Space Based Solar Power Study

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Office of Technology, Policy, and Strategy

Space Based Solar Power

International Space Based Solar Power Activities

National Aeronautics and Space Administration

U.S.
Advancing power beaming from and in space for economic development, net-zero goals, and national goals

Europe
Created SBSP program for net zero goals and national goals

Japan
SBSP development codified in law for national goals

SBSP research and development has been accelerating over past five years (2018 – 2023)

SBSP studies, design concepts, and technology developments are funded around the world by academic, commercial, and government communities for economic development, net-zero goals, and national goals.

LEGEND

- Academic Concepts/Studies
- Private Sector Concepts/Studies
- Private Sector Technology Development
- Civil Government Concepts/Studies
- Civil Government Technology Development
- National Security Concepts/Studies
- National Security Technology Development
- National Goal

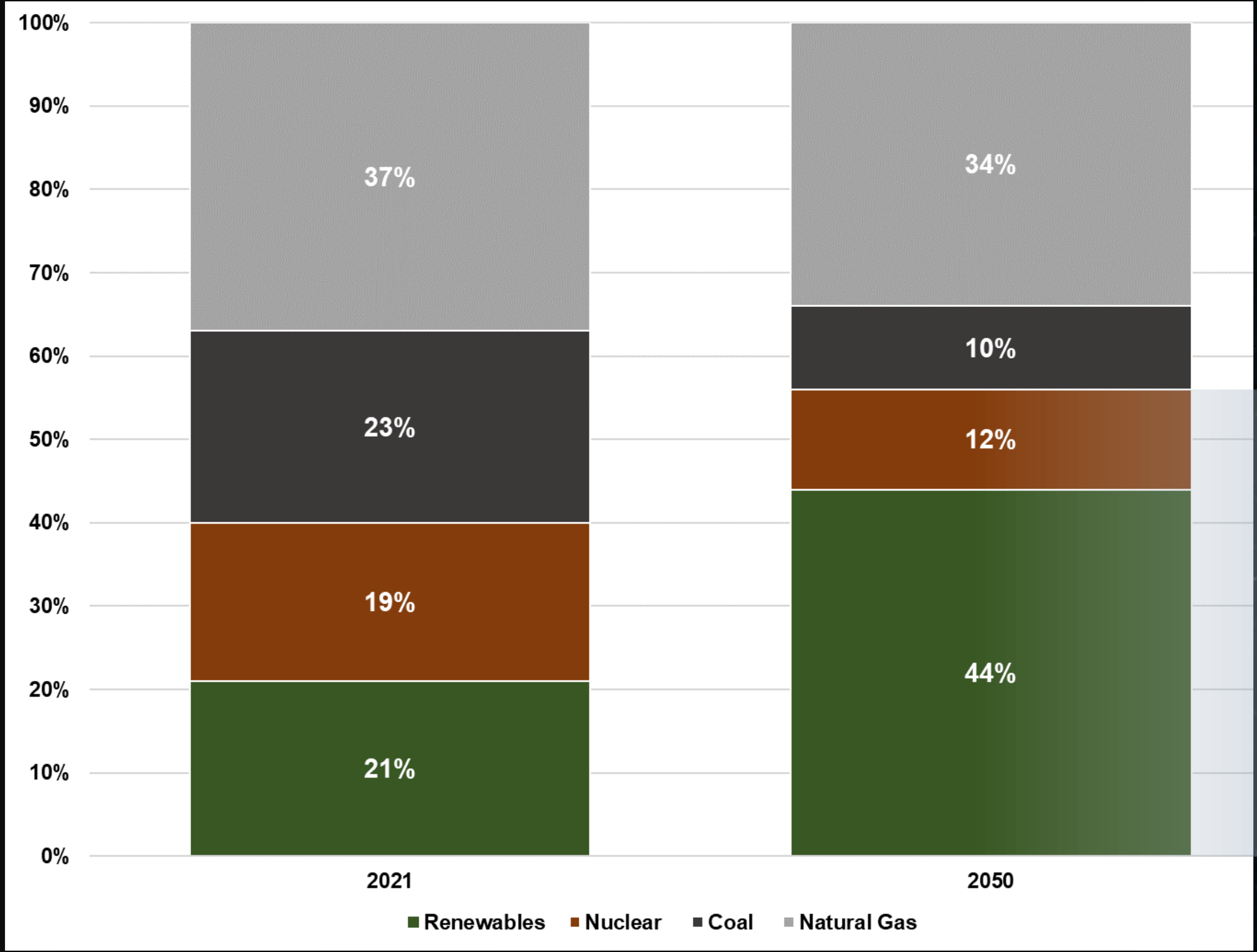
Concepts/Studies: Conceptual descriptions,, architectures, and concept of operations, typically published in peer reviewed journals or books, or presented at conferences

Technology Development: Engineering schematics, designs, and actual hardware at lower tiers of supply chain (e.g., component level as opposed to system level)

National goal: Law or long term 5 year plane, published as national policy

Motivation

*"**Net zero** means cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests for instance."* - United Nations



U.S. Electricity Generation, Energy Information Administration, 2021

- U.S. electric power sector produces 25% of U.S. greenhouse gas emissions – most are CO_2 emissions from coal and natural gas
- Is SBSP a renewable source of electricity generation that can contribute to achieving net zero

U.S. will need to generate 70% of U.S. electricity from renewable sources to reach net-zero by 2050, Bouckaert et al., 2021

U.S is not projected to make this target using current sources of renewable electricity generation

Scope and Study Questions

Why

Purpose: Evaluate the potential benefits, challenges, and options for NASA to engage with growing global interest in space-based solar power (SBSP)

Q1: Under what conditions would SBSP be a competitive option to achieving net zero green house gas emissions compared to alternatives?

Q2: If it can be competitive, what role, if any, should NASA have in SBSP development?

What

Assess two representative designs of SBSP systems. Designs loosely based on existing publicly available designs from 2006 and 2013. First order assessments of first of a kind systems.

Where

Collect solar energy in Geostationary orbit, convert to microwave radiation, transmit energy to Earth, receive on Earth, convert to power, and deliver to power grid.

When

Q1: Launch and assembly begins 2038 - 2043 depending on SBSP design. Initial operations in 2050 until 2080.
Q2: Now

How

The Aerospace Corporation developed initial models. OTPS further developed models then verified and validated models to characterize and estimate costs and climate impact

Guided by stakeholder and subject matter expert feedback and literature: 30+ discussions, 100 documents

