ABSTRACT

Solar power is a reality. Today, increasing numbers of photovoltaic and other solar-powered installations are in service around the world and in space. The Solar Power Satellite has been hailed by proponents as the answer to future global energy security and dismissed by detractors as impractical and uneconomic. This paper reviews recent design and feasibility studies, advances made in enabling technologies (particularly wireless power transmission) and the development of supporting infrastructure. It identifies current progress towards practical demonstrations of space solar power technology that could lead to an economically viable Solar Power Satellite system.

INTRODUCTION

In 1990, the world demand for power exceeded 10 terrawatts (10X10^12 Watts) thermal, with about 30% of the thermal energy being used to produce electricity [1]. That year, the nations of the Organization for Economic Cooperation and Development (OECD) used more than two-thirds of the world’s total electrical power of >10.5 terrawatt-hours [2]. Energy demand is estimated to increase by more than 60% from the present 382 Quads (1999) to 612 Quads in 2020 and electricity, with an annual growth rate of 2.7% between 1999 and 2020 will outpace growth of other energy use, reaching more than 22.4 terrawatt-hours [2].

The idea for a Solar Power Satellite that would help meet the growing energy needs of developed and developing nations was conceived by Dr. Peter Glaser in 1968 [3]. Dr. Glaser's concept was orbiting satellites converting solar energy and transmitting the energy to earth via a radio frequency energy beam. Solar Power Satellites placed in geosynchronous equatorial orbit 35,800 kilometers above Earth's surface would be continuously illuminated for most of the year, have the same rotational period as the Earth and therefore be fixed over one location at all times, enabling the satellite to deliver almost uninterrupted power to a ground receiving site.

SYSTEM ARCHITECTURES

The first major attempt to conceptually design and evaluate a complete Solar Power Satellite system was by the US Department of Energy (DOE) and US National Aeronautics and Space Administration (NASA): the 1977-1980 DOE/NASA systems definition studies. The studies defined a Solar Power Satellite reference system including the satellite configuration and all of the supporting infrastructure [4]. The "completed" system would provide a generating capacity of 300 gigawatts from 60 satellites. The satellites were designed to have five gigawatt generating capacity; use photovoltaic cells for energy conversion; use wireless energy transmission at 2.45 GHz; be based at geosynchronous orbit; be assembled on-orbit with human support of automated machinery; and have a thirty-year operational life. The estimated non-recurring cost of $100 thousand million (for infrastructure and the first operational Solar Power Satellite system providing 5 gigawatts) contributed to the general impression of the Solar Power Satellite as an expensive program.

Several independent assessments were made of the DOE/ NASA study. A report by the National Research Council of the United States National Academy of Sciences [5] concluded that while solar energy from space was technically feasible, the reference system assumptions were too optimistic, especially in the areas of photovoltaic cell performance and probable launch costs. The assessment recommended further relevant research be tracked and the situation assessed from time to time, but that implementation not be pursued at that time.

Japanese interest in Space Solar Power followed closely the 1981 establishment of the Institute of Space and Astronautical Science of Japan (ISAS) within the Ministry of Education [6]. Two prototype Space Solar Power Satellite designs were developed.

In the early 1990s, the idea of using the Earth’s largest satellite as a platform for collecting solar energy with photovoltaic materials manufactured in situ and beaming the power to earth was proposed as a Lunar Solar Power option [1].

Since the completion of the DOE/NASA systems definition study in 1980, much progress has been realized in research and technology development. Progress has been made in photovoltaic cell efficiency, transportation, space structures, robotics and other
areas. New studies were begun to reassess the feasibility of the Solar Power Satellite concept. The most notable of these was the “Fresh Look” study undertaken by NASA in 1995-1996 [7].

Based on interest generated by the “Fresh Look”, the US Congress suggested a follow-on study. NASA began the Space Solar Power Concept Definition Study [8] in 1998 to evaluate the results from “Fresh Look”. In addition to identifying, developing and analyzing system concepts and technologies for solar power satellites, and evaluating the potential commercial markets and economic feasibility of space solar power, applications of SSP concepts for space exploration and transportation were developed. The bulk of the system modeling and evaluation effort was applied to “Sun Tower”, an innovative gravity gradient stabilized modular satellite and derivative architectures, although a “Sandwich” concept [9] received some analysis in this study and continues to be investigated in Japan. The study validated much of the “Fresh Look” results, however, the “Sun Tower” middle-earth-orbit was found to be impractical.

