# An Economic Assessment of Space Solar Power as a Source of Electricity for Space-Based Activities

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## Abstract

We develop a conceptual model of the economic value of space solar power (SSP) as a source of power to in-space activities, such as spacecraft and space stations. We offer several estimates of the value based on interviews and published data, discuss technological innovations that may compete with or be complementary to SSP, and consider alternative institutional arrangements for government and the private sector to provide SSP.

**Key Words:** innovation, government policy

**JEL Classification Numbers:** O33, O32, L98

## Contents

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## I. Introduction and Overview

> *"... some designers believe they can estimate the spacecraft program's entire cost by the power budget alone."*
>
> *"... the sun is king. Worship him."*

Electrical power on spacecraft is so critical and expensive that a spacecraft design handbook begins its chapter on power subcomponents with those words.[1] Engineers use batteries, solar cells and arrays, radiators, and a host of other devices to create power systems that are able to survive extreme vibration during launch and then operate in a harsh space environment. But the moving parts of solar arrays can fail to operate or wear out quickly. Furthermore, the systems are difficult or impossible to repair once the spacecraft is in orbit. The power supplies are also heavy and bulky, and spacecraft can ill afford their weight and volume.

This research paper explores power systems in spacecraft design and economics and the alternative that may be offered by space solar power (SSP).[2] SSP is a satellite or system of satellites that collect solar energy, convert it into usable electrical power, and then transmit the power to another spacecraft, or "customer." SSP might be thought of as a gas station or power depot for fueling other spacecraft. It would free spacecraft from having to carry their own power

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[1] Wertz and Larsen (1996, 178–79).

[2] Engineering research on SSP as a source of power for the terrestrial power grid began in earnest in the 1970s under the auspices of the U.S. National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy. The most recent assessments of SSP, again focusing primarily on using SSP for terrestrial power, were carried out under NASA's sponsored research project, the Space Solar Power Exploratory Research and Technology (SERT) Program, during 1998-2000. Research papers produced in SERT more fully describe various engineering designs of SSP. Another SERT-sponsored study, of future electricity markets and the competitive challenges facing SSP as a source of power to earth (see Macauley and coauthors, 2000), focused on the demand for SSP for earth from the same economics perspective as this paper takes in considering demand for SSP for space use.

supply other than some backup for peak demand or emergencies. SSP has to date largely been considered a source of power for activities on earth, but in-space activities may represent a potentially large market and perhaps be served by SSP sooner than terrestrial customers.

In this report, we estimate the value of SSP for a variety of space-based uses that might arise in the next decade or two. We find that the potential market penetration of SSP—that is, the willingness of potential customers to adopt a new power technology like SSP—is promising although, like many future markets premised on new technology, somewhat uncertain. We base our estimates on interview surveys of spacecraft designers and operators and information in the literature on spacecraft power system design and cost. We find that potential customers have minimal installed base and stranded costs in their investment in existing power equipment, and they are accustomed to accepting new technologies. These characteristics sharply contrast with terrestrial power markets, where customers often resist new technology. However, some space customers, while amenable to substitutes for their current power systems, are also averse to taking risk, either actual or perceived, if a new technology has not been flight tested and otherwise proven reliable. The critical importance of power supply for space activities sharpens this risk aversion in the case of customer acceptance of SSP. For this reason, early SSP demonstration projects would be desirable to build the market. Of particular usefulness in introducing SSP to space markets and mitigating risk in the near term would be demonstration of SSP as a cofire power supply—that is, as a supplement to work in tandem with, rather than fully substitute for, an existing power system on a spacecraft.

We also discuss technologies now in development that are likely either to complement or to substitute for SSP. SSP is unlikely to be deployed for at least a few years, or maybe longer, and innovation in other power-related technologies—lighter-weight spacecraft, more capable batteries, and increasingly efficient solar cells—will meanwhile proceed apace. Hence, innovation in these technologies and their future operating costs will affect the future economic value of SSP. We briefly survey these technologies and recommend that SSP designers apprise themselves of their development through technical interchange meetings, working synergistically with complementary technologies and bearing in mind the future costs of competing technologies.

Because we believe that SSP may someday be operated as a quasi-private or even fully private entity, we also discuss some possible institutional arrangements for SSP. These possibilities have implications for the financing of such a system. In this discussion we draw from recent commentaries on deregulated electricity markets.

There are several considerations that we do not address. We do not forecast values for SSP as a potential source of space propulsion or estimate the value of SSP for well-into-the-future activities that may find SSP useful, such as space manufacturing or space tourism. For such activities, SSP could offer advantages over alternative power systems. There may also be new activities that could not take place without an alternative like SSP.

Our report also does not address engineering configuration, deployment, or cost estimates in building and operating an SSP for space-based activities. Our objective is to illustrate a method and offer estimates of the *demand* side of the equation, in the hopes that it will figure into engineering design and cost management on the supply side. We suggest that the next stage of economics research would be fruitfully paired with engineering discussions in a "technology meets the market" identification of economically optimal operating parameters through simulation models, detailed surveys, or other approaches. To this end, we also recommend that potential customers be at the table in future SSP discussions.

A final note is that our report is written for a general audience. We use the rest of this section to describe SSP and spacecraft power systems. Readers familiar with these systems can skip to the economic analysis in section II. In section III we discuss technologies that may compete with or complement SSP and thus define the future SSP market. In section IV we discuss possible institutional designs for the ownership and operation of SSP, arguing that these need not necessarily be government functions but could involve the private sector. We offer conclusions in section V.

## *I. a. What Is SSP?*

An SSP system is a satellite or set of satellites that collects solar energy, convert it to usable power, and transmits it to spacecraft. It is essentially a gas station in space.[3] Figure 1 illustrates the concept. On the left is something like a huge solar panel; in fact, SSP has been

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[3] An SSP system could consist of single satellite or a network of satellites. Communal spacecraft could offer higher reliability and easier load balancing among peaks and valleys in power demand, much in the same way that individual homes derive cheaper and more efficient power from a network of large central power stations than by using a small generator at each home. Details of the most recent concepts for SSP design are documented in a series of briefing materials from three workshops for the NASA-sponsored Space Solar Power Exploratory Research & Technology (SERT) Program during 1998 – 2000. Some of the most recent information and analyses are in Feingold and Carrington, 2000; Howell and Mankins, 2000; and American Institute of Aeronautics and Astronautics, 2000b. Kazanowski and coauthors, 1988, and Grey and Deschamps, 1989 offer more detailed descriptions of the concept of an SSP deployed for powering in-space activities. See also additional references in Grey and Deschamps.

called a “solar array on steroids.” On the right, customers—other spacecraft—obtain some of their power requirements from the SSP station rather than having to be fully self-sufficient. (Customers may still need to store some energy if they are not co-orbiting with the SSP satellite, or if they desire some redundant or backup power.) Figure 2 shows existing options for power supply in space and also roughly indicates, in the shaded region, the capability that SSP could offer.

Table 1 lists some of the existing and future space activities that could become SSP customers.[4] Potential customers include commercial telecommunications and remote sensing satellites, government research and defense satellites, and in-orbit spacecraft servicing systems that would repair satellites. Power requirements for spacecraft vary markedly, as does the cost of power systems. For this reason, the potential value of SSP depends on customers’ existing or near-term technical opportunities for designing and operating other power systems, and on their budgets. In addition, as we noted earlier, it is possible that SSP could allow wholly new types of space activities.

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[4] American Institute of Aeronautics and Astronautics, 2000a, offers a detailed discussion of these and other uses of space-based SSP.

