The views and opinions expressed in this document are those of the authors and do not necessarily reflect the official policy or position of any agency of the U.S. government.

SPACE SOLAR POWER
DEVELOPMENT | GROUP

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