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Solar orbital power: Sustainability analysis

Aleksander Zidanšek [a,b,c,*], Milan Ambrožič [a,b,c], Maja Milfelner [b,c], Robert Blinc [a,b], Noam Lior [d]

[a] Jožef Stefan Institute, Jamova cesta 39, Ljubljana, Slovenia
[b] Jožef Stefan International Postgraduate School, Jamova cesta 39, Ljubljana, Slovenia
[c] Department of Physics, Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška 160, Maribor, Slovenia
[d] University of Pennsylvania, Department of Mechanical Engineering and Applied Mechanics, Philadelphia, PA 19104-6315, USA

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ABSTRACT

Solar power plants positioned in space for terrestrial electricity use have been proposed due to the ever-rising world energy consumption and its environmental impacts. This idea is analysed here in the context of sustainability of such power generation. To that end we have performed some new economic, environmental and social effects analysis of electricity generation by solar space power plants of both photovoltaic and solar thermal types power using the best currently available technology. The plants in the analysis were assumed to be in different Earth orbits, or on the Moon built by a robotised factory. One of our results is that both economically and environmentally the best scenario may be to launch a thermal solar power plant to the geostationary orbit from the Moon. Electricity produced in this way could be economically competitive to that generated by fossil fuels on Earth already for as few as 100 space power plants of about 5–10 GW each. This option is also deemed socially responsible with its capacity to reduce poverty with large amounts of cheap clean energy, and environmentally friendly, because it produces more than a hundred times less emissions than the same amount of electricity produced from fossil fuels on Earth.

1. Introduction

Human demand for energy is increasing exponentially, and exploitation of conventional energy sources based primarily on coal, oil, gas and nuclear power stations is connected with many economic and environmental challenges. It is expected that power consumption will be 1.5–3 times larger by the middle of this century than it is today. This is particularly true for electric power [1]. Today humans use energy at the average rate of about 16 TW of which about 85% comes from fossil fuels. The Earth intercepts about 170,000 TW of power from the Sun, from which about half reaches the Earth's surface.

Generation of power in space for terrestrial use has many advantages as proposed by Glaser in 1968 [2]. Space power generation is usually associated with solar energy, but also other energy sources, such as nuclear, could be used. Since the original idea of Glaser a large scientific and financial effort has been invested into this idea in many countries [3]. For instance, analysis of thermal cycles and working fluids for power generation in space predicted that it is possible to obtain a thermal efficiency 58–63% with the Brayton cycle using diatomic gases [4]. More recently the US National Research Council study group found that solar power satellites have a bright future due to technological advances, in particular in advanced composite materials, robotics, wireless power transmission and solar cell technology [5]. Pacific Gas and Electric Company even agreed to purchase 200 MW of orbital power over a fifteen-year period from Solaren Corporation starting from the year 2016 [6] (even though such a system does not exist yet).

Solar power plants on Earth are among the promising long-term energy options. While they are in principle capable of covering human demand for energy with lower environmental impact, they are nevertheless associated with many difficulties. Two of the major ones are the large terrestrial areas they occupy per unit power production, and their intermittent and time-varying nature.

The most serious challenge to use orbital solar power at the present state of the art is cost, mainly for transport of the power station to space, as well as effective, safe, and efficient power transmission to Earth, security of equipment in space, e.g. from the impact of meteorites, and international agreements regarding the rights to use and share space.

* Corresponding author. Jožef Stefan International Postgraduate School, Jamova cesta 39, Ljubljana, Slovenia. Tel.: +386 1 4773117; fax: +386 1 4773110.

E-mail addresses: aleksander.zidansek@ijs.si (A. Zidanšek), milan.ambrozic@uni-mb.si (M. Ambrožič), maja.milfelner@uni-mb.si (M. Milfelner), robert.blinc@ijs.si (R. Blinc), lior@seas.upenn.edu (N. Lior).

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The advantages however are [3]:

1) no atmospheric obstruction and terrestrial surface limitations,
2) nearly continuous and constant solar energy intensity,
3) almost ideal heat sink (very low temperature),
4) practically unlimited space,
5) much smaller imposition on terrestrial surface,
6) weightless conditions diminish the need for structural materials,
7) less danger for humans in the case of accidents,
8) longer lifetime of equipment, since there is no corrosion.
9) simple energy distribution (via microwaves or laser beams, for example) and no need for pipelines, tankers, transport vehicles, etc., and less electric transmission lines,
10) possible additional application, for defense against collision of Earth with meteorites (e.g. powerful lasers designed to transport energy can be used to deflect dangerous meteorites) etc.

There seems in principle to be no reason why solar energy in space could not meet the energy needs of the Earth's population in future at a reasonable cost, either with materials launched from Earth, or with power stations on the Moon using local construction materials. Solar energy converted in space for use on Earth, "Space Solar Power" (SSP), relies on the nearly continuous energy of the Sun converted directly into electricity with solar cells or indirectly via thermal power cycles. In the prevalent approach for the transmission of this power to Earth, the electric energy is consequently transformed into microwave beams. The transmitting antenna directs a microwave beam to one or more receiving antennas (which convert the microwave energy to DC electricity) at desired locations on land or offshore. For safety the microwave beam is planned to be made diffuse enough to avoid damage to objects (including birds and insects) flying through it, and to the atmosphere. At the receiving antenna (rectenna) the microwaves are to be relatively safely and very efficiently converted into electricity that is distributed by electrical transmission lines to users. It is noteworthy that several microwave beams can be transmitted to Earth, each to a different rectenna, with the rectennas positioned in a way that minimizes the length of hard-wire terrestrial distribution lines. For a test, NASA transmitted a 30 kW beam over a distance of one mile to a rectenna and converted this beam to electricity with a total system efficiency of 82% as early as in 1975, so that only 18% of energy was lost [7]. Another approach is to convert the electricity generated in space to laser light that is beamed to Earth and converted there to electricity by using photovoltaic cells [8].

In this paper we review and update some economic, environmental and social effects of electricity production in solar space power plants using the best currently available technology. We consider satellites in low and geostationary Earth orbit, and also the Moon as the final destination for the energy plants or the place for building and launching the power stations to desired Earth's orbit. It is noteworthy that transporting materials from the Lunar surface into orbit takes less than five percent of the energy needed to do so from the Earth.

