# Deployment of 1 GW Power Generation on the Lunar Surface

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**Abstract** - *The Moon has been shown to receive over 13,000 TW of energy from the sun. It is possible that a portion of this energy could be harvested and used to support a variety of exploration missions or commercial endeavors. How can this energy be captured? Even when limiting the scope of the problem only to that of power generation, it is clear that significant industrialization of the lunar surface would be required, necessitating an extensive logistical chain to Earth. This paper explores the concept of a 1 GW pilot plant and explores some of the issues associated with deployment of the necessary hardware and personnel to build up a power generation infrastructure on the Moon.*

**Keywords:** Moon, beamed power, lunar solar power, Criswell, Ignatiev, microwave.

## 1 Introduction

Since the 1970s there has been periodic interest in the use of the Moon as a source of energy for Earth. Because the Moon receives more than 13,000 terawatts of power from the sun [1], it is viewed as an attractive source of energy. (Global energy usage in 2008 was approximate 15 TW [2].) However, discussions of full global utilization of lunar power are often difficult to grasp. Thus, there is interest in evaluating a smaller utilization of lunar power, on a scale more comparable with a single terrestrial coal fired or nuclear power plant. Consequently, this paper will analyze a 1 GW pilot power plant on the lunar surface.

## 2 Assumptions and Scope

This paper is not a comprehensive, end-to-end sizing assessment of a lunar power generation and beaming system. In order to bound the problem, this paper only addresses a portion of deployment of the power generation capability on the lunar surface and incorporates specific assumptions.

### 2.1 Solar Cell Fabrication

Professor David Criswell [1] of the University of Houston is one of the longtime proponents of lunar solar power. Professor Criswell and University of Houston colleague Dr. Alex Ignatiev [3] have devised an architecture that involves the use of robots on the surface of the Moon to manufacture solar cells through the utilization of lunar resources. The two do not appear to have documented any design analysis for these robots, but describes them as 150-200 kg units capable of producing on average 1 m$^2$ of solar cells per hour, resulting in ~200 kW per year fabrication rate [3]. For purposes of this paper, these estimates will be used.

Criswell and Ignatiev have also published descriptions of a vacuum deposition process [3] to manufacture solar cells from lunar regolith. This is the process that will be assumed for power generation on the lunar surface in this paper.

### 2.2 System Efficiency

The National Society of Black Engineers (NSBE) Houston Space Chapter recently achieved 30% system efficiency in a power beaming demonstration unit. While this unit is not representative of a lunar deployed system, for purposes of this analysis activity, it will be assumed that the lunar power plant transmits to Earth with 30% efficiency. Thus, in order to deliver 1 GW to an Earth-based receiver, the lunar plant must transmit 3.33 GW. While there would also be losses in a lunar transmitter, for purposes of this paper these loses will not be considered and it will be assumed that generation of 3.33 GW power will result in delivery of 1 GW power to Earth.

### 2.3 Power Usage

Power generated on the Moon could be intended for a number of different purposes. The first of which is power beaming to Earth for terrestrial use. Other purposes include beaming to spacecraft, usage by a lunar outpost or colony, or lunar industrial use (e.g. manufacturing plants such as propellant production or aluminum fabrication). For power beaming to Earth, this paper assumes a simplistic form of power beaming that involves line of sight transmission only. (Other architectures invoke massive orbital reflector satellites that form a network allowing power beaming to locations on Earth where the

Moon is not overhead.) The Nevada Test Area is an example of a potential location for a line of sight rectenna (receiving antenna) farm, assuming power received is intended for the Las Vegas service area. In such an architecture, lunar power is intermittent, available only when the Moon is visible from the receiving site. This type of power would not normally directly feed a utility grid, but would instead service secondary or time-scheduled power options, such as providing power to a fuel cell manufacturing plant, molten salt thermal plant, or other facility capable of receiving power for predicted intervals of time. It could be co-located with other renewable energy plants such as a solar thermal farm, wind farm, photovoltaic farm.

The paper will limit its scope primarily to analyses related to the buildup of a power generation architecture on the Moon. Other than the assumptions above, it will not address transmission or receipt of power.

## 2.4 Human-Robot Interaction

Operational tasks such as surface surveying, robot route planning, quality inspections, and asset scheduling will need to be conducted. Some aspects of these tasks are better conducted by lunar surface robotic assets, while others should be conducted by lunar crews, and yet others should be conducted by ground support personnel on Earth.

