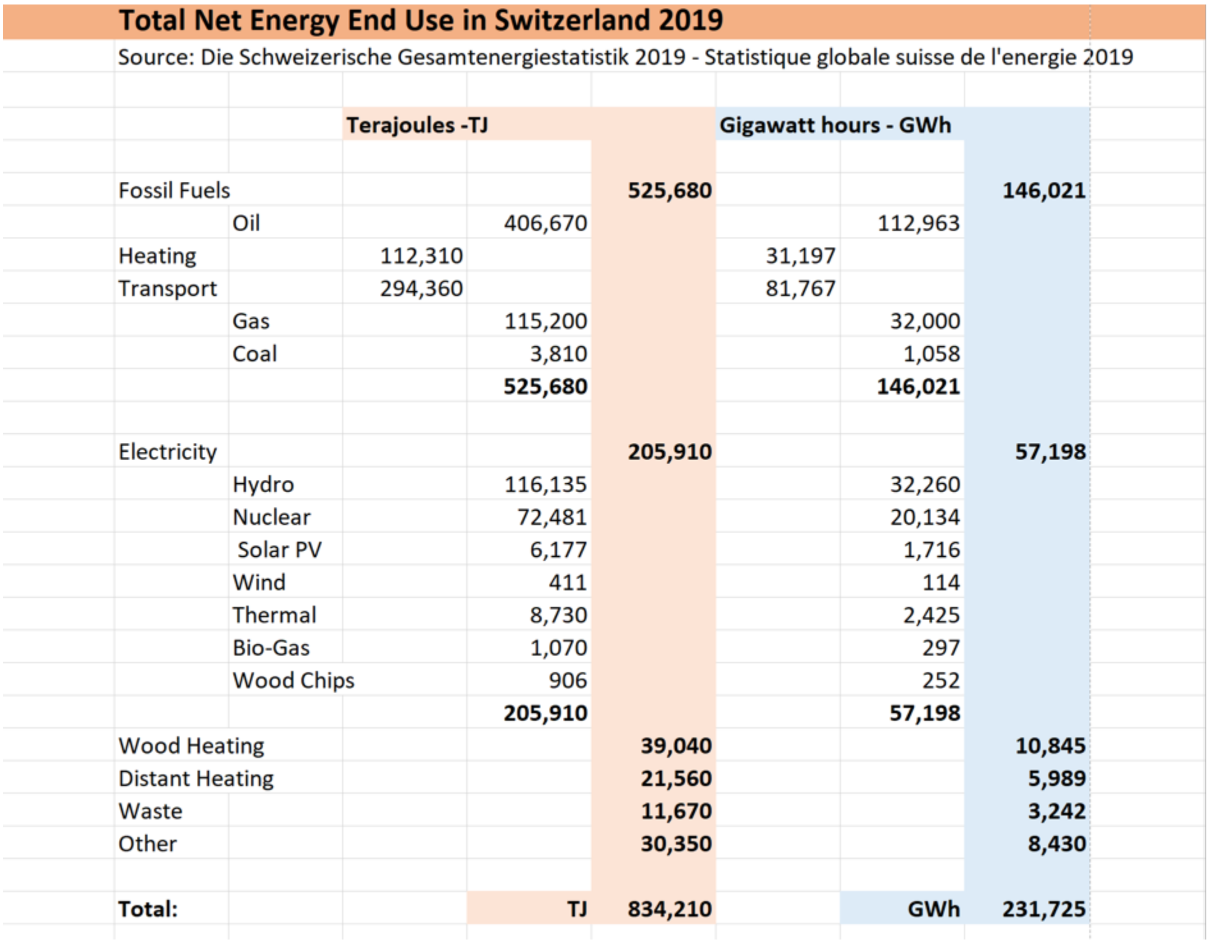
The Swiss government's approach is to improve energy efficiency by about 20% through construction measures such as better house insulation and to forbid future installations of oil and gas heating. This will be in addition to implementing regulation policies on energy use and carbon fossil fuels to reduce CO_2 emissions. Other policies are being set to reduce per capita energy consumption by 16% in 2020, 43% by 2035 [3] and to reduce average per capita electricity consumption by 13% in 2035. With a projected 20% increase in population with a corresponding amount of energy consumption, the policies resulting in a 20% reduction in overall energy use are approximately self-cancelling. Therefore, this analysis uses current energy consumption data from 2019 for arriving at a plausible energy demand estimate for the year 2050.

Based on information published by the Swiss government (Schweizerische Gesamtenergie-Statistik 2019 – Swiss Total Energy Statistics 2019 - Fig. 1) states that in 2019 total net end-use energy consumption was 834,210 TJ which, when converted to gigawatt hours, equals 231,725 GWh [a] or 26.5 GW [b]. Using the energy data from 2019, this analysis assumes that Switzerland would require a minimum of 27 GW of electrical generation capacity operating 24/7 to cover all its energy uses, which corresponds to an annual production of at least 236,520 GWh or 237 TWh. [4]

[a] 834,210,000 ÷ 3,600 = 231,725
[b] 231,725 ÷ 8,760 = 26.45

Of the 26.5 GW of energy consumed in 2019, 14% came from hydroelectricity, 8.7% from nuclear power, 63% from carbon fossil fuels (oil, natural gas, coal) and 14.3% from renewables (wind, solar, wood, waste, biogas) (Fig. 2). Therefore approximately 72% of Switzerland's energy consumption must be replaced by a non-fossil-fueled technological solution. This means approximately 19 GW [a] of energy providing 166,842 GWh [b] or about 167 TWh of power will need to be replaced. As shown in this analysis, optimistic increases in local energy production from hydroelectricity, wind and solar (PV) can only supply up to 91 TWh by year 2050.

[a] 26.5 GW * 0.72 = 19 GW
[b] 231,725 GWh * 0.72 = 166,842 GWh



Total Net Energy End Use in Switzerland 2019

Source: Die Schweizerische Gesamtenergiestatistik 2019 - Statistique globale suisse de l'energie 2019

		Terajoules -TJ			Gigawatt hours - GWh		
Fossil Fuels				**525,680**			**146,021**
	Oil		406,670			112,963	
Heating		112,310			31,197		
Transport		294,360			81,767		
	Gas		115,200			32,000	
	Coal		3,810			1,058	
			525,680			**146,021**	
Electricity				**205,910**			**57,198**
	Hydro		116,135			32,260	
	Nuclear		72,481			20,134	
	Solar PV		6,177			1,716	
	Wind		411			114	
	Thermal		8,730			2,425	
	Bio-Gas		1,070			297	
	Wood Chips		906			252	
			205,910			**57,198**	
Wood Heating				**39,040**			**10,845**
Distant Heating				**21,560**			**5,989**
Waste				**11,670**			**3,242**
Other				**30,350**			**8,430**
Total:			**TJ**	**834,210**		**GWh**	**231,725**

Figure 1. Total Net Energy Use in Switzerland 2019

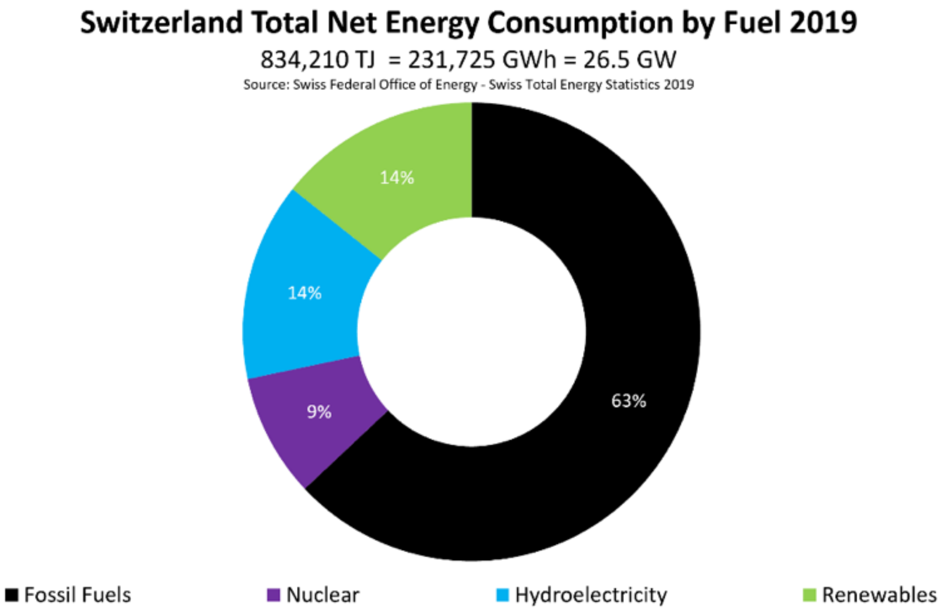


Figure 2. Switzerland's Energy Consumption by percentage.

1.1 Swiss Nuclear Power is Being Phased Out

In 2013, Switzerland's nuclear reactors with a combined capacity of 3.23 GW produced 24.8 TWh of electricity, down 5.8% from 2007, when 26.4 TWh was produced. With the closing of the nuclear power plant Mühleberg in December 2019 current nuclear power capacity in Switzerland is now only 2.87 GW. In 2019 nuclear power represented 9% of Switzerland's total energy consumption by producing approximately 20,134 GWh or 20.1 TWh.

- Beznau 1 & 2: 365 MW each = 730 MW (0.73 GW)
- Gösgen: 970 MW (0.97 GW)
- Leibstadt: 1,165 MW (1.17 GW)
- *Mühleberg: 355 MW (0.36 GW) (decommissioned 2020)*

For reference, the Swiss nuclear power plant Gösgen has a nominal capacity of almost 1-GW [a] which is a typical size for many nuclear reactors. It has an operable availability of 90% which means the reactor is off-line 10% of the time for maintenance or refueling. Thus, a typical 1-GW nuclear power plant can produce 7,884 GWh [b] or 7.9 TWh of electrical energy when operating 90% of the time. Gösgen's power production potential is a bit less at 7,647 GWh [c].

[a] 970 MW = 0.97 GW
[b] 1 GW * 0.9 * 8,760 =7,884 GWh
[c] 7,884 * 0.97 = 7,647.5 GWh

According to the Swiss government's "Energy Strategy 2050", [6] nuclear power will be phased out. No new nuclear plants will be built. Existing plants will operate until they are deemed unsafe to continue. Thus, with a 90% availability Swiss nuclear power capacity which now could provide 22.6 TWh (2.87 * 8,760 * 0.9 = 22,627 GWh = 22.6 TWh) will be steadily reduced as the remaining nuclear power plants are shut down.

1.2 Hydroelectric Power in Switzerland

Currently hydroelectricity is Switzerland's most import source of renewable energy representing 14% of its total energy consumption. It provides 56% of the 60 TWh of electricity consumed in Switzerland yearly. As of December 31, 2019, there were 674 hydropower plants in Switzerland with a capacity of at least 300 kilowatts and which produce a combined average of around 36,567 GWh per annum. According to the 2019 Swiss energy statistics this amount was 32,260 GWh. Hydroelectric power production cannot be significantly scaled above current levels and Switzerland's Energy Strategy 2050 expects this to grow to 38,600 GWh by 2050.[7]

1.3 Wind Power in Switzerland

Switzerland is not particularly suitable for wind power. In 2019, a total of 37 wind power plants produced around 114 GWh of electricity.[8] Suisse Eole, the organization for wind energy in Switzerland predicts that wind energy could provide up to 4,300 GWh by the year 2050.