2. Concepts for space power plants

The two primary choices for the location of space power plants are satellites in some orbit, or on celestial bodies such as the Moon (Fig. 1). Here we focus on systems generating electricity either by thermal (Fig. 2a) or photovoltaic (Fig. 2b) devices. The thermal systems use solar heat to drive a thermal cycle (e.g. Brayton, Rankine, Ericsson or Stirling) that generates shaft power which drives a generator to generate electricity. The generated electricity is converted to microwaves, and transmitted to Earth via a high frequency oscillator and amplifier such as klystron (energy storage may also be implemented). Photovoltaic power plants generate electricity by direct solid-state conversion from the incident solar radiation, and are otherwise the same as the solar thermal power plant. In both cases the power plants are constructed from parts, which are lifted into the orbit with a rocket (e.g. Ariane or Falcon) either from Earth or from the Moon. Here the photovoltaic power plant lifted from the Earth represents the original NASA/DOE idea

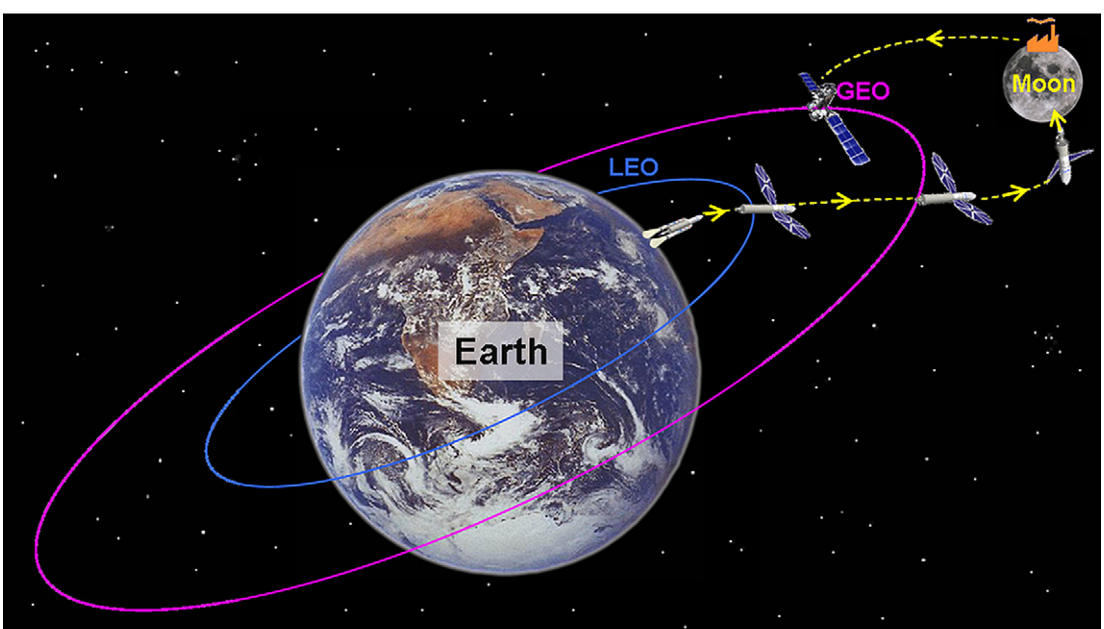

Fig. 1. Schematic presentation of the solar orbital power concept. The satellites would be launched from Earth to LEO or to GEO. They can also be lifted with the power they produce from LEO to GEO or to the Moon. The Moon can be used for large scale manufacturing, and the satellites can be launched from the Moon to GEO, which is the optimal location for solar orbital power.