While some simple maintenance tasks can be completed robotically, many repairs will require human intervention. It is likely that robotic systems will be able to recover any failed hardware and return it to a repair facility in the outpost. Autonomous systems may even be able to diagnose equipment failures and specify corrective measures. However, at the outpost, human skilled repair will be necessary to repair unexpected failure modes. This may involve welding, soldering, mechanical part fabrication, etc.

There are several transportation tasks that will either be performed by human or robotic assets. This includes transport of materiel and crew from Earth and transport of cargo within the surface outpost(s).

Surface deployment involves the transition of cargo from a lunar lander to its point of operational use on the lunar surface. Cargo may consist of any of the following items: manufacturing robots, raw materials, outpost habitats and support hardware, and outpost consumables.

## 2.5 Supporting Outpost Capabilities

Building up a power generation capability on the Moon will require supporting outpost capabilities. It is not conceivable that the architecture described by Criswell and Ignatiev can be executed without a human presence on the Moon. The first question concerns whether manned presence is required on one or both limbs. Just like any other celestial body, the Moon has a day-night cycle. Clearly, a solar power plant on the Moon does not work during night. However, because the Moon is tidally locked with Earth, one side always faces the Earth. When one limb (extreme edge of the side facing Earth) is in night, the other limb is in day. Thus, for continuous power transmission, two identical solar array farms must be constructed on the Moon, one on each limb. It is likely that both farms will require a supporting outpost in the local vicinity.

The number of crew needed to deploy and sustain a 1 GW power generation capability will of course grow during the buildup phase. This paper will not attempt to size the crew size or lunar outpost required to support the lunar solar power system.

# 3 Launch and Deployment

How would such a system be launched be to the Moon? Because the regolith processing robots are small, there are multiple options for launch vehicles and lunar landers. Is it more efficient to use super heavy lift boosters like the Saturn V or greater numbers of smaller boosters like the commercial rockets under development such as the Falcon 9?

## 3.1 Comparison of Launch Architectures

In order to compare the potential boosters for delivery of a lunar solar power system several important factors must be weighed.

What is the payload capacity of the booster? This is the most obvious cost from the perspective of the system engineer attempting to place payload on the Moon. Clearly, the greater the payload capacity, the more Cell Pavers can be delivered per flight.

What are the launch costs associated with the booster in question? Launch costs only represent the cost of using a particular rocket and do not include costs for manufacturing the payload and delivering to the launch site. Thus, it is important to not make the mistake of assuming the launch costs represent the entire budget necessary for launching a payload. However, this is an important parameter for trading against different launch vehicle providers.

What is the launch cost per Cell Paver robot delivered to the surface of the moon? This is a direct function of the rocket's payload capacity and launch costs. For simplicity, the design of the lunar lander and other payload upper stages are being ignored in this study, though in reality the same booster could have substantially different payload delivery capabilities depending on the design of lunar landers and upper stages. The "gear ratio" (mass in

LEO/payload landed on the moon) has been cited in literature for cargo delivery to the lunar polar regions as approximately four [4], but this does not match with detailed design analysis conducted during the Constellation Program for the Altair Lunar Lander. The DAC-4 (Design Analysis Cycle) version of the Altair was estimated to have a cargo capacity of 14,500 kg alongside an Ares V payload capacity to LEO of 188,000 kg, resulting in a gear ratio of approximately 12.96, more than three times that estimated in the high level parametric studies.

What is the total number of flights required to establish a 1 GW power generation capability? The number of rockets utilized will both decrease the cost per rocket and increase the total acquisition cost.

How long will it take to deploy a 1 GW power generation capability? This implies costs beyond merely the launch costs. A workforce must be employed to support the power system deployment beyond merely the launch team. The more years it takes to get the system up and running, the longer this deployment team must remain employed and the greater the total life cycle costs. While it might save x number of launch cost dollars to spread launches over a greater number of years (e.g. more launches of a lower capacity booster) it will also increase y number of operations dollars to maintain the deployment team.

## 3.2 Boosters for Comparison

This paper limits analysis the potential boosters for use in this lunar solar power system to a set of American public or private launch vehicles in the medium to heavy lift class, as shown in Figure 1.