1.4 Solar Power in Switzerland

As much emphasis is being placed on solar energy production to meet Switzerland's goals, it is necessary to understand how photovoltaic (PV) solar power is calculated and how it is being implemented in Switzerland.

A. Calculating Solar Power in Switzerland

365 days * 24 hours = 8,760 hours in one year

The radiation of the Sun (solar irradiance) perpendicular to an area of 1 m^2 is about 1 kW on the Earth's surface on a sunny day, with the Sun at noon, at the equator.[9] Multiplied by the hours in one year, theoretically this 1 m^2 would produce 8,760 kWh of energy in one year.

$1\ kW/m^2 * (24\ h/day) = (24\ kWh/m^2)/day$
$(24kWh/m^2)/day * (365\ days/year) = (8{,}760\ kWh/m^2)/year.$

Photovoltaic cells directly convert solar irradiance into direct-current (DC) electricity. A converter is used to convert DC into alternate current (AC) before grid feed-in. In Switzerland, small-scale, roof-top PV installations are most common. About half of the installed capacity is in units below 100 kW, about half in units above 100 kW. In terms of numbers of installations, more than half of the units are installed on single-family houses. However, in terms of installed capacity, PV units on industrial and agricultural buildings are more important. Fig. 3. shows the yearly solar irradiance in the regions of Switzerland. The average yearly irradiance in the Swiss plateau (Mittelland) is 1100 kWh/m^2.[10]

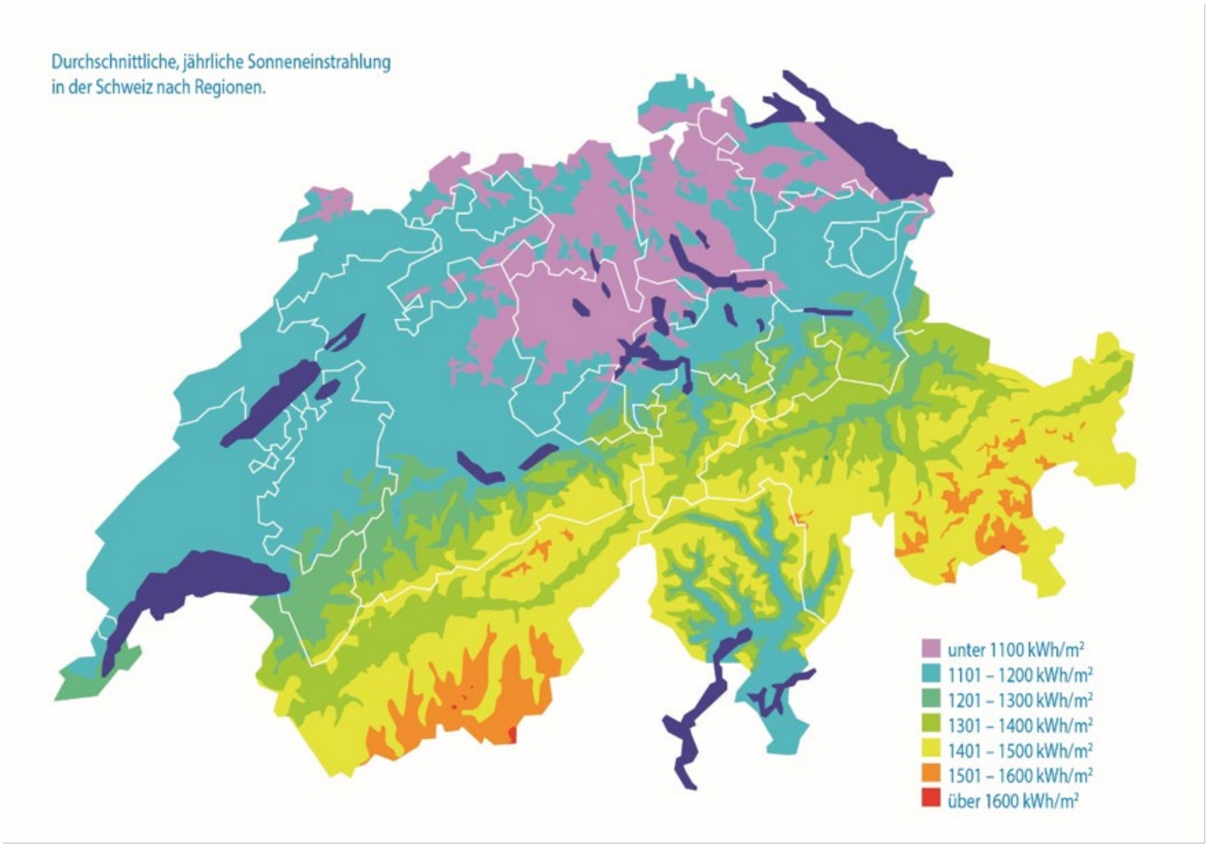


Figure. 3. Solar Irradiance in Switzerland (Graphic credit: Swisssolar)

The efficiency of solar photovoltaic cells to convert sunlight into energy is between 10% to 25%. The efficiency factor of solar power has to do with the quality of the photovoltaic system used and with the geographical location. The geographical latitude of Switzerland is about 470 N.

The actual efficiency of PV in Switzerland is about 13%. Thus, 1,100 kWh per year * 0.13 (efficiency) = **143 kWh per year** is produced from a single 1 m^2 solar PV panel in the Swiss plateau.

(100 watts per hour * 13% (efficiency) = 13 watts per hour)

B. Swisssolar – the Swiss Solar energy Professionals Association

Swisssolar published actual data in an article on 14. July 2020: [11] “2.5 gigawatts of installed solar power – yet we need 20 times more” (“2.5 Gigawatt installierte Solarleistung – wir brauchen 20-mal mehr”). They also published a Factsheet.[12] This information was based on a study completed with the Swiss Federal Office of Energy SFOE (Bundesamt für Energie - BFE) published on July 10, 2020 “Markterhebung Sonnenenergie 2019” [13] They report that the 2.5 GW of solar photovoltaic capacity currently installed provides 2,400 GWh of electrical power. They propose to increase this by 20 times by the year 2050 to 50 GW which would provide 48,000 GWh or 48 TWh.

The following information was contained in their Factsheet:

Newly installed solar power in 2019	350 Megawatt (MW)
Newly installed PV modules	2,000,000 m^2
2019 solar PV production	2,400 Gigawatt hours (GWh)
Total surface area used to date	19,000,000 m^2
Percentage of electrical use	4%
Average cost of solar power	CHF 0.12/kWh

From this information the following useful data can be extracted:

In Switzerland, 1-GW of installed solar power provides 960 GWh of electrical power.

(2,400 GWh ÷ 2.5 GW = 960)

2,400 GWh represents 4% of Switzerland's electrical energy use

60 TWh (2,400 GWh ÷ 1,000 ÷ 0.04 = 60) is approximately the amount of electricity that is currently consumed in Switzerland. This amount only represents about one-fourth of Switzerland's total energy consumption which, using this figure, total energy consumption would be approximately 240 TWh. This figure reflects the net amount of energy consumed in 2019 as reported by the Swiss government mentioned above which was 231,725 GWh or 232 TWh.[14] 60 TWh is confirmed by WorldData.info which cites that Switzerland's current electrical energy consumption is indeed 58.46 TWh which is 6.67 GW).[15]

(58.46 * 1000 ÷ 8,760 = 6.67)

As 2.5 GW of solar PV uses 19 km^2 of surface area, 1 GW of installed PV requires 7.6 km^2 . This means that 50 GW of solar power would require approximately 380 km^2.

Actual PV efficiency factor = 12.63 %
(2,400,000 Wh ÷ 19,000,000 m^2 = 0.1263) (19 million m^2 * 0.1263 = 2,399.7 GWh)

2,400 GWh represents the yearly energy use of 600,000 Swiss homes @ 4,000 kWh each

25-30 m^2 of solar PV are needed to produce 4,000 kWh
(30 * 143 kWh = 4,290 kWh)

Homeowners in Switzerland can use an online calculator offered by the Swiss Federal Office of Energy (SFOE) to calculate the solar energy generation potential of their house. This website states that the average four-person household in Switzerland consumes 3,500 kWh per year and the expected electricity yield would be valued at CHF 0.10/kWh.[16]

1.5 Energy Overview for Switzerland in TWh

Estimated Energy Needed in 2050:	**237 TWh**
Current Fossil Fuels & Nuclear Power:	**169 TWh** (146 TWh + 23 TWh)
Currently Installed Nuclear Power:	*23 TWh (22,627 GWh - to be phased out)*
Combined Conventional Energy Sources:	**32 TWh** (31,523 GWh)

Potential Hydroelectric Power in 2050: **38.6 TWh** (38,600 GWh)

Potential Wind Power in 2050: **4.3 TWh** (4,300 GWh)

Potential Solar Power in 2050: **48 TWh** (48,000 GWh)

Potential Renewable Power for 2050: **91 TWh** (90,900 GWh)

Total Energy all Sources for 2050: **123 TWh** (32 TWh + 91 TWh)

Additional Energy Needed in 2050: **114 TWh**
(237 TWh - 123 TWh = 114 TWh)

Estimated total capacity needed 24/7 for Switzerland in 2050: **27 GW providing 237 TWh**

Capacity needed to replace fossil fuels and nuclear energy in 2050: **13 GW providing 114 TWh**
(13 GW * 8,670 = 113,800 GWh)

It is important to note that the risk of climate change may negatively impact the performance of terrestrial solar power in the form of increased cloudiness in a warmer scenario or more snowy conditions in a cooler scenario.

1.6 Switzerland's Energy Options are Limited

Nuclear power is obviously not an option because Swiss policy has mandated that current nuclear power plants will not be replaced once these plants reach their end of operational life - although replacing the existing plants on their current locations would probably make energy and economic sense. However, there would not be enough suitable locations providing sufficient cooling for additional nuclear plants even if these could be built. Wind and hydroelectricity cannot be significantly scaled beyond present estimates.

Swisssolar reports that the worldwide installation of solar power capacity was 630 GW which would only be the equivalent of 95 nuclear power stations similar in size to Gösgen (.97 GW).[17] Based on a worldwide average, this indicates that the 6.63 solar power (PV) plants would be required to equal the energy of one 1-GW nuclear power plant. Due to its less favorable geographic location, 8 solar power (PV) plants would be needed in Switzerland.