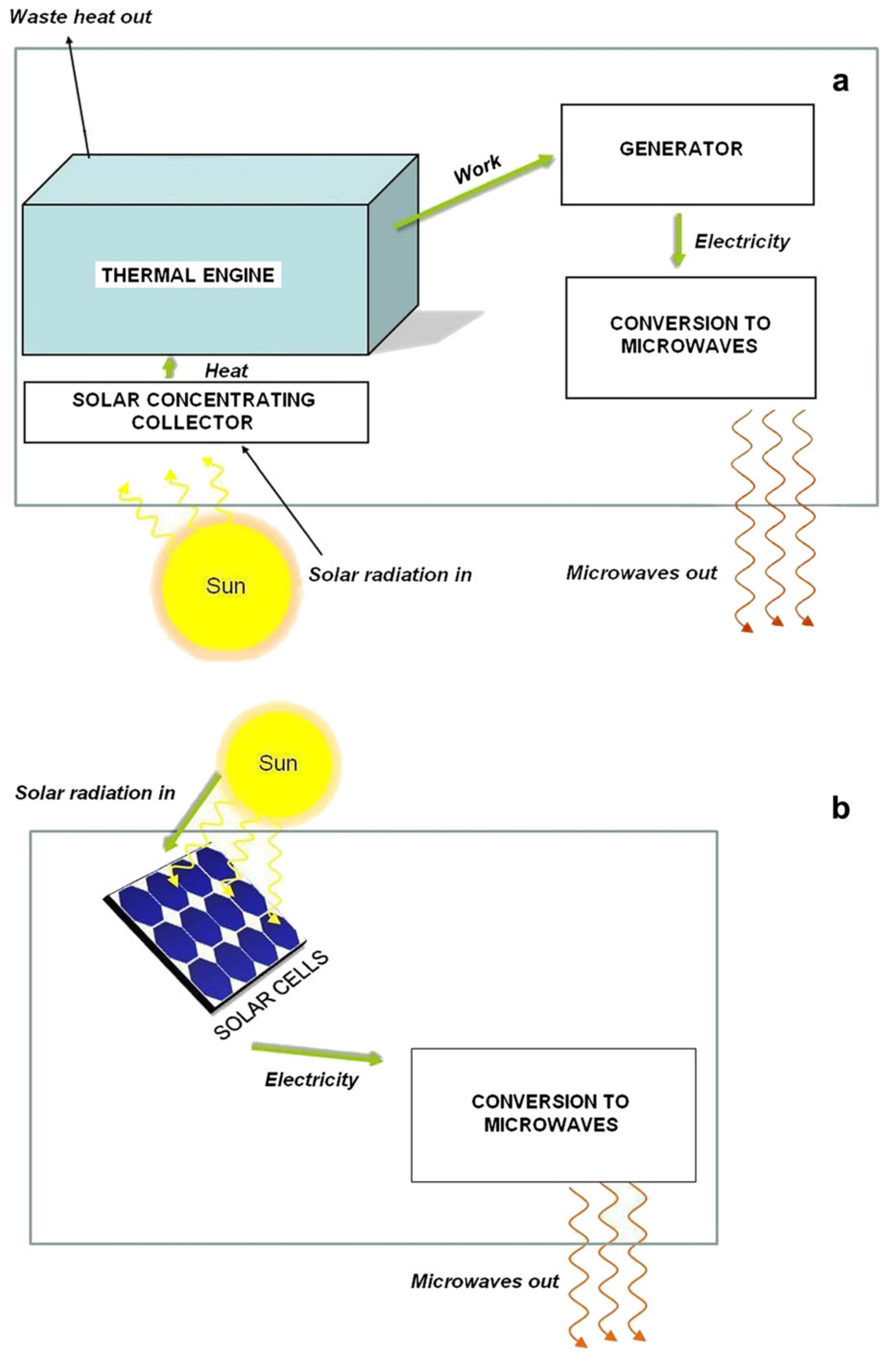

Fig. 2. Schematic presentation of the solar orbital power plant: (a) Solar thermal power uses heat from the Sun to power the turbines. The generated electricity is converted to microwaves, and transmitted to Earth. (b) Photovoltaic power plant uses solar cells for generation of electricity, and is otherwise the same as the solar thermal power plant.

[9]. Other combinations of energy source and power plant location represent improvements of this idea.

After the satellites are in space, they send the generated power back to Earth by microwaves (Fig. 3) or lasers. The radiative energy is then converted on Earth to electricity for distribution and use.

According to the launching and final location of these power stations, the following possibilities have been selected for this analysis:

(1) from Earth to a low Earth orbit (LEO) – about 200 km above the Earth surface,
(2) from Earth to a geostationary Earth orbit (GEO) where the satellite is always above the same point on the Earth surface – 35,785 km above the sea level if directly above the equator,
(3) from Earth to Moon at an average distance of $(3.82)10^5$ km
(4) from Moon to GEO – distance approximately $(0.346)10^6$ km.

For all above mentioned cases we roughly estimate (or find in available literature) the emissions of carbon dioxide (CO_2) produced during the system lifetime, which includes the production of the rocket fuel and combustion of it, and also its production by manufacturing the materials needed for both the rocket and the satellites. We also roughly estimate the cost of the system's production and launch. We also mention some social impacts of using these technologies, and thus attempt to address the sustainability of these systems, recalling that sustainability analysis founded on the consideration of economic, environmental and social impacts.

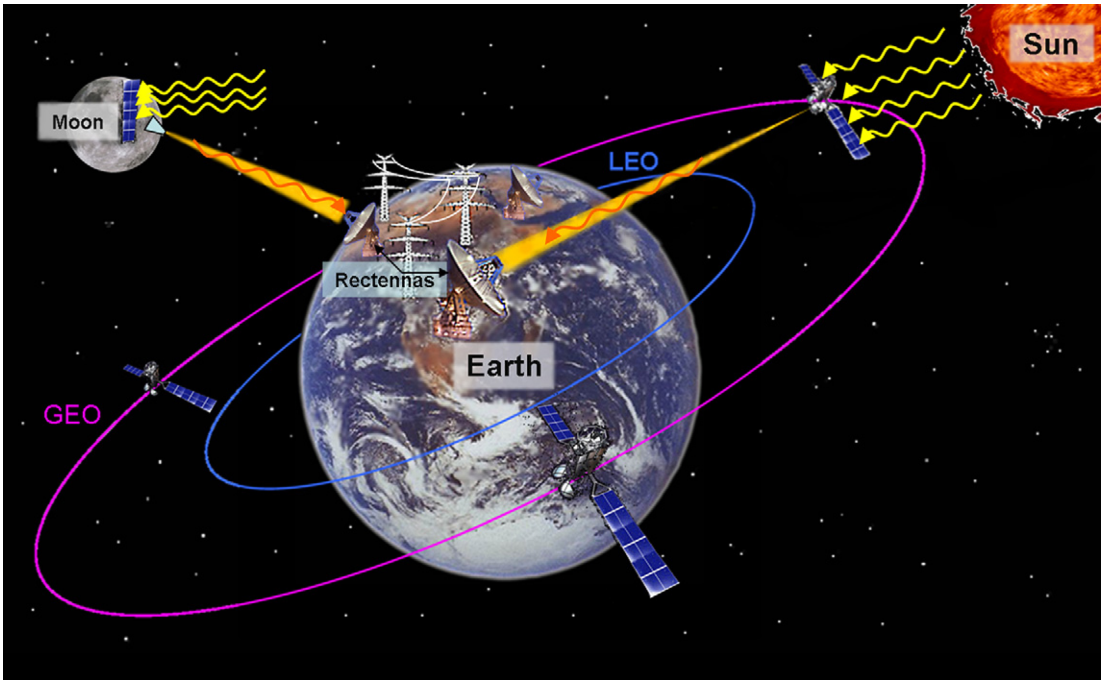

Fig. 3. Schematic presentation of the transfer of power from space or Moon to Earth. Large antennas are used in the orbit to transmit microwaves, and another large receiving antenna (rectenna) is used on Earth to receive the power from the microwaves and convert it to electricity for distribution and use.

3. Emission analysis

Since there are many different possibilities for both production and launch of the solar power satellite, we had to find a reference to which our analysis would compare. We chose to estimate CO_2 emissions as a common indicator for environmental sustainability. Although these emissions are difficult to estimate and depend strongly on the development of technology, we can get a good picture about the potential of each proposed solution to reduce the emissions. It is also important to keep in mind that CO_2 emissions represent only a part of the entire environmental damage that may be caused by the energy production. We used the model of Asakura et al. [10] of CO_2 emissions, which was developed based on assumptions about the DOE/NASA reference system [9].

We choose the rocket for carrying the satellites as either the well-known Ariane 5 ECA [11] (with a mass of 85 tons, carrying a 6 ton satellite to GEO and 14 ton satellite to LEO) or SpaceX Falcon 9 Heavy (a U.S. novel commercial rocket reportedly capable of lifting over 28,000 kg to Low Earth Orbit, and over 12,000 kg to Geostationary Transfer Orbit, planned to enter service this year [12]). We selected the Falcon 9 vessel because of its intended full reusability. It already won the contract from NASA to resupply the International Space Station. This reusable rocket is expected to significantly lower the cost of transport into the orbit [12].