NASA began the Space Solar Power (SSP) Exploratory Research and Technology (SERT) Program in 1999. SERT continued the satellite concept definition and analysis work and funded fundamental technology research as well as a wireless power transmission demonstration project. In addition to defining SSP applications for science, exploration and other commercial use, SERT addressed a number of critical technology elements for solar power satellites, including transportation (both earth-to-space and in-space), robotic assembly, power generation, power management and distribution, thermal management and wireless power transmission [10]. The U.S. National Science Foundation/NASA/Electric Power Research Institute Joint Investigation of Enabling Technologies for SSP (JIETSSP) (2002-2005) [11] is continuing research in selected technology areas: e.g., robotics, photovoltaic conversion, thermal management, wireless power transmission and economic/environmental analysis.

For direct microwave wireless power transmission to the surface of the earth, a limited range of transmission frequencies is suitable. Frequencies above 6 GHz are subject to atmospheric attenuation and absorption, while frequencies below 2 GHz require excessively large apertures for transmission and reception. Frequencies other than 2.45 GHz, particularly 5.8 GHz and 35 GHz are being given greater attention as candidates for microwave wireless power transmission in studies and experiments. The mass and size of components and systems for the higher frequencies are attractive. However, the component efficiencies are less than for 2.45 GHz, and atmospheric attenuation, particularly with rain, is greater.

Satellite and system architectures based on laser wireless power transmission were first considered seriously during the SERT program. Laser systems have one major advantage for power transmission, which is aperture collection efficiency. Whereas microwave power transmitting and receiving antennas are sized in kilometers, laser systems can be sized in meters. A secondary advantage is that laser based systems lend themselves more readily to incremental deployment than microwave based systems. However, the major hurdle that laser based systems face is atmospheric losses, especially due to rain attenuation.

With the lower delivered power per site design criteria of the current studies compared to the DOE/NASA Reference System, beam safety has minimal influence on the design of a microwave based solar power satellite system, however, it has been a major factor for laser based systems [12].

TECHNOLOGY DEVELOPMENT

Progress has been made in a number of technologies relevant to space solar power and the development of an economic solar power satellite since the Reference System [10]. Photovoltaic cell efficiency has risen [13]; inflatable structures have been demonstrated in space [14, 15]; propulsion, thermal management and power management technologies have all advanced [16]; infrastructure technologies such as robotics have come of age [17, 18]; and space transportation scenarios necessary to support the massive launch requirements necessary to solar power satellite deployment are being developed along with the new, reusable launch technology necessary to bring transportation cost down to economically viable levels.

Development of more efficient microwave tube devices has been stimulated primarily by commercial applications. Although conversion efficiency is not yet as high as for magnetrons, solid state radio frequency transmitting systems show promise and are improving [19]. The Japanese in particular continue development of solid state devices for the Solar Power Satellite systems and experiments they are planning [20, 21]. Improvements are being reported for RF to DC conversion devices [19].

Recent work on diode pumped lasers at 1.06 µm laser light conversion in a Yb:YAG laser suggests overall electric conversion efficiency approaching 40% [22, 23]. Photovoltaic conversion efficiencies have been measured for Si of 45% at 1.02 µm, [24] and for GaAs of about 52% at 0.84 µm [25] and 68.5% at 0.83µm [26]. However, this is a much lower conversion efficiency than that demonstrated by microwave components.
DEMOnSTRATIONS

In addition to laboratory demonstrations, several large scale projects are planned. A demonstration of a microwave powered rover was completed by the Boeing Company under the SERT program [27]. The Japanese SPS 2000 project [6, 28] is intended to demonstrate a functioning solar power satellite system including the wireless transmission link and develop the ground infrastructure in several locations to provide the basis for a space solar power market. A French point-to-point terrestrial project planned for La Réunion will supply electricity to the remote village of Grand-Bassin [29]. The distance of the wireless link is 700 m. The National Space development Agency of Japan (NASDA) invited two teams of Japanese companies to submit proposals for a space solar power demonstration satellite [30]. The satellite would be capable of generating between 10 kilowatts and 1 megawatt of power. NASA has developed a series of flight demonstration model systems leading to development of a functioning solar power satellite [10]. They progress in the level of satellite power from Model System Category (MSC) 1 at 100 kilowatts to MSC 4 at 1 gigawatt.

Although research and laboratory projects continue, funding remains uncertain and distant for large-scale demonstrations.

REFERENCES

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