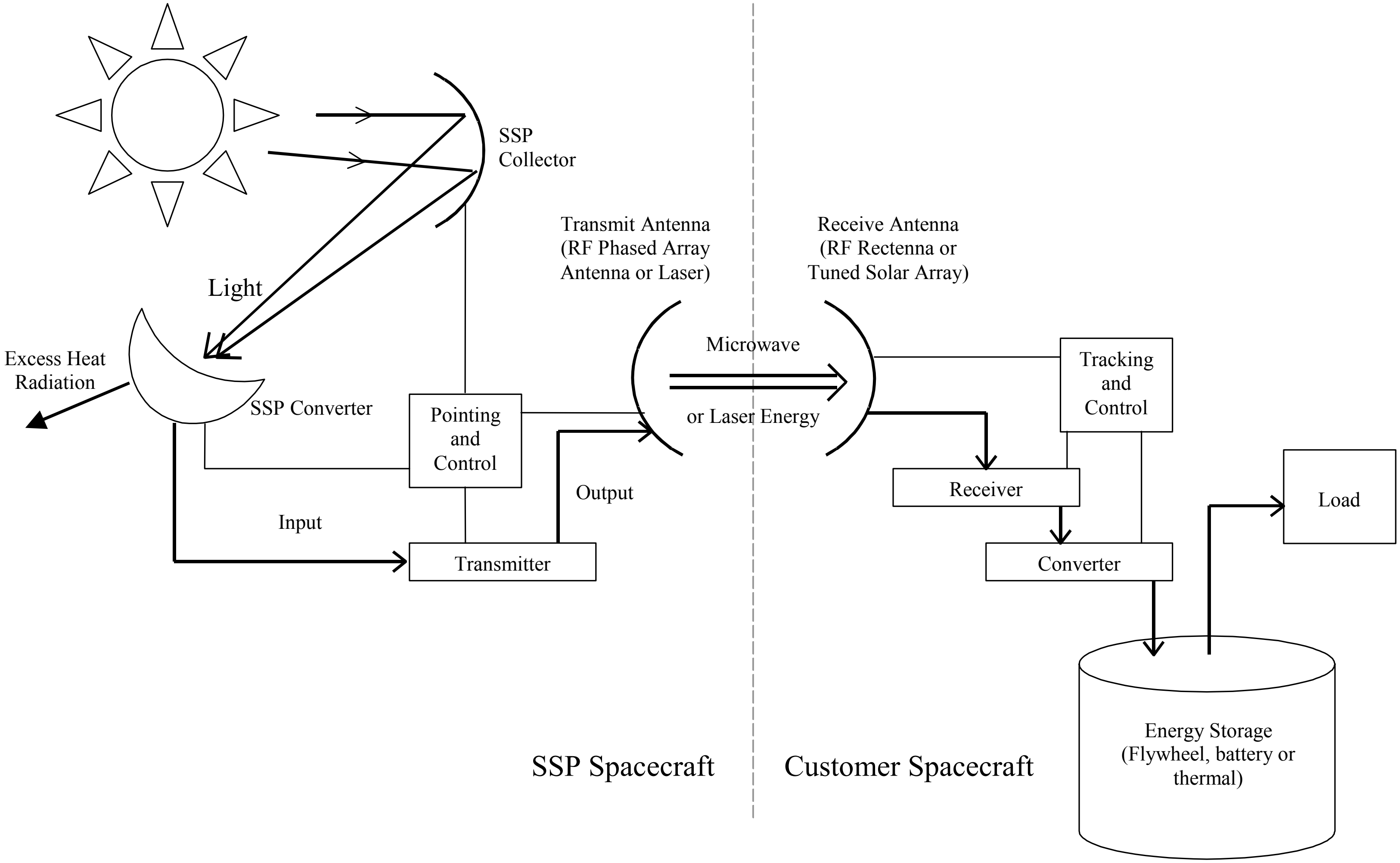

**Figure 1. Concept of SSP Architecture**

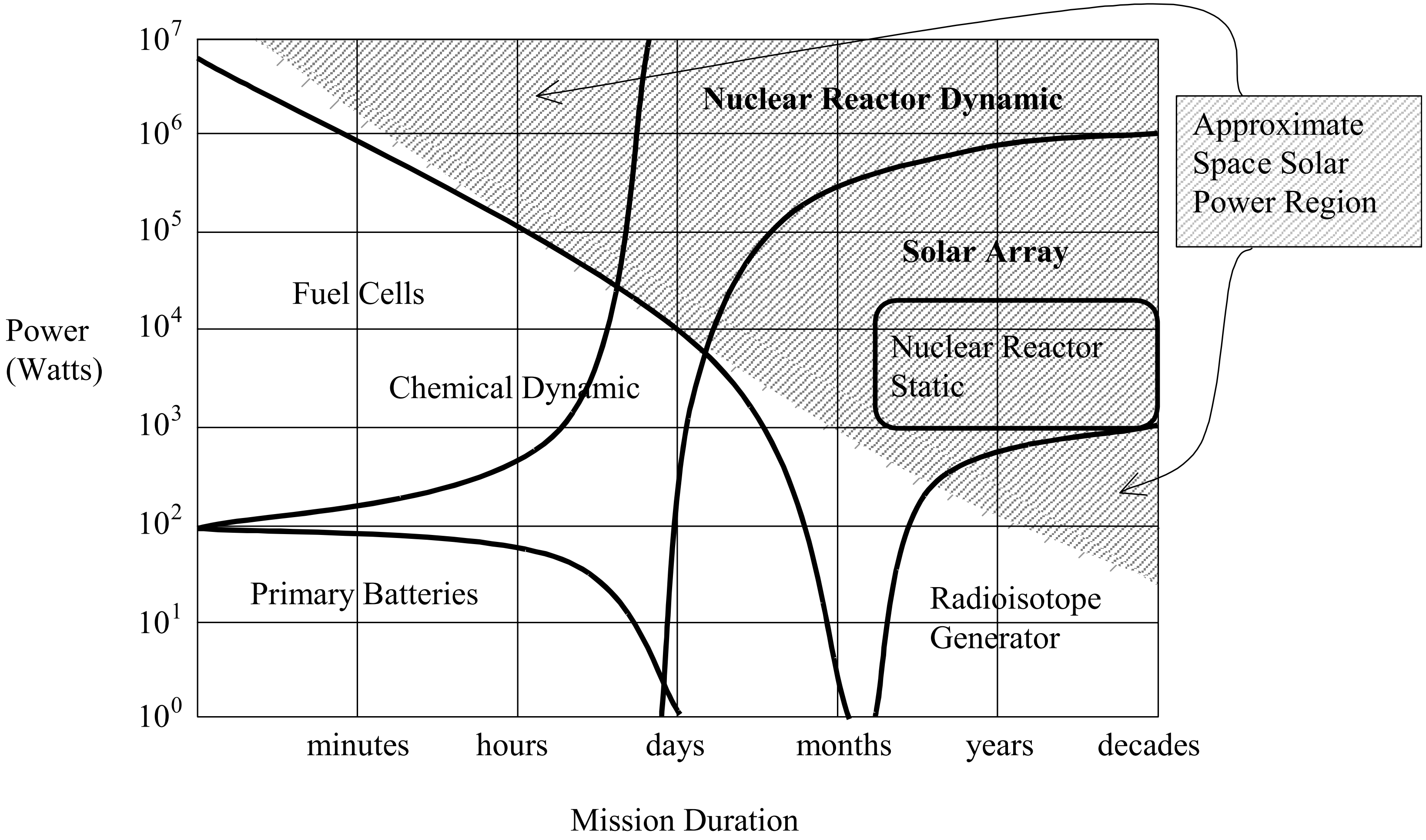

**Figure 2. Options for Various Mission Power Needs and Durations**

Source: Adapted from Hyder and coauthors, 2000

Geostationary and low-earth-orbit communication satellites
Space stations
Science research spacecraft
Interstellar probes
Military spacecraft (including radar, reconnaissance, and navigation)
Meteorological spacecraft
Remote sensing spacecraft
Vehicles for surface exploration of planets
Space manufacturing facilities
Space travel and tourism industries
In-orbit spacecraft servicing and repair systems

**Table 1. Potential SSP Customers**

Engineers are currently discussing a host of technical issues in designing an SSP system, and full demonstrations of all of the required technologies are probably at least several years into the future. As Figure 1 shows, the componentry, transmission dispersion and path loss, and any added risk of failure from system complexity are variables that engineers must control to make SSP a cost-effective power source. Because the actual power capacity will depend on what SSP is designed to do, in Figure 2 we show the options as a range.