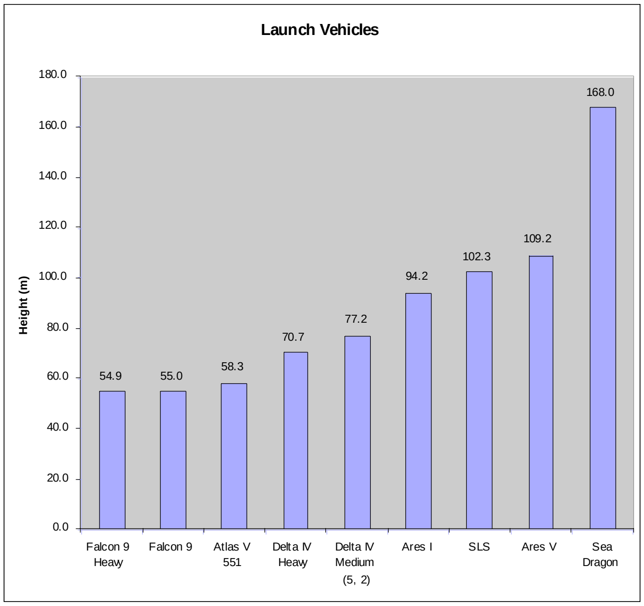


Figure 1. Launch Vehicle Comparison

### 3.2.1 United Launch Alliance

United Launch Alliance is a joint venture of Lockheed Martin and the Boeing Company that operates the Atlas and Delta series of rockets.

Atlas V 551 Specifications:

- Payload to LEO: 18,814 kg
- Predicted Cell Pavers to Lunar Surface: 6
- Launch Cost: $138,000,000

Delta IV Medium (5,2) Specifications:

- Payload to LEO: 10,300 kg
- Predicted Cell Pavers to Lunar Surface: 3
- Launch Cost: $150,000,000

Delta IV Heavy Specifications:

- Payload to LEO: 22,977 kg
- Predicted Cell Pavers to Lunar Surface: 7
- Launch Cost: $254,000,000

### 3.2.2 Space X

Space X is a relatively young launch vehicle provider, created by PayPal founder Elon Musk, with the vision to dramatically drive down the cost of launch services with its Falcon series of rockets.

Falcon 9 Specifications:

- Payload to LEO: 10,450 kg
- Predicted Cell Pavers to Lunar Surface: 3
- Launch Cost: $59,500,000

Falcon 9 Heavy Specifications:

- Payload to LEO: 53,000 kg
- Predicted Cell Pavers to Lunar Surface: 17
- Launch Cost: $125,000,000

### 3.2.3 NASA Constellation

The now cancelled Constellation program began design work on the Ares family of rockets.

Ares I Specifications:

- Payload to LEO: 24,500 kg
- Predicted Cell Pavers to Lunar Surface: 8
- Launch Cost: $176,000,000

Ares V Specifications:

- Payload to LEO: 188,000 kg
- Predicted Cell Pavers to Lunar Surface: 61
- Launch Cost: $1,000,000,000 [assumed value]

### 3.2.4 NASA Exploration

The Space Launch System has been created to replace the Ares rockets to enable human spaceflight beyond Low Earth Orbit. The rocket is scalable, but this analysis will only consider the super heavy variant.

Space Launch System Specifications:

- Payload to LEO: 130,000 kg
- Predicted Cell Pavers to Lunar Surface: 42
- Launch Cost: $1,000,000,000 [assumed value]

### 3.2.5 Concept Studies

In 1963, a study was conducted by Aerojet to develop follow-on rockets to replace the Saturn V. This study resulted in a feasibility study and preliminary design for the Sea Dragon, a sea launched, mega-heavy lift booster. While this design was never pursued, the Sea Dragon represents one of the most powerful chemical propellant rockets ever studied and for purposes of this paper is considered a bounding case for the "big, dumb, booster" philosophy.

Sea Dragon Specifications:

- Payload to LEO: 508,477 kg
- Predicted Cell Pavers to Lunar Surface: 166
- Launch Cost: $305,086,200 in 1963 dollars, extrapolated to $2,199,620,654 in 2011 dollars.

## 3.3 Launch Frequency Analysis

As shown by the annual launch rate in Table 1, it is clearly impractical to deploy a lunar solar power system by means of an annual flight manifest, regardless of booster selection. The worst cases occur with the Falcon 9 and Delta IV Medium (5,2) boosters, requiring over a century of launches to reach operational capability. Even under the best case, use of the Sea Dragon mega heavy lift booster requires fifteen years. The launch costs, however, do appear attractive under the Falcon 9 Heavy case, with only a $5.5 billion launch cost. But spreading that cost over 44 years means the system is never deployed in a practical period of time.

