The Solar Umbrella: Insights from Below

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Outline

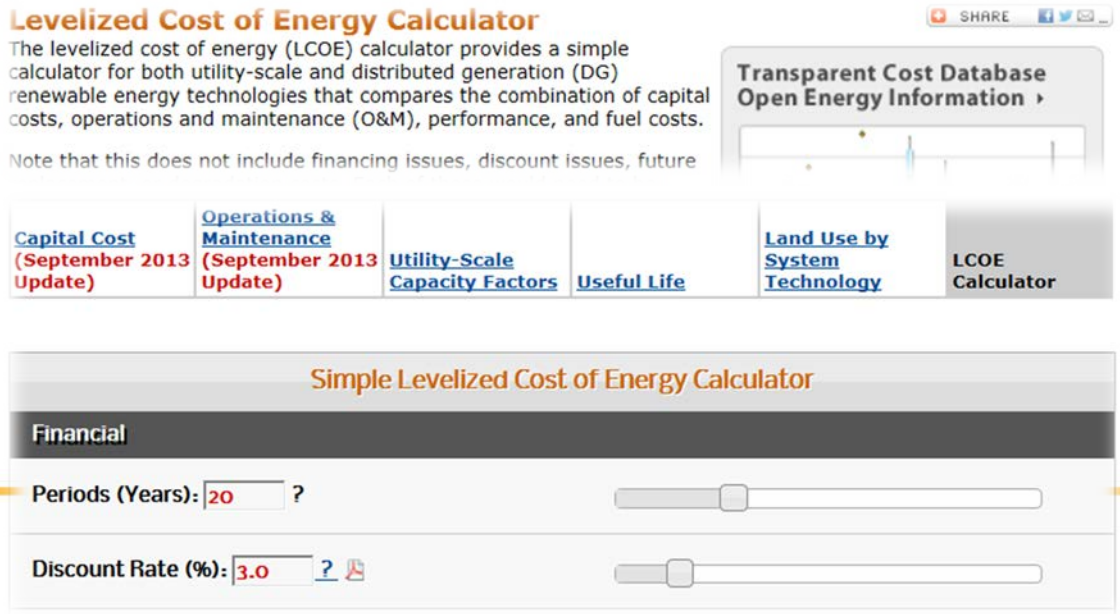
- Context
- Economic Calibration
- Technical Concept
- Cost Results
- Lesson Learned
- Future Recommendations

Speaker Context

- On leave from Caltech Jet Propulsion Laboratory
- AAAS Science & Technology Policy Fellow, US Department of Energy, Solar Energy Technologies Office, Washington, DC
- SunShot Initiative (from web)
  - Vision
    - The SunShot Initiative vision is to make the total cost of solar energy economically viable for everyday use, so that all Americans will benefit from this clean renewable energy resource.
  - Mission
    - The SunShot Initiative is a collaborative national effort to make the United States a leader in the global clean energy race by fueling solar energy technology development. SunShot will enable ***widespread, large-scale adoption*** of solar across America by making solar energy systems ***cost-competitive with other forms of energy by the end of the decade***.

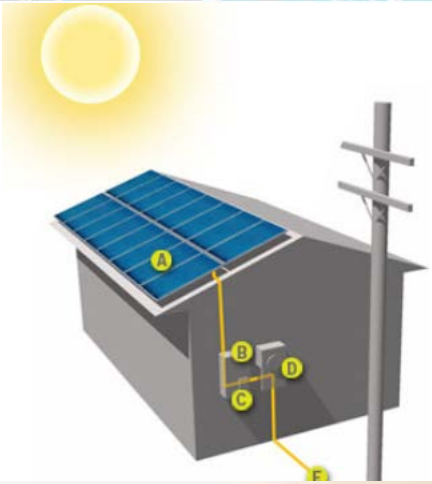
What is Low Cost?