### *I. b. Electrical Power Systems (EPS) in Space*[5]

We next discuss the choices available to potential SSP customers in the conventional power supply technologies with which SSP will compete. Electrical power generation systems on spacecraft are a major factor in determining the overall ability of the spacecraft to accomplish its mission. The first artificial satellite, Sputnik, carried a battery that provided just one watt of power. Since then, the sophistication of spacecraft has increased power demands by many orders of magnitude (see Figure 3).

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[5] Much of the discussion in this section is from Hyder and coauthors, 2000; Wertz and Larson, 1996; and Cochran and coeditors, 1985.

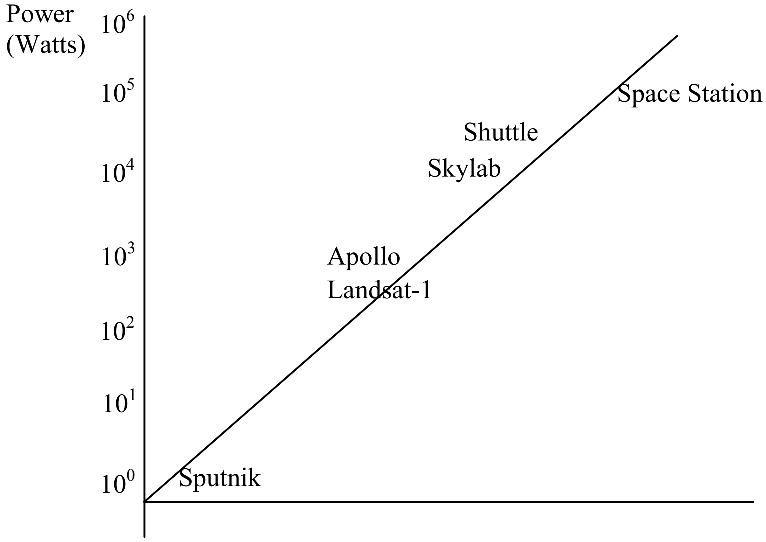

**Figure 3. The Growth in Requirements for Spacecraft Power**

Source: Hyder and coauthors, 2000

Moreover, the lifespan of spacecraft power systems is a determinant of the lifespan of the spacecraft. Sputnik lasted just three weeks; the International Space Station, with replaceable batteries and long-lived solar arrays, is designed to last decades, but even its power infrastructure has been challenging to install, debug, and operate.[6] Because greater mass, more power, and longer lifespans typically render spacecraft more expensive to design, launch, and operate, opportunities to (a) reduce mass or reallocate it to the payload of the spacecraft, (b) add power, and (c) increase lifespans are crucial to space activities.

Power is used for communications, data gathering and handling, vehicle attitude control, guidance, and propulsion. If one of these functions fails, a spacecraft may yet have some limited capability, but if the power system fails, the spacecraft becomes useless debris. Producing power is also complicated. Waste heat is generated and must be dissipated, but the virtual absence of matter around a space vehicle makes radiation the only economical means of waste heat disposal. Because space is an inefficient heat sink, large, heat-dissipating radiators must sometimes be

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[6] Pioneer 10, launched in 1972, had an 8-watt signal (equal to the power of a night light) and still communicates with antennas that comprise NASA's Deep Space Network for tracking and communications. Pioneer 10's signal strength is presently .3 billionths of a trillionth of a watt. See http://spacescience.com/headlines/y2000/ast02mar_1.htm (accessed in March, 2000).

employed, adding weight and volume to the spacecraft (which hikes the cost of its launch) and increasing the possibility of meteoroid damage. Components are also subjected to extreme temperatures, and the usefulness of batteries decreases at low temperatures. During launch, the spacecraft and its systems undergo extreme vibration and high acceleration. Other design challenges are limited or nonexistent repair capabilities an inherently low efficiency of energy conversion and storage devices.

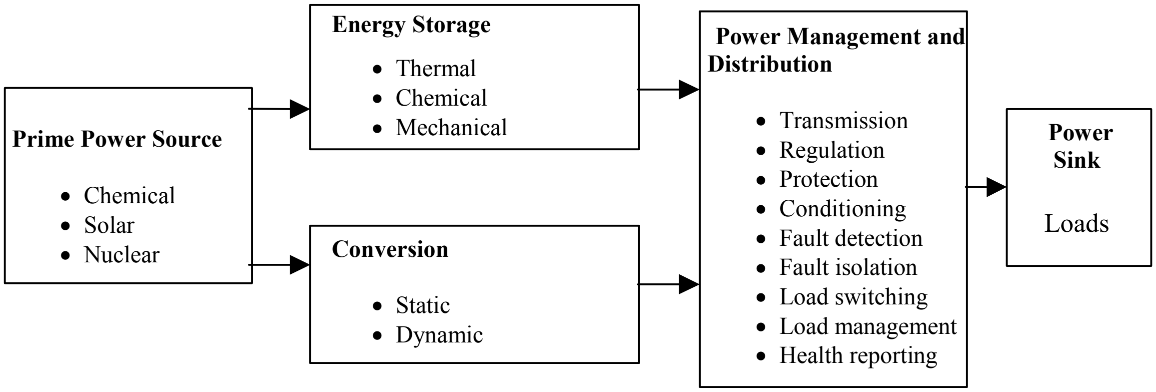

**Figure 4. Components of the EPS**

Figure 4 shows the elements of the electrical power system (EPS). Power can be provided by three sources: solar radiation, chemical (as with a battery or fuel cell), and nuclear (most typically, using radioisotopes). These sources all produce heat for conversion into usable electricity through static processes (e.g., using solar cells) or dynamic processes (e.g., using turbines). For spacecraft that are able to use the sun’s energy, a combination of solar cells and electrochemical systems (such as batteries or fuel cells) are the typical components of a power system.[7] After conversion, the electricity is delivered via the power management and distribution system to individual spacecraft components and subsystems as needed. Usually, spacecraft need to store some energy (for example, if they use solar arrays and have an eclipse period when they are not in view of the sun, or if their power demands exceed the output of their primary power sources). Regardless of the power source, energy storage can employ thermal, chemical, or mechanical technologies.

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[7] Spacecraft designed to explore the outer planets, out of the range to make use of solar energy, have used nuclear-based energy systems.

In designing the power system, engineers face a range of trade-offs and interrelationships among components. Figure 5 illustrates these interactions.

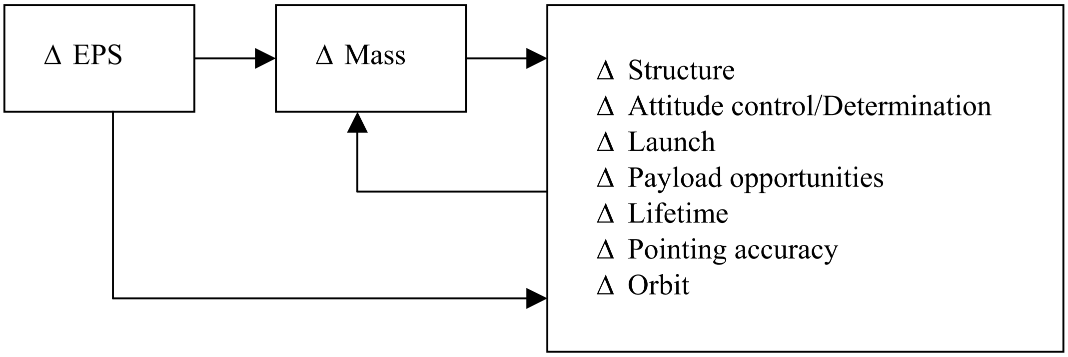

**Figure 5. Changes in EPS may change other system components**

These choices are important in considering the economic value of an SSP system because they reflect what designers could do if SSP replaced much or all of EPS. Since SSP would transmit power to the spacecraft, many of the interdependencies could be reconfigured, sized differently, or perhaps eliminated. Changes in EPS could affect other system components directly, such as the spacecraft's lifespan or choice of orbital location. Changes could also indirectly influence other subsystems by changing the spacecraft's mass and subsequently making it easier to control, less expensive to launch, or easier to direct its functions in space. One of the scarcest resources for designers is spacecraft mass. In general, mass is both expensive to launch and requires additional control of the spacecraft while in operation. Figures 6 and 7 illustrate the percentages of mass consumed by EPS and its components for typical spacecraft (although it should be noted that these percentages can vary markedly with the type of spacecraft).[8]

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[8] For some unique spacecraft, power systems may be a larger percentage – 50 to 75% (see National Research Council, 2000, and Wertz and Larsen).

