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Does the use of space solar power for in-space activities really make sense: An updated economic assessment

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ABSTRACT

Advocates of space solar power propose its use as a mechanism for solving terrestrial and orbital power problems. These craft collect solar radiation via their solar panels and transmit it in a more concentrated form to receiving spacecraft or ground stations. This more concentrated transmission (e.g., via laser or microwave radiation) alters the power generation equation for the receiving craft or station, as it allows smaller (both in terms of mass and volume) receiving hardware to be utilized. It also offers other prospective benefits, such as the possibility of receiving power in eclipse and the reduced deterioration rate of radio antennas, as compared to solar cells (removing the need to include extra generation capability to offset lifetime deterioration). This paper seeks to answer the question of whether the use of SSP to power other in-space craft is justified, from an economic perspective. It considers factors that can be assessed both quantitatively and qualitatively.

1. Introduction

In Ref. [1], Macauley and Davis projected the potential estimated willingness to pay (EWTP) of spacecraft operators for annualized watts of power. An annualized watt of power, which is equivalent to 8.76 kwh (kilowatt hours), was found to be worth between $500 and $6700 to the operators. This stands in stark comparison to the $0.61 that (as an example) a terrestrial industrial customer would have paid for 8.76 kwh of power on Earth in January 2014 [2]. Of course, there are no higher power transmission lines running to satellites in orbit and getting power there (and making it available for onboard use) accounts for a significant portion of this expense.

This paper presents a model for assessing alternate power generation technologies and comparing them to the conventionally used onboard generation approach. It specifically assesses this value in terms of microwave power transmission, which has been considered in prior work; however, the model could be applied to other prospective power transmission approaches, as well. This model considers more easily assessed quantitative measures, such as the cost per kwh. It also considers prospective benefits that could be provided, if required by the mission design. These are assessed qualitatively herein as part of a general-case analysis, as particular mission requirements are needed to allow a quantitative assessment of their value.

From this, several prospective power solutions for spacecraft in Earth orbit are evaluated. Using this comparison, the efficacy of space-to-space power transmission as an enterprise is assessed.

2. Background

Wireless power transmission's origin lies in the work of David Hughes, who made the first radio transmission in 1879 [3,4]. Heinrich Hertz, in 1886, demonstrated the wave-property of radio transmissions and also their ability to be transmitted across empty space [5]. Nikola Tesla suggested the use of radio for power transmission [6] and, in 1900, was granted two patents related to the wireless transmission of electricity [7,8]. Further work, in the 1930s, critical to microwave wireless power transmission (MWPT) resulted in the development of the klystron tube [9] and microwave cavity magnetron [10]. Starting in the 1950s, William Brown at Ratheon actively developed MWPT for applications such as remotely powering a beam-riding helicopter or aerial platform [9]. In 1968 [11], Peter Glaser proposed the concept of space-based solar power (SBSP) and received a patent for this in 1973 [12]. In 1975, the Jet Propulsion Laboratory demonstrated this practically, transmitting 37 kw over a one-mile distance (and receiving and converting 84% of this initial energy to direct current) [13]. A variety of studies of the SBSP concept have been performed by the U.S. National Aeronautics and Space Administration (NASA) and U.S.

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Department of Energy (DoE), starting in 1976 [14], documenting the growing feasibility [15–18] of the technologies required to support SBSP. During the 1980's and 90's interest in the concept was seen in Japan, European and Canada, resulting in two microwave power transfer experiments [19,20]. In 2008, Mankins demonstrated transmission over a greater distance: 148 km [21]. A more detailed discussion of the foregoing can be found in Refs. [22–24].

The use of MWPT has been suggested across a variety of contexts. Building from Brown's initial experiments, its use for powering aerial craft has been expanded to powering UAVs. In 1980, the Stationary High Altitude Relay Program (SHARP) was designed [25]. A one-eighth (1/8th) size SHARP was tested in 1987 [22]. In 1992, the Microwave Lifted Airplane eXperiment (MILAX) demonstrated the ability to keep a beam pointed at a moving target [26].

The initial SBSP concept was to transmit power to the Earth from geostationary Earth orbit [11,12]. It has also been suggested for use in powering lunar science missions, by Oda and Mori [27] and Little and Brandhorst [28], such as using a rover to search for resources to support future habitation in the polar regions. Potter [29] and Bock, Burz and Cowgill [30–32] demonstrated the efficiencies that could be gained by launching solar power satellites (SPSs) from the moon which have been largely constructed from in-situ materials. Zidanšek et al. [33] propose the launch of SPSs from the moon to geostationary Earth orbit. Lusk-Brooke and Litwin [34], Charania, Olds and Depasquale [35], and Xin et al. [36] looked at the economics of a utility provider (prospectively serving several different classes of customers). Macauley and Davis [1] discussed the utility of SBSP for serving spacecraft craft from other spacecraft. Prior work has also looked at the use of SBSP for supporting small spacecraft's power needs as part of an orbital service model [37], to support a human mission to Mars [38] and to support lunar industry [39].