Increasing the flight rate as shown in Table 2 to two launches per year makes only negligible improvement. The increase of flight rate does demonstrate that the annual launch rate had made maximum use of the Cell Pavers' ability to operate between flights, but that does not overcome the slow delivery of additional rovers. Nor does an increase from one flight per year to two. The Sea Dragon case only decreases by about five years. And unfortunately, the total launch costs increase due to an increase in total flights – in this case a maximum of 150 flights with the Falcon 9 and Delta IV Medium (5,2) down to a minimum of 21 flights with the Sea Dragon.

The quarterly launch rate in Table 3 allows the Ares V and Space Launch System boosters to move under the fifteen year mark, but all boosters still require too many years for practical deployment of a 1GW lunar-based power generation system. More disquieting is the rise in annual launch costs as the number of flights increases. In truth, these launch costs would decrease as the number of boosters increases, but this analysis does not address those potential cost savings.

A bi-monthly launch rate brings all boosters under the half century mark for delivery of a 1 GW power production system to the Moon. Table 4 also indicates that all boosters other than Ares V, SLS, and Sea Dragon require greater than a hundred flights to deliver the lunar power system, ranging from 109 flights of the Falcon 9 Heavy to a whopping 259 flights each for the Falcon 9 and Delta IV Medium (5,2).

A monthly launch rate as shown in Table 5 enables the Sea Dragon to deploy a 1 GW lunar power system within 4.11 years and 51 flights, easily within the construction timetables for terrestrial power plants of similar capacity. However, the annual launch costs are staggering at roughly $27 billion, significantly greater than the entire NASA budget. The Falcon 9 Heavy only requires $1.5 billion annual launch costs, but takes 12.74 years to deploy the power system with 156 flights.

Table 1. Annual Launch

| 3.3 GW Capability | Annual Launch | | | | | |
|---|---|---|---|---|---|---|
| | Payload Capacity to LEO (kg) | Years | # Flights | Per Launch Costs | Total Launch Costs | Annual Launch Costs |
| Atlas V 551 | 18,814 | 76 | 76 | $138,000,000 | $10,488,000,000 | $138,000,000 |
| Delta IV Med (5,2) | 10,300 | 107 | 107 | $150,000,000 | $16,050,000,000 | $150,000,000 |
| Delta IV Heavy | 22,977 | 70 | 70 | $254,000,000 | $17,780,000,000 | $254,000,000 |
| Falcon 9 | 10,450 | 107 | 107 | $59,500,000 | $6,366,500,000 | $59,500,000 |
| Falcon 9 Heavy | 53,000 | 44 | 44 | $125,000,000 | $5,500,000,000 | $125,000,000 |
| Ares I | 24,500 | 66 | 66 | $176,000,000 | $11,616,000,000 | $176,000,000 |
| Ares V | 188,000 | 24 | 24 | $1,000,000,000 | $24,000,000,000 | $1,000,000,000 |
| Space Launch System (Full Capacity) | 130,000 | 29 | 29 | $1,000,000,000 | $29,000,000,000 | $1,000,000,000 |
| Sea Dragon | 508,477 | 15 | 15 | $2,199,620,654 | $32,994,309,815 | $2,199,620,654 |