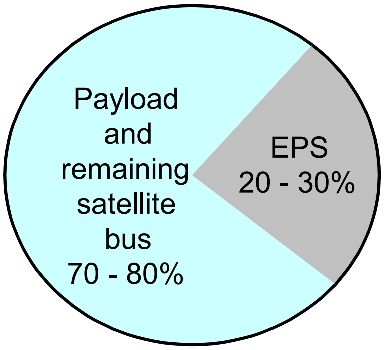

**Figure 6. Mass consumed by a spacecraft's electrical power system (EPS)**

Source: Reinhardt, 2000; Morgan and Gordon, 1989

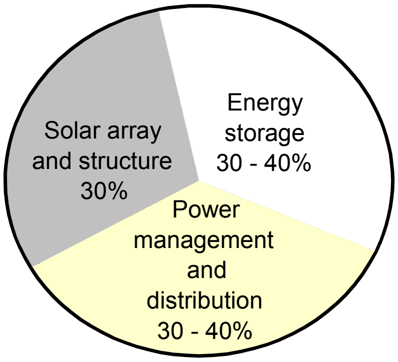

**Figure 7. Mass consumed by components of the electrical power system**

Source: Reinhardt, 2000

The attractiveness of SSP in freeing up mass could be lower launch costs or additional payload. The substitution of SSP for EPS will not fully eliminate this mass, however. For instance, customers of SSP would require storage for baseload power if they were not co-orbiting with SSP or needed additional power for some other reason; they would also need additional power for receiving and conversion systems; and they may need shielding if the use of SSP creates electromagnetic interference with spacecraft operation. Most spacecraft engineers and other experts whom we interviewed for this report emphasized the need for on-board storage and backup power and expressed concern about the potential for signal interference.

Choices such as these underlie determination of the economic value of SSP. In the next section we discuss some approaches to estimating this value.

## II. Estimated Willingness to Pay for a Unit of Power

In this section we first describe an expression for the value of a unit of power to a spacecraft designer or operator. We assume that the value of SSP is related to the cost of EPS and also indirectly related to the additional design and operating characteristics of a spacecraft, as discussed above. In addition, we assume that customers will also consider cost-reducing innovation in alternative power systems that compete with SSP. In other words, the cost and performance of EPS technologies with which SSP will compete as customers design their spacecraft will also determine customers' willingness to pay for SSP.

We assume that a potential customer's estimated willingness to pay per spacecraft is as follows:

*Base amount:* EPS (including any innovation-induced price change in alternative EPS)

*Add value of:* Other benefits (e.g., mass reduction, attitude or guidance)

*Subtract value of:* Other costs (e.g., storage and conversion, signal interference)

Figure 8 depicts what we seek to measure in EWTP. The horizontal axis, Q, represents the quantity of power (say, in kilowatts), and the vertical axis, P, measures price per unit quantity. The downward-sloping customer demand curve, D, illustrates that willingness to pay for the first few units of power is quite high and gradually decreases as more and more power is supplied for a given customer's activity (i.e., with no commensurate change in spacecraft capability). The upward-sloping supply curve, S, illustrates existing (or "defender") technologies, $S_0^{DT}$; existing technologies that might be improved through technological innovation, $S_1^{DT}$; and SSP, $S_1^{SSP}$.

The intersections at $P_0^{DT}$, $P_1^{DT}$, and $P_1^{SSP}$ indicate prices for each technology. The shaded rectangle, area $P_1^{DT}abP_1^{SSP}$, is the area of interest: it represents the extent to which SSP offers benefits in the form of less expensive power. This area is what we seek to measure. Note that this area takes account of innovation-induced price changes in EPS alternatives. This *net surplus* is relevant in measuring the value of technologies that are deployable in the future, since improvements in existing technologies continue.

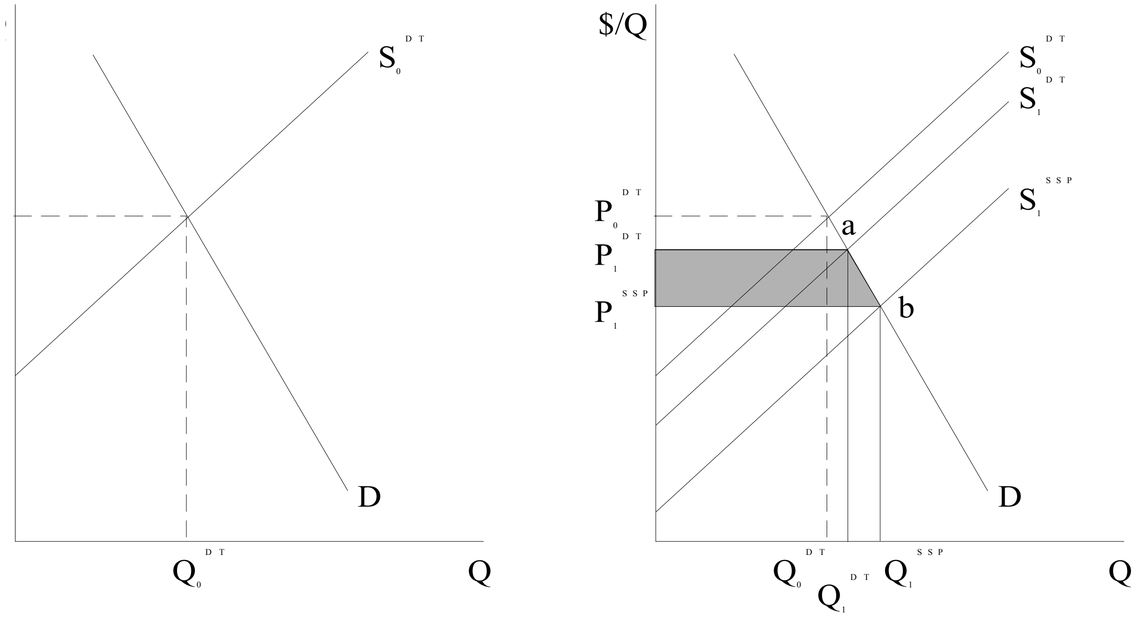

**Figure 8. Derived Demand for New Technologies: Illustration of Net Surplus Change**

This approach also has implications for the value of activities that SSP could enable but that otherwise might not take place. For example, if aggregate EWTP based on customers whose economic value can be measured is large enough to justify the cost of deploying SSP, then any future enabled activities are "icing on the cake" in justifying investment in SSP. If, however, aggregate EWTP appears unlikely to cover the costs of SSP, then the economic viability of SSP depends on the expected value of these activities. In addition, if aggregate EWTP based simply on the near-term customer classes we identify here could justify SSP, then the private sector might be more willing to play a role in financing and operating SSP. Otherwise, government support of SSP may be required to cover costs to enable, say, space exploration.[9]

### *II. a. Estimates*

In this section we discuss approaches to EWTP by conventional customer classes—that is, spacecraft systems that would operate in the next five years or so and thus be closely modeled

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[9] The justification for government support of technologies rests, of course, on a much broader discussion than we offer here in order to weigh competing alternative uses of the government funding, whether the expected benefits justify the costs, and so forth.

on systems in operation now. We do not consider EWTP for missions that might be enabled by SSP—that is, altogether new systems or applications that could not be undertaken without SSP. Although these possible activities are an important aspect of discussions about SSP, they are much more difficult to quantify. In addition, we view our marginal analysis as consistent with development plans for SSP technology in the near and medium term.