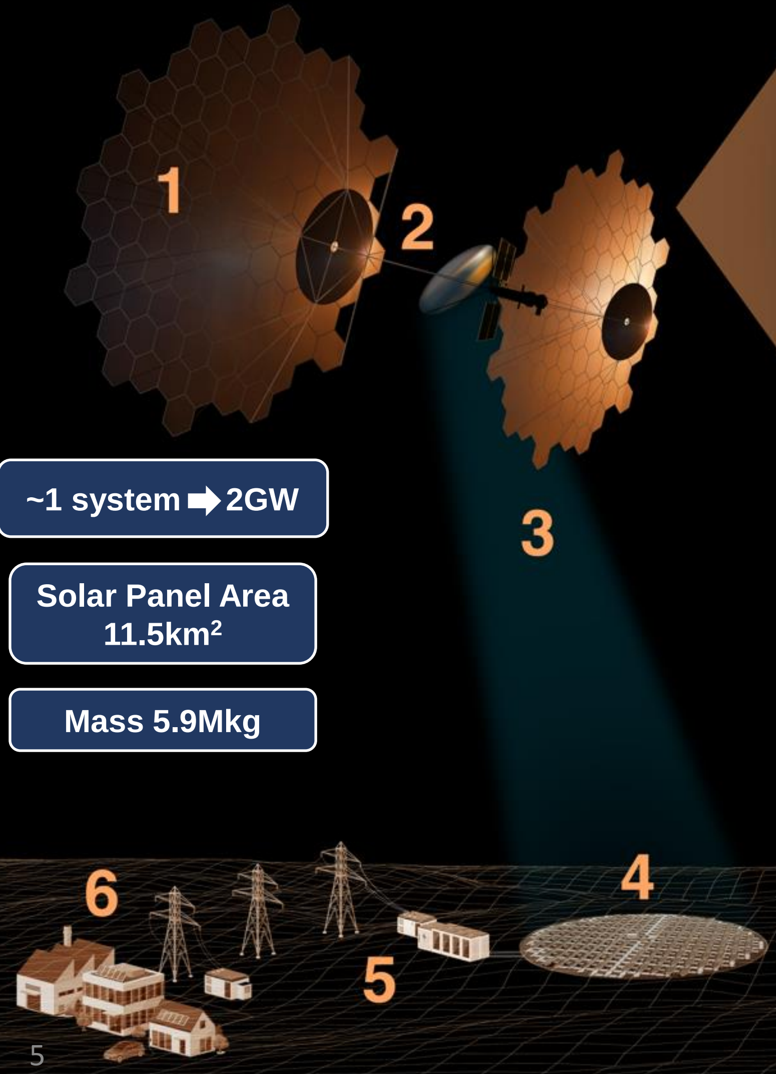
Space Based Solar Power

Functional Diagram

National Aeronautics and Space Administration

Systems in GEO Normalized to 2GW

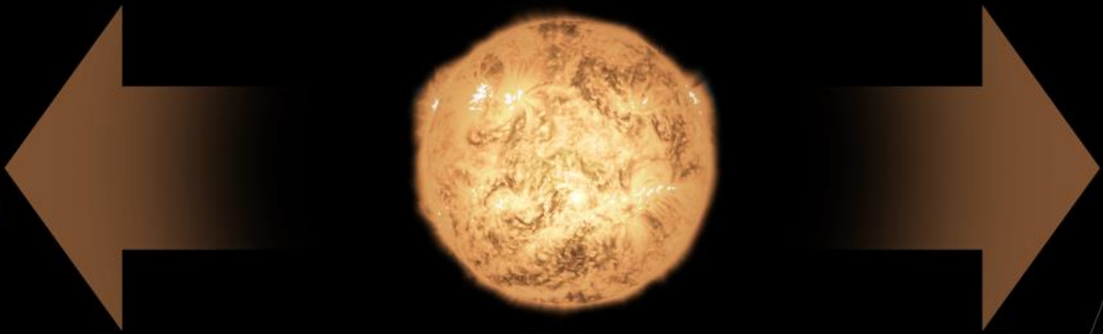
Innovative Heliostat Swarm Concept



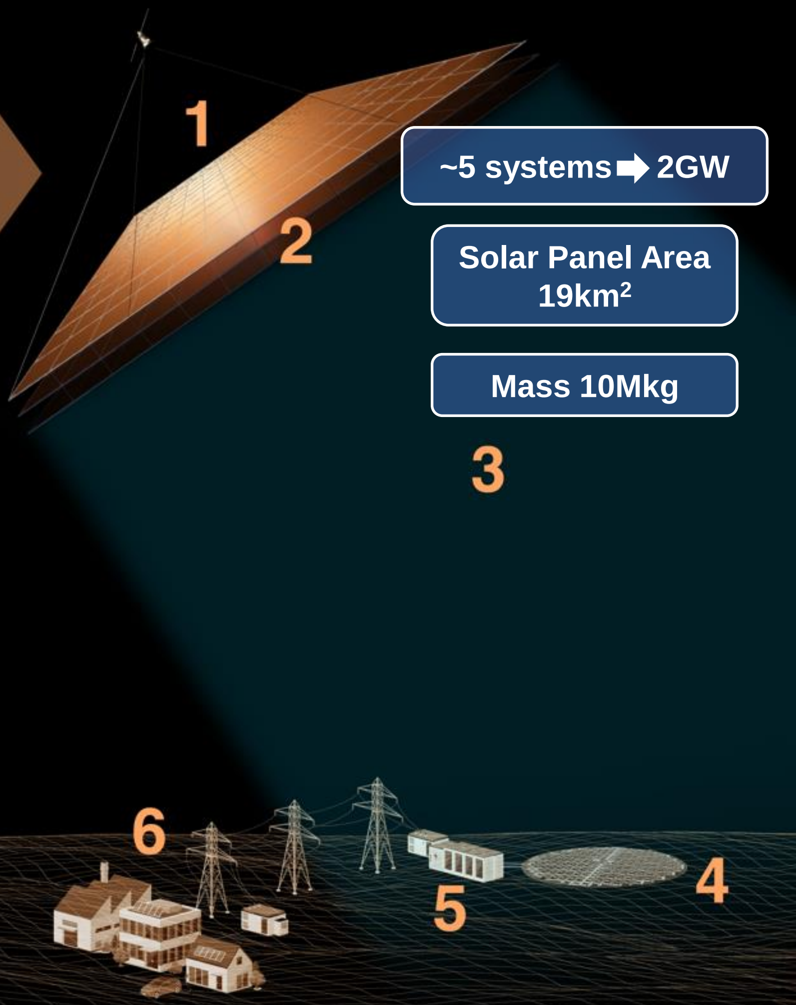
~1 system ➡ 2GW

Solar Panel Area 11.5km^2

Mass 5.9Mkg



Mature Planar Array Concept



~5 systems ➡ 2GW

Solar Panel Area 19km^2

Mass 10Mkg

Space Based Solar Power Functions

1. Collect
Solar panels receive solar energy

2. Convert
Converters turn solar energy into electricity; then into microwave

3. Transmit
Antenna array beams microwave energy to ground station rectennas

4. Receive
Rectenna receives microwave energy

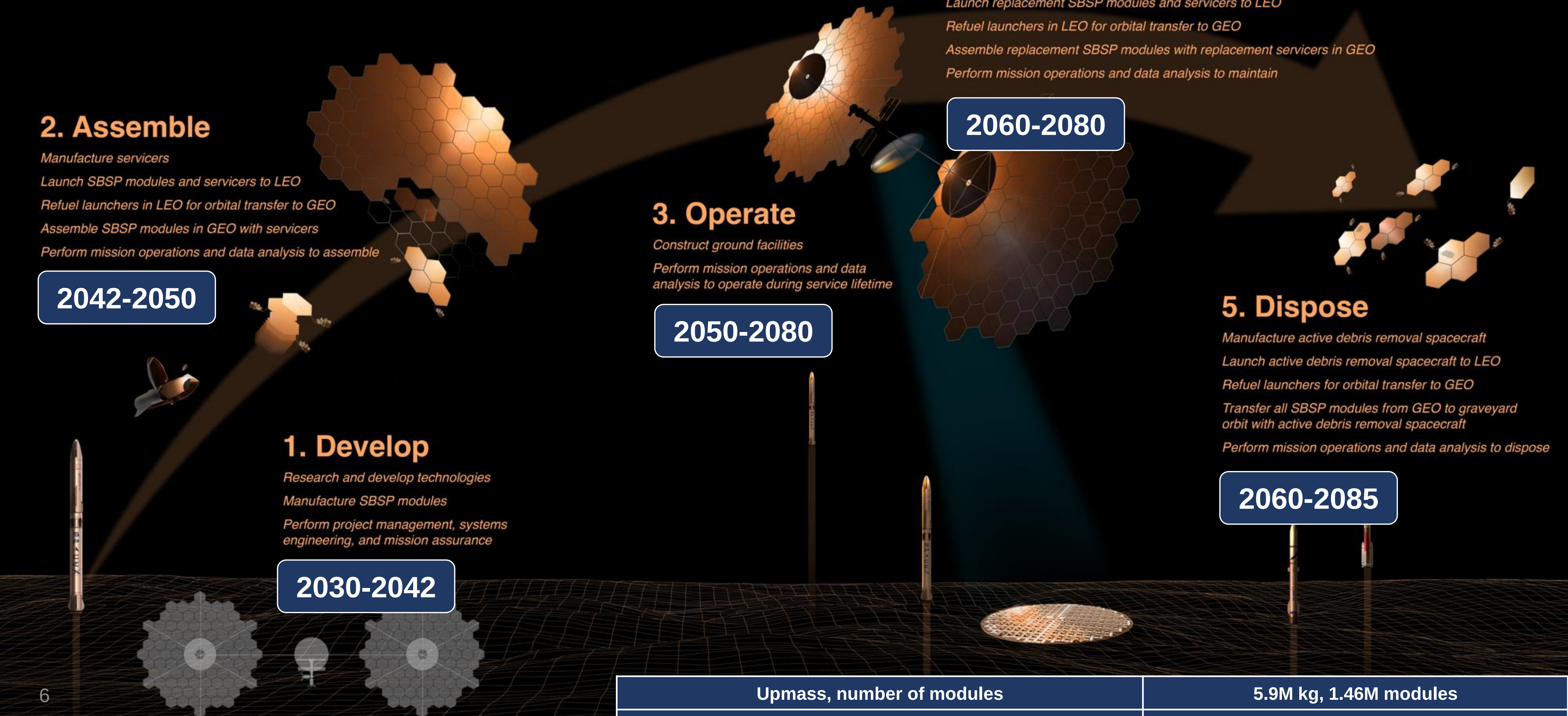
5. Convert
Converters turn microwave energy into electricty