Ariane 5 needs about 2.5×10^{13} J of energy for launching from the Earth to LEO, 4.5×10^{13} J to GEO, 4.8×10^{13} J to reach the Moon, and 2.6×10^{13} J for launching from the Moon to GEO. There are two types of propellant for the Ariane 5, which are both used during the launch [11]:

1) a solid one is used in Ariane's 2 solid busters which burns for about 130 s – a mixture of 476 tons of propellant in the two solid boosters consisting of 68 wt.% of ammonium perchlorate (oxidizer), 18 wt.% of aluminum (fuel) and 14 wt.% of polybutadiene (binder), and
2) a liquid one is used in its main cryogenic stage which burns for about 600 s (a cryogenic mixture of liquid oxygen and liquid hydrogen in the mass ratio of 5.1:1).

Falcon uses rocket fuel LOX/RP-1, which is a highly refined form of kerosene with added liquid oxygen. Mass of the fuel load is not yet available, however this fuel is very similar to the one that NASA used in their calculations in the 70's [9]. We therefore used the NASA estimations for the CO_2 emissions [9,10] for the rocket Falcon, and we made our own estimations for the CO_2 emissions for the Ariane system. According to the chemical formula of polybutadiene we estimated the CO_2 emissions for the four considered missions and for different types of satellites (Table 1). The CO_2 emissions for all used materials are also included, assuming that the rocket weights around 85 tons and consists of 35% aluminum, 15% of carbon fibre reinforced plastic (CFRP) and 40% of steel [11]. We note that the emissions could possibly vary significantly depending on how the energy for production of materials is acquired (for example: electricity from thermal or hydro power station). For the estimation of emissions for the production of a satellite we assumed a similar material composition as for the rocket.

The results in Table 1 have been calculated based on the model of Asakura et al. [10] who divided the contributions to launch emissions (mainly propellant and materials for the production of rocket), production of the satellite (mainly material and energy), production of photovoltaics and production of the rectenna for microwave power transmission back to Earth. In Table 1a we calculated launch emissions for a thermal power satellite for different types of launch vehicles and in Table 1b we calculated the same parameters for a photovoltaic satellite. The CO_2 emissions for the production of thermal power equipment have been estimated based on the analysis of Lechon et al. [13] and for the production of photovoltaics based on the analysis of Kato et al. [14]. A similar size and mass of the thermal power satellites was assumed. In Table 1 we calculated launch emissions for different types of launch vehicles. As regards the GEO orbit, roughly similar values of CO_2 emissions are obtained in Table 1 for all three systems, both for photovoltaic and thermal power satellites. The calculated CO_2 emissions of the Asakura's estimate [10] for the original NASA plans [9] and CO_2 emissions for the launch with Ariane 5 are very similar, and the difference is due to a larger estimate of CO_2 emissions for

Table 1
Comparison of the CO_2 emissions[a], in kg/W of net electric power generated at the rectenna on Earth, of the rocket and power generation satellite, for launching into LEO, GEO, to the Moon and from the Moon to the GEO.

	Earth–LEO	Earth–GEO	Earth–Moon	Moon–GEO
a) Solar thermal power[a]				
Ariane 5 ECA [11]	3.4	4.0	4.1	0.4
SpaceX Falcon 9 Heavy [12]	4.0	5.1	5.3	0.5
b) Solar photovoltaic power[a]				
DOE/NASA concept [9]		7.5		
Ariane 5 ECA [11]	4.5	5.1	5.3	0.5
SpaceX Falcon 9 Heavy [12]	5.1	6.3	6.4	0.6

[a] In the evaluation of the CO_2 emission due to propellant for Ariane we took account of three contributions: emission directly from burning solid propellant, emission for production of aluminum in the fuel and hydrogen is estimated to be produced with low carbon emissions, less than 10% of those for the same amount of energy from fossil fuels. We also take into account 30% losses during space to Earth transmission. In the evaluation of the CO_2 emission due to materials for the rocket for Falcon we took into account the reusability of its parts and estimated them to about one half of Ariane's. For the fuel we used properties of the rocket grade kerosene.

the construction of the Ariane 5 rocket based on available data of its material composition [11]. Falcon 9 Heavy is better in its material construction because all stages are designed for reuse and therefore its launch costs are lower. Its emission values are however a little higher, because it uses rocket grade kerosene, which produces about 3.15 times its mass as CO_2 emissions during its complete combustion.

We also assumed zero emissions for the launch from the Moon, because local materials and fuels from the Moon would be used, so there are no emissions on Earth. However, in reality there is a need to launch initial materials and robots as well as maintenance for the robotic factory on the Moon, so the real emissions are not zero. Since the complete information about these emissions is unavailable, we make the following approximations: these emissions are estimated to be a few percent of the emissions for Earth to GEO, and depend on the total number of satellites built on the Moon. This is based on the assumption that a robotic factory on the Moon can be built with a launched mass similar to one space power station. This assumption should have a correct order of magnitude. Namely, one would only have to transport from Earth the robots, computers, electronics and some building materials which are not available on the Moon. Also there could be some electronic and semiconductor parts, which could not be produced on the Moon and should be transported from the Earth. However, at least for the solar thermal power station, most of its mass is actually for the satellite structure and the container for the liquid, which could be built from materials on the Moon. The percentage of mass that should be launched from the Earth depends mainly on the advances in robotic technology and also on the speed of building orbital solar power plants. An estimate by Koelle from 1997 [15] demonstrates that even with technology from a decade ago and an important role of human labor on the Moon our estimate is reasonable. After high initial investment costs the necessary funding requirement are reduced significantly after about 10–15 years [15]. If more robotic work is used instead of human labor, and if robots also build new robotic factories on the Moon, this process could be even more efficient.

When such a robotic factory builds 100 space power stations, the total CO_2 emissions per 1 W of power would therefore be about 1% of those for the launch from the Earth. Since it is rather difficult to estimate the exact mass of the launched mass necessary to build a robotic factory, this is a rough estimate, which is however inversely proportional to the total number of space power station built on the Moon.