[a] 8.0 * 960 hours = 7,680 GWh. Compared to Gösgen = 7,647.5 GWh.
(7,884 * .97 = 7,647.5)

To put this in perspective and to have a better picture of Switzerland's energy dilemma, it would take the equivalent of 15 nuclear power plants the size of Gösgen (0.97 GW) to provide the needed **114 TWh** [a] of electrical power to meet Switzerland's 2050 energy requirements and its mandates to replace both nuclear power and carbon fossil fuels. Yet, the only apparent clean energy option is solar photovoltaic power which is only projected to expand to 50 GW providing just 48 TWh by the year 2050.

[a] (15 * 7,647.5 = 114,712 GWh)

Therefore, to achieve the equivalent of energy production with solar power would require 119 GW of installed solar capacity [a] in addition to the 50 GW already planned for 2050, i.e., **169 GW** of installed solar PV in total. However, this amount of produced energy would only be useful if it could be stored and utilized efficiently which is currently not the case, although additional pumped-storage hydroelectricity is under consideration.

[a] (114,000 ÷ 960 GWh = 118.7 GW)

As the Swisssolar factsheet shows, 2.5 GW of installed capacity requires 19 km^2 of surface area indicating that 1-GW of solar PV requires 7.6 km^2 of surface area. Thus, 169 GW (119+50) of installed solar power capacity would require approximately **1,284 km^2** of surface area or about 3% of the total surface area of Switzerland. At CHF 30,000 each, 1 million rooftop PV installations would cost about **CHF 30 billion**.

Concerning the cost of energy dependence, according to the Swiss PlusEnergieBau (PEB)-Studie, over the past 25 years Switzerland spent over 177 billion Swiss francs for the importation of energy from other countries. [18],[19] This means that Switzerland could hypothetically invest **7 billion Swiss francs per year** in an energy independence program over the next 25 years, less the amounts of energy imports remaining as alternative capacity is created.

The current price of electricity in Switzerland is 0.207 Swiss Franc (CHF) per kWh for households and CHF 0.157 for businesses and this includes all components of the electricity bill such as the cost of power, electricity distribution and taxes. [20] Using the average amount of CHF 0.182 per kWh multiplied by the 2019 consumption of electricity 58.64 TWh gives the electrical energy market value of CHF 10,369,720,000, or **CHF 10.4 billion.** Applying this formula to all energy consumed Switzerland in 2019 which was 231,725,000,000 kWh (231,725 GWh) indicates the approximate value of the Swiss energy market which is CHF 42,173,950,000 or **CHF 42.2 billion.** These financial estimates are relevant when considering Switzerland's future energy options.

1.7 Energy Perspectives 2050+

In November 2020, the Swiss Federal Office of Energy released an update on its 2050 energy strategy called *Energy Perspectives 2050+* dedicated to its long-term target of Switzerland becoming net-zero CO_2 by the year 2050. The report anticipates the population of Switzerland will increase to 10.3 million and the gross domestic product (GDP) will increase by around 38% by 2050. Passenger traffic will increase by 17% and freight traffic by 31%. The number of electrified vehicles will increase to 3.6 million.

Despite these increases, domestic energy consumption (excluding air traffic) will decrease by 31% from the current 783,000 TJ (220 TWh) to 524,000 TJ (146 TWh). New renewable energies will provide 39 TWh (Photovoltaics 33.6 TWh, Wind 4 TWh) or 46% of the gross electricity generation and hydropower will increase to 45 TWh or 53% - an increase of 10% compared to today's production. This indicates that gross electricity generation will increase by 33% to 84 TWh. The report does not anticipate any new technologies appearing that will change the situation.

Much emphasis is placed on the development of pumped-storage hydropower plants to store excess summer PV production for later use in winter. Electricity is used to pump water up to a mountain reservoir where it is stored until needed and then released to generate electricity on demand.[21] Only 75-85% of the original energy can be recovered using this storage technology. In 2019, hydropower plants in Switzerland had a combined average capacity of 4.2 GW of which 48.5% was produced in run-of-river power plants, 47.2% in storage power plants and approximately 4.3% in pumped-storage power plants: i.e., about 0.1 GW. [22]

1.8 Summary: Switzerland's Energy Dilemma

To replace fossil fuels and to divest completely from nuclear power by 2050 and to meet its policy goals and energy requirements, Switzerland will need approximately 27 GW of electrical generating capacity operating 24/7 providing 237 TWh of CO_2 neutral energy. In addition to 32 TWh of conventional non-fossil fuel energy production (thermal, waste, biogas, wood heating) that will remain in place, 91 TWh could conceivably be supplied by optimal increases in hydroelectric, wind and solar PV. Taken together these energy resources can optimistically produce about 123 TWh which is only about **52% of the 237 TWh of the energy needed yearly** in 2050 which would still leave ***a deficit of 114 TWh*** that must be covered by a reliable CO_2 neutral energy alternative operating 24/7. Even in Switzerland's ambitious Energy Perspectives 2050+ plan which relies on massive reduction of energy use, there still remains a deficit of 30 TWh.

(146 TWh – 116 TWh (84 TWh renewables and 32 TWh conventional) = 30 TWh)

The only terrestrial solution would appear to be solar photovoltaics with 2.5 GW of capacity currently in operation and with 50 GW of installed PV capacity projected for 2050. This analysis has shown that an additional 119 GW of installed solar power capacity would be required to provide the 114 TWh needed and combined with the anticipated 50 GW of solar PV that is planned, this would require more than 1,284 km^2 of surface area - *if this electricity could be stored and distributed efficiently which is currently not the case.*

Based on actual Swisssolar data 2.5 GW of the currently installed solar power (PV) provides 2,400 GWh whereas, 2.87 GW of currently operational nuclear power would provide 22,627 GWh of electricity – almost 10 times as much.

2 Part Two: A Space Energy Option for Switzerland

Fortunately, there is *Space Energy Option* to address Switzerland's energy dilemma. Generally referred to as Space Solar Power (SSP), Space-Based Solar Power (SBSP) and more recently as *Astroelectricity* by Michael Snead in his book with the same name.[23] *ASTROSTROM* is the German translation and the term used in this analysis.

For some, this option may sound like pure science fiction, for the energy and financial experts it is rejected as being both economically unfeasible and technically, too challenging. The hard-core environmentalists and green techno-politicians may not want to consider this option as it would be major competition for their renewable energy agenda relying only on terrestrial sources. As pointed out in the analysis of the *Energy Dilemma*, Switzerland does not have a scalable and feasible terrestrial energy alternative. Therefore, the *Space Energy Option* should be looked at in more detail.

2.1 Energy from Space

The idea of harnessing energy in space originated with the Russian and Soviet rocket scientist and astronautical pioneer Konstantin Eduardovich Tsiolkovsky in 1926.[24] In 1941, science fiction writer Isaac Asimov published the short story “Reason”, in which a space station transmits energy collected from the sun to various planets using microwave beams. [25] However, the technical concept of delivering clean solar energy from space in the form of a Solar Power Satellite (SPS) was introduced by Peter Glaser in 1968 which he patented in 1973.[26]

The basic concept consists of an exceptionally large satellite with photovoltaics in Earth orbit which would capture solar energy and convert it into electrical power and use wireless power transmission (WPT) to send this energy to a ground station on Earth via a microwave or laser beam where it would be captured by a large receiving or rectifying antenna called a rectenna. This rectenna converts the energy into AC electrical current that is then fed into the existing electrical grid. Solar photovoltaics installed in space are not affected by the atmosphere, clouds, water, dust, snow, or sand as are PVs installed on Earth.

Furthermore, they are illuminated by the Sun in Geostationary Earth orbit (GEO) 99.94% of the time - 8,755 hours/year. Sunlight in space has an energy density of roughly 1,350 W/m^2, whereas sunlight at midday near the equator on Earth has an energy density of roughly 1,000 W/m^2. Converting sunlight into electrical power, then converting this into electromagnetic waves, beaming this to Earth and then converting the beam into electricity has an end-to-end efficiency of approximately 80%.

Roughly 5 GW of raw sunlight yields about 1.25 GW of baseload electrical power transmitted to the rectenna which then outputs 1 GW of electrical power. At local midnight near the spring and fall equinoxes, a GEO space solar power platform will enter the Earth’s shadow and temporarily stop collecting sunlight. This lasts for about one hour. Backup gas driven generators or pump-storage hydro-power must provide electricity during this period. The total period of outage will be about 0.5% of the year, yielding a capacity factor of about 99.5% compared to 90% for a typical nuclear power plant and 13% for solar PV in Switzerland. All the technological components of this concept already exist and have been tested and verified – although not yet in space at the scale and distances necessary.

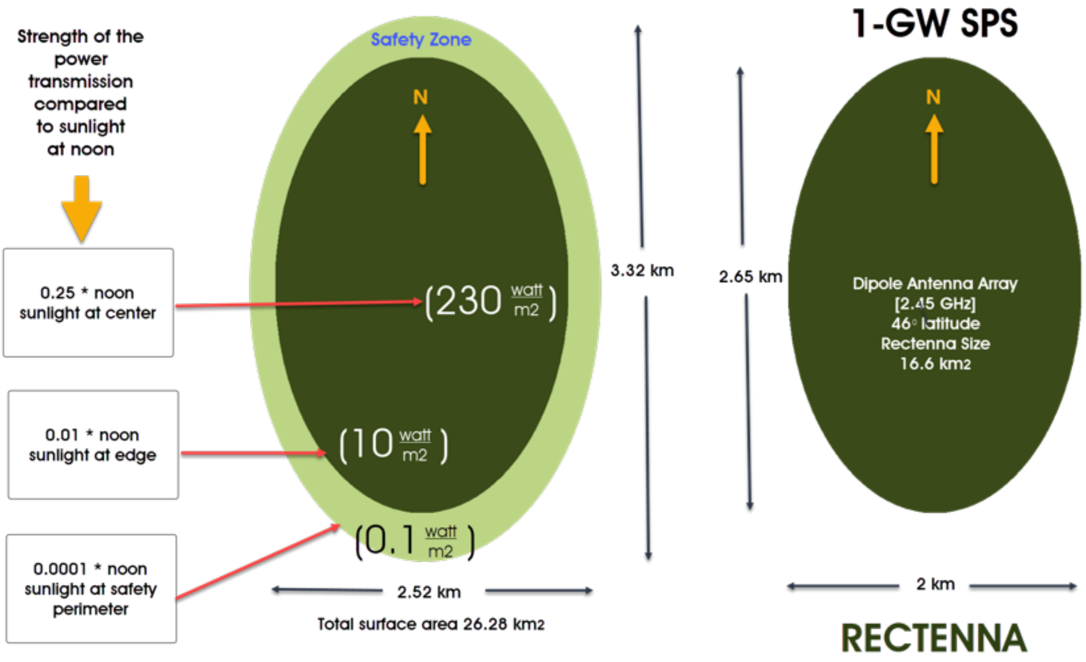


Figure 1. Rectenna for a 1-GW SPS

In its simplest form, the rectenna would be made up of a wire-mesh back-screen, mounted perpendicular to the beam with antenna elements mounted at regular intervals in front. There are many ways that these elements could be designed, but typical would be small half-wave dipoles mounted a few centimeters apart with a rectifying diode for each element. The dipoles receive the radio-frequency energy, and the rectifying diodes convert the radio energy directly to electricity. The rectenna will intercept more than 99% of the microwave energy and convert it directly to electricity using diodes, while allowing most of the sunlight to pass through. As a result, it would be possible to use the land underneath the rectenna for agriculture or even for ground-based photovoltaics.[27] For a 1-GW SPS the estimated size of the rectenna would be approximately 16.6 km^2 or 26.5 km^2 when including a safety zone around the perimeter. (Fig.1).