6. Deliver
Final power delivered to homes and businesses

Space Based Solar Power

Representative Design One: Innovative Heliostat Swarm Concept

National Aeronautics and Space Administration



1. Develop

Research and develop technologies

Manufacture SBSP modules

Perform project management, systems engineering, and mission assurance

2030-2042

2. Assemble

Manufacture servicers

Launch SBSP modules and servicers to LEO

Refuel launchers in LEO for orbital transfer to GEO

Assemble SBSP modules in GEO with servicers

Perform mission operations and data analysis to assemble

2042-2050

3. Operate

Construct ground facilities

Perform mission operations and data analysis to operate during service lifetime

2050-2080

4. Maintain

Manufacture replacement SBSP modules and servicers

Launch replacement SBSP modules and servicers to LEO

Refuel launchers in LEO for orbital transfer to GEO

Assemble replacement SBSP modules with replacement servicers in GEO

Perform mission operations and data analysis to maintain

2060-2080

5. Dispose

Manufacture active debris removal spacecraft

Launch active debris removal spacecraft to LEO

Refuel launchers for orbital transfer to GEO

Transfer all SBSP modules from GEO to graveyard orbit with active debris removal spacecraft

Perform mission operations and data analysis to dispose

2060-2085

Upmass, number of modules	5.9M kg, 1.46M modules
Number of launches Total = Assemble + Maintain + Dispose	**2321 =** (59 + 708) + (118 + 1416) + 20

Space Based Solar Power

Representative Design Two: Mature Planar Array

National Aeronautics and
Space Administration

4. Maintain

Manufacture replacement SBSP modules and servicers

Launch replacement SBSP modules and servicers to LEO

Refuel launchers in LEO for orbital transfer to GEO

Assemble replacement SBSP modules with replacement servicers in GEO

Perform mission operations and data analysis to maintain

2055-2080

2. Assemble

Manufacture servicers

Launch SBSP modules and servicers to LEO

Refuel launchers in LEO for orbital transfer to GEO

Assemble SBSP modules in GEO with servicers

Perform mission operations and data analysis to assemble

2037-2050

3. Operate

Construct ground facilities

Perform mission operations and data analysis to operate during service lifetime

2050-2080

5. Dispose

Manufacture active debris removal spacecraft

Launch active debris removal spacecraft to LEO

Refuel launchers for orbital transfer to GEO

Transfer all SBSP modules from GEO to graveyard orbit with active debris removal spacecraft

Perform mission operations and data analysis to dispose

2060-2085

1. Develop

Research and develop technologies

Manufacture SBSP modules

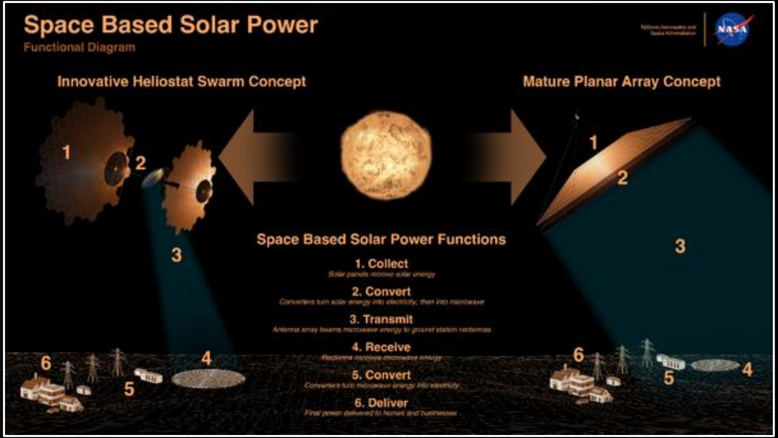
Perform project management, systems engineering, and mission assurance

2030-2037

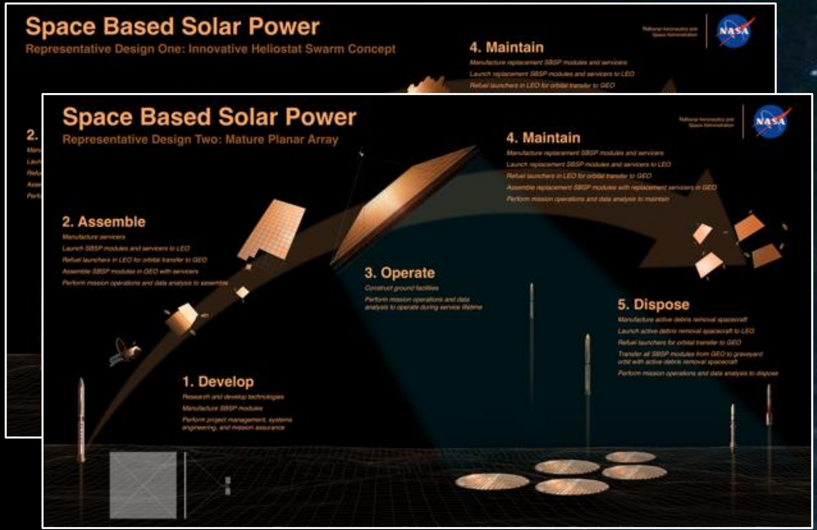
Upmass, number of modules	10M kg, 2M modules
Number of launches (Total = Assemble + Maintain + Dispose)	**3960 =** (101 + 1212) + (201 + 2412) + 34

Methodology

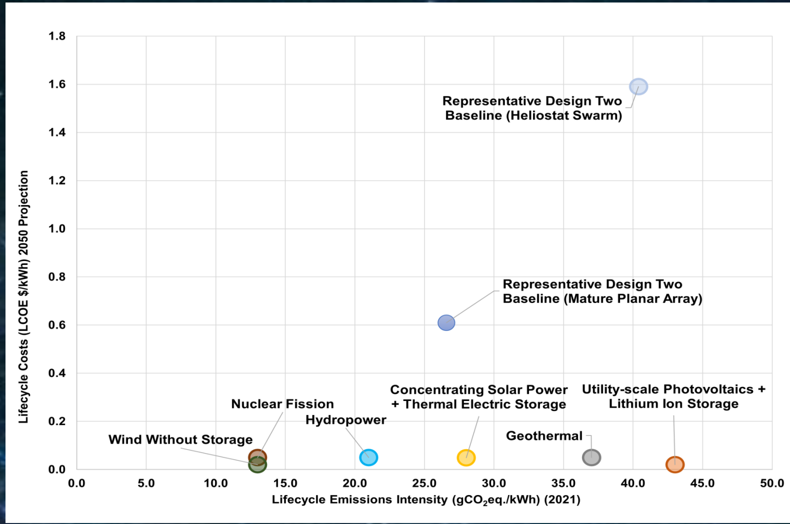
Decomposition → **Lifecycle** → **Output**



- 2 reference designs normalized to 2GW power transmission
- 6 functions: collect, convert, transmit, receive, convert, deliver
- 87 parameters (including WBS elements): subsystems that perform six functions



- Arrange 87 parameters (including WBS elements) into ConOps
- ConOps lifecycle: develop, assemble, operate, maintain, and dispose



- Lifecycle cost to generate electricity vs. Lifecycle emissions intensity to generate electricity
- $/kWh vs. gCO_2 equivalent/kWh