Currently we get about 85% of the world energy from fossil fuels. They generate about 10 MJ of energy per 1 kg of CO_2 emissions. We compare this to the solar power satellite emission results shown in Table 1, assuming 25 years of operation for the solar power satellite. In its lifetime 1 W of space solar electric power will thus produce about 760 MJ of energy, if we assume that it operates 95% of the time, and we would get more than 500 MJ of energy to Earth, if we assume 70% efficiency of the energy transmission system [16]. In this paper we define efficiency as the ratio between the electricity delivered by the rectenna into the terrestrial transmission line and the electricity generated in space as the input to the space microwave transmission system. All the data in the tables are calculated for the power received at the rectenna on Earth. If we produce the same amount of energy on Earth from oil (energy density about 40 MJ/kg), we get about 50 kg of CO_2 emissions at 100% thermal efficiency and 1oad factor. For a more realistic efficiency of about 30% these emissions are about 150 kg, i.e. two orders of magnitude more than for a typical space power station. This means that all the described Earth launched solar power satellites produce about one order of magnitude less CO_2 emissions than fossil fuels for the same amount of generated electricity. If the satellites are built and launched from the Moon, the emissions are even lower. With this result it is important to keep in mind that CO_2 emissions are not the only cost to environment. Among other environmental impacts it is for example important to take into account that the rocket fuel emissions may also destroy ozone, and it is important to explore the possible effects of microwaves and laser beams on the ionosphere. However, such a clear advantage of orbital solar power satellites demonstrates that this is indeed a very sound energy technology from a global warming reduction point of view.

4. Cost analysis

Unobstructed by the Earth atmosphere, the intensity of solar radiation in an orbit close to the Earth is about 1.35 kW/m^2 which is available almost 24 h per day the whole year long. This energy can be used in a number of ways to produce power. We will consider two ways of conversion of solar radiation into electric energy: 1) direct conversion via photovoltaic (PV) cells and 2) conversion to heat for operating some type of thermal power cycle as mentioned above.

We estimated the cost of each case in a way similar to that we used to calculate CO_2 emissions. We divided the contributions to launch costs (mainly propellant and material), production of the satellite (mainly material), production of photovoltaics and production of the rectenna for microwave power transmission back to Earth.

The newer PV cells, such as the thin film multi-band gap, »rainbow« (can utilize each component of the solar radiation spectrum), and »quantum dot« types could in principle achieve the overall efficiency above 60%. Arrays of this type are projected to have a specific power of 1000 W/kg, 600 W/m^2. One of the system concepts for low cost is the »Sun tower«. It consists of about 15 km long common tether made of both electrical and mechanical support cables, which is attached to about thirty 1-MW PV modules, and at its end to a 200–300 m diameter 250 MW FET device phased RF generator-transmitter aimed rectenna on Earth [3].

Another way of converting solar energy to electricity is so called solar dynamic power systems. They use solar heat to generate electrical power via a thermal engine. The solar radiation is intercepted by a concentrator which focuses it on the engine's working fluid (the highest results are when the diatomic gases are used – N_2, H_2) in different thermal cycles (such as Brayton, Rankine, Ericsson, Stirling). Under conditions examined in Ref. [4], the thermal efficiency of Brayton cycles was predicted to reach around

60%, around 72% for the Rankine cycle and around 72% for the Ericsson cycle.

We estimate the cost for producing the photovoltaics satellite at about US $4 per W electric power, and about US $2 per W for thermal power. Generation of 150 W electric power per 1 kg mass of the satellite (Table 2a) also seems reasonable, as this was the initial DOE/NASA estimate [9]. This ratio might be improved to 1000 W/kg (Table 2b), however the technology is not yet available for large scale production [2]. Launching a 6 ton satellite to the GEO orbit or a 17.9 ton one to LEO orbit costs about US $120 million for Ariane 5 [11], and it is predicted that launching a 27.5 ton satellite to LEO or a 15 ton satellite to GEO orbit costs about US $90 million for the Falcon 9 Heavy [12]. Since the costs for the production of the satellite don't depend on the means of transport, they are not given in Table 2. For the total costs of 1 W of power one should therefore add the price of the satellite production. This price depends on technology. If we assume a similar price to that for production of solar power plants on Earth, this would add about US $4 [14] to the price calculated in Table 2. One can expect that this price would decrease with improvements in solar technology.

If we assume a realistic value of 150 W electric power at rectenna per 1 kg of launch mass (the initial DOE/NASA estimate [9]) or even a futuristic value of 1000 W/kg, we notice that competitive prices of orbital energy can only be achieved with launches from the Moon. For launching from Earth, it is currently believed that the best future possibility is the development and use of low cost highly reusable unmanned space transport systems such as the VentureStar program estimated to attain launch cost of about US $500 per kg [3]. It is of course possible that further advances in technology will reduce these prices.

Since NASA estimated that building the power satellites on the Moon would be cheaper than launching them from Earth for as few as thirty 10 GW satellites [17], the idea to use the Moon for robotic building of the satellites seems a promising possibility. The satellites could then either be used on the surface of the Moon or launched into the GEO orbit, which would have some benefits for energy transport to Earth. Namely, GEO orbit gets light from the Sun almost all the time, while a given point on the surface of the Moon gets it only about 50% of the time. Also, a satellite in the GEO orbit is above the same place on Earth all the time, and it is about ten times closer to Earth, so the transfer of energy to the surface is easier.

The most important challenge for the scenario of launching from the Moon is the state of the art of robotic technology. When reliable robots that could work with very little human supervision become available, building the power stations on the Moon will become relatively cheap, because after the initial launch of the construction system to the moon there would be minimal labor costs (for supervision of the factories on the Moon from Earth), and most of the raw materials and energy sources would be obtained locally from the Moon without environmental impact on Earth. The NASA Apollo missions found that Lunar soil is composed of useful elements, such as O: 42% (by mass), Si: 21%, Fe: 13%, Ca: 8%, Al: 7%, Mg: 6%, other: 3% [17]. The elements for space power station construction materials (Fe, Al), for glass reflectors (Si, O) and for semiconductor devices (Si) are thus abundant, and the very small amounts of other necessary elements (impurities for silicon based integrated circuits, etc.) can be brought from Earth. Also, as these materials, machines and energy would be produced by the robots with little or no human supervision, their price is likely to be small compared to their price on Earth. While this vision is rather futuristic, advances in technology, in particular in robotics, are very promising [5]. There is no principal objection that would prevent building a robotic factory on the Moon, which would produce space power stations. If we assume that the launch of a similar mass as the one required for a large 10 GW power station is enough to build a robotic factory on the Moon, then the price of one solar power station would drop to about 1% of the price for launch from the Earth after 100 solar power stations are built. These estimates are consistent with a recent analysis by Globus [18].

According to one of NASA's visions, electromagnetic mass accelerators (mass drivers) could be used to fire small packets of construction materials from the Moon to the exact location in the Earth's orbit where the construction of solar power plant would be done [19]. Mass driver technology was tested under the sponsorship of the Space Studies Institute (SSI) [20].