3. Evaluation framework

The fundamental notion of the utility of supplying concentrated power via microwave or laser transmission is that the receiving spacecraft can be (1) modified to cost less or (2) derive some sort of other benefit from this mode of power supply. Fig. 1 depicts the value proposition of these two sources.

Cost savings are derived from reducing the spacecraft's mass and volume, due to (1) being able to receive more power per square meter of receiving surface and (2) not having to factor in solar panel deterioration. The latter (deterioration) requires the spacecraft to be equipped with additional generation capabilities (i.e., more mass and volume) to compensate for the decreased generation capability of the solar panels over time. Radio antennas, on the other hand, suffer degradation at a dramatically lower rate. Thus, most missions can be designed with a single lifetime-wide collection capacity for MWPT-derived power. The increased generation capability required increases the cost of the design and development of the spacecraft as well as of its launch. Thus, MWPT spacecraft enjoy savings in these areas. Some level of onboard solar generation may, however, be required in anticipation of prospective emergency conditions.

The cost savings that might be enjoyed are offset by the cost required to design, develop and deploy the MWPT transmitting craft and its associated launch costs. The transmitting craft must have greater generation capabilities than if the solar power generation was onboard, due to the loss that occurs from beam-spread between the transmitting and receiving craft. These cost factors are summarized in Fig. 2.

A variety of other benefits can be provided by SBSP using MWPT. The applicability and particular level of utility of each is driven by mission specifics. Fig. 3 provides an overview of these benefit areas.

SBSP can provide power in eclipse, either using onboard batteries (if it too is in eclipse) or via placement in an orbit where its path to the Sun and receiving craft is not blocked. For example, a network of SPSs in geostationary orbit would be able to provide consistent power throughout the orbit to other spacecraft in lower altitude orbits. This may allow a reduction in the need for onboard batteries in the receiving craft. Given that batteries are responsible for roughly one-third of EPS-attributable failures in low-Earth orbit craft [40], this may result in greater spacecraft reliability (in addition to mass and volume savings).

SBSP, presuming that power is not being supplied continuously at the maximum level supportable by the receiving array/spacecraft, may be able to provide power on an on-demand basis. This may allow power levels onboard the spacecraft to be increased during key mission periods or for particular high-power tasks. This could be performed by transmitting power for a longer period of time (necessitating onboard batteries to store this power for later use or to be recharged after depletion) or by transmitting a greater power density level, at a given time. This allows peak generation demand equipment costs to be borne by multiple missions, instead of each mission having to design to satisfy its end-of-life peak power demand period requirements through onboard generation (resulting in capacity that may not be used much of the time).

If mission lifetime is constrained by power generation capabilities (i.e., by the degradation of solar panels resulting in a power level that is too low to perform mission activities at some point), SBSP may be able to extend mission lifetime. However, this may not be applicable for many missions due to lifetime being constrained by some other factor. These other factors include orbital deterioration, the lifespan of other spacecraft components and the need for the mission to continue at all.

For a mission that would otherwise be lifetime-constrained by power, the use of SBSP could extend it to a point where it is all but certain that another component or factor would become the constraining factor. As part of its assessment for the Phoenix Program, the Defense Advanced Research Projects Agency (DARPA) studied existing communications spacecraft. They found that while most spacecraft components would have 25 year lifespans, the communications antenna's useful lifespan could be as high as 100 years [41]. Using a SBSP utility (which replaced solar panels and/or supply craft on a regular cycle to maintain ample generation capability) or ground based supply, the mission could effectively continue – from a power perspective – far longer than would likely be needed. As an example, a communications or GPS satellite (which didn't become technically obsolete) using an antenna with

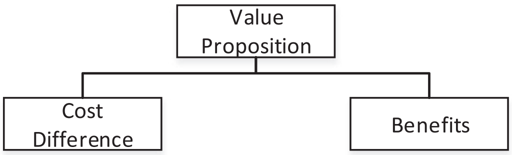

Fig. 1. Overall value proposition.

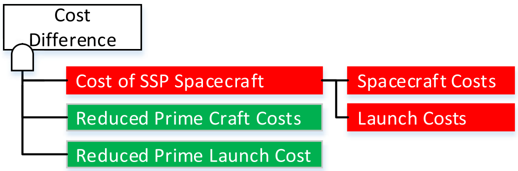

Fig. 2. Cost difference value proposition elements.