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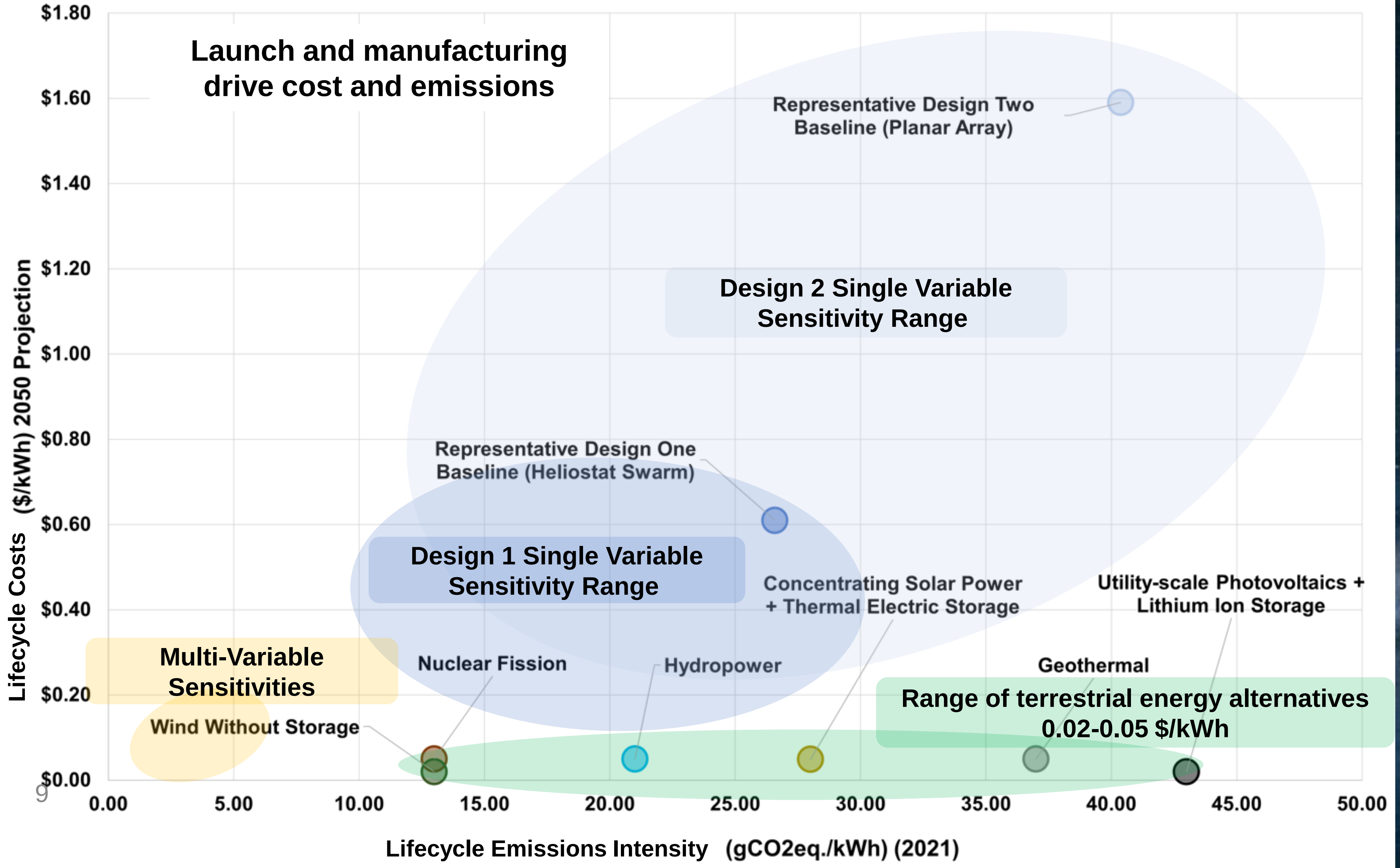
Q1: Under what conditions would SBSP be a competitive option to achieving net zero green house gas emissions compared to alternatives?

SBSP is expensive and may produce emissions like terrestrial alternatives



Calculate sensitivity range of cost and emissions intensity to generate electricity

BASELINE DESIGNS
Define assumptions for 2050

Not cost competitive
0.61, 1.59 $/kWh;
Similar emissions to some

SENSITIVITY RANGES
Vary cost and emissions drivers

Not cost competitive
0.20, 0.45 $/kWh;
Similar emissions to some

COMBINE SENSITIVITIES
Multi-variable combination of sensitivities

Cost is competitive
0.03, 0.08 $/kWh;
Emissions less than terrestrial

Office of Technology, Policy, and Strategy

Revisit Q1: Under what conditions would SBSP be a competitive option to achieving net zero green house gas emissions compared to alternatives?

SBSP is expensive and may produce emissions like terrestrial alternatives

IF

- Decrease launch cost by 50%
- Use electric propulsion orbital transfer vehicle to transfer to GEO orbit
- Increase solar cell efficiency by 15%
- Extend hardware lifetime by 5 years
- Reduce servicers first unit cost and debris vehicles first unit cost by 90%
- Decrease manufacturing learning curves by 5%

THEN

- SBSP performs better on cost and emissions than terrestrial renewable energy production technologies

	Baseline	Multi-Variable Sensitivity
Launch Cost (+15% block buy discount)	[Beyond] $1,000/kg ($850/kg)	[Beyond] $500/kg ($425/kg)
Orbital Transfer Method	[Comparable] 12 refuel launches	[Beyond] Electric Propulsion (+17.2% mass, mfg cost)
Reuses of each launch vehicle	[Beyond] 100	[Beyond] 100
Solar Cell Efficiency	[Comparable] 35%	[Beyond] 50%
Operations Costs	[Beyond] 1.2M / month	[Beyond] 1.2M / month
Hardware Lifetime	[Below] 10 years	[Comparable] 15 years
Initial Hardware Costs (Module, Servicer, Debris)	[Beyond] 1 M, [Below] 1 B, [Comparable] 500 M	[Beyond] 1M, 100M, 50M
Manufacturing Learning Curves (Module, Servicer, Debris)	[Beyond] 75%, [Comparable] 85%, [Below] 90%	[Beyond] 70%, 80%, [Comparable] 85%
Results		
LCOE $/kWh Renewables studied: .02 - .05	0.61 and 1.59	0.04 and 0.08
Emissions ($gCO_2eq./kWh$) Renewables studied: 8 – 43	26 and 40	3 and 4

Assumed capabilities *Beyond*, *Comparable*, or *Below* demonstration to date? Beyond Comparable Below

Q2: If it can be competitive, what role, if any, should NASA have in SBSP development?

NASA is developing technologies to meet future mission needs. These key technologies enable SBSP as a use case. SBSP is not a driver for NASA technology development.

UNDIRECTED ORGANIC DEVELOPMENT

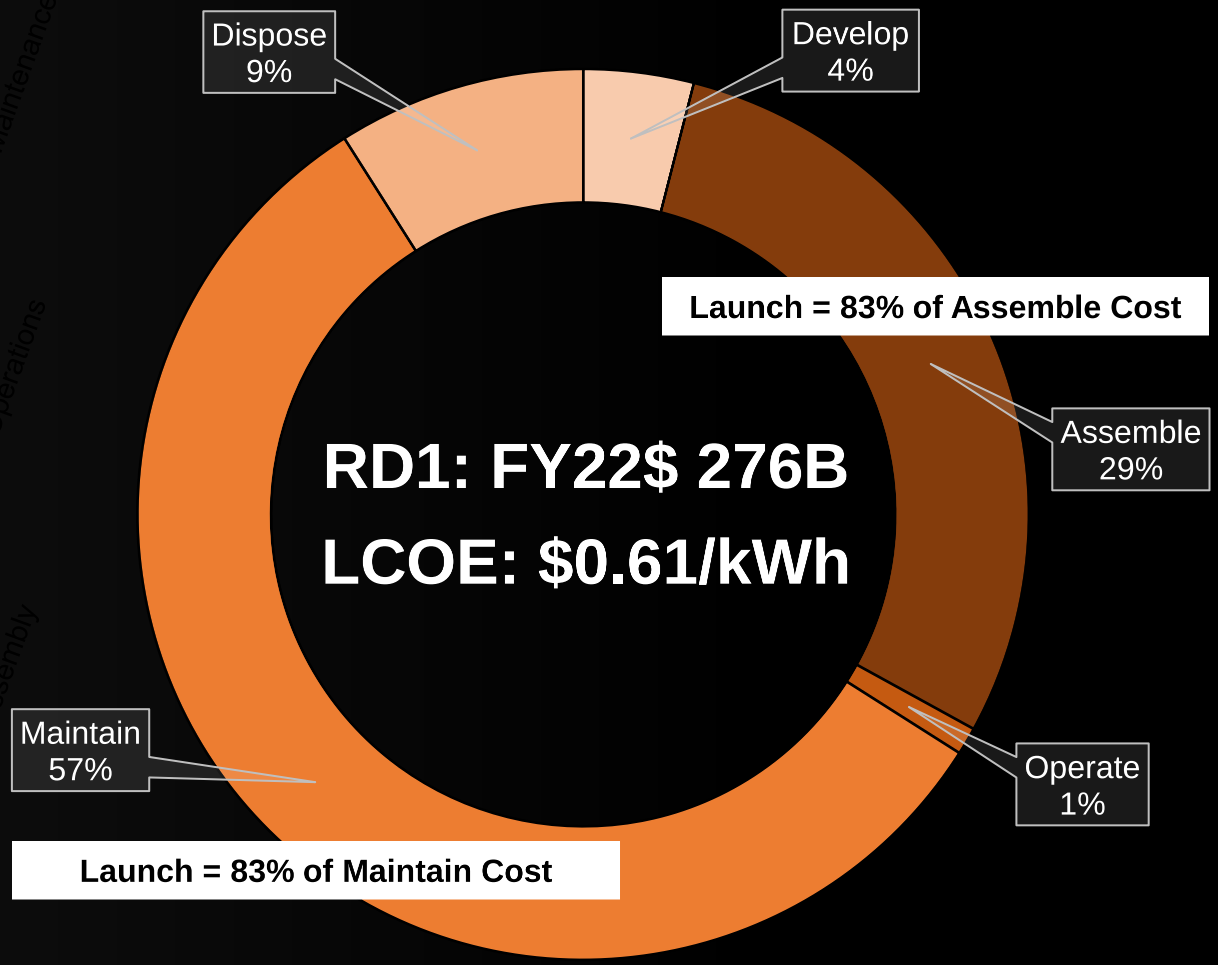
NASA is developing ISAM, autonomy for distributed systems, and power beaming. Continuing to invest in these capabilities will make SBSP systems more technically feasible in the future. This requires no change to current investments.