Our approach to estimating EWTP is twofold. First, we gathered information about EWTP from interviews with spacecraft program managers and designers. We also gathered information about EPS from published sources in spacecraft design books and other reference material. Appendix A lists the interview questions we used and experts with whom we spoke.

Second, we conducted econometric analysis for one customer class, small satellites, for which detailed and consistently measured data on existing EPS systems and other spacecraft components are available. In this analysis, we estimate marginal values using a hedonic regression model of spacecraft attributes.

An important control in both approaches is our assumption that total spacecraft cost and the amount and type of its services should be held constant when we calculate the value of SSP. In other words, we model EWTP based on a fixed overall budget for the spacecraft and take as given the spacecraft's science mission, its supply of telecommunications services, and so forth. Because many customers, particularly in the government sector, have fixed budgets, we believe this is a tenable assumption. Future research could explore the effect of SSP when allowing total cost to vary while holding constant the amount and type of services provided, or by holding costs constant and allowing services to vary.[10]

### II. a. i. Estimates Based on Interviews and Published Data

Table 2 gives estimates potential customers' willingness to pay based on interviews and published data, to answer the question, "How much might spacecraft designers or owners be willing to pay for an SSP substitute for EPS, holding power requirements constant?" The estimates are based on the size and cost of EPS (amortized for the spacecraft's design life). Appendix B contains our assumptions and data sources. The customer classes we include are "conventional" in the sense of representing near-term potential uses of SSP and well-documented

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[10] This is equivalent to allowing for income effects in addition to substitution effects in economic analysis of price or cost changes.

spacecraft and systems for which fairly detailed information is available for making estimates. It is much more difficult to estimate EWTP for activities that may be enabled by SSP but for which fewer details are available.

Our examples include small science spacecraft, such as Clementine, Explorers, and Discovery class missions, and small radar missions (which we choose to illustrate because they are particularly power hungry). We also consider large geostationary communications satellites (commercial GEO) and the international space station.

Column (i) reports the annualized EPS value. Column (ii) expresses this value in dollars per watt. In column (iii) we evaluate the total annual power demand as the product of column (i) and the estimated number of spacecraft in that class expected to be operating during the time period indicated. We caution that our estimates do not include additional costs or benefits that might occur in using SSP.

**Table 2. Estimated Willingness to Pay (EWTP) by Conventional Customer Classes**

| | *(i)* | *(ii)* | *(iii)* |
|---|---|---|---|
| | *EPS replacement* | *EPS replacement* | *Total EWTP* |
| *Customer class* | *$ (annualized)* | *$/watt (annualized)* | *$/year* |
| Small spacecraft | | | |
| NASA science | $2.7M | $3,400–$6,700[a] | $16.2M (2005–2010) |
| Radar mission | $2.4M–$9.6M[b] | $500–$800[b,c] | $56M–$230M (2010–2020) |
| | | $2,000–$3,200 | |
| Commercial GEO | $6.9M–$11.6M[b] | $2,700–$4,400[b] | $1,242M–$2,088M (2005–2010) |
| International space station | $78M | $1,200/w | $78M (2000–2010) |

Notes:

[a] Lower bound is based on beginning-of-life power; upper bound is based on average power.

[b] Range depends on fraction of cost allocated to EPS.

[c] Range is based on assumptions about power requirements.

Estimates range from about $500 to $6,700 per watt, depending on the customer and assumptions about the fraction of cost allocated to EPS and the choice of power requirement that serves as a reference. This observation may be useful for SSP designers in considering various customer bases. Also of note is that differences in the relative size of aggregate demand estimates among types of customers may help guide design of a near-term SSP. By indicating which customer classes might have the highest EWTP, the estimates could help determine the SSP orbital location and decide whether SSP is best deployed to co-orbit or consist of a network of depots at various locations. Our estimates indicate a very large market for serving commercial geostationary satellites. As an aside, since SSP is typically discussed as a means of generating electrical power for terrestrial uses, it is interesting to note that these estimates per watt are far larger than projections of per-watt costs of space-to-earth SSP.[11]

### II. a. 2. Econometric Estimates

Our measurements in this section represent marginal valuation of power, in that we seek the value of an increment rather than a large change in available power. This approach is appropriate if SSP offers small rather than very large amounts of power, or if SSP is used to augment on-board power. For this reason, the estimates in this section are somewhat comparable with the average values in Table 2, column (ii).

Our model is in the spirit of the hedonic regression models typically used to value attributes of goods and services , such as characteristics of housing and other consumer durables.[12] The estimates are often referred to as shadow values, since the values of product attributes are usually not explicit but embodied in the products' total worth to the consumer. We use a simple model to explain variation in the implied value of a unit of power, using spacecraft cost as the dependent variable and spacecraft attributes as independent variables. An advantage of the hedonic estimates over the interview data is that hedonics enable us explicitly to incorporate spacecraft attributes that may be affected by changes in the EPS.[13]

Our data are from a 1998 RAND Corporation study of small spacecraft costs (see Sarsfield 1998) for 16 missions, including NEAR, DSI, and Clementine. For the missions in the

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[11] Projections of future costs of terrestrial electrical power are on the order of 5 cents per kilowatt hour (kWh) in 2010–2020 (see Macauley et al. 2000). Estimating cents/kWh in space depends on assumptions about energy use per unit time but are likely to be at least several thousand dollars per kWh. As a further illustration, the published price list for commercial use of ISS lists 1 additional kWh beyond the standard package at $2,000.

[12] Hedonic analysis was first used to separate price, quantity, and quality changes in new automobiles (Griliches 1971).

[13] Our approach is similar to the typical "cost estimating relationship" (CER) used by spacecraft designers to evaluate engineering and cost relationships among system components. Wertz and Larson (1996) offer an excellent discussion of CERs. In our model, we attempt a multivariate approach to include more explanatory variables than in a typical CER, but we also lose some of the flexibility in the CER functions.

study, the average total cost[14] was \$145 million; the average dry mass was 407 kg; and the average EPS represented about 5% (around \$7 million) of the average cost (although the EPS cost has a wide range in the sample). As noted earlier, this cost alone can be misleading as a guide to EWTP because of the interdependencies between EPS and other components. Our model seeks to address these interdependencies, although as we note below, the model is limited.

The model we estimate is

$$\text{Spacecraft cost} = \alpha + \beta_1 \text{ design life} + \beta_2 \text{ beginning-of-life power} + \beta_3 \text{ near earth} +$$

$$\beta_3 \text{ dry mass} + \beta_3 \text{ pointing accuracy} + \varepsilon \qquad \text{(A1)}$$

In this equation, the coefficients $\alpha$ and $\beta$ are parameters to be estimated, and $\varepsilon$ is a mean-zero, normally distributed error term. The fitted coefficients are estimates of shadow values—the amount that represents willingness to pay for marginal changes in the corresponding attributes.

Total spacecraft cost is measured in millions of dollars. Explanatory variables are design life (years); beginning-of-life power (watts); whether the mission is near earth or to a distant comet, asteroid, or planet (a dummy variable taking the value 1 if near earth; such missions often have lower power requirements[15]); dry mass (kilograms); and pointing accuracy of the spacecraft (in degrees). The number of explanatory variables that we can include on the right-hand side of these equations is limited by the number of total observations we have. Equation (A1) represents the best-performing equation, based on our experimenting with other variables, such as downlink data rate, central processor capacity, transmitter power, mass memory, and battery type, many of which are correlated with each other or did not add additional explanatory power.