The robotic factory on the Moon would still require some remote supervision from the Earth and occasional service flights to the Moon, but the price of solar power stations would decrease inversely proportional to the number of power stations built. Even if we assume that about 10% of the mass for the orbital power station should come from the Earth, the price is still one order of magnitude lower than if the satellite is built and launched from the Earth.

Comparison of costs for solar orbital power and some typical terrestrial sources is given in Table 3.

The error estimates depend mainly on the speed of the technology development in areas like launching to the orbit, robotic technology, production of rectenna, manufacturing in the orbit and on the Moon.

The prices we calculate are conservative estimates and there are many possibilities to further reduce the prices. For example, there are new concepts which promise cheaper launching, for example Boeing X-37. There is also an experimental Indian launch vehicle called Avatar, which promises to launch for US $67 per kg [24]. This is almost fifty times cheaper than launch with Falcon, and would reduce the difference in price between solar orbital power plant and Earth-based solar power plant to less than US $0.45 per Watt at a realistic estimate of 150 W per 1 kg. Another commercial venture – Space Island group – even estimated the price of generated electricity to be US $0.10 per Watt with an estimated launch already in 2012. They plan to use used fuel tanks as orbital

Table 2
Comparison of launch costs in US$/W of net electric power generated for use at the rectenna on Earth, for launching into LEO, GEO, to the Moon and from the Moon to the GEO. The prices were calculated for the launch price of US $120 million for Ariane [11] and US $90 million for Falcon [12]. We also take into account 30% losses during the energy transmission from space to Earth.

	Earth–LEO	Earth–GEO	Earth–Moon	Moon–GEO
a) Estimate for 150 W of generated power per 1 kg of the payload launch mass				
DOE/NASA concept [9]		Up to $7/W[a]		
Ariane 5 ECA [11]	$63/W	$190/W	$211/W[b]	$21/W[c]
SpaceX Falcon 9 Heavy [12]	$31/W	$71/W	$79/W[b]	$8/W[c]
b) Estimate for 1000 W of generated power per 1 kg of the payload launch mass				
Ariane 5 ECA [11]	$10/W	$29/W	$32/W[b]	$3/W[c]
SpaceX Falcon 9 Heavy [12]	$5/W	$11/W	$12/W[b]	$1/W[c]

[a] This estimate was for the complete system together with the launch, however it seems way too optimistic.

[b] Price for the launch to the Moon has been estimated so that additional 4% of safety factor has been added to the launch to GEO for maneuvering and landing on the Moon.

[c] Estimate based on the price of launching from Earth with a similar demand for energy. We assume that the first rocket is launched from Earth with materials, robots, electronic and other parts necessary to establish a robotic factory, which would launch at least 100 satellites of similar mass as the initial launch to the Moon. For these satellites we assume that about 90% of their mass would come from local sources on the Moon. Since the materials and fuel should be mined from the Moon with a robotic system, the real price would comprise the price of manufacturing and launching the components for the robotic system and supervision of its operation from Earth. This price could be significantly lower with an increasing number of satellites.

Table 3
Comparison of costs for solar orbital power and some typical terrestrial sources. Only currently available technologies have been considered to estimate the costs. The data are rough estimates and change with the improvement of technology.

	Production costs in US$/MWh electricity delivered to terrestrial transmission lines	CO_2 emissions, kg/MWh electricity delivered to terrestrial transmission lines	Availability, in years, of known energy resources, based on current global consumption rates
Fossil fuels (coal)	25–55[a]	1100[c]	Hundreds (coal)
Nuclear fission	21–31[a]	15[c]	Thousands (for breeding technologies)
Hydroelectric power	10–$80[a]	100 kg[c]	$>10^8$ (lifetime of the Earth)
Solar power on the Earth	150[a]	≈25[c]	$>10^9$ (lifetime of the Sun)
Space solar launched from the Earth	≈$400[b]	≈ 40[d]	$>10^9$ (lifetime of the Sun)
Space solar launched from the Moon[e]	9[b]	0.4[d]	$>10^9$ (lifetime of the Sun)

[a] Production costs per MWh of energy have been estimated by NEA, IEA and OECD [21] for different countries, and should be understood as a very rough estimate. For coal about 1/3 of the estimated costs is for investment, about 20% for maintenance and about 45% for fuel. For nuclear fission about 50% of the estimated costs is for investment, about 30% for maintenance and about 20% for fuel. For small hydro the price is above US $40, and for large hydro the price can be as low as US $10.
[b] Best results from Table 2 have been used from space solar power estimates using a discount rate of 5% and lifetime of 25 years.
[c] CO_2 emissions have been estimated from reference [22] and for solar power from reference [23]. These numbers have large uncertainties, and should be understood only as orders of magnitude.
[d] CO_2 emissions have been used from Table 1 and calculated for 1 MWh using 25 year lifetime and 95% availability of the orbital power plant.
[e] It should be noted again that the production and environmental costs for the space solar power stations launched from the Moon the above mentioned factor 100 in the ratio of total mass of stations to the necessary mass sent from Earth is considered; this brings 100 times smaller values than obtained by NASA.

stations and rent them to commercial users for tourism, research and other applications. In this way they claim that they could recover the complete price of the launch in one year [25]. Although this is a rather optimistic estimate, it represents further evidence that our estimates may be achievable already with the existing technology. There is however also a physical limit for a minimum amount of energy required for launch. Namely, the law of gravity requires that the minimum amount of energy per unit mass $w_{\min}$ invested to launch an object into the orbit at a distance l from the Earth surface is

$$w_{\min} = \frac{Gm_Z(r_Z + 2l)}{2r_Z(r_Z + l)}, \quad (1)$$

where G is the gravitational constant, m_Z mass of Earth, and r_Z radius of Earth. All losses as well as rotation of Earth are here neglected. From Eq. (1) the minimum energy required for launching of 1 kg into the LEO orbit is 31.2 MJ and 57.7 MJ into the GEO orbit. This is roughly equivalent to US $1 for LEO and US $2 for GEO. Since one also has to launch the rest of the rocket and the fuel in addition to the payload, one should add about two orders of magnitude. This means that it is in principle possible to launch with costs estimated for Avatar, however further reductions are not possible without changing the concept of rocket launch.

Also in robotic technology the price of computer hardware is expected to significantly decrease. Namely, for the last 40 years the price was reduced by approximately a factor of 10 every 10 years. Since a similar trend is expected for at least the next 10 years, this provides further opportunities to reduce the prices.