The Swiss Alps cover 60% of Switzerland's total 41,285 km^2 and are situated south of the Swiss Plateau. As such, the rectenna could be fixed on a south facing slope of a mountain in an unpopulated region (Fig. 5). The many years of engineering experience acquired for the construction of ski lifts and gondola systems will be an asset. To save on surface area, more than one microwave beam from more than one SPS could be focused on the same rectenna. For transmitting the power to the ground, frequency bands around 2.45 Gigahertz (GHz) or 5.8 GHz have been proposed, which, as these are within the microwave radio windows of the atmosphere and, as the power level is well known, the intensity of the transmission cannot harm animals or people.

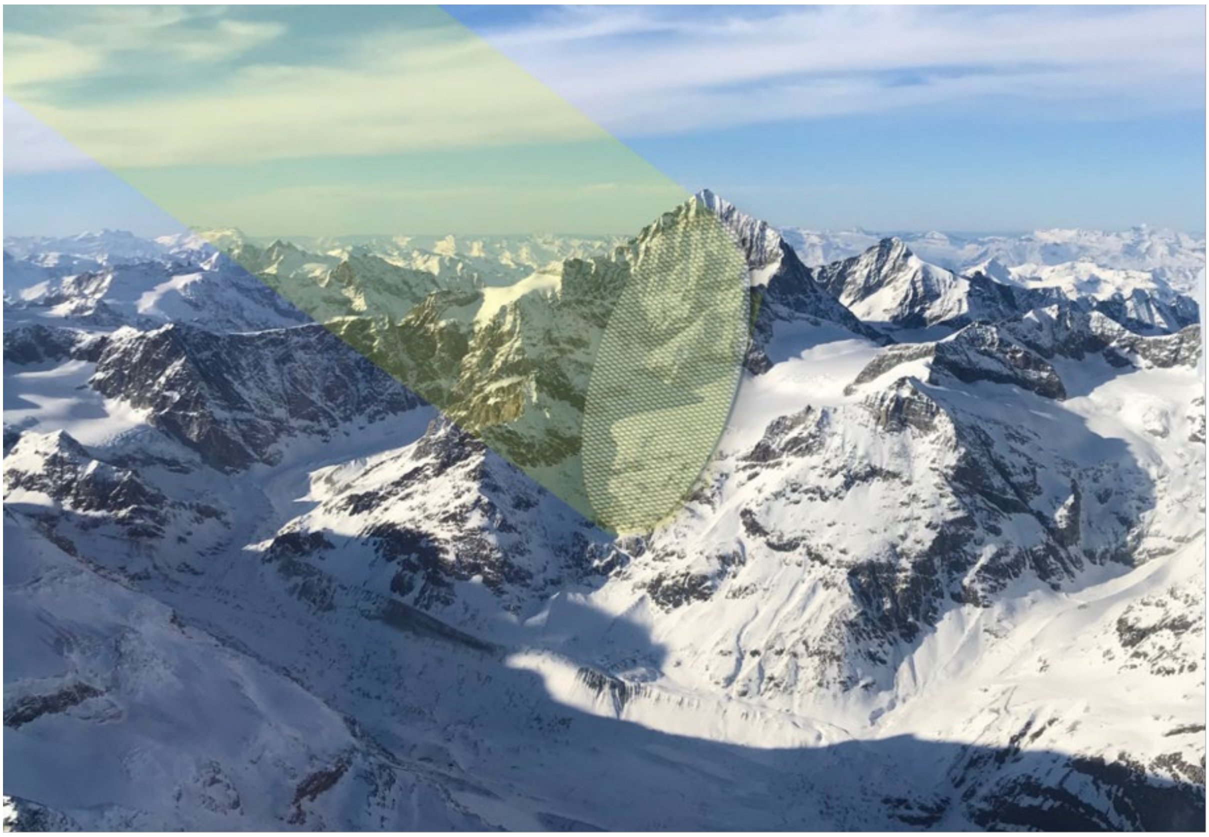


Figure 2. A Rectenna in the Swiss Alps

Space-Based Solar Power (SBSP) was examined in a detailed study by NASA and the US Department of Energy in the 1970s and more recently by the International Academy of Astronautics (IAA) in 2011. [28] The lead author of the IAA study, John Mankins has updated this information in his book "The Case for Space Solar Power" published in 2014 and he has since further developed the concept – he now calls "SPS-ALPHA Mark-II" - via his own company. [29] The unique characteristics of the SPS-ALPHA Mk-II as opposed to earlier SPS designs are that the SPS would be constructed out of numerous, mass produced, interlocking modules that would be assembled in low Earth orbit (LEO) by robots. Once assembled, it would use its own electrical energy to power an ion solar electric propulsion (SEP) system or an Orbital Transfer Vehicle (OTV) to transfer the SPS to a geosynchronous orbit (GSO). In his publication "New Developments of Space Solar Power" Mankins describes in detail both the evolution of the SPS technological concept and the economic implications.[30]

Most space experts see no significant technological obstacles nor any engineering challenges that could not be mastered once a determined space power development program has been initiated. Until now, the biggest obstacle to implementing the *Space Energy Option* that is always mentioned by its critics is the initial cost to build and launch a solar power satellite. However, even a modest commitment to developing energy from space would automatically create a market for space solar power technologies that would consequently reduce both the manufacturing and the launch costs substantially in so far that space solar power could be economically competitive with existing terrestrial energy options.

For additional reference, various approaches and economics of Space-Based Solar Power are discussed in detail in these six books:

- Frank P. Davidson, L.J. Giacoletto, & Robert Salked, Eds. (1978) *Macro-Engineering and the Infrastructure of Tomorrow.* AAAS Selected
  Symposium 23, Westview Press, Boulder (CO), 131-137
- P. Glaser, F. Davidson, & K. Csigi, (1998) *Solar Power Satellites*, Wiley
- Don M. Flournoy, (2011) *Solar Power Satellites*, Springer
- Ralph Nansen, (1995, 2012) *Sun Power: The Global Solution for the Coming Energy Crisis*, Ocean Press 1995, Nansen Partners 2012
- John Mankins, (2014) *The Case for Space Solar Power*, Virginia Edition Publishing LLC

- Michael Snead, (2019) *Astroelectricity,* Spacefaring Institute LLC

Switzerland would be an ideal country to initiate a determined space solar power development program for several reasons. It obviously has the need. It also has the high technical and manufacturing expertise as well as the financial resources to become an *Astrostrom Startup Nation*. Significantly, it is a founding member of the European Space Agency (ESA) which would allow Switzerland to draw upon the expertise of this multinational space organization and perhaps convince its ESA partners to participate in a collaborative program which would be mutually beneficial as each member nation has their own energy dilemma. In addition, Europe has its own launch capability which could be optimized for space solar power development. A determined Swiss space power program, once implemented, could supply a large percentage of Switzerland's future energy requirements with a $C0_2$ neutral energy source that is inexhaustible, and which would be – most importantly – both scalable and economically competitive.

Energy from space would have a positive impact in any future climate change scenario. Obviously, an inexhaustible source of clean solar energy would reduce Switzerland's reliance on carbon fossil fuels in an anticipated warming scenario. Likewise, if climate change goes in the opposite direction leading to a severe cooling scenario, a SPS could be re-purposed as a Snow Melting Satellite (SMS) to provide needed warmth and electrical power to specific locations.[31]

2.2 Replacing Fossil Fuels

Fossil fuels consumption in Switzerland in 2019 totaled 146,021 GWh of that amount 56% (81,867 GWh) was used for transport. As an alternative to using fossil fuels, providing electricity for an increasing number of electric vehicles is an obvious application for recharging the batteries. However, a more environmentally friendly and convenient solution would be to use the plentiful electricity from space to create hydrogen fuel by splitting water into hydrogen and oxygen by electrolysis. The hydrogen gas is then compressed and delivered to existing filling stations and supplied to vehicles that have hydrogen fuel cells that power their electric motor. The exhaust of this process is pure water vapor. The refueling process is similar in convenience to that of refueling today's gasoline and diesel vehicles.

A 2 MW electrolysis plant already exists in Switzerland that can produce up to 300 tons of hydrogen per year which would provide fuel for 50 lorries or 1,700 cars.[32] In 2017, there were over 6 million motor vehicles in Switzerland of which 5.32 million were cars or utility vehicles.[33] To provide hydrogen fuel to these vehicles, approximately 6.26 GW of reliable electrical power will be necessary.

France and Germany have announced that they will invest billions in hydrogen technology. The European Commission has announced a strategy for achieving carbon neutrality through renewable hydrogen. Hydrospider AG is a company that is pioneering this technology in Switzerland. The South Korean auto and truck manufacturer Hyundai will supply 1,600 hydrogen-powered lorries by 2025. The first seven vehicles were delivered in October 2020. [34]

2.3 Is Astrostrom Encomically Competitive?

As none of the existing terrestrial energy options – hydroelectric, wind, solar (PV) or nuclear power - can be sufficiently scaled to meet the energy needs of Switzerland – or the world for that matter –being economically competitive is perhaps not the most important factor. However, to answer the critics and to show that harvesting energy in space can indeed become economically viable, it should also be compared with other conventional and alternative energy generation technologies using the following criteria. Space-Based Solar Power should be:

- sufficient, scalable, and sustainable
- affordable when compared to other energy systems
- economical and potentially profitable
- must satisfy Switzerland's 2050 Energy strategy

As wind and solar PV systems in Switzerland will be mainly decentralized and widely distributed the cost of energy will be the main factor for comparison for these sources. In contrast, nuclear power production is a concentrated and centralized power production system which can be for comparison when building a comparable system. Thus, this analysis will show that a Swiss Astrostrom system would be in the same cost range as building a new nuclear power station and will provide sufficient energy that is price competitive with available terrestrial alternatives.

There is a complex method proposed by the US Energy Information Administration (EIA) to make these comparisons. Referred to as the levelized cost of electricity (LCoE) and the levelized avoided cost of electricity (LACE) these are, respectively, estimates of the revenue required to build and operate a generator over a specified cost recovery period and the revenue available to that generator over the same period.[35] The actual LCoE of building and operating any power plant is very complicated as these involve fuel costs, subsidies, taxation, operating costs, interest paid to finance the system, environmental costs, decommissioning costs, etc. A simple LCoE formula to make such comparisons is: the net cost of construction and installation of the system divided by the productivity (lifetime in years * total kWh/year) = cost per kWh.