Our results are as follows:

$$\text{Spacecraft cost} = \underset{(8.77)^{***}}{35.00} - \underset{(1.29)^{***}}{6.91} \text{ design life} + \underset{(.003)^{**}}{.006} \text{ beginning-of-life power} - \underset{(5.48)}{8.40}$$

$$\text{near earth} + \underset{(.012)^{***}}{.163} \text{ dry mass} - \underset{(.935)^{***}}{3.95} \text{ pointing accuracy} \quad \text{adjusted } R^2 = .98 \qquad \text{(A2)}$$

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[14] Total mission cost is defined in the study as the cost from inception to completion and includes design, development, launch, and data review and archiving. However, we observed some possible inconsistencies in some of the data related to launch costs when we compared them with other information in the published literature. We don't think these effects affect our results significantly, however.

[15] Hyder et al. (2000, 74) note this characteristic.

The explanatory power of the equations is strong, as indicated by the goodness-of-fit measure, $R^2$, adjusted for degrees of freedom. The standard errors of the coefficients are in parentheses. Triple asterisks (***) indicate significance at the 5% or better level, and double asterisks (**) indicate significance at the 10% level. From (A2), larger beginning-of-life power, dry mass, and pointing accuracy increase cost (lower values of pointing accuracy indicate increasing accuracy). The sign on design life is significant and indicates that longer lifespans reduce costs. This result seems counterintuitive, but longer missions may be designed to be "simpler," all else equal, or simpler spacecraft have a longer design life because there may be fewer components for breakage. Wertz and Larson (1996) comment that spacecraft cost is insensitive to design life for very short missions (in our sample, design life ranges from 0.7 to 4 years).[16] In any case, this result captures something fundamentally different about long-mission versus shorter-mission spacecraft. The coefficient on near-earth is insignificant but has the expected sign (spacecraft destined for near-earth research are also less costly than those heading to more distant destinations).

From (A2), an additional watt of power at the beginning of the spacecraft's life adds $6,000 to average spacecraft cost, controlling for the other components. This result is consistent with the upper range of estimates in Table 2. The econometrically estimated result allows us better to control for the effect of changes in power on other subsystems. This approach may be useful in further SSP customer evaluation. The approach requires data that are consistently measured and a large enough dataset to include sufficient explanatory variables.

## III. Complementary and Competing Technology Developments

In this section we briefly discuss technologies now in development that may complement or substitute for SSP as a source of power.[17] SSP is not expected to be deployed for the next decade or so, and these technologies will improve in the interim. Hence, the maturation and operating costs of these technologies will affect the future economic value of SSP. In addition, a host of technologies being developed for SSP, including solar cells, energy conversion techniques, and new approaches to power management (radiating waste heat, distributing power

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[16] Wertz and Larson (1996, 314).

[17] SSP may also serve as a source of power for propulsion in space, but we do not consider this application.

to various spacecraft operations), could in turn affect the pace and direction of innovation among complementary and competing technologies.

Figures 9 and 10 illustrate some of these technological developments. Figure 9 shows the general trend toward reduced mass in civilian science spacecraft, reflecting innovation in many spacecraft components. The advantage of SSP in reducing mass may thus be lessened to some extent by the time of its deployment if significant reductions have already been obtained. In commercial geostationary satellites, gallium arsenide solar cells and better thermal radiators to dissipate heat have enabled mass reductions in EPS itself.[18] But the overall trend in this customer class has been toward larger overall mass, subject to the lift capability of launch vehicles, to lengthen the lifespan of the spacecraft and to make better use of geostationary orbital locations. In this case, further mass reductions in the power supply enabled by SSP could be reallocated to, for example, communications payload or additional maneuvering fuel.

Figure 10 illustrates trends in battery performance for all types of customers. Batteries and fuel cells can provide primary power and thus directly compete with SSP, or they could be used in tandem with SSP as a source of secondary or backup power during eclipse periods or to augment power during times of peak demand. As the figure suggests, the trends in battery performance reflect increasing capability for both primary and secondary batteries. As SSP comes closer to deployment, the performance and price of new battery technologies is likely to affect the extent to which customers want to use and are willing to pay for SSP.[19]

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[18] See U.S. Department of Transportation (1999).

[19] Secondary batteries are used only for energy storage and load buffering, not as a source of primary power. Improving efficiency of secondary batteries translates into lower mass for a given amount of energy storage and hence peak power capability. Primary batteries are used only for short missions as a source of prime power or for one-time events, such as launch.

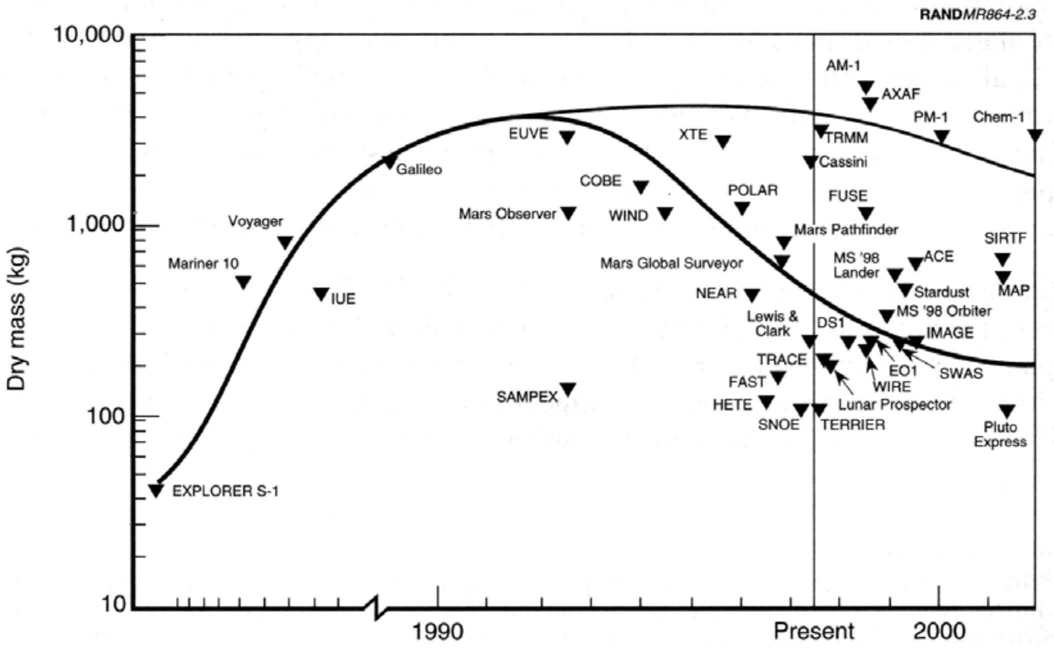

**Figure 9. Mass Trends in Civilian Science Research Spacecraft.**

Source: Sarfield (1998, 14)

