ECONOMIC FEASIBILITY OF ALTERNATIVE TECHNOLOGICAL CONCEPTS TO HARNESS RENEWABLE ENERGY FROM SPACE

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Abstract

The provision of global renewable energy services is a key challenge of the 21st century. Space sector resources have contributed immensely to the advancement of the information and communications industries, environmental monitoring and Earth observation and hold enormous potential to enhance the provision of global renewable energy services. Energy from space technologies have been assessed in the research literature using two distinct technological concepts namely orbiting solar reflectors (OSR) and solar power satellites (SPS). However, previous studies have discussed these two technological concepts separately, focusing on either one of them. In this paper, we analyse the long-term economic feasibility of OSR and SPS for utility-scale electricity generation of approximately 2 GW under a trend of falling Earth to orbit transportation costs. We evaluate their net present value and assess the conditions for which these technologies will become economically viable. We also discuss the prospects of a reduction in Earth to orbit transportation costs and discount rate to improve the economic feasibility of energy from space technologies.

1. Introduction

Decarbonisation of electricity systems and the provision of clean energy services is a key challenge of the 21st century. The large-scale usage of renewable energy sources for electricity generation is a vital aspect of the progressive strategies adopted by different countries to protect the environment. For this reason, several policies have been introduced by governments across the world to incentivize renewable energy utilization in the electricity sector. The impact of some of these policies have been discussed and analyzed in the literature [1,2].

In addition, renewable energy utilization in the electricity sector has also been further enhanced by the growing participation of non-generating flexible technologies including energy storage and flexible demand which also substantially improves the economic efficiency of low-carbon electricity systems [3,4].

To achieve net zero carbon emissions, increased electrification of heat and transport networks is being witnessed. This requires a large-scale increase in the electrical supply using renewable energy sources.

The enormous potential of the space sector to enhance the provision of global renewable energy services is attracting growing interest from academia, government and industry. Space sector resources have already contributed immensely to the advancement of the information and communications industries, environmental monitoring and Earth observation. In this regard, technological concepts to harness renewable energy from space proposed in the seminal works of Oberth [5] and Glaser [6] have attracted renewed interest.

1.1. Energy from Space technologies

The utilization of space for energy production on the Earth has been assessed in the research literature using two distinct technological concepts namely orbiting solar reflectors (OSRs) and solar power satellites (SPS).

1.1.1. Orbiting Solar Reflectors: OSRs as space satellites are ultralight weight reflectors deployed in space to reflect sunlight from space to specified locations on the Earth and other planetary bodies. OSR as a concept was introduced in the work of [5]. The reflected sunlight can be used for different purposes including solar power generation, agricultural food production, night time illumination on Earth and other planetary bodies, climate engineering etc [7, 8].

The United States National Aeronautics and Space Agency (NASA) carried out studies in the late 1970s on the use of a system of OSRs for terrestrial power generation and published a preliminary technological assessment in [9].

A few recent studies [10,11] have focused on the use of OSR to enhance terrestrial solar power generation. A key advantage of OSR is that they can provide additional illumination for solar energy generation in critical dawn and dusk hours where electricity demand is high, and solar energy generation is low. OSR are usually deployed in low Earth orbit (LEO) and as a result, a constellation of multiple reflectors can only provide illumination to a given location for few hours of the day. However, they can visit multiple locations within a day.

In line with the worldwide decarbonisation of electricity generation, the solar energy industry is growing very fast. Large capacity sized terrestrial solar power plants are being constructed and developed which though not driven by the possible deployment of OSR, can benefit from the additional illumination provided by the OSR. The results obtained in [9] shows that the solar power plants will receive better economic value when integrated with OSR.

1.1.2: Solar Power Satellite: The second technological concept to harness energy from space is using SPS. SPS as a concept was introduced in the 1968 seminal work of Peter Glaser [6]. SPS operates to collect solar energy in space, convert it into microwave energy and transmit the microwave energy to purpose-built Earth stations, where it is received using a receiving antenna (rectenna) and converted into electrical energy for use on the Earth. The microwave beam experiences approximately 7% losses (much lower than light absorption) while being transmitted to the Earth [12].

SPS can operate in different orbits but is usually considered to operate in geostationary Earth orbit (GEO) for baseload electricity generation. Several SPS technologies have been proposed in the literature, including Integrated Symmetrical Concentrator [13], SPS ALPHA [14], SPS-OMEGA [15], CASSIOPeiA [16]. However, only SPS ALPHA is being considered in this study.

Some of the differences between both OSR and SPS technologies are discussed in [11]. Previous studies have mainly discussed these two technological concepts separately. In [17], the long-term economic feasibility of investment in OSR is compared with that of investment in energy storage. The economic feasibility of using SPS ALPHA for providing 20 MW of electricity for mining operation is analysed in [18].

In this paper, we compare the economic feasibility of OSR and SPS as alternative energy from space technologies. The rest of this paper is organized as follows. Section 2 presents the assumption in this study, an overview of the parameters for the different energy from space technologies is defined in section 3. Results are discussed in section 4.