In 2017, the Paul Scherrer Institute conducted a major study under contract to the Swiss Federal Office of Energy called "Potentials, costs and environmental assessment of electricity generation technologies" which looked at the LCoE of various energy technologies. [36]

The following table lists various energy technologies: hydro power, wind power, photovoltaic (PV) rooftop (~30 kW) and PV industrial (~100 kW) as well as their expected potential and the estimated electricity generation costs over the years 2020 -2050.

Cost of Electricity (CoE)

	2020 Current TWh	2050 Potential TWh	CoE 2020 CHF/kWh	CoE 2050 CHF/kWh
Hydro Power	32.2	38.6	0.17-0.30	0.17-0.30
Wind Power	0.1	4.3	0.13-0.21	0.09-0.15
Solar PV (30 kW)	2.4	48	0.11-0.16	0.10-0.14
Solar PV (100 kW)	0	?	0.10-0.18	0.07-0.10
Nuclear Power	23	0	0.07-0.08	-

Looking first at nuclear power, a 2011 cost analysis for the construction of a Pressure Water Reactor (PWR) type nuclear power plant for Switzerland undertaken by the Swiss firm Prognos AG, estimated the construction costs to be about 6,400 Swiss francs (CHF) per kW which equals CHF 6.4 billion per GW and the LCoE would be between 71-77 CHF/MWh or about CHF 0.07.5/kWh. [37]

There are two nuclear power plants in Western Europe currently under construction using a third generation EPR design (Evolutionary Power Reactor) which can be used as a more actual reference:

Hinkley Point C nuclear power station – a 3.2 GW facility in Great Britain that is expected to eventually cost £22.5 billion ($29 billion – CHF 26 billion). [38]

Flamanville in Manche, France begun in 2007 – 1.6 GW facility is now expected to eventually cost €12.4 billion ($14 billion / CHF 12.5 billion) [39]

Flamanville costs = $8.75 billion for 1-GW ($14 billion ÷ 1.6 = $8.750 billion (CHF 7.8 billion)
Hinkley Point C costs = $ 9.01 billion for 1-GW ($29 billion ÷ 3.2 = $9.0625 billion (CHF 8.1 billion)

Figure 3. Construction of Hinkley Point Nuclear Power Station

Photo by Nick Chipchase [40]

Using these examples, the average cost is approximately $9 billion or about CHF 8 billion per GW to construct a nuclear power plant today. This amount is based on what is referred to as the Engineering, Procurement and Construction costs or EPC and does not include fuel, maintenance, waste disposal nor future decommissioning costs. To calculate the LCoE these costs must be included and divided by the expected operational lifetime of 60 years. For more information see: World Nuclear Association: Economics of Nuclear Power .[41]

2.4 LCoE of an Astrostrom Power Station

Regarding an Astrostrom power station - a Solar Power Satellie (SPS) - the comparable EPC is for the construction and the launch of the SPS. The lifetime of the SPS structure once placed in GEO is essentially unlimited, although the solar modules would need to be serviced after 20-30 years. Due to their modular design and robotic assembly in space, this should not significantly impact the operating costs when this maintenance becomes necessary to extend the operational lifetime of the SPS. In contrast to nuclear power, there would be no recurring fuel, waste disposal or decommissioning costs. A SPS does not have many of the ongoing maintenance and fuel costs associated with nuclear power nor does it have the waste disposal and decommissioning costs. With regards to decommissioning, any satellite launched today must provide a plan for its removal from orbit. Large solar power satellites in GEO would most likely be parked further out into space where their valuable materials could be eventually recycled. Thus, whereas nuclear power will become progressively more expensive to construct and operate, space solar power satellites would likely become progressively less expensive. On the other hand, the throughput of launching an SPS directly from the surface of Earth into GEO is expensive, environmentally problematic and logistically complicated.

SPS-ALPHA Mark-II

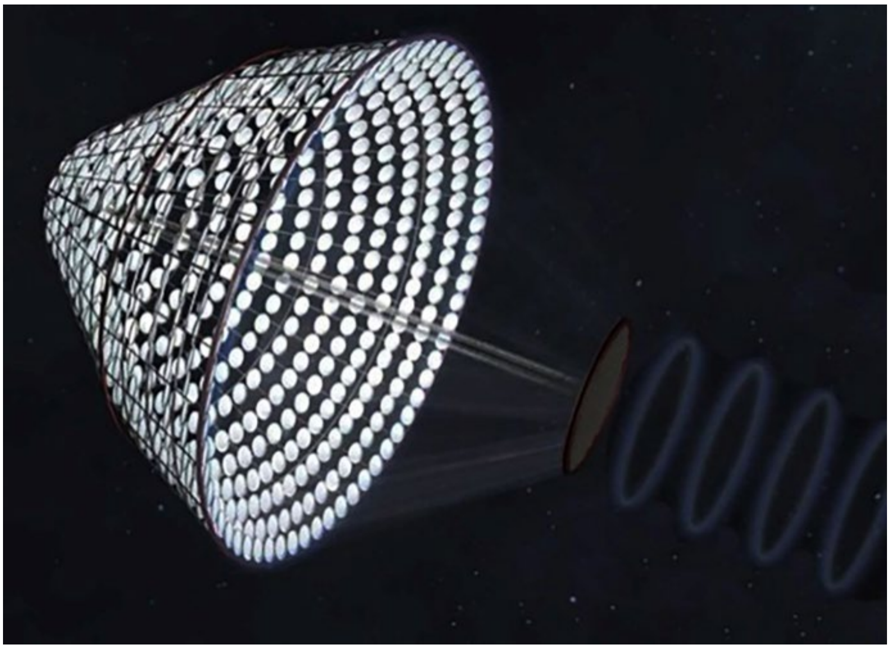
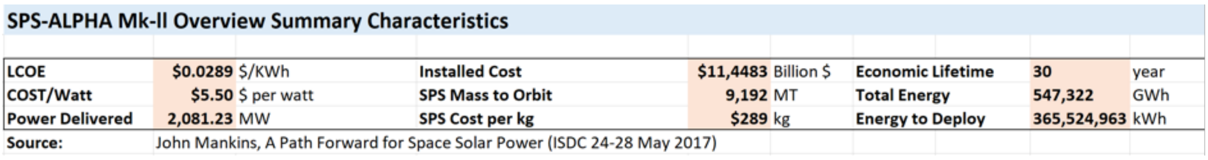


Figure 4. SPS-ALPHA Photo NASA/John Mankins

John Mankins' SPS-ALPHA Mk-II concept considers the SPS components will be assembled in LEO and then these will be transferred to GEO using either a reusable Orbital Transport Vehicle (OTV) or an integrated ion Solar Electric Propulsion (SEP) system powered by electricity generated by the SPS itself.[42] Based on the latest SPS-ALPHA Mark-II design, Mankins estimates that his 2.1-GW SPS would have an overall mass of 9,192 MT, generating ca. 547,322 GWh over a period of 30 years. With an installed cost of $11.5 billion (Fig. 5) . In his example the LCoE would be about $0.03 per kWh.[43] This indicates a launch cost of approximately CHF 7.8 billion or CHF 856/kg ($8.8 billion $960/kg) and the cost of the LEO-to-GEO transfer is not indicated.

SpaceX's Falcon Heavy is the largest rocket launcher that is currently operational. SpaceX advertises that its Falcon Heavy Expendable Version has the capacity to place 63.8 tonnes of payload into LEO for CHF 80.25 million ($90 million) which is about CHF 1,257/kg ($1,410/kg). According to a Tweet by Elon Musk (12 February 2018) , the capacity of the Partially Reusable version with two recoverable side boosters and an expendable core would launch 10% less payload or 57 tonnes and would cost CHF 85 million ($95 million) [44]. However, due to the characteristics of the Falcon payload fairing, the actual capacity is reduced substantially – probably 20 tonnes or less into LEO. As such, it would take approximately 460 Falcon Heavy launches to place a SPS-ALPHA MK-II into LEO. After assembly it would need to be moved into GEO by some means.



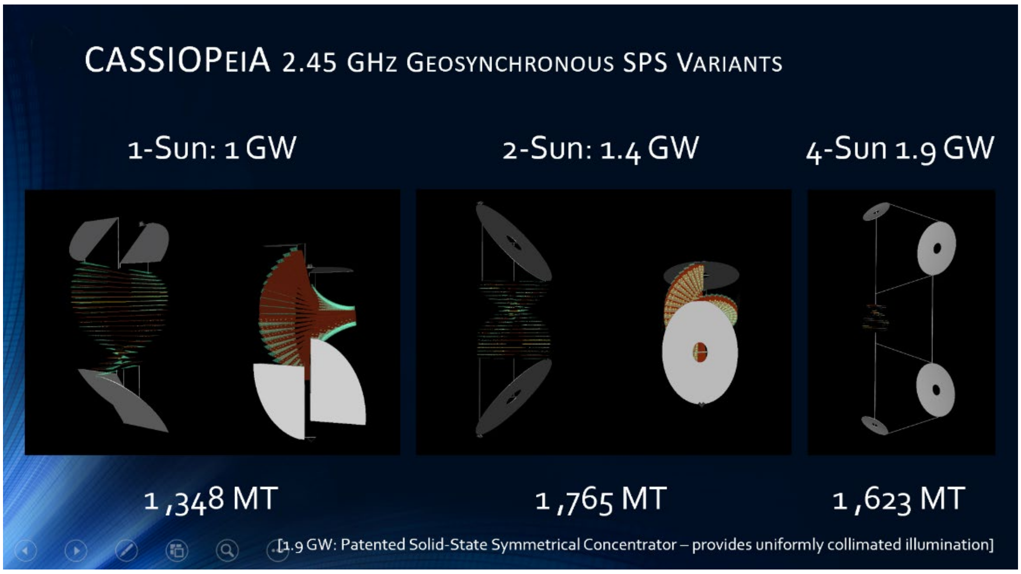
SPS-ALPHA Mk-II Overview Summary Characteristics

LCOE	$0.0289	$/KWh	Installed Cost	$11,4483	Billion $	Economic Lifetime	30	year
COST/Watt	$5.50	$ per watt	SPS Mass to Orbit	9,192	MT	Total Energy	547,322	GWh
Power Delivered	2,081.23	MW	SPS Cost per kg	$289	kg	Energy to Deploy	365,524,963	kWh
Source:	John Mankins, A Path Forward for Space Solar Power (ISDC 24-28 May 2017)							

Figure 5. LCoE of SPS-ALPHA MK-II 2.1 GW SPS (Mankins 2017)

CASSIOPeiA

Another recent SPS concept is called CASSIOPeiA (Constant Aperture, Solid-State, Integrated, Orbital Phased Array) introduced by Ian Cash and under development in the U.K. with the participation of the British government. [45] As seen in Fig. 6., CASSIOPeiA can be configured in various ways to deliver different amounts of power. In this concept a 2-GW CASSIOPeiA SPS with 2 Sun reflectors would have a target mass of 2,045 MT which is substantially less mass to orbit when compared with the Mankins' design for the equivalent power output. This would reduce the launch costs substantially especially for placing the SPS in a geosynchronous orbit (GSO). According to Ian Cash, the Falcon payload configuration only allows for 8 tonnes to be placed directly into GSO and a 2-GW CASSIOPeiA with a mass of 2,045 tonnes would require approximately 256 Falcon Heavy launches.