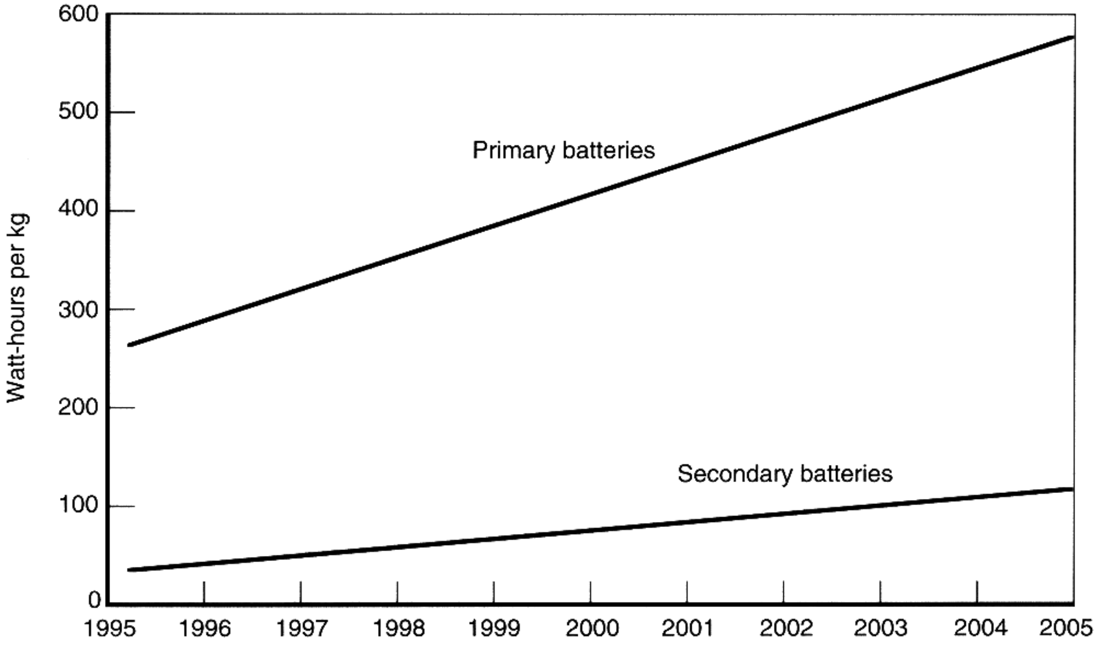

**Figure 10. Battery Technology Development**

Source: Sarsfield (1998, 85)

If detailed quantitative information were available about the expected prices and capabilities of these technologies, their prices could be included in our economic model. Including them would help estimate the extent to which newly available complements and existing substitute technologies might affect future willingness to pay for SSP. Consistent and comparable quantitative cost information is unavailable for these technologies, however.

## *III. a. Complementary Technological Developments*[20]

Complementary technologies include innovations in power supply, storage, and management and distribution.

### III. a. 1. Power Supply

*Solar cells.* Since the beginning of the space program, solar cells have been the primary source of electrical power in space. The biggest disadvantage is that solar cells are not very efficient in converting solar heat into energy; at the present time, their efficiency is around 14% to 20%. Silicon solar cells, the most mature type of solar cell technology, are highly susceptible to radiation damage, which reduces their efficiency. Technological innovation is focusing on new materials that are more resistant to radiation and more efficient. When combined with other semiconductor materials (single-junction or multijunction or bandgap cells), even greater efficiencies are attainable. Solar cells are also now being deposited on thin films of different types of materials to obtain very low mass.

*Solar concentrator arrays.* Solar concentrators use precise pointing, lenses, and reflectors to focus solar energy onto a photoelectric array. Concentrators use fewer array elements than conventional solar arrays and thus have a lower total area and mass. Solar concentrators can be used in combination with other power conversion systems. They can take the form of inflatable concentrators or be more rigid. One program, SCARLET, has been developed under NASA's New Millennium Program and has undergone successful testing in space.

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[20] Much of the discussion in this section is based on Hyder et al. (2000), Sovie (1999), and Cochran et al. (1985).

### III. a. 2. Energy Storage

*Rechargeable batteries*. Rechargeable secondary batteries store energy in chemicals and can be repeatedly charged and discharged (primary batteries can be used only once). The performance of batteries degrades with time and the number of charge-discharge cycles. Developments in nickel hydrogen and lithium rechargeable batteries are expected to dramatically improve battery performance and life over the next six or so years.

*Flywheel generators*. A flywheel system stores kinetic energy in a spinning mass and, like a rechargeable secondary battery, can be repeatedly charged and discharged. The principal advantage of a flywheel is that its stored energy and its power output are independent design variables (to achieve a given maximum power output, a battery must usually be sized for a much larger energy storage capability than is required). Flywheels to be used on crewed spacecraft require a containment vessel in case the flywheel breaks apart. For robotic spacecraft, the additional mass of a containment vessel is traded off with the risk of flywheel failure. Among several ongoing programs, the most mature flywheel development is for the international space station.

### III. a. 3. Power Management and Distribution

Innovations here include more efficient power converters; high-voltage, low-leakage supercapacitors; high-power switches; and components and systems that can withstand higher energy density while occupying less mass and volume. The new technologies will have increased operating life, greater radiation tolerance, and better thermal management.

## *III. b. Competing Technologies*

Competing technologies are largely alternative power supplies.

*Primary batteries*. These are like the familiar consumer batteries: single-use energy storage devices that cannot be recharged. They are self-contained and deliver electrical power from stored chemical energy through a reaction. Primary batteries are typically used for short missions or mission phases, such as launch, one-time events, or firing pyrotechnic devices. They typically have a higher energy density than rechargeable batteries. Researchers are reducing mass and increasing power, largely through use of different materials.

*Nuclear systems*. Nuclear power operates independently from sunlight and has consequently been the principal power technology for exploring the outer planets, where sunlight is weak. A few earth-orbiting satellites also use nuclear power because it eliminates the need to store energy for eclipse periods. Generally, cost and safety issues have been obstacles to the use of nuclear power in space. Although SSP would not compete with nuclear power deployed in far distant exploration, SSP could compete with use in earth orbits.

Two types of nuclear systems have been used: radioisotope thermoelectric generators (RTGs) and reactors. RTGs produce electrical energy through the interaction of a radioactive heat source and a thermoelectric generator. Reactor technology in the Space Nuclear Auxiliary Power (SNAP) program used a fission nuclear reactor with liquid-metal cooling and thermoelectric conversion. Both the United States and the former Soviet Union have conducted space reactor research, but only the latter has put reactors into operational space missions. All U.S. nuclear systems have been RTGs except for the experimental flight of a reactor power system (SNAP-10A) in 1965. The Galileo mission to Jupiter, the Ulysses mission to explore regions of the sun, and the Cassini mission to Saturn use RTGs. NASA and the Department of Energy at various times have sponsored research on advanced radioisotope power systems as possible future upgrades to RTGs with greater efficiency and lower mass.

## *III. c. Complementary* and *Competing Technologies*

A variety of innovations offer new technologies that promise to both compete with and complement SSP.

### III. c. 1. Power Supply and Energy Storage

*Fuel cells.* Unlike battery cells, fuel cells store their fuel externally. During operation they convert the fuel (usually liquid hydrogen or methanol) to electrical energy by combining the fuel with an oxidant. The fuel must be replenished to maintain operation. Fuel cells have been used successfully on NASA’s Gemini, Apollo, shuttle, and Spacelab programs—programs involving crewed operations. Fuel cells are convenient for flights involving crews because the system can be supplied with enough fuel for a short duration and provide water and heat for life support. For longer missions, rechargeable batteries are usually preferred. Research on fuel cells currently includes experiments with alternative fuels, regenerative fuel cycles, and materials for the membrane that separates the fuel and the oxidant. Fuel cells could be used in combination with an electrolysis cell that uses excess electrical energy, as could be derived from SSP, to electrolyze water and generate hydrogen and oxygen.[21]

### III. c. 2. Power Conversion

*Thermodynamic systems*. Compared with photovoltaic systems, thermodynamic cycles offer greater efficiency. Thermodynamic systems, which can use solar or nuclear energy sources, have been demonstrated to have long lives but have not yet been tested in space, and they are subject to sudden failure. The most recent designs based on the Stirling cycle (invented in the 19th century by a Scottish minister, Robert Stirling) use pistons and helium and operate much like a combustion engine. Although the Stirling cycle can attain relatively high conversion efficiency under a wide range of power loads, most systems have fairly high mass for space applications. The Brayton cycle uses a turbine, compressor, and rotary alternator to generate power using an inert gas working fluid. A version of the Brayton cycle was used by NASA in the 1980s as a ground-based test for power for the space station. The Rankine cycle is commonly used as the steam cycle in commercial power plants. For space applications, a liquid metal or an organic compound, such as toluene, is the working fluid. The Rankine cycle was also evaluated in the 1980s for possible use on the space station, but operation in the zero-gravity or microgravity space environment requires specially designed components.