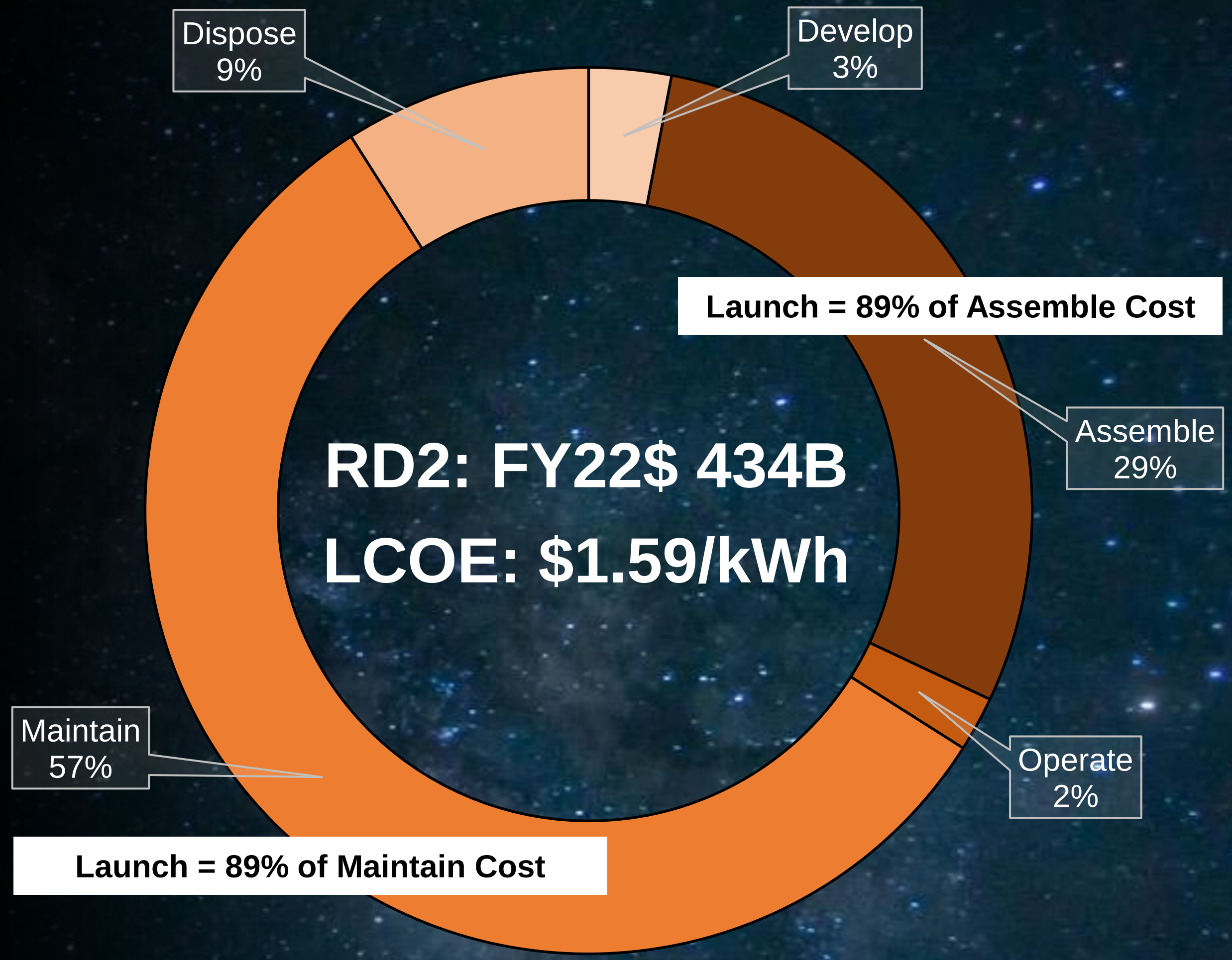
PURSUE NEW PARTNERSHIPS

NASA could become a SBSP technology development partner with other government agencies, industry, academia, or international partners. Partnering may offer impactful and cost-saving opportunities for the agency and SBSP's future development.

In either approach, we recommend deep-dive studies of SBSP every few years, and near-term follow-on studies for mission applicability

Cost Results



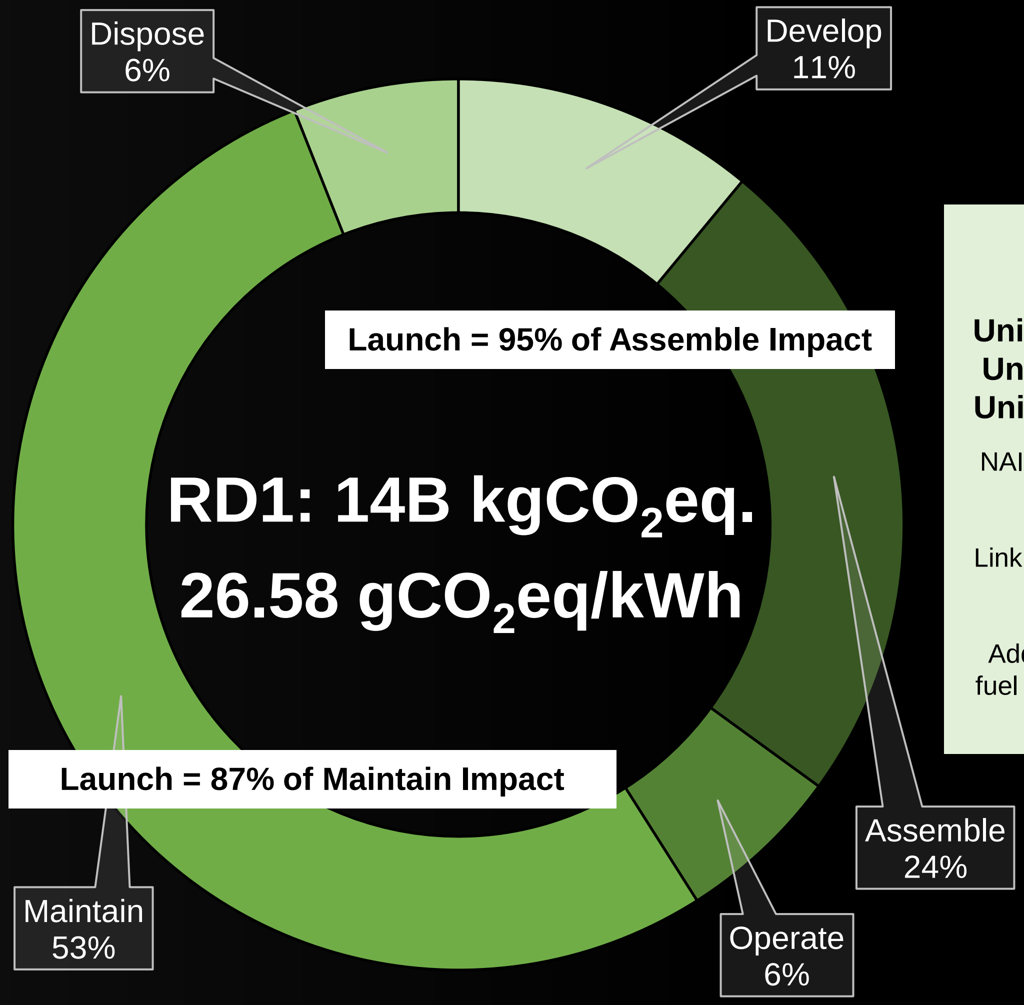


Levelized Cost of Electricity ($/kWh)

$$\frac{CRF \times CAPEX + FOM}{CF \times 8{,}760\ (\frac{hours}{year})}$$

CRF = Percentage of the year in which power is generated
CAPEX = Capital Expenditures = Development + Assembly
FOM = Fixed Ops & Maintenance = Operations + Maintenance + Disposal
CF = Capital Recovery Factor, 30-year lifetime, default discount rate of 3%