CASSIOPEIA 2.45 GHZ GEOSYNCHRONOUS SPS VARIANTS

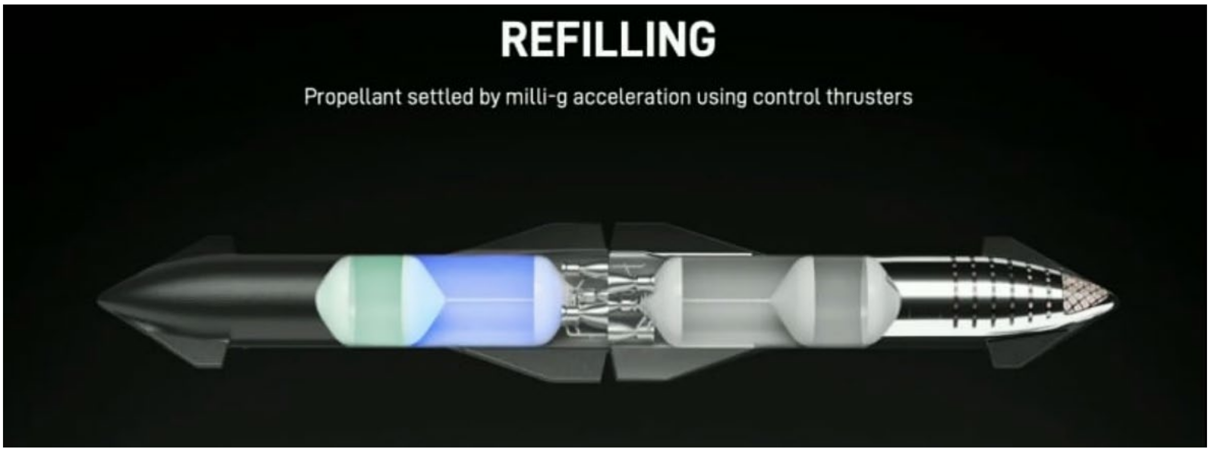
1-Sun: 1 GW	2-Sun: 1.4 GW	4-Sun 1.9 GW
1,348 MT	1,765 MT	1,623 MT

[1.9 GW: Patented Solid-State Symmetrical Concentrator – provides uniformly collimated illumination]

Figure 6. CASSIOPeiA SPS Variations

Website: www.internationalelectric.com/space-solar/

Starship Super Heavy



REFILLING

Propellant settled by milli-g acceleration using control thrusters

Figure 7. Starship and Refilling Fuel Tanker (Credit: SpaceX)

However, there is another rocket launcher currently under development by SpaceX called the *Starship*. This will be a fully reusable *super heavy launcher* that could place 100 - 156 MT into LEO. Starship also allows for a launch into LEO and a 'refilling' or a refueling of the rocket with a second launch that would then then take the payload into GEO. This double launch concept - hardware + refilling - is the most interesting launch option available which is expected to be operational by 2023 (Fig.7) . This analysis uses the Starship double launch approach to calculate the LCoE of an CASSIOPeiA SPS with a capacity of 2-GW. The estimated mass delivered to GEO is 58.3 MT.

LCoE 2-GW CASSIOPeiA	Swiss Francs	US Dollars
Total Cost	**CHF16,620,424,614**	**$18,639,640,000**
($100 million ÷ 141,000 kg = CHF 633/kg / $710/kg)		
2,045 MT Earth-to-Orbit (GEO)		
58.3 MT in GEO per 1 Starship + 1 Refuel Tanker (Cash 2021)		
36 Starship + 36 Refueling Launches @ CHF 89 million / $100 million	CHF 6,420,030,495	$ 7,200,000,000
Rectenna/Infrastructure (Cash 2021)	CHF 610,794,568	$685,000,000
SPS Manufacturing Cost: CHF 3,381/kg / $3,792/kg (Cash 2021)	CHF 6,914,586,844	$7,754,640,000
Operations Space/Ground (+/- CHF 89 million / $100 million/year * 30)	**CHF 2,675,012,706**	**$3,000,000,000**
Cost/Watt Installed	**CHF 7.00**	**$7.81**
Power Delivered 17,432 GWh/year (99.5% availability)		
Total Energy Delivered 522,960 GWh (30 years)		
Cost of Electricity	**CHF 0.032/kWh**	**$0.036/kWh**

Cash Flow Scenario for a 2-GW 2-Sun CASSIOPeiA
Energy Price: CHF 0.12/kWh (the price for solar power in Switzerland)

Delivered power: 17,432,000,000 kWh
Yearly revenues: 17,432,000,000 kWh * CHF 0.12 = CHF 2,091,840,000
Cost of electricity CHF 0.032/kWh: 17,432,000,000 kWh * CHF 0.032 = CHF 557,842,000
Difference: CHF 2,091,840,000 - 557,842,000 = CHF 1,534,016,000
Margin 10 % → CHF 1,534,016,000 * 0.9 = CHF 1,380,614,000
Profit = ca. CHF 1.4 billion/year

Capital Investment Payback Scenario @ 0.12 CHF/kWh

Amortization Scenario for a 2-GW CASSIOPeiA
CHF 16,620,424,614 ÷ CHF 1.4 billion per year = **12 years**

GEO is not the only deployment scenario for CASSIOPeiA, Ian Cash has also proposed a four-SPS constellation that, when deployed in an 8-hour highly elliptical orbit , could provide continuous baseline power to three rectennas in different geographical locations - an approach that could be developed and shared by a consortium of nations such as Switzerland, Canada and Japan. Indeed, the title of Ian Cash's presentation at the 2018 International Astronautical Congress in Bremen, Germany was "CASSIOPeiA - Solar Power Satellite - Breaking the Non-Scaling Paradigm". [46] Cash estimates that the best LCoE would be for the 4-sun, 1.4 GW variant in an 8-hour highly elliptical orbit which would give a CHF 0.021/kWh. For the GEO case, the best

LCoE is for the 4-sun 2-GW variant would be CHF 0.024/kWh. The above LCoE calculation is for a 2-Sun 2-GW variant with a CHF 0.032//kWh. Any of these would be competitive with Switzerland's terrestrial energy options.

2.5 Future Developments

Other reusable launch systems are currently under development such as the *Skylon* which is a single-stage-to-orbit (SSTO) rocket plane by the company Reaction Engines in the U.K with the participation of ESA and the British government. Russia's state-owned space corporation Roscosmos has plans to compete with SpaceX with the development of a reusable launcher by 2024 called *Amur* that will have a first stage that could be reused up to 100 times. The first version of this rocket is similar in capacity to SpaceX's Falcon 9; however, "heavy lift" and "super heavy lift" versions are planned to follow.[47] [48]

Obviously, a determined program to launch multiple SPSs would result in lower launch costs and lower construction costs while creating a large market for heavy lift launch vehicles. This would lower the cost per kWh to make Astrostrom competitive with *any* terrestrial energy system. However, one problem remains which is called the 'throughput' - the logistics of launching many SPSs would require many, many rocket launches.

2.6 A Space Elevator – The Green Road to Space

Perhaps the most optimistic future launch system is the Space Elevator (SE) which consists of a tether extending outwards from Earth 100,000 km and connected to a counterweight in orbit such as a space station or a large solar power satellite. The Earth terminus would be located on the equator. Instead of using rocket fuel and rockets, large payloads would be attached to the tether and these would 'climb' into orbit using electricity. Payloads could be dropped off at various orbits including GEO (35,786 km). In its initial configuration a SE could deliver 14 tonnes a payload a day and at full operational capacity payload capacity would increase to 79 tonnes a day. As such, the components of a 5,000 MT SPS-ALPHA could be installed in GEO 63 days , or a 2,045 MT CASSIOPeiA in just 26 days.

Currently being researched by the International Space Elevator Consortium (ISEC), they report that an apparent breakthrough has occurred in the development of a new material to be used for the tether called ' Single Crystal Graphene' (a new material with 2D characteristics) which has been shown to be strong enough and could be manufactured long enough to make a SE technically feasible. The ISEC projects that an initial SE could be operational by 2037 and this would obviously revolutionize access to space from Earth making it both routine and inexpensive, i.e. less than CHF 100 per kilogram.[49] In this scenario, to launch a 2-GW CASSIOPeiA would only cost about CHF 205 million instead of CHF 6.5 billion using Starship.

A Space Elevator could also be built on the Moon and extend out to 61,350 km to the Earth-Moon Lagrange point (EM L-1) which would be an ideal assembly point for SPSs built with lunar materials. The advantage of a Lunar Space Elevator is that the tether could be built using materials that are currently available. [50] [51] [52]

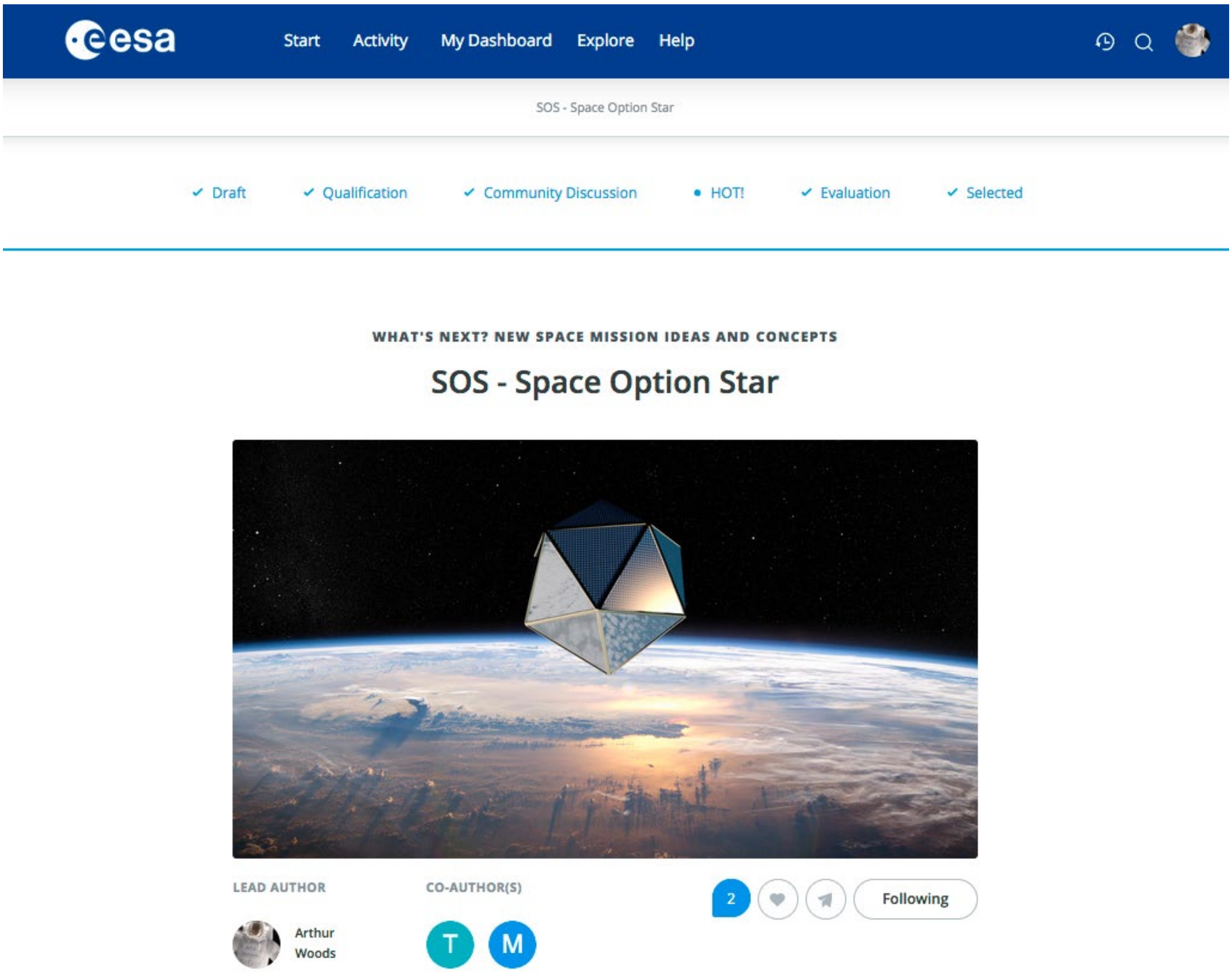
A Space Elevator would revolutionize all of the scenarios mentioned in this analysis. and would surely be a game changer in the development of any Astrostrom program.