The estimated prices will be further reduced is the orbital solar power plants are built at a slower pace. In this way, more can be built in the orbit or on the Moon, and the need for launching is reduced.

The above analysis can be compared with a recent calculation for one of these scenarios by Ongaro and Summerer [26]. They compared prices of solar electricity produced on Earth and in space. If the price of electricity produced in space was lower, they calculated the maximum price of launch, for which solar electricity produced in space would not be more expensive than that produced on Earth. They found that under peak load scenarios the required launch costs must be less than about $700 per kg launch mass for a plant of 100 GW generation capacity, assuming that the compared power station on Earth also used pumped hydro energy storage. This price depends only slightly on total power, e.g. it increases to about US $900 per kg for 150 GW capacity. Under the base-load scenarios the situation is even worse. In this case the competitive launch cost must drop to about US $400 per kg launch mass for a 100 GW capacity plant. More details have also been published [27–29], however this price is much lower than current launch costs.

Terrestrial solar power plant located in a non-populated and currently unused terrain in north-African Egypt as well as a system of distributed relatively small solar tower plants in the south-European sunbelt have been studied as reference terrestrial systems [26] for all considered power levels (0.5–500 GWe) and for peak load as well as base-load power supply. Detailed information on the solar terrestrial plant concepts in this comparison are given in Ref. [26] and references therein. In the case of base-load scenarios, terrestrial solar tower plants with local hydrogen storage were predicted to generate electricity at costs between €0.076 and €0.09 per kWh for the largest (500 MWe) and the smallest (500 GWe) plants, respectively [26].

5. Social impact

Estimation of the sustainability of solar space power generation requires also the evaluation of the associated social impacts. The Human Development Index (HDI) is one of the most popular measures of social development measured since 1975. The sustainable development index (SDI) is a more complex measure, which includes institutional (disaster & human cost, disasters & economic damage, SD indicator coverage, SD strategy, SD membership, internet, telephones, R&D expenditure), economic (GNP, GDFI, CAB, external debt, ODA, materials, energy use, renewable energy, energy efficiency, municipal waste, hazardous waste, nuclear waste, recycling, car use), social (poverty, equity, unemployment, F/M wages, child weight, child mortality, life expectancy, sanitation, safe water, health care, child immunization, contraception, primary schools, secondary schools, illiteracy, crowding, crime, population growth, urbanization) and environmental (CO_2, other GHG, CFC's, urban air, cropland, fertilizer, pesticides, forest area, wood harvesting, desert & arid land, squatters, phosphorus, coastal population, aquaculture, water use, BOD, faecal coliform, key ecosystems, mammals & birds, protected areas) indicators and is available from JRC Ispra [30]. Since there are many different concepts for space solar power, and many complex metrics, it is difficult at this time to provide an accurate general analysis of their social impact, but it should be determined during the feasibility assessment phase when specific systems are defined for evaluation.

Regarding employment, the simplest case of photovoltaic satellites launched from Earth seems to decrease the number of necessary jobs, but improve their quality as further elaborated below. We will estimate the lowest and the highest limits. One limit for the number of jobs lost can be estimated from the introduction of Earth-based solar photovoltaics systems. A study in Spain found that about 3–4 jobs were created for each installed MW of solar power, however due to the inefficiencies of subsidies many more jobs were lost elsewhere in the economy, so that the total effect of photovoltaic solar power was the loss of about 9 jobs per MW [31]. Here the main problem was that there was a kind of rebound effect. Namely, the state subsidies for renewable energy destroy more than twice as many jobs as are created with investments in the renewable energy. This destruction of jobs is even worse for solar energy, which requires above average subsidies. However, this result has been calculated only for the production of solar energy on Earth with existing technology, which requires large subsidies.

The other limit for the estimated jobs lost could be taken as the total number of jobs for energy creation. This is about 5 jobs per MW for fossil fuels such as coal. Here the estimate is that about 1.4 million people in the US create about a billion ton coal per year [32], which gives about 5 jobs per MW of useful power. This number is probably even higher, because jobs related to operation of the plant, fuel transportation, waste disposal, etc. are not taken into account. If the energy production is shifted from domination of fossil fuels to cheap and clean production of energy in the orbit, there will however be no need for energy subsidies and the price of energy will decrease significantly.

Better technology such as robotic production facility for solar power satellites on the Moon would, in the long term, require a very small – almost negligible – number of jobs for the production of energy systems as compared with the current number of jobs in the energy sector. However, it would require no subsidies, since the calculated price of energy shown in Table 3 is at least two times smaller than the price of energy from fossil fuels. Therefore there would be no loss of jobs due to the rebound effect. On the contrary, reduced price of electricity would free resources elsewhere in the economy and therefore create new jobs. The estimates for job creation of investments in coal technologies vary, but it is not below the average in the industry [33]. Therefore the capital liberated from the investments in coal would create at least as many jobs as would be destroyed by reducing the use of coal. Also, the savings from the reduced price of energy would create additional jobs, and with data from Table 3 we can estimate that the total effect on employment would be about 3 jobs created per 1 MW of space solar power, if it is produced on the Moon and installed in the orbit.

In comparison, Solnick [34] states that a large decrease in energy prices could add about 0.4% to the total number of jobs. Globally this would amount to about 1 added job per MW. It is however important to note that Solnick calculated this result only for small changes in the energy prices, and that global economy changed a lot since that study. His results were calculated for conditions around the year 1980, and large amounts of very cheap clean energy would create many positive changes in society, which are hard to quantify. They would very likely more than offset the expected loss of jobs in energy production, which is estimated to be between 4 and 9 jobs per MW of installed electric power. Also, there would be additional jobs needed for the production and launch of the rockets, for maintenance and remote control of the satellites, robotic factories on the Moon, rectennas and the development of other technologies necessary for the operation of orbital power stations. Given the uncertainties related to all these factors, even the order of magnitude is not certain, and it is quite possible that jobs would not be lost, but would even be generated. Our estimate discussed in the previous paragraph, that about 3 jobs would be created per 1 MW of installed power, seems therefore reasonable.

Other important aspects of social impact are difficult to estimate quantitatively at his time. It is obvious in any case that a higher level of education will be needed for the development of space technology including enhancement of the level of terrestrial robotisation as well as information and communication technology. If energy is obtained from space, we will need less land for energy production. Low price of clean energy from orbital sources could also contribute to improved social equity, reduction of poverty, increased life expectancy and other millennium development goals.