2. Assumptions

The underlying assumptions used for this study are summarized below for clarity:

- We consider utility scale electricity generation, therefore, for each energy from space technology considered in this study, we have selected the design option which generates approximately 2 GW of electricity. The specific quantity of electricity generated differs slightly for each energy from space technology.
- A discount rate of 10% is considered for this capital project. In calculating the long-term economic investment, this discount rate is applied to both the initial investment and revenue.
- The time frame for manufacture, assembly and transportation of the satellite is specified for each technology.
- An operational lifetime of 30 years is assumed for all satellites.
- The cost for transporting satellites into orbit (launch cost) is falling due to technological advancement. Based on observed trends in industry, a range of launch cost is considered from 1400 $/kg to 20 $/kg. The SpaceX Falcon Heavy Launcher can transport satellites into low Earth Orbit (LEO) at a cost of approximately $1400 per kg [19]. There is high optimism that this cost can reduce, we assume approximately 20 $/kg using the Space X Starship launcher as a lower bound [20].
- A constellation of multiple OSR is used to deliver energy for an hour each day at dawn and dusk to five different locations. While the SPS ALPHA is used to generate energy all year round (baseload generation) for only one location.
- The electricity generated is traded on the wholesale electricity market. Considering that the OSR operates in hours of higher-than-average electricity prices, we assume a fixed average price of 70 $/MWh for the energy generation of OSR. For the SPS ALPHA, we assume that the baseload electricity generated is traded at an average price of 50 $/MWh.

3. Case Studies

In this section, we present an overview of important parameters of the different technologies considered in this study.

3.1. OSR: Revenue and Cost Calculations

Using the additional illumination from the OSR, the solar farms across the five locations can generate up to 2065 MWh of energy at dawn and dusk. This involves the use of a constellation of approximately 590 satellites which weighs a total of 4637.4 tonnes. The OSR configuration is adapted from [8,17].

The annual revenue earned from the additional electricity generation is a function of the electricity price and the annual electrical energy generation. A fixed average wholesale electricity price of 70 $/MWh is considered for the dawn and dusk electricity generation aided by the OSR across the five locations of operation throughout the operational lifetime of the OSR (30 years). The annual energy generation of 7,160,387.5 MWh is obtained from multiplying the capacity of the system (2065 MW), annual operational hours across the multiple locations (2 hours), number of locations (5) and a capacity factor of 95%. Over the 30-year operational lifetime, the annual gross revenue is $501,227,125.

The costs associated with the installation and deployment of the OSR into the operational orbit includes the manufacturing, transportation and maintenance costs. Similar to the values used in [11,17], a manufacturing cost of 375 $/kg and a yearly maintenance cost of 5.63 $/kg is considered for the OSR constellation. The OSR will operate in low Earth orbit (LEO), a range of transportation costs is considered for the Earth to LEO transportation varying from 1400 $/kg to 20 $/kg.

3.2. SPS ALPHA – Revenue and Cost calculations

SPS ALPHA was initially designed by John Mankins in 2012 [14], with an updated design presented in [21]. Different configurations of the satellite can be considered to generate different amounts of power. For this study, the design configuration selected for SPS ALPHA has the capacity to generate 2081 MW and weighs 9192 tonnes. The ground station which comprises of the receiving antenna and the microwave to electricity conversion system has a diameter of 6000 metres. SPS ALPHA provides baseload generation and is assumed to have a yearly capacity factor of 99.5% resulting in an annual electricity production of 18,138,412.2 MWh. A fixed wholesale electricity price of 50 $/MWh is used to calculate the annual revenue of $906,920,610 for the 30 years lifetime of the project.

The costs associated with the deployment of SPS ALPHA into the operational orbit includes the manufacturing, transportation and maintenance cost. The manufacturing cost is assumed to be 289 $/kg, obtained from [22], the ground station has a cost of 15 $ per square metre, and a yearly maintenance cost of $100 million [22] for both space and ground facilities is considered for the SPS ALPHA.

Although SPS ALPHA operates in geosynchronous Earth orbit (GEO), as discussed in section 2, the spacecraft launch vehicle is only used to transport it to the LEO and solar electric propulsion is used for transfer to GEO. Hence, the transportation costs only involve the Earth to LEO transportation costs. Note that the solar electric propulsion costs are assumed to be part of the SPS system development costs.

A summary of the key cost and revenue components are presented in Table 1 below.

Table 1: Summary of the key characteristics.

	OSR	SPS ALPHA
Generated Electricity	2065 MW	2081 MW
Mass	4637.4 tonnes	9192 tonnes
Manufacturing Cost	375 $/kg	289 $/kg
Ground System Cost	Not Applicable	15 $/m^2
Annual Maintenance Cost	$26,551,080	$100 million
Transportation Cost	Same as cost to LEO	Same as cost to LEO
Annual Revenue	$501,227,125.	$906,920,610
Construction timeframe	2 years	3 years

4. Results

The long-term economic viability of using different energy from space technologies to generate approximately 2 GW of power is discussed in this section. The net present value (NPV) is calculated for each technology. The initial cost for each technology comprising the manufacturing, transportation and ground system cost is evenly spread across the respective development timeframe. The annual revenue earned by the different energy from space technologies as calculated in section 3 is constant for the 30-year operational lifetime assumed in this study.