- Common Metrics
  - Levelized Cost of Energy (LCOE) is the **constant unit cost** (per kWh or MWh) of a payment stream that has the same **present value** as the total cost of building and operating a generating plant over its life- usually 20 years
    - Great for comparing technologies with different operating characteristics
    - DOE National Renewable Energy Lab (NREL) has simplified calculator
  - Capital Cost ($/W) is an input to LCOE and a good benchmark for solar technologies



Economic Calibration

- Framing
  - Utility-Scale Terrestrial Solar Power -> ~2.25 $/W (CA)
  - Residential Solar Power -> ~4.50 $/W
  - Concentrated Solar Power -> ~0.15 $/kW-h
- DOE SunShot goals:
  - 1 $/W includes cost of inverter, Balance of System hardware, soft cost, and module
  - 0.06 $/kW-h Levelized Cost of Energy
  - If these metrics are hit . . . Solar technologies will be at parity with conventional power generation -> *market does the rest!*



Study Objectives

- *Inject into the literature* a scalable Technology Demonstration Mission of an end to end system design with cost estimate
- *Identify critical subsystem development* which is necessary to drive down overall system level costs
- *Demonstrate that power beaming is feasible* through engineering implementation
- This is NOT:
  - A means to produce electricity at cost parity with the marketplace
  - A full exploration of the trade space

Design Summary

- *5.8 GHz* power beam frequency
- Transmitting from *LEO, 1620 km*
- Thin-film photovoltaic with conversion efficiency 12.5%
- 3750 m^2 disk solar array producing 640 kW and deployed from spacecraft bus
- 25 m diameter transmitting antenna deployed from spacecraft bus
- Free space transmission efficiency of 1%
- Peak power density of 0.023 W/m^2 - below 10 W/m^2 public safety limit
- 575 m rectenna diameter with surface area of 0.26 km^2
- Total spacecraft weight: 4,641 kg
- Power collected on ground: 6.4 kW

Friis Transmission Equation

- Far Field assumptions
- Energy Transmission:

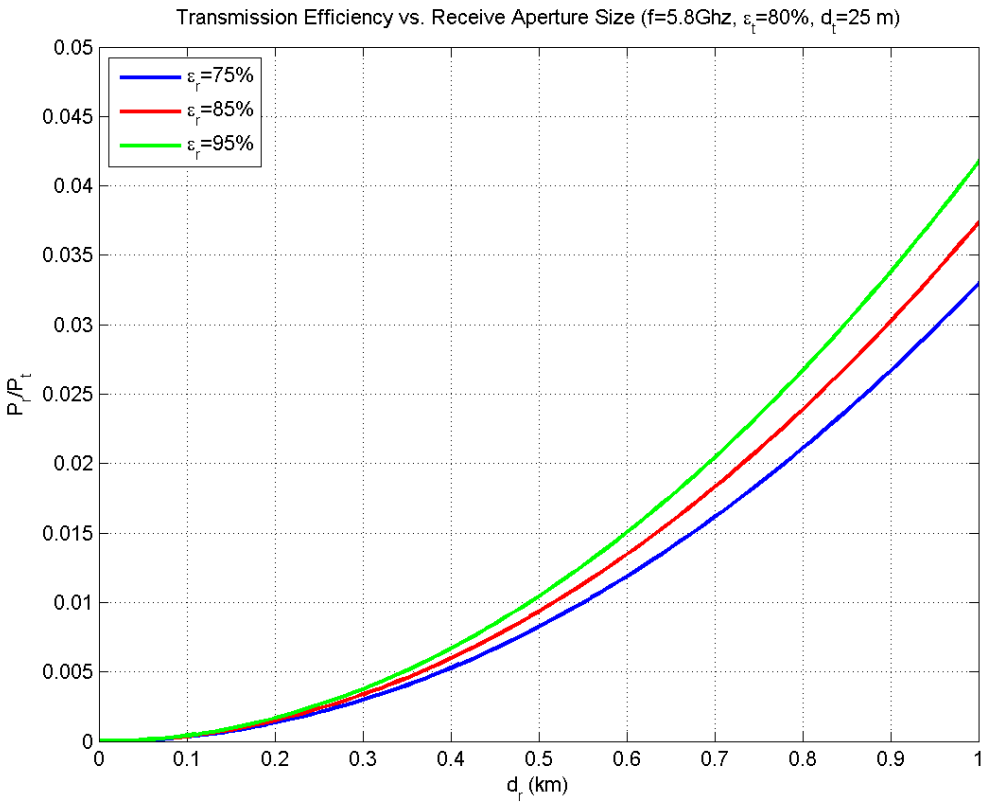
$$\epsilon_{trans} = \epsilon_r \epsilon_t \frac{A_r A_t}{\lambda^2 R^2}$$