6. Discussion

While our analysis tentatively indicates that the solar orbital power concept may be economically, environmentally and socially acceptable, there is an issue of the large initial investment. While small orbital power stations are already planned by the private sector, the scenario with manufacturing on the Moon requires a larger investment. Old estimates from NASA in the 70s put the break-even point at 30 power stations of 10 GW each [17]. NASA also sponsored 1977 Ames Summer Study on Space Settlements and Industrialization Using Nonterrestial Materials (not taking into account technological advances in the last 30 years) that the cost of initial investment is US $50-100 billion, and that the first 30 GW of power would be available in 10 years with the first 10 GW plant already in 8 years. This price can be further reduced if the satellites are launched into LEO orbit, and lifted from there using their own power [35]. Ideas from O'Neill et al. [36] simplify manufacturing on the Moon and allow for a smaller scale start-up, which would multiply itself. We can therefore take the above estimate of US $50 billion as a sufficient initial investment for this scenario, even if technological advances in the last 30 years are not taken into account. It is noteworthy that this investment, while large, is only a small fraction of the US $550 billion estimated for the DESERTEC project [37] intended to provide electricity for much of Western Europe and the Middle-East and North Africa region by generating it from solar energy in the deserts of North Africa and transmitting it via high voltage DC lines to Europe.

There are also some other effects of providing energy from space to Earth. The undesirable effects include losses of transmitting microwaves through the atmosphere, which heat the atmosphere. Since losses are estimated to less than 1% in the atmosphere [38] and about 15% at the rectenna [39], this is significantly less than losses for either internal combustion engine or losses for Earth-based photovoltaics. The desirable effects include location of power plants far away from people's homes and very stable production of energy independent of weather almost 24 h a day.

For sustainability analysis it is also important that the more solar orbital power is used, cheaper it will become to build new solar power satellites. Namely, large amounts of cheap energy from space will reduce the prices of energy and raw materials needed for the production of new units. This property of solar orbital power is exactly the opposite to most other energy sources and in particular of fossil fuels, which become more expensive with use because of the depletion of non-renewable resources.

It is interesting to compare the concept of solar orbital power with other promising clean energy sources.

Nuclear fusion has been a promising source of cheap clean energy for a long time [40–42]. In spite of significant multi-billion US $investments it is unlikely that any commercial power would be available in the next three decades [42]. The most optimistic scenario of ITER plans to introduce the first demonstration power plant called DEMO designed to produce 2000–4000 MW of power in the early 2030s, and put fusion power into the grid in the best case scenario in 2040. It can therefore not contribute to the reduction of environmental stress in the next 30 years, and other technologies are necessary for the transition period.

Solar photovoltaics on Earth are severely limited by a finite amount of insolation due to daily variations and weather fluctuations. In order to solve this problem it has been suggested to place the solar power plants in the desert areas with high average insolation. DESERTEC is a practical example of this idea [37]. It offers both environmental and social benefits via reduction of greenhouse gases on one hand and economic opportunities to underdeveloped countries. There are however many real or perceived risks associated, such as regulatory, political, and *force majeure* (which includes terrorism) [43]. Also, there is less than 40% of sunlight available in the best parts of the deserts close to the equator and without atmospheric influences. In addition to losses due to energy transport over large distances from the deserts to the metropolitan areas this increases the price of the DESERTEC concept so that it is comparable to solar orbital power. Large scale solar plants in the desert also change the albedo and thus usually contribute more to heating of the atmosphere as solar orbital satellites. In addition to a more stable practically 24-h a day supply of power from solar orbital satellites this presents a strong case for feasibility of large scale solar orbital power as compared to the power from the deserts.

Solar orbital power appears thus to be competitive both to nuclear fusion and to solar energy from Earth. This is consistent with the findings of Globus [18] who stated that the »wisest energy policy from an environmental perspective may be to encourage wind and ground solar, particularly on rooftops where no land is consumed, combined with a vigorous SSP development effort«. We concur that a combination of distributed, intermittent renewable energy production with the large scale and steady potential of SSP could prove best, especially when the space power fraction can be substantially built from lunar materials.

7. Conclusions

We have analysed some economic, environmental and social aspects of sustainability for electricity production in solar space power plants using current technology. While space solar power is still way too expensive for launches from the Earth, there are several technological possibilities to reduce this price. For a large scale application of orbital power stations both environmental impact and costs can be significantly reduced. The first option is to build and employ reusable space vehicles for launching the satellites, instead of rockets, which is the main recommendation by NASA, and the second option is to build the satellites and rockets in space (e.g. on the Moon). An old NASA estimate shows that this would be economical for as few as 30 orbital satellites with 300 GWe of total power [17]. The costs could be even further reduced, if the first satellite is launched into the low Earth orbit, and then uses its produced energy to lift itself into a higher GEO orbit or even to the Moon [35]. If the satellites and rockets are then built on the Moon in robotic factories, we estimate that:

- The environmental impact of the orbital solar power plants would become significantly lower than for any Earth-based power plant except perhaps nuclear fusion. Measured by CO_2 emissions, it would be about 0.5 kg per W of useful power, and this number would even decrease with improved technology and larger scope;
- The production cost of the orbital solar power plants could also become significantly lower than for any Earth-based power plant except perhaps nuclear fusion. It is estimated as about US $1 per W of useful power, and would also decrease with improved technology and larger scope;
- The social impact of cheap and clean energy from space is more difficult to estimate, because space power satellites seem to be connected to a significant loss of jobs. It is however difficult to estimate the benefits of a large amount of cheap clean energy, which would most likely more than offset the negative effects of lost jobs, and we estimate that about 3 jobs would be created in the economy per 1 MW of installed useful power.

One could therefore expect a net positive effect of solar power satellites on sustainability. These effects seem to be the most positive, if thermal power satellites are used, which are built in a robotic factory on the Moon and then launched into the GEO orbit.

The concept presented in this paper has some significant advantages over many other proposed concepts for large scale energy production on Earth. For example, nuclear fusion promises to become a clean and cheap source of energy, however even in the best case scenario it can't become operational before 2040. Solar orbital power concept can become operational in less than a decade and produce large amounts of energy in two decades. It is also important that the price as well as environmental impact of solar orbital power are expected to decrease with scale. In addition to expected increase in employment this makes solar orbital power an important alternative to other sustainable energy sources.

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