Climate Impact Results



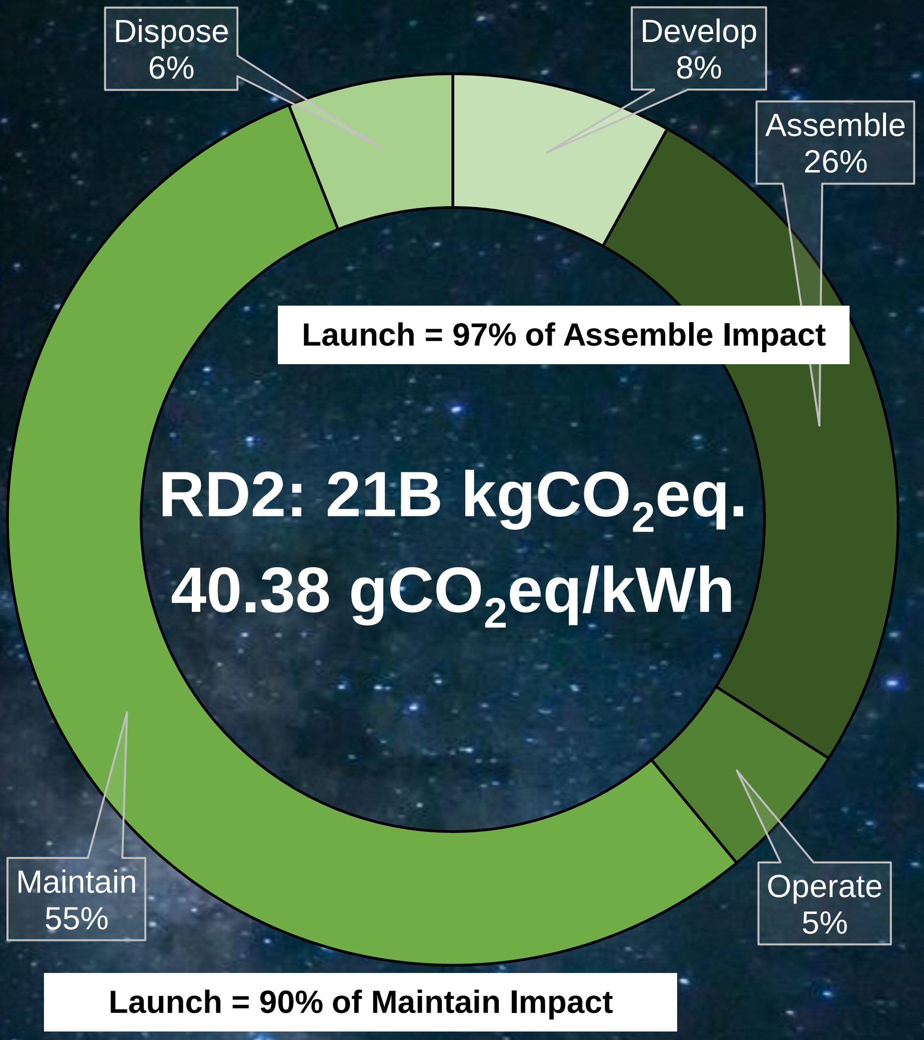
Economic Input Output – Life Cycle Analysis ($kgCO_2eq$)

Unit mass (kg) x NAICS ($kgCO_2eq/kg$)
Unit money (\$) x NAICS ($kgCO_2eq/\$$)
Unit area (m^2) x NAICS ($kgCO_2eq/m^2$)

NAICS = North American Industry Classification System

Link monetary values and masses of the industry sector to their environmental inputs/out

Additional emissions impacts of launch vehicle fuel use (extraction, production, delivery covered above)



Emissions Intensity to Generate Electricity ($gCO_2eq./kWh$) = Economic Input Output – Life Cycle Analysis ($kgCO_2eq.$) ÷ 2GW System ÷ 30 year Lifetime

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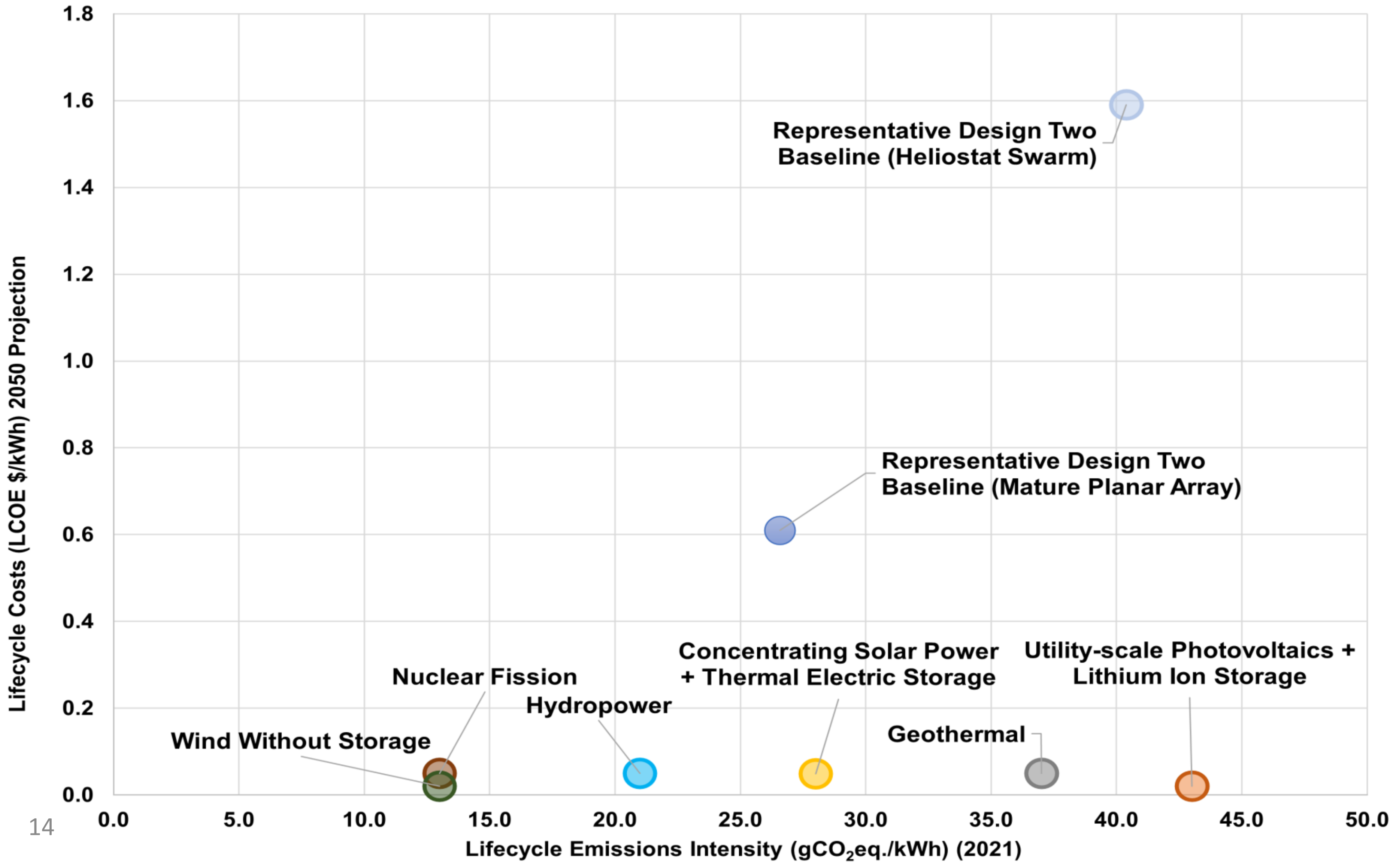
Q1: Under what conditions would SBSP be a competitive option to achieving net zero green house gas emissions compared to alternatives?



Cost-competitive?