- Power density:

$$\epsilon_{trans} = \frac{P_r}{P_t}$$

- Internal efficiencies

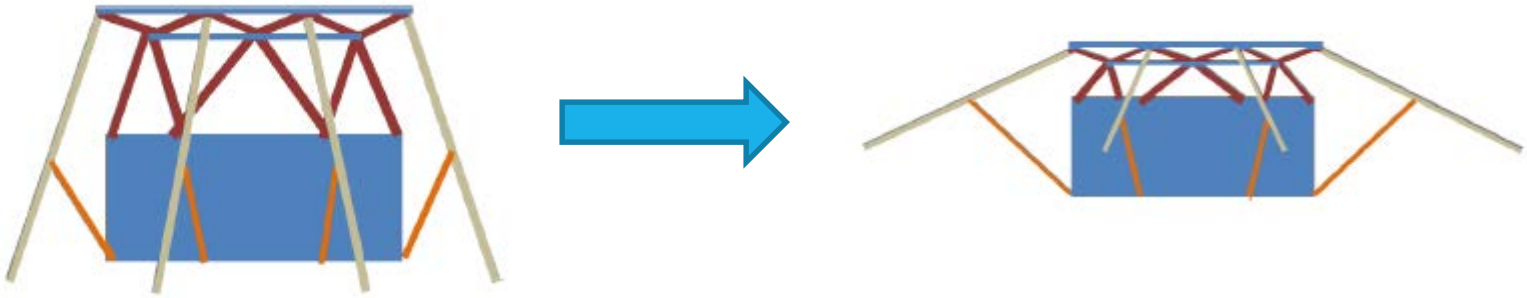
$$p_d = \frac{A_t P_t}{\lambda^2 R^2}$$



Solar Array Design Summary

TABLE I
SOLAR ARRAY DESIGN SUMMARY

Specification	Description
Solar Array Type	Thin film PV
Solar Array Efficiency	12.5%
Solar Cell Type	CP1, a-Si:H
Size, Outer Radius	35.5 m
Specific Power per solar cell (W/kg)	4300
Specific Mass per solar cell (kg/m^2)	0.03
Power Density (W/m^2)	170
Power Output (kW)	640
Total Material Mass (kg)	112.5