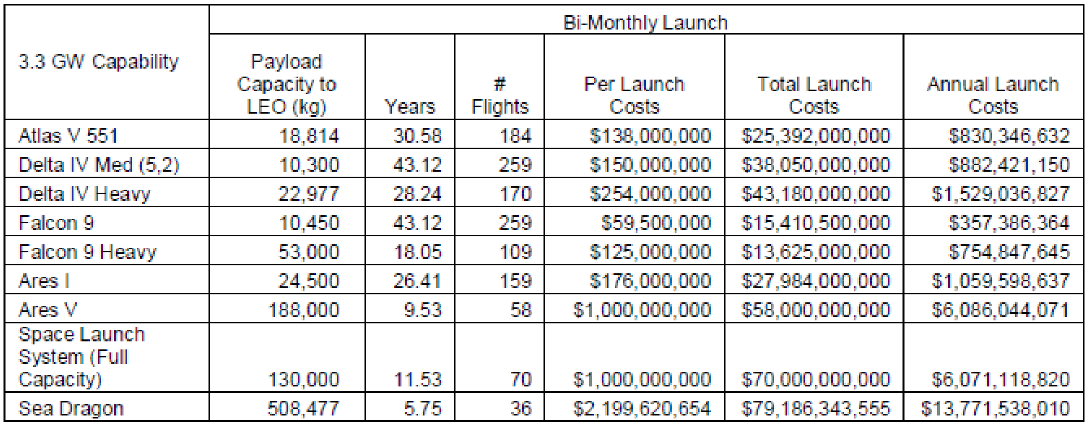
Table 2. Semi-Annual Launch

| 3.3 GW Capability | Semi-Annual Launch | | | | | |
|---|---|---|---|---|---|---|
| | Payload Capacity to LEO (kg) | Years | # Flights | Per Launch Costs | Total Launch Costs | Annual Launch Costs |
| Atlas V 551 | 18,814 | 52.64 | 106 | $138,000,000 | $14,628,000,000 | $277,887,538 |
| Delta IV Med (5,2) | 10,300 | 74.7 | 150 | $150,000,000 | $22,500,000,000 | $301,204,819 |
| Delta IV Heavy | 22,977 | 49.13 | 99 | $254,000,000 | $25,146,000,000 | $511,825,768 |
| Falcon 9 | 10,450 | 74.7 | 150 | $59,500,000 | $8,925,000,000 | $119,477,912 |
| Falcon 9 Heavy | 53,000 | 31.59 | 64 | $125,000,000 | $8,000,000,000 | $253,244,698 |
| Ares I | 24,500 | 45.62 | 92 | $176,000,000 | $16,192,000,000 | $354,932,047 |
| Ares V | 188,000 | 16.55 | 34 | $1,000,000,000 | $34,000,000,000 | $2,054,380,665 |
| Space Launch System (Full Capacity) | 130,000 | 20.05 | 41 | $1,000,000,000 | $41,000,000,000 | $2,044,887,781 |
| Sea Dragon | 508,477 | 9.97 | 21 | $2,199,620,654 | $46,192,033,740 | $4,633,102,682 |

Table 3. Quarterly Launch

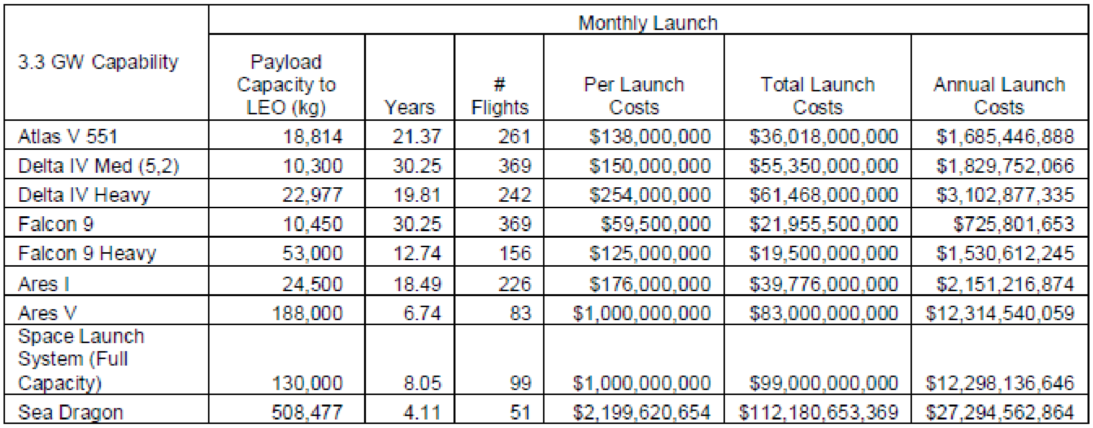
| 3.3 GW Capability | Quarterly Launch | | | | | |
|---|---|---|---|---|---|---|
| | Payload Capacity to LEO (kg) | Years | # Flights | Per Launch Costs | Total Launch Costs | Annual Launch Costs |
| Atlas V 551 | 18,814 | 37.4 | 151 | $138,000,000 | $20,838,000,000 | $557,165,775 |
| Delta IV Med (5,2) | 10,300 | 52.61 | 212 | $150,000,000 | $31,800,000,000 | $604,447,824 |
| Delta IV Heavy | 22,977 | 34.41 | 139 | $254,000,000 | $35,306,000,000 | $1,026,038,942 |
| Falcon 9 | 10,450 | 52.61 | 212 | $59,500,000 | $12,614,000,000 | $239,764,303 |
| Falcon 9 Heavy | 53,000 | 22.19 | 90 | $125,000,000 | $11,250,000,000 | $506,985,128 |
| Ares I | 24,500 | 32.16 | 130 | $176,000,000 | $22,880,000,000 | $711,442,786 |
| Ares V | 188,000 | 11.72 | 48 | $1,000,000,000 | $48,000,000,000 | $4,095,563,140 |
| Space Launch System (Full Capacity) | 130,000 | 14.21 | 58 | $1,000,000,000 | $58,000,000,000 | $4,081,632,653 |
| Sea Dragon | 508,477 | 6.98 | 29 | $2,199,620,654 | $63,788,998,975 | $9,138,825,068 |