The initial development cost and the annual revenue, net of the annual operation costs gives the cashflow which is discounted by a yearly rate of 10% over the development and operational lifetime considered. A summation of the discounted cashflow over the entire development and operational period of the satellite gives the net present value.

For the cost proportions at the highest launch cost, the launch cost gives 78.62% of the total cost incurred for the OSR and 80.16% of the total cost for the SPS ALPHA. We analyse the impact of reducing launch costs on the net present value for both OSR and SPS ALPHA.

Fig. 1. shows the net present value for a range of launch costs to LEO (1400 $/kg to 20 $/kg) for the OSR and SPS ALPHA energy from space technologies considered and assumptions used. At the highest launch cost considered, both technologies have a negative NPV which indicates that they are not economically feasible at that launch cost.

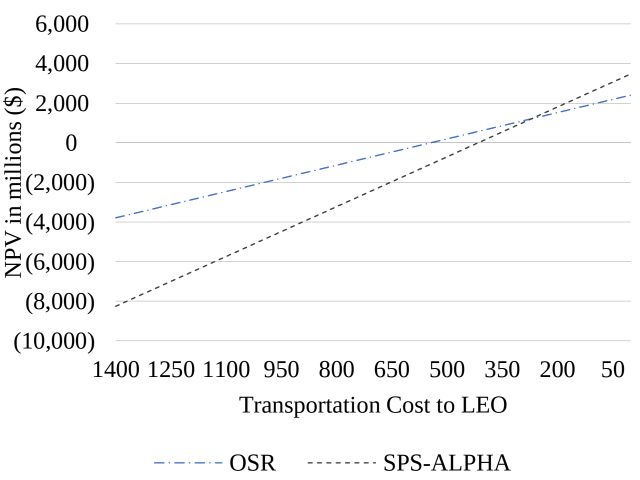

Figure 1:The net present value (NPV) for the considered technologies at different launch costs to LEO

For the OSR, while it earns a lower revenue from the sale of generated electricity, its NPV (although negative) is higher than the NPV for the other technologies. An NPV of $0.00 was however realised for the OSR when the launch cost to LEO reduces to 543 $/kg. This is the launch cost at which the OSR becomes financially viable.

Next, we consider the NPV for the SPS ALPHA. Note that the total transportation cost is the launch cost to LEO, since in-space transportation of the satellite is provided by solar electric propulsion. In calculating the NPV, the investment cost is spread evenly over the first three years (years 0, 1, 2) of building and deploying the satellite into the desired orbit. For this reason, its NPV is lower despite having higher annual revenue.

As seen in figure 1, a breakeven was achieved (NPV of $0.00) at a launch cost of 414 $/kg. implying that for a 10% discount rate, the investment only becomes financially viable when the launch cost reduces to 414 $/kg.

Using a discount rate of 5% as assumed in prior studies of [7,17]. For the OSR, the NPV at the highest launch cost is negative (- $907.77 million) and breakeven is achieved at a launch cost of 1194 $ per kg. However, for the SPS ALPHA, the NPV at highest launch cost is – 3290.89 million $, and breakeven is achieved at a launch cost of 1007 $ per kg.

To complete the study, we determined the discount rate at which both OSR and SPS ALPHA becomes financially viable under the highest launch cost. This rate is the internal rate of return (IRR).

The OSR becomes financially viable (achieves positive NPV) when the discount rate is not more than 3.82%. As for the SPS ALPHA, financial viability is achieved with a discount rate of up to 2.57%.

The results obtained are summarized in Table 2 below.

Table 2: Summary of the results obtained

		OSR	SPS-ALPHA
10% Discount Rate	Breakeven Launch Cost	543 $/kg	414 $/kg
	NPV @ Launch Cost of 1400 $/kg	- $ 3789.29 million	- $ 8256.80 million
5% Discount Rate	Breakeven Launch Cost	1194 $/kg	1007 $/kg
	NPV @ Launch Cost of 1400 $/kg	- $ 907.77 million	- $ 3,290.89 million
IRR		3.82%	2.73%

5. Conclusions

Energy from space technologies can make significant contributions to the provision of clean energy and the decarbonisation of electricity generation.

This paper analyses the long-term economic feasibility of different energy from space technologies – namely OSR and SPS ALPHA – to generate approximately 2 GW of electrical power. The analysis involved calculating the net present value (NPV) under different Earth to orbit transportation costs. For the OSR and SPS ALPHA to be considered economically feasible under our framework, the Earth to LEO transportation cost must reduce to 543 $/kg and 414 $/kg respectively.

These results have been obtained considering a discount rate of 10%. As the technologies become more proven, the risk associated with these technologies will reduce and the discount rate used for the economic feasibility will also reduce. With a discount rate of 5%, the breakeven launch cost for OSR increases to 1194 $/kg and that of SPS ALPHA increases to 1007 $/kg.

Prospects of a reduction in the Earth to orbit transportation costs and discount rate improves the economic feasibility of the energy from space technologies.

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