2.7 Switzerland's First Steps?

The United States was the first country to seriously look at SBSP in a series of high-level technical studies beginning in the 1970's and continuing into the present. In 2020, the U.S. military launched a power beaming experiment (WPT) on their secretive X-37B spaceplane. Japan began looking at SBSP in the late 1980's and has since carried out a long-distance demonstration of WPT of 10 kW of power. It has plans to launch a SPS demonstrator in the next few years with the goal to launch a commercial SPS by 2030, most likely as a part of an international consortium. India has an obvious need for harnessing energy from space and has participated in several international initiatives to pursue SBSP. China makes no secret about its interest in developing space energy options, whether SBSP or mining Helium-3 on the Moon for fusion energy. The father of the Chinese space program Wang XiJi stated: *"The world will panic when the fossil fuels can no longer sustain human development. We must acquire space solar power technology before then… Whoever obtains the technology first could occupy the future energy market. So, it's of great strategic significance."* [53] In

November 2020, the U.K. government commissioned a study in the feasibility of SPS to meet their 2050 net-zero carbon economy goals.

Beginning in 2004, the European Space Agency (ESA) has since conducted a number of studies assessing the feasibility of harnessing energy in space. In ESA's 2020 call: *"What's next? New space mission ideas and concepts",* which attracted 201 proposals, four proposals were selected, i.e., short listed, for further development including ESA's own energy from space proposal and, from our team in Switzerland, *"S⊕S-Space Option Star"* – which is an in space demonstration of WPT representing a logical early step for any Astrostrom development program.



WHAT'S NEXT? NEW SPACE MISSION IDEAS AND CONCEPTS

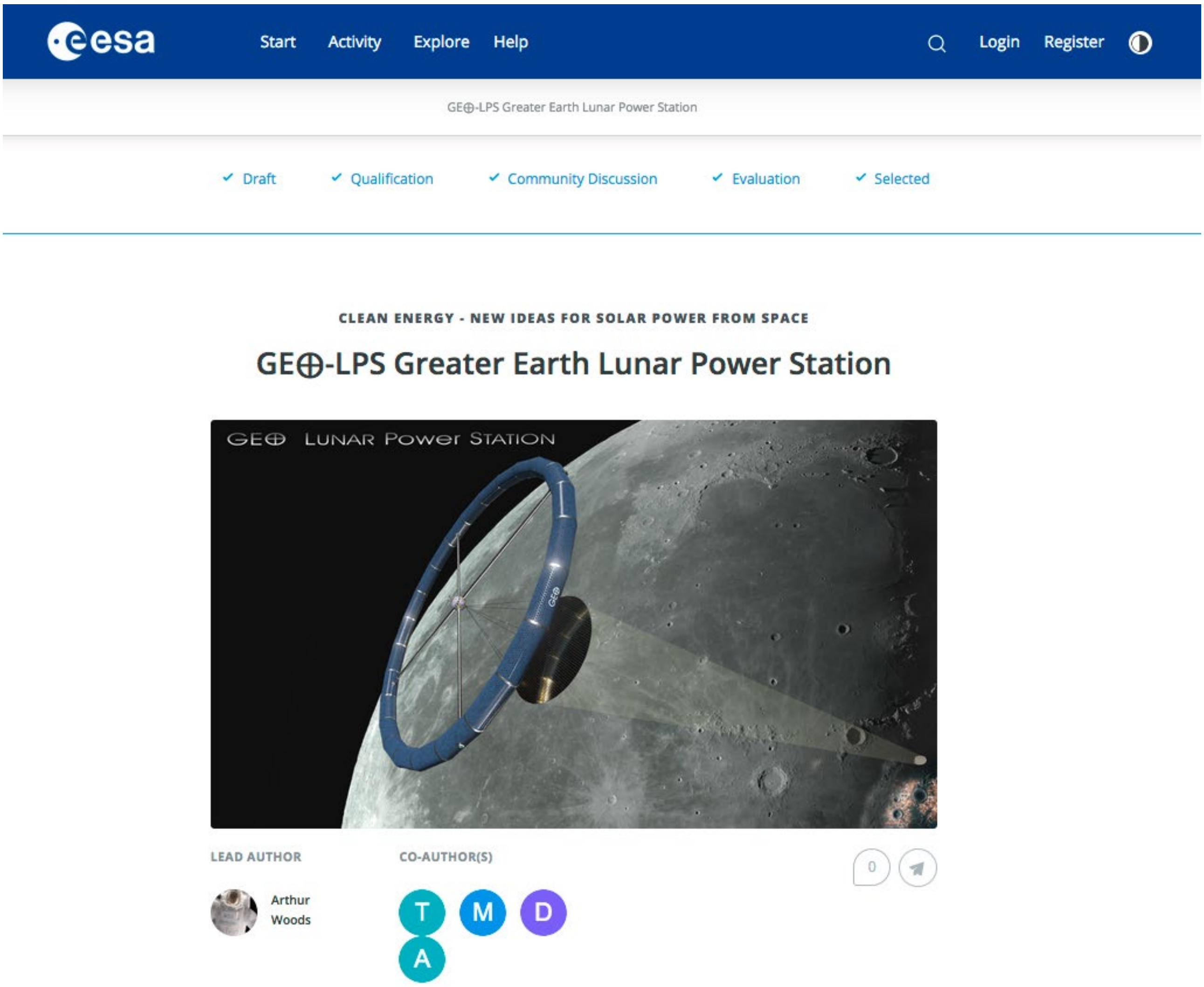
SOS - Space Option Star

LEAD AUTHOR: Arthur Woods

CO-AUTHOR(S)

ideas.esa.int

In ESA's call for *"Clean Energy - New Ideas for Solar Power from Space"* 85 proposals were submitted and the our Swiss teams' proposal "*GE⊕-LPS Greater Earth Lunar Power Station (GE⊕-LPS)*" was selected for under further evaluation. The GE⊕-LPS is a habitable space solar power station in lunar orbit that is designed to provide solar energy for lunar operations. Astrostrom and space tourism could become synergistic economic drivers for future space development.



CLEAN ENERGY - NEW IDEAS FOR SOLAR POWER FROM SPACE

GE⊕-LPS Greater Earth Lunar Power Station

GE⊕-LPS is currently undergoing evaluation.

ideas.esa.int

Note: Switzerland's 2021 contribution to the European Space Agency is €172.6 million.

2.8 Conclusions

Energy from space is both clean and scalable and its land use requirements are much less than terrestrial systems. Without sufficient energy it will be necessary to continue to import increasing amounts of energy from other nations which may or may not be CO_2 neutral. Lacking a viable energy solution, Swiss government measures designed to radically reduce per capita energy use through increased taxation, incentives and penalties would significantly decrease industrial productivity and consequently lower the Swiss standard of living if sufficient energy is not available in 2050. The cost to build and launch one GW of Astrostrom is comparable to that of constructing a one GW nuclear power station. The LCoE, however is less than any terrestrial alternative.

Switzerland has an e*nergy dilemma* in that its government has decreed to replace fossil fuel use by the year 2050 with a CO_2 neutral energy source and to divest from nuclear power. Hydroelectric, wind and terrestrial solar (PV) energy sources, though important and useful, cannot be sufficiently scaled to meet these national energy goals even with drastic reductions in energy consumption. **Taken together these terrestrial energy**

resources can optimistically produce about 123 TWh which is only about 52% of the 237 TWh of the energy needed yearly in 2050.

Having sufficient energy to power Swiss society is more important than having the most price competitive source of energy. However, using current published costs and anticipated quantity discounts, this analysis shows that the cost of building and launching a SPS can be economically with the cost of building a nuclear power station. Launch market developments would make the construction and launch of subsequent SPSs progressively more affordable. Using the current cost of solar power in Switzerland which is CHF 0.12/kWh, the payback time also becomes shorter and while progressively delivering more return on investment.

Over the past 25 years Switzerland spent over 177 billion Swiss francs for the import of energy from other countries which indicates it has the means and the motivation to invest 7 billion Swiss francs a year in the development of a determined space power program. Such a program could result in achieving energy independence by 2050 that is CO_2 neutral with a positive return on investment beginning with the first SPS and with subsequent SPSs generating a profit. The 2019 value of the Swiss energy market was CHF 42.2 billion.

In May 2021, the International Energy Agency published ***Net Zero by 2050: A Roadmap for the Global Energy Sector*** which it calls the world's first comprehensive study to lay out a cost-effective transition to a net zero energy system while ensuring stable and affordable energy supplies, providing universal energy access, and enabling robust economic growth. The report states that a surge in clean energy investment can bring jobs and growth. **To reach net zero emissions by 2050, annual clean energy investment worldwide will need to more than triple by 2030 to around $4 trillion (CHF 3.6 trillion).** [54]

Based on this analysis, seven 2-GW CASSIOPeiA systems would solve Switzerland's *Energy Dilemma* by meeting its future energy needs and climate obligations (13 GW needed). At CHF 16 billion each including yearly operations, the total cost would be CHF 112 billion (or less) over the next thirty years. Selling electricity at CHF 0.12/kWh, which is the price of terrestrial solar power in Switzerland today, an Astrostrom power station would be amortized after only 12 years of operation. After this amortization period, the station would generate about CHF 1.4billion in yearly profit revenues.