Table 4. Bi-Monthly Launch



| 3.3 GW Capability | Bi-Monthly Launch | | | | | |
|---|---|---|---|---|---|---|
| | Payload Capacity to LEO (kg) | Years | # Flights | Per Launch Costs | Total Launch Costs | Annual Launch Costs |
| Atlas V 551 | 18,814 | 30.58 | 184 | $138,000,000 | $25,392,000,000 | $830,346,632 |
| Delta IV Med (5,2) | 10,300 | 43.12 | 259 | $150,000,000 | $38,050,000,000 | $882,421,150 |
| Delta IV Heavy | 22,977 | 28.24 | 170 | $254,000,000 | $43,180,000,000 | $1,529,036,827 |
| Falcon 9 | 10,450 | 43.12 | 259 | $59,500,000 | $15,410,500,000 | $357,386,364 |
| Falcon 9 Heavy | 53,000 | 18.05 | 109 | $125,000,000 | $13,625,000,000 | $754,847,645 |
| Ares I | 24,500 | 26.41 | 159 | $176,000,000 | $27,984,000,000 | $1,059,598,637 |
| Ares V | 188,000 | 9.53 | 58 | $1,000,000,000 | $58,000,000,000 | $6,086,044,071 |
| Space Launch System (Full Capacity) | 130,000 | 11.53 | 70 | $1,000,000,000 | $70,000,000,000 | $6,071,118,820 |
| Sea Dragon | 508,477 | 5.75 | 36 | $2,199,620,654 | $79,186,343,555 | $13,771,538,010 |

Table 5. Monthly Launch



| 3.3 GW Capability | Monthly Launch | | | | | |
|---|---|---|---|---|---|---|
| | Payload Capacity to LEO (kg) | Years | # Flights | Per Launch Costs | Total Launch Costs | Annual Launch Costs |
| Atlas V 551 | 18,814 | 21.37 | 261 | $138,000,000 | $36,018,000,000 | $1,685,446,888 |
| Delta IV Med (5,2) | 10,300 | 30.25 | 369 | $150,000,000 | $55,350,000,000 | $1,829,752,066 |
| Delta IV Heavy | 22,977 | 19.81 | 242 | $254,000,000 | $61,468,000,000 | $3,102,877,335 |
| Falcon 9 | 10,450 | 30.25 | 369 | $59,500,000 | $21,955,500,000 | $725,801,653 |
| Falcon 9 Heavy | 53,000 | 12.74 | 156 | $125,000,000 | $19,500,000,000 | $1,530,612,245 |
| Ares I | 24,500 | 18.49 | 226 | $176,000,000 | $39,776,000,000 | $2,151,216,874 |
| Ares V | 188,000 | 6.74 | 83 | $1,000,000,000 | $83,000,000,000 | $12,314,540,059 |
| Space Launch System (Full Capacity) | 130,000 | 8.05 | 99 | $1,000,000,000 | $99,000,000,000 | $12,298,136,646 |
| Sea Dragon | 508,477 | 4.11 | 51 | $2,199,620,654 | $112,180,653,369 | $27,294,562,864 |

## 3.4 Energy Industry Relevance

Shell reports that they anticipate spending $100 billion from 2011-2014 to support new energy production [5]. Thus, significant expenditures are within the capability of the energy industry. But do they rise to the level of even the deployment costs of a 1 GW power plant on the Moon?