No

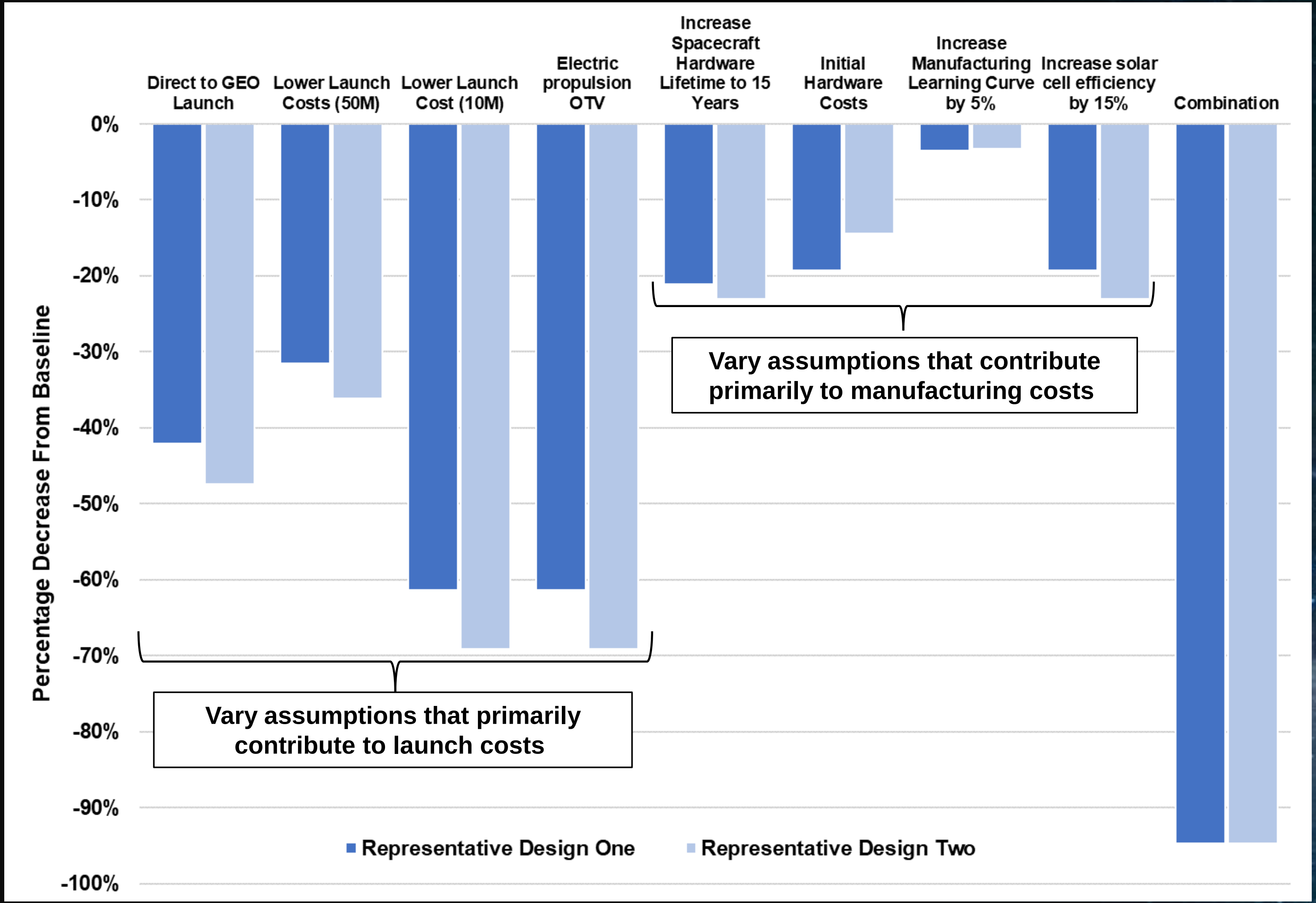
Baseline assessment did not show a cost-competitive SBSP solution compared to 2050 projections for terrestrial renewable electricity production technologies

Climate-competitive?

Yes, to some alternative renewable electricity production technologies

OTPS Office of Technology, Policy, and Strategy

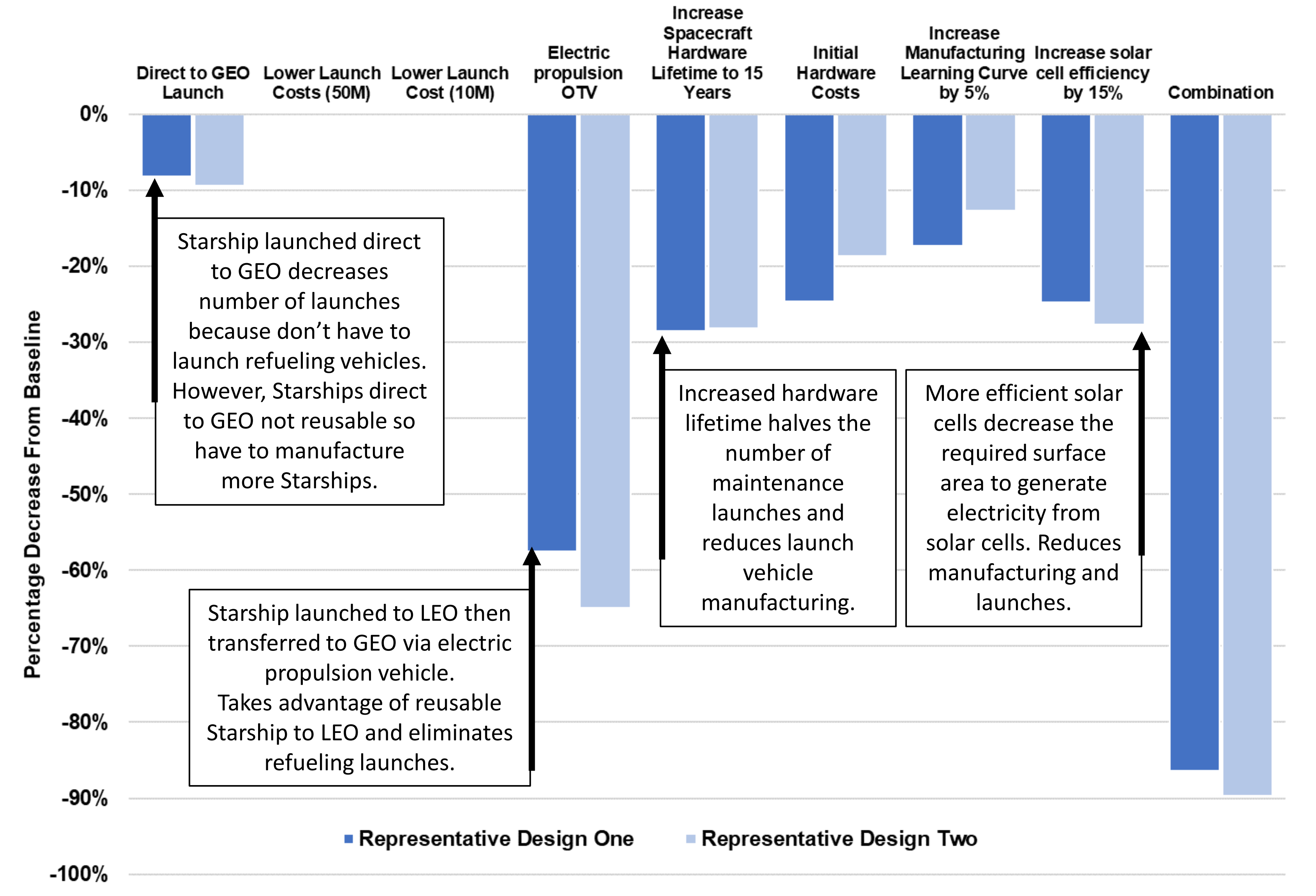
Sensitivity Analysis



Phase	Changes to Baseline Assumptions	
Develop	Solar cell efficiency	35% to 50%
	Hardware lifetime	10 to 15 years
	First unit cost, modules	$1M to $100,000
	Manufacturing learning curve	75% to 70% - modules
Assemble	Launch cost: Starship to LEO, 15% block buy discount	$100M to $50M to $10M
	Launch vehicle reuse	100 times to 0
	Orbital transfer from LEO to GEO, 4 months to GEO	12 refuel launches to 0 refuel launches
	First unit cost, servicers	$1B to $100M
	Manufacturing learning curve	85% to 80% - servicers
Maintain	Manufacturing learning curve	85% to 80% - servicers 75% to 70% - modules
Dispose	First unit cost, debris vehicles	$500M to $50M
	Manufacturing learning curve	90% to 85% - debris