*Static systems*. Thermoelectric generators, alkali-metal thermal to electric converters (AMTEC), amd thermophotovoltaic converters (TPV) are approaches to converting thermal to electrical energy. AMTEC and TPV are considered possible upgrades to the thermoelectric generator now used as a component of RTGs. TPV has fewer moving parts, an advantage over AMTEC, particularly in space.

## IV. Institutional Design

A separate but related factor in considering SSP economics pertains to the choice of institutional organization for an SSP system. The costs of launching and operating an orbital power depot consisting of a network of SSP satellites could be very different from those of a single SSP satellite that co-orbits with its customer spacecraft. That simple example is

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[21] See discussions in National Research Council, Space Studies Board (2000, 26–28), and Hyder et al. (2000, 231–32).

comparable to the differences between large-scale, public power utilities and smaller-scale generators in terrestrial electricity markets.[22] It would also be interesting if SSP revolutionized spacecraft energy management to allow it to be adjusted much more flexibly than the fixed energy budget provided by the power system. In a spacecraft, power management is load management; in a terrestrial system, energy providers manage energy to adjust to customers' needs.[23] Financing, ownership, and operation could range from government ownership and operation or a government and commercial joint venture to, for example, a commercial wholesale cooperative. In this section we discuss some of these considerations.

In traditional terrestrial power markets, electricity transactions take place under specific supply contracts between two parties, the generators and their distributors, marketers, or final customers. In contract (or forward or futures) markets, the commodity is bought and sold under contracts that specify a future delivery date and fix a price. An alternative, reflecting a trend toward smaller-scale local distribution companies, is short-term power transactions coordinated by a centralized spot market, where electricity is bought and sold as needed. A spot market could be run by a "poolco," which coordinates suppliers and customers in the network. Under a poolco, long-term contracts can protect parties from the risks of major price fluctuations.

It may be that to facilitate up-front investment financing of SSP, a contract market would best ensure capital for initial operating years. As SSP matures and the number of operators increases, poolco arrangements may become attractive. In addition, various government customers (for example, developers of NASA science spacecraft) could use purchasing agents at their respective agencies (NASA, the Department of Defense, the National Oceanic and Atmospheric Administration) to negotiate under the contract market arrangement, or coordinate to represent these buyers in a poolco. Similarly, low-earth-orbit (LEO) constellations of communications satellites might arrange themselves to represent their purchases in a poolco.

The ownership and financing of SSP may be handled as a commercial venture—perhaps in partnership with government during initial operation but then becoming a commercial wholesale cooperative. The role of government in financing the experimental and development costs of SSP may be useful if the technology components have application in other government activities, although even this opportunity could be met by private sector research and

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[22] Much of this section is based on discussion in Brennan et al. (1996).

[23] Hyder et al. (2000, 4).

development. And, once SSP is fully deployed, the private sector could be the more efficient operator—an outcome consistent with restricting the role of government to research and development, as many space policymakers and other observers have urged.

Further SSP development might therefore involve representatives of customers as well as SSP designers, and it might even involve electric utility managers as general advisers. The coordination of potential institutional design and engineering design could help SSP become an economically viable reality.[24]

## V. Conclusions

We offer approaches to estimating the market for the use of SSP as a source of power to in-space activities. We suggest a conceptual model and estimates based on two approaches, the annualized cost of EPS from interviews and engineering data, and econometric estimation for a customer class for which the necessary data are available. We also indicate the relative market sizes of different classes of potential customers. Because those customers' willingness to pay is likely to be affected by technological innovation in EPS alternatives to SSP, we also briefly discuss some of the ongoing developments in competing and complementary technologies. Finally, we speculate about institutional arrangements for government and the private sector in serving as possible suppliers of SSP. In future research, refining the market estimates to better account for the benefits and costs of SSP could proceed in tandem with specific deployment and cost scenarios for supplying it. Many of the experts whom we interviewed for the study indicated their willingness to represent a customer point of view in serving on future SSP engineering design teams. For advocates of SSP as a source of terrestrial power, future study could also consider overlap in developing SSP for in-space power as well and thus contribute to setting priorities for SSP engineering research.

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[24] SSP research for terrestrial power has included representatives of the utility industry, for instance, in its advisory groups.

## Appendix A

### *Interviews*

In conducting our study of SSP, we spoke with the following space engineers and researchers in spacecraft power design:

- Ronald (Joe) Sovie, NASA Lewis Research Center;
- Robert Pan, Aerospace Corporation;
- Ramesh Gupta, COMSAT Laboratories;
- Hari Vaidyanathan, COMSAT Laboratories;
- Prakash Chitre, COMSAT Laboratories;
- David M. Van Buren, Tecstar, Inc.;
- Christopher Armao, SRS Technologies;
- Dan Beary, Lockheed Martin; and
- Major Ron Fortson, Discoverer II Program Office.

Our interviews focused on the questions below. We were unable to obtain detailed answers for all of these questions.

1. What are the power requirements of your space activity during routine operation in orbit? If possible, please give your answer as a plot of instantaneous peak power versus time, with reference to specific on-orbit or maneuvering or other operational states. Please also provide an estimate of continuous (RMS) power requirements and anticipated duty cycle. In a multiple satellite application, would the power requirements be synchronous, or would the peaks and valleys average out?
2. How useful would an in-orbit “power plug” be if it were configured as in our two candidate systems? Could you provide an estimate of willingness to pay in terms of offset of costs of other subsystems, or cost savings for the entire activity? Which components or subsystems could be eliminated or reduced in size? How much weight savings would be possible?

3. Would there be a “takeback” offset of any savings, in that your activity would need some minimum of residual or redundant on-board storage and receiving, pointing, or conversion modules for using the power plug?
4. What alternative configuration or power output of the plug would be more useful for you if the candidate systems we described above weren’t optimal? Please make reference to your current and anticipated power management needs.
5. What would be the associated cost savings with this alternative configuration? How much larger are they than the savings estimated for the candidate systems?
6. If an autonomous external power plug system providing (a) 100–200 kW in 2005, (b) 10–20 MW in 2015, (c) 1–2 GW in 2025, and (d) 100–200 GW in 2035 were available to provide continuous, uninterrupted power to your spacecraft, what breakthrough activities, missions, or capabilities could you accomplish that you could not otherwise?
7. Would a plug enable you to conduct your activity significantly differently from usual operations? Are there entirely new or different activities that a plug would facilitate? Are there missions that you simply do not currently plan to undertake solely because of anticipated power limitations?

## Appendix B

### *Data and Assumptions for Estimated Willingness to Pay by Conventional Customer Classes*

**NASA small spacecraft**

The range in columns (i) and (ii) is based on data from Sarsfield (1998). The data contain information for 16 small science spacecraft, including total mission cost and characteristics of the spacecraft and their mission. Column (iii) is estimated using projections at the NASA budget Web site for future numbers of small spacecraft planned by the agency, by year, accessed in 1998 at www.nasa.gov.

**Small radar**

All estimates are based on information from the Discoverer II program office of the Defense Applied Research and Planning Agency as of June 2000 and use the cost per watt in terms of nonrecurring spacecraft costs, the amount of required continuous power, expected spacecraft lifespans, and the number of spacecraft expected to be in operation annually during the period indicated. The program has been subject to significant funding uncertainty, but we still consider it a good example for near-term small radar spacecraft that might be SSP customers.

**Commercial geostationary satellites**

The ranges are from designers of geostationary spacecraft and Morgan and Gordon (1989) and are based on the mass fraction represented by EPS and total costs of spacecraft launch and operation. Column (iii) is based on the number of geostationary satellites expected to be in orbit annually during the period indicated, from projections by the Federal Aviation Administration, Office of Commercial Space Transportation, and the Commercial Space Transportation Advisory Committee (COMSTAC). The estimate assumes an average power requirement per spacecraft based on current technology.

**International space station**

Estimates are based on information in Covault (2000). For the capital recovery factor, we use the following conventional approach: $[i/((l+i)^n - 1)] + i$, where $i$ is the discount rate and $n$ is the spacecraft lifespan. We assume the discount rate is 5% for all customer classes.

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