Cost estimates for coal-fired plants have increased substantially in recent years, with estimates as high as $3,500 per kW [6], which would translate into a cost of $3.5 billion for a 1 GW plant. Nuclear plants are more expensive still, with estimates ranging from $5,500 to $8,100 per kW [7], translating to costs of $5.5 to $8.1 billion for a 1 GW plant.

If we could wait 44+ years for a lunar solar plant to come online, then a Falcon 9 Heavy launch platform might make economic sense with its $5.5 billion launch costs at an annual flight rate, as compared against a nuclear power plant. Unfortunately, it is unlikely that any energy company could tolerate such a lengthy construction period. And deployment in a reasonable (4-8 year) timeframe is only achievable with the Sea Dragon at an estimated cost in the hundred billion dollar range. While Shell is on the record committing to spend $100 billion for new energy sources, neither it nor any other company could be expected to do so simply to deploy a 1 GW power plant.

# 4 Forward Work

This paper only addresses deployment of solar power generation, but this is by no means a complete assessment of the lunar surface architecture. Additional work is required to evaluate deployment of microwave power transmission systems on the lunar surface, lunar outpost logistics, and limits of ISRU for solar cell and transmitter production.

Within the scope of the deployment analysis, additional work is also required to identify or design lunar landers associated with each booster under consideration, including cargo handling systems to accommodate and offload the Cell Pavers. Unique characteristics of each lander design can help optimize the number of Cell Pavers each booster can deliver to the lunar surface. Further, the Cell Paver design itself should be revisited. It is highly unlikely that the small rovers developed by the University of Houston are the optimal system for industrial lunar development – no more so than a household lawn mower is optimal for maintaining a football field.

Further study is also needed in the area of cost optimization for boosters under development or conceptual boosters. In particular, application of lessons learned from Space X Falcon boosters and other aerospace industry low cost development activities should be applied to a Sea Dragon class mega booster in order to propose a transportation architecture capable of delivering Cell Pavers to the lunar surface within a timeline and budget to make lunar solar power more competitive against terrestrial alternatives.

## 5 Conclusions

Traditional NASA procurement models for heavy lift launch systems are not viable for large scale space development. An Ares V or SLS model cannot compete against Falcon 9 or Falcon 9 Heavy concepts when viewed from a cost perspective.

However, inexpensive, light to medium boosters also are not viable for large scale space development due to the staggering number of launches required as compared against super heavy lift rocket systems. Neither Falcon 9 nor Falcon 9 Heavy boosters could deploy a large quantity of mass to the moon in a timeframe competitive with Ares V or Sea Dragon.

Deployment timelines for the Sea Dragon and Ares V are within the ballpark of terrestrial power plant construction. Space Launch System and Falcon 9 Heavy appear to fall just outside the ballpark and all other boosters appear sufficiently long in duration to make them not worth further consideration.

When considering that the total lunar power system deployment (including personnel, raw materials not available on the Moon, transmitter and other construction, etc.) may require approximately twice the number of launches as just that to deploy the Cell Paver robots, it is likely that only the Sea Dragon remains within a timeline that is viable for development alongside terrestrial power systems. Thus, it is clear that a lunar power system can not be deployed on the lunar surface absent a Sea Dragon class rocket, but with per launch costs on the order of Falcon series rockets.

This would seem to imply a need for a new engine development as the Falcon 9 Heavy has probably pushed the limits of clustering. It would be interesting to see what a Space X type operation could do with a 2012 revisit of the Sea Dragon concept. Such development is probably prerequisite to any large scale human activity beyond Low Earth Orbit.

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## References

[1] D. Criswell, “Solar power via the moon,” *The Industrial Physicist*, Vol. 8, No. 2, pp. 12-15, April/May 2002.

[2] D. MacKay, *Sustainable energy – without the hot air*, UIT Cambridge Ltd, Cambridge, England, 2009.

[3] A. Ignatiev, “Solar cell development on the moon for lunar solar power,” Moon Base Conference, Washington DC, October 2005.

[4] D. Rapp, *Human missions to Mars: Enabling technologies for exploring the red planet*, Springer, South Pasadena, California, 2010.

[5] Shell, “Future energy,” Internet URL: http://www.shell.com/home/content/aboutshell/future_energy/, December 2011.

[6] D. Schlissel, A. Smith and R. Wilson, *Coal-fired power plant construction costs, synapse energy economics*, Cambridge, MA, July 2008.

[7] D. Schlissel and B. Biewald, *Nuclear power plant construction costs, synapse energy economics*, Cambridge, MA, July 2008.