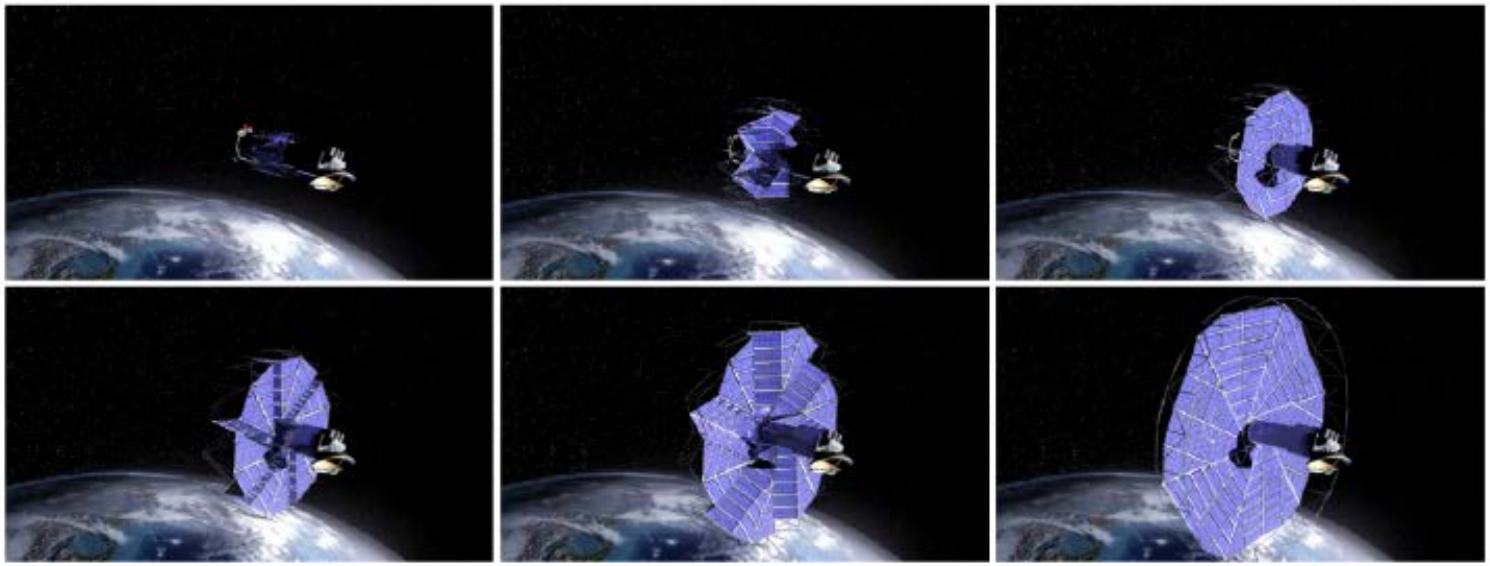


Transmitting Array

- DC to RF conversion
- Gallium Nitride Solid State Power Amplifier
- Deployable that accommodates some level of thickness
- Origami option

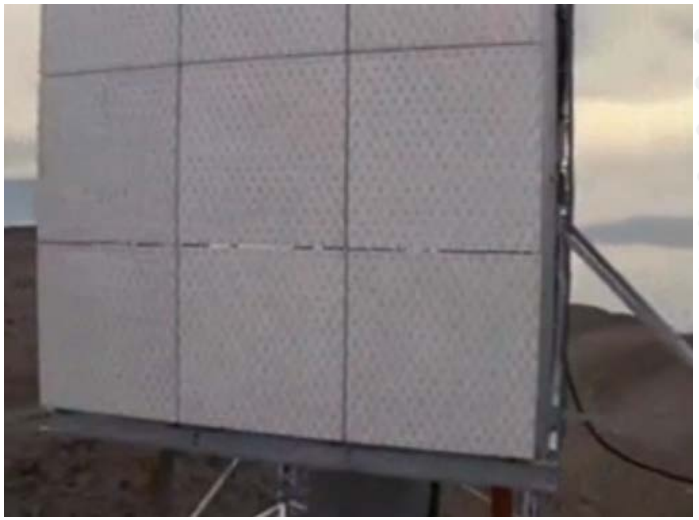
TABLE II
TRANSMITTING ARRAY DESIGN SUMMARY

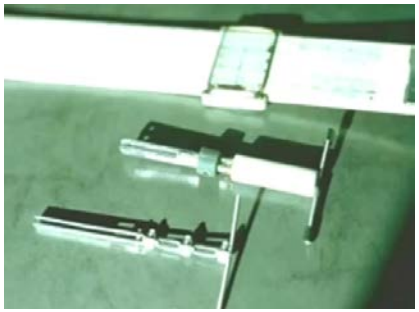
Specification	Description
Subarray Type	Solid-State GaN
Max Converter Power Output (W)	59
GaN Converter mass (kg)	0.001
Specific Mass (kg/m^2)	33.9
Specific Power (kW/m^2)	1.3

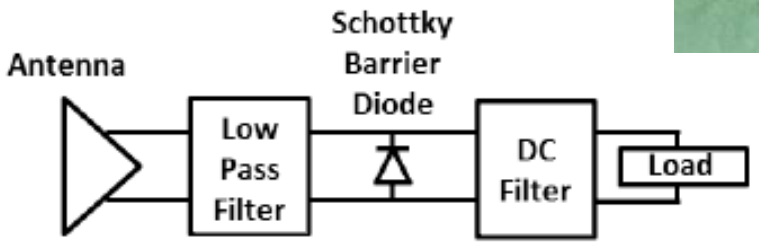


Rectenna Design

- Goldstone heritage
  - Dickinson et al.
  - Highest power demonstration 2kW to date
- 85% efficiency
- 2.5 cm dipole length
  - Hand tunable
- 0.023 W/m^2
- Manufacturing curve







Mass *Estimates*

Element	*Weight (kgs)*
Uncrewed Earth Orbiting Spacecraft	4,641.00
Spacecraft Bus Subsystems	4,641.00
Structures & Mechanisms	2,475.00
Solar Array	240.00
Guidance, Navigation and Control	50.00
Thermal Control	175.00
Transmitter	1,250.00
Electrical Power and Distribution	101.00
Command, Control & Data Handling	110.00
Attitude Determination & Control	240.00

Cost Modeling

- NASA/Air Force Cost Model (NAFCOM)
- CERs based on heritage database provided by NASA and multi variable input
- CERs heavily based on:
  - **Mass**
  - Manufacturing Methods
  - Engineering Management
  - New Design
  - Funding Availability
  - Test Approach
  - Integration Complexity
  - Pre-Development Study
  - **Technology Maturity Index (TMI)**

TABLE III
ESTIMATED COST FOR SSP TECHNOLOGY DEMONSTRATION

WBS Element	Flight Unit	DDT&E	Total
1.0 Spacecraft	65.86	460.20	526.06
1.1 Spacecraft Subsystems	56.31	301.36	357.66
Solar Array	3.05	5.43	8.48
Transmitter	1.13	144.63	145.76
Spacecraft Bus	52.12	151.29	203.42
Structures & Mechanisms	30.75	85.47	116.23
Power Management & Distribution	2.79	11.25	14.04
ADCS	5.59	15.28	20.87
Guidance Navigation & Control	0.26	0.54	0.79
CC&DH	7.18	12.84	20.01
Thermal Management System	5.56	25.91	31.48
1.2 System Integration	9.55	158.85	168.40
2.0 Program Support	9.88	69.03	78.91
3.0 Vehicle Level Integration	4.54	31.75	36.30
4.0 Rectenna	0.00	0.00	64.13
5.0 Falcon 9 Launch Services	0.00	0.00	56.5
Total Mission Cost	80.28	560.99	761.9

Cost Considerations

- Cost viability was not core to study
- Capital Cost Metrics
  - $120,000 /W
  - 1.4 W/kg
- LCOE calculation would need to include
  - Performance degradation for thin-film: 7 year life span
- ***Caution: economic viability analysis has high uncertainty during TDM phase for SSP***

Lessons Learned

- Maybe Thin-film (i.e., amorphous silicon) wasn't such a good idea
  - Performance degradation over time
  - Quality Control and performance has high uncertainty
- What is the status of retro-directive phased-array technology?
  - The largest phased array that has been tested in this mode (for power beaming?) is 8x8
- Inefficiency of the power electronics that drives the antenna may be closer to ~20%, a severe hit to the end-to-end efficiency calculation, previously ~85%.
- Two alternative flight demos:
  - (1) on ISS, using ISS power;
  - (2) hitch a ride and leverage standardized payload integration, such as ESPA ring
- Capturing public interest was determined to be of higher value in the TMD than delivering power at a price point comparable to that of terrestrial solar
  - How do you quantify value of public interest?
- Existing deployable solar array development programs could be leveraged to cut down on overall system costs
  - ATK MegaFlex, DSS Mega-ROSA, and L'Garde Sunjammer.

Future Technical Recommendations

- Modular wins out in the long run
  - Launch cost $1,000/lb and going down . . .
  - Approx. 10% of TDM study cost due to launch
- Leverage the construction of one rectenna by using several modular satellites beaming to same location
- Robotic assembly or printed manufacturing of rectenna is low hanging fruit that can enable greater free space transmission efficiency

Recommendations for the Community

- Dial back SSP energy security arguments -> EIA estimate is 1% of oil used for electricity production
- Re-Branding of the concept
  - Possibly remove ‘Space’ from concept label
- Learn from Concentrated Solar Power
  - Huge Startup Investment, 2+ billion USD
  - Selling point is storage (thermal)
  - Currently underwritten by DOE loan guarantee program
  - Funded since 70s and part of all future renewable energy projections
- International market is where we will find greatest success
  - EIA projections for US electricity load is flat
  - Displacing existing energy production will be difficult!