A determined space power program - even by a small nation such as Switzerland - would catalyze the creation of a large world market for reusable super heavy launch vehicles that would subsequently provide economies of scale and stimulate competition in the launch market. This in turn would significantly further reduce launch costs for Switzerland and other countries. Similarly, this would also impact the manufacturing costs of the SPS elements which would also become progressively less expensive as demand increases. Additional economies of scale and production would occur if a determined program to harvest energy in space was carried out in cooperation with other countries. This program would possibly lead to the lunar-based option (LBSP) of producing the SPS elements on the Moon utilizing lunar resources and assembling the SPS in lunar orbit. Finally, the fast-track development of the *SOS Space Option Star* would immediately add Switzerland to the roster of countries dedicated to addressing the *energy dilemma* and the *climate emergency* with energy from space.

Switzerland has the need, the technical means, and the financial resources to become an Astrostrom Startup Nation and perhaps lead an international collaborative effort to supply the world with inexhaustible clean energy.

3 About the Author

This research has been carried out by Arthur R. Woods, an astronautical artist and independent researcher with two art projects successfully flown on the Russian Mir space station. He is a member of the International Academy of Astronautics and co-chair of the Moon Village Association Cultural Considerations Working Group.

ACRONYMS

GW	Gigawatt	**LBSP**	Lunar-Based Solar Power
GWh	Gigawatt-hours	**LSP**	Lunar Solar Power
kWh	Kilowatt-hours	**SBSP**	Space-Based Solar Power
MW	Megawatt	**SSP**	Space Solar Power
TW	Terawatt	**SPS**	Space Power Satellite
TWh	Terawatt-hours	**SEP**	Solar Electric Propulsion
TJ	Terajoule	**OTV**	Orbital Transfer Vehicle
MT	Metric Ton	**LEO**	Low Earth Orbit
EPC	Engineering, Procurement, Construction	**GEO**	Geosynchronous Orbit
ESA	European Space Agency	**WPT**	Wireless Power Transmission
LCoE	Levelized Cost of Electricity	**ETO**	Earth-to-Orbit
BFE	Bundesamt für Energie	**GE⊕**	Greater Earth
SFOE	Swiss Federal Office for Energy	**S⊕S**	Space Option Star

REFERENCES

1. What is the Energy Strategy 2050?, SFOE – Swiss Federal Office of Energy, https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050/what-is-the-energy-strategy-2050.html
2. Switzerland National projections, https://www.bfs.admin.ch/bfs/en/home/statistics/population/population-projections/national-projections.html
3. Energy Strategy 2050 once the new energy act is in force https://www.bfe.admin.ch/bfe/en/home/politik/energiestrategie-2050.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZW4vcHVibGljYX/Rpb24vZG93bmxvYWQvODk5Mw==.html
4. Die Schweizerische Gesamtenergiestatistik, https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.html
5. Overall Energy Statistics, SFOE, Energy Consumption in Switzerland 2019, https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/overall-energy-statistics.html
6. Energy Strategy 2050, Swiss Federal Office of Energy, https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050.html
7. SFOE, Hydropower, https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/hydropower.html
8. Wind Energy Plants, Bundesamt für Energie (BFE) https://www.uvek-gis.admin.ch/BFE/storymaps/EE_WEA/index.php?lang=en
9. Solar irradiance, Wikipedia, https://en.wikipedia.org/wiki/Solar_irradiance
10. “Potentials, costs and environmental assessment of electricity generation technologies” Paul Scherrer Institute, https://www.psi.ch/sites/default/files/import/lea/HomeEN/Final-Report-BFE-Project.pdf
11. 2.5 Gigawatt installierte Solarleistung – wir brauchen 20-mal mehr, Swisssolar, 14.07.2020 https://www.swissolar.ch/en/services/medien/news/detail/n-n/25-gigawatt-installierte-solarleistung-wir-brauchen-20-mal-mehr/
12. Faktenblatt: Strom von der Sonne, Swisssolar: https://www.swissolar.ch/fileadmin/user_upload/Solarenergie/Fakten-und-Zahlen/Branchen-Faktenblatt_PV_CH_d.pdf
13. Markterhebung Sonnenenergie 2019: https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/sector-statistics.html
14. Energy, What’s new? Federal Statistical Office, FSO, https://www.bfs.admin.ch/bfs/en/home/statistics/energy.html
15. Energy consumption in Switzerland, https://www.worlddata.info/europe/switzerland/energy-consumption.php
16. How much electricity or heat can my roof produce? https://www.uvek-gis.admin.ch/BFE/sonnendach/index.html
17. 2.5 Gigawatt installierte Solarleistung – wir brauchen 20-mal mehr, Swisssolar, 14.07.2020 https://www.swissolar.ch/en/services/medien/news/detail/n-n/25-gigawatt-installierte-solarleistung-wir-brauchen-20-mal-mehr/

18. Grösstes Solar-Kraftwerk der Schweiz https://www.schweizerbauer.ch/politik--wirtschaft/agrarwirtschaft/groesstes-solar-kraftwerk-der-schweiz-51052.html
19. Medieninformation PlusEnergieBau (PEB) - Gebäudestudie 2019 https://www.solaragentur.ch/news/medieninformation-plusenergiebau-peb-gebaeudestudie-2019
20. Switzerland Electric Prices, https://www.globalpetrolprices.com/Switzerland/electricity_prices/
21. Energieperspektiven 2050+: Zusammenfassung (PDF) https://www.bfe.admin.ch/bfe/de/home/news-und-medien/medienmitteilungen/mm-test.msg-id-81356.html
22. Hydropower, SFOE https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/hydropower.html
23. Michael Snead,*(2019) Astroelectricity*, Spacefaring Institute LLC, Kindle
24. Michael Snead, 108 – Konstantin Eduardovich Tsiolkovsky: Humanity's spacefaring future-teller, https://www.spacefaringamerica.com/?p=2180
25. Issac Asimov, Reason, short story, Wikipedia, https://en.wikipedia.org/wiki/Reason_(short_story)
26. Peter E. Glaser, (1968). "Power from the Sun: Its Future". Science. 162 (3856): 857–61
27. Ralph Nansen - Sun Power: The Global Solution for the Coming Energy Crisis, Nansen Partners, 2012
28. International Academy of Astronautics Assessment of Space Solar Power, NSS, https://space.nss.org/international-academy-astronautics-space-solar-power-press-conference-responses/
29. John Mankins, 2017, A Path Forward for Space Solar Power: SPS-ALPHA Demonstrations to Operations, (ISDC 2017) http://www.spacedevelopmentfoundation.org/wordpress/documents/2017/06/a-path-forward-for-space-solar-power-sps-alpha-demonstrations-to-operations.pdf
30. John Mankins, New Developments in Space Solar Power, NSS Space Settlement Journal, December 2017, https://space.nss.org/wp-content/uploads/NSS-JOURNAL-New-Developments-in-Space-Solar-Power.pdf
31. Patrick Collins & Marco C. Bernasconi, Risk Analysis of Climate Change, and Potential SPS Contribution to Global Warming or Global Cooling Mitigation, https://thespaceoption.com/risk-analysis-of-climate-change-and-potential-sps-contribution-to-global-warming-or-global-cooling-mitigation/
32. Switzerland's driving role in the green hydrogen revolution. Swissinfo.ch https://www.swissinfo.ch/eng/switzerland-s-driving-role-in-the-green-hydrogen-revolution/46079974
33. More than six million vehicles now in Switzerland, swissinfo.ch, https://www.swissinfo.ch/eng/road-traffic_more-than-six-million-vehicles-now-in-switzerland/43883624
34. Hydrospider, Hyundai Motor's Delivery of XCIENT Fuel Cell Trucks in Europe Heralds Its Commercial Truck Expansion to Global Markets, https://hydrospider.ch/en/hyundai-motors-delivery-of-xcient-fuel-cell-trucks-in-europe-heralds-its-commercial-truck-expansion-to-global-markets/
35. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020*, EIA, U.S. Energy Information Administration, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf%20%20%20Accessed%2024.5.2020
36. "Potentials, costs and environmental assessment of electricity generation technologies" Paul Scherrer Institute, https://www.psi.ch/sites/default/files/import/lea/HomeEN/Final-Report-BFE-Project.pdf
37. Kosten neuer Kernkraftwerke, Prognos, 2011, https://pubdb.bfe.admin.ch/de/publication/download/5797
38. *Hinkley Point nuclear plant building costs rise by up to £2.9bn* https://www.theguardian.com/uk-news/2019/sep/25/hinkley-point-nuclear-plant-to-run-29m-over-budget
39. *EDF warns of added costs of Flamanville EPR weld repairs*. World Nuclear News, http://world-nuclear-news.org/Articles/EDF-warns-of-added-costs-of-Flamanville-EPR-weld-r
40. Nick Chipchase, Hinkley Construction, Wikipedia: CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=79841499
41. World Nuclear Association: Economics of Nuclear Power https://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx
42. Ion thruster, Wikipedia, https://en.wikipedia.org/wiki/Ion_thruster
43. Musk, Elon [@elonmusk] (12 February 2018). "Side boosters landing on droneships & center expended is only ~10% performance penalty vs fully expended. Cost is only slightly higher than an expended F9, so around $95M" (Tweet) – via Twitter.
44. CASSIOPeiA, Space-Based Solar Power, International Electric Company, https://www.internationalelectric.com/space-solar
45. Elon Musk [@elonmusk] (23 May 2019). "Aiming for 150 tons useful load in fully reusable configuration, but should be at least 100 tons, allowing for mass growth" (Tweet) – via Twitter.
46. CASSIOPeiA, Space-Based Solar Power: Breaking the Non-Scaling Paradigm, International Electric Company 2018 IAC, Bremen, Germany https://elisashebaroblog.files.wordpress.com/2018/10/cassiopeia-breaking_the_non-scaling_paradigm-iac-2018.pdf
47. Spaceflight Now: Elon Musk offers update on SpaceX's Starship mega-rocket - 31 August, 2020 https://spaceflightnow.com/2020/09/01/elon-musk-offers-update-on-spacexs-starship-mega-rocket/
48. Russia to develop super-heavy launch vehicle based on Amur methane-fueled rocket, TASS, https://tass.com/defense/1208767
49. *Space Elevators: The Green Road to Space*, 2021, International Space Elevator Consortium https://www.isec.org/20211-study
50. *Jerome Pearson, Eugene Levin, John Oldson and Harry Wykes, 2005, Lunar Space Elevators for Cislunar Space for Space Development*, https://www.academia.edu/21310727/Lunar_Space_Elevators_for_CisLunar_Transportation
51. Emily Sandford, 2020, *The Lunar Space Elevator*, YouTube https://www.youtube.com/watch?v=L1ytpj3y21E

52. Zephyr Penoyre, Emily Sandford, 2020, "The Spaceline: a practical space elevator alternative achievable with current technology", Acta Astronautica, submitted: https://arxiv.org/abs/1908.09339
53. Namrata Goswami, *China's Get-Rich Space Program* , The Diplomat, Feb. 28,2019 https://thediplomat.com/2019/02/chinas-get-rich-space-program/
54. International Energy Agency, May, 2021, "Net Zero by 2050: A Roadmap for the Global Energy Sector" https://www.iea.org/reports/net-zero-by-2050