Percent decrease in <u>cost</u> from the baseline assumptions

Sensitivity Analysis



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Dispose	First unit cost, debris vehicles	$500M to $50M
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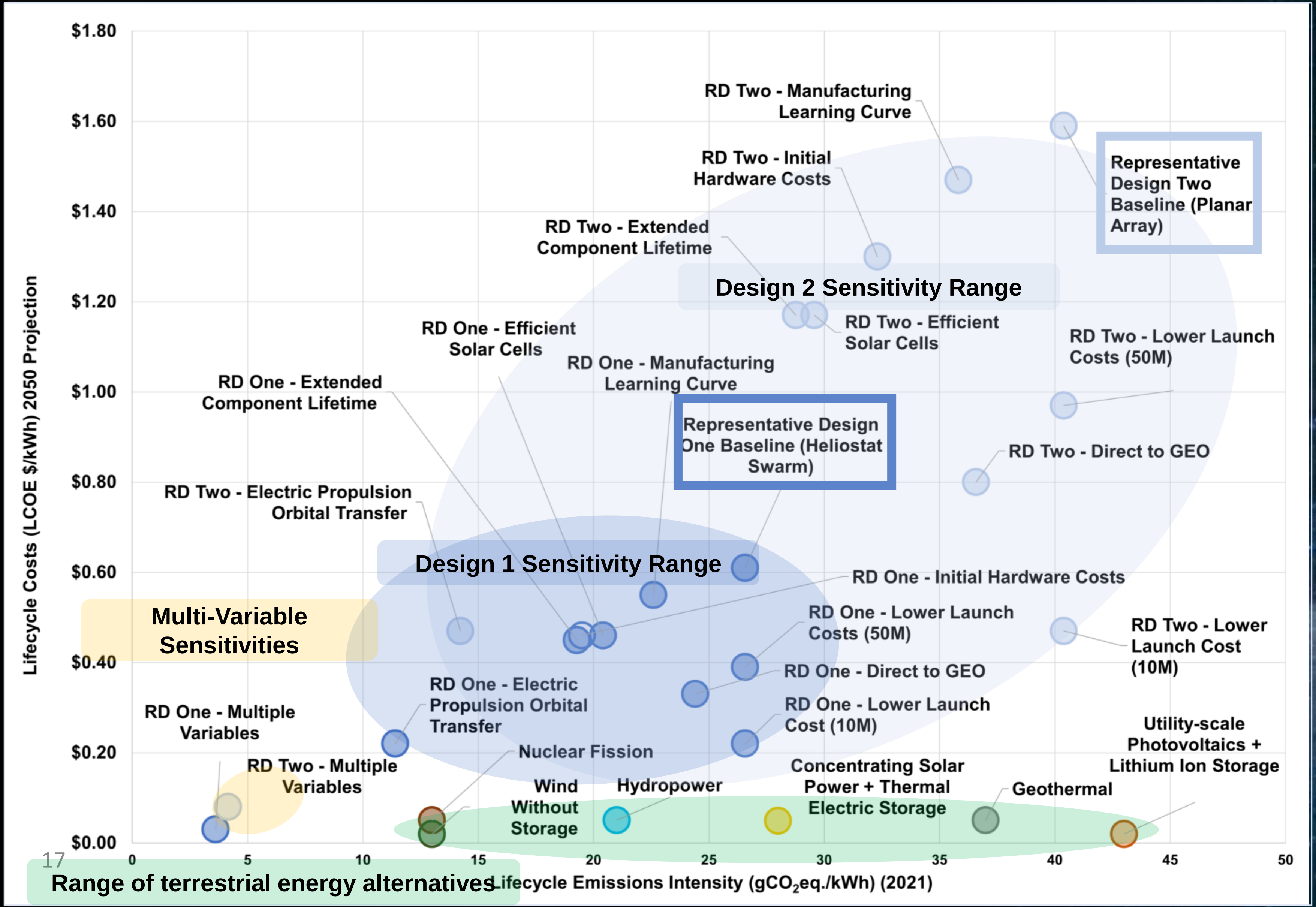
Revisit Q1: Under what conditions would SBSP be a competitive option to achieving net zero green house gas emissions compared to alternatives?



Cost-competitive?

No, for individual changes to baseline assumptions

Yes, if a future exists where individual changes to baseline assumptions are combined

Climate-competitive?

Yes, with some terrestrial alternatives, even more when using electric propulsion for orbital transfer

Yes, if a future exists where individual changes to baseline assumptions are combined

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Revisit Q1: Under what conditions would SBSP be a competitive option to achieving net zero green house gas emissions compared to alternatives?

SBSP is expensive and may produce emissions like terrestrial alternatives

IF

- Decrease cost of access to space by 50%
- Use electric propulsion orbital transfer vehicle to transfer to GEO orbit
- Increase solar cell efficiency by 15%
- Extend hardware lifetime by 5 years
- Reduce servicers first unit cost and debris vehicles first unit cost by 90%
- Decrease manufacturing learning curves by 5%

THEN

- SBSP performs better on cost and emissions than terrestrial renewable energy production technologies

	Multi-Variable Sensitivity	Baseline	High-cost Sensitivity
Launch Cost (+15% block buy discount)	$500/kg ($425/kg)	$1000/kg ($850/kg)	$1500/kg ($1,275/kg)
Orbital Transfer Method	Electric Propulsion (+17.2% mass, manufacturing cost)	12 refuel launches	12 refuel launches
Reuses of each launch vehicle	100	100	50
Solar Cell Efficiency	50%	35%	35%
Operations Costs	1.2M / month	1.2M / month	500k/year for every 2,800 kg (87-148M / month)
Hardware Lifetime	15 years	10 years	10 years
Initial Hardware Costs (Module, Servicer, Debris)	1M, 100M, 50M	1 M 1 B 500 M	5M 1B 500M
Manufacturing Learning Curves (Module, Servicer, Debris)	70%, 80%, 85%	75% 85% 90%	85% 95% 95%
Results			
LCOE $/kWh Renewables studied: .02 - .05	0.03 and 0.08	0.61 and 1.59	4.18 and 10.73
Emissions ($gCO_2eq./kWh$) Renewables studied: 8 - 43	3 and 4	26 and 40	286 and 360

Assumed capabilities *Beyond*, *Comparable*, or *Below* demonstration to date?

Beyond Comparable Below

Q2: If it can be competitive, what role, if any, should NASA have in SBSP development?

SBSP studies, design concepts, technology developments funded worldwide by academic, commercial, and government communities for economic development, net-zero, and national goals

Baseline reference designs analyzed

- Not cost-competitive with terrestrial energy alternatives though climate-competitive with some
- Require leaps in technology development over current SOA to field operational systems in 2050

Challenges exist to operational development, however, ongoing improvements occurring

- Large-scale ISAM
- Autonomous distributed systems
- Power beaming

Challenges exist to reducing system costs, however, ongoing improvements occurring

- Launch costs
- Manufacturing at scale
- Launch cadence

Challenges and Opportunities

Challenges to operational system development

1. Large-scale ISAM needed for Assembly and Maintenance ConOps phases and many technologies are untested
2. Large scale autonomous distributed systems across km in GEO needed for Assembly, Operations, and Maintenance ConOps phases
3. Power beaming from space to ground is nascent and was demonstrated from LEO in 2023

Challenges to reducing system costs

1. Starship launch cost of $50M may not be reached by 2050
2. Manufacturing at scale will be required to lower manufacturing costs in the Development ConOps phase
3. Launch cadence needed for Assembly and Maintenance ConOps phases may not be realized due to competing demands for Starships

Regulatory and other challenges

1. Active removal of SBSP debris to graveyard orbit may not be the best option in 2050
2. Spectrum allocation is finite and subject to regulation
3. Orbital slot allocations are increasingly contested and require prior planning for SBSP systems
4. Security requirements to ensure infrastructure and operations like terrestrial power plants

Ongoing Improvements to Technical and Economic Needs

Advances for Technology Needs

1. Large-scale ISAM
    - Government and private sector are working to advance ISAM technologies including NASA, Northrop Grumman, AFRL, Orbit Fab, KMI, and Orbital Composites and Virtus Solis
    - Current offerings for debris removal and servicing are untested
2. Large scale autonomous distributed systems
    - Broad effort by USG and NASA specifically to advance distributed autonomy at increasingly large scales
3. Power beaming
    - DARPA and international partners are currently developing novel wireless power transmission systems for use in space. NASA is funding research for wireless power transmission on the Moon.

Advances for Economic Needs

1. Electric propulsion for orbital transfer vehicles is now commonplace, but at much smaller scales than required. NASA's NEXT engine specs could deliver SBSP payloads.
2. Emerging alternative launch technologies, if proven, could significantly impact cost.
3. Megaconstellation manufacturing has surpassed historical production rates.
4. Novel materials could significantly reduce the mass of the in-space SBSP system.
5. Alternative architectural changes to SBSP are being studied, such as MEO constellations.

Q2: If it can be competitive, what role, if any, should NASA have in SBSP development?

Maintain the status quo

Currently working on key technologies for SBSP and could continue to fund these areas without adding SBSP as an explicit funding line

Pursue partnership opportunities to advance SBSP

SBSP technology requirements also benefit NASA missions, increasing partnership activities may offer impactful and cost-saving opportunities for the Agency

Near-term follow-on study recommendations

- Detailed technical evaluation of SBSP
- Regulatory and policy challenges
- Industrial base/supply chain impacts
- Launch cadence feasibility
- Electric propulsion technology advancement
- Efficiencies associated with multiple satellites

Conclusion

Purpose: Evaluate the potential benefits, challenges, and options for NASA to engage with growing global interest in space-based solar power (SBSP)

Q1: Under what conditions would SBSP be a competitive option to achieving net zero green house gas emissions compared to alternatives?

Q2: If it can be competitive, what role, if any, should NASA have in SBSP development?

Evaluated two representative designs

Q1

- SBSP is expensive and not cost competitive with terrestrial renewable electricity production
- SBSP provides limited benefit to climate and partially competitive with terrestrial renewable electricity production
- Combination of lower launch costs, improved manufacturing at scale, increased solar cell efficiency, longer hardware lifetime, and electric propulsion orbital transfers vehicles lead to SBSP that is cost and climate competitive with terrestrial renewable electricity production

Q2

- Option 1: Maintain the status quo, NASA continues to invest in capabilities for NASA missions that also enable SBSP
- Option 2: Pursue new partnerships, NASA could partner with entity that is pursuing SBSP capabilities

Further study is required to assess SBSP's terrestrial use-cases in more detail or for NASA-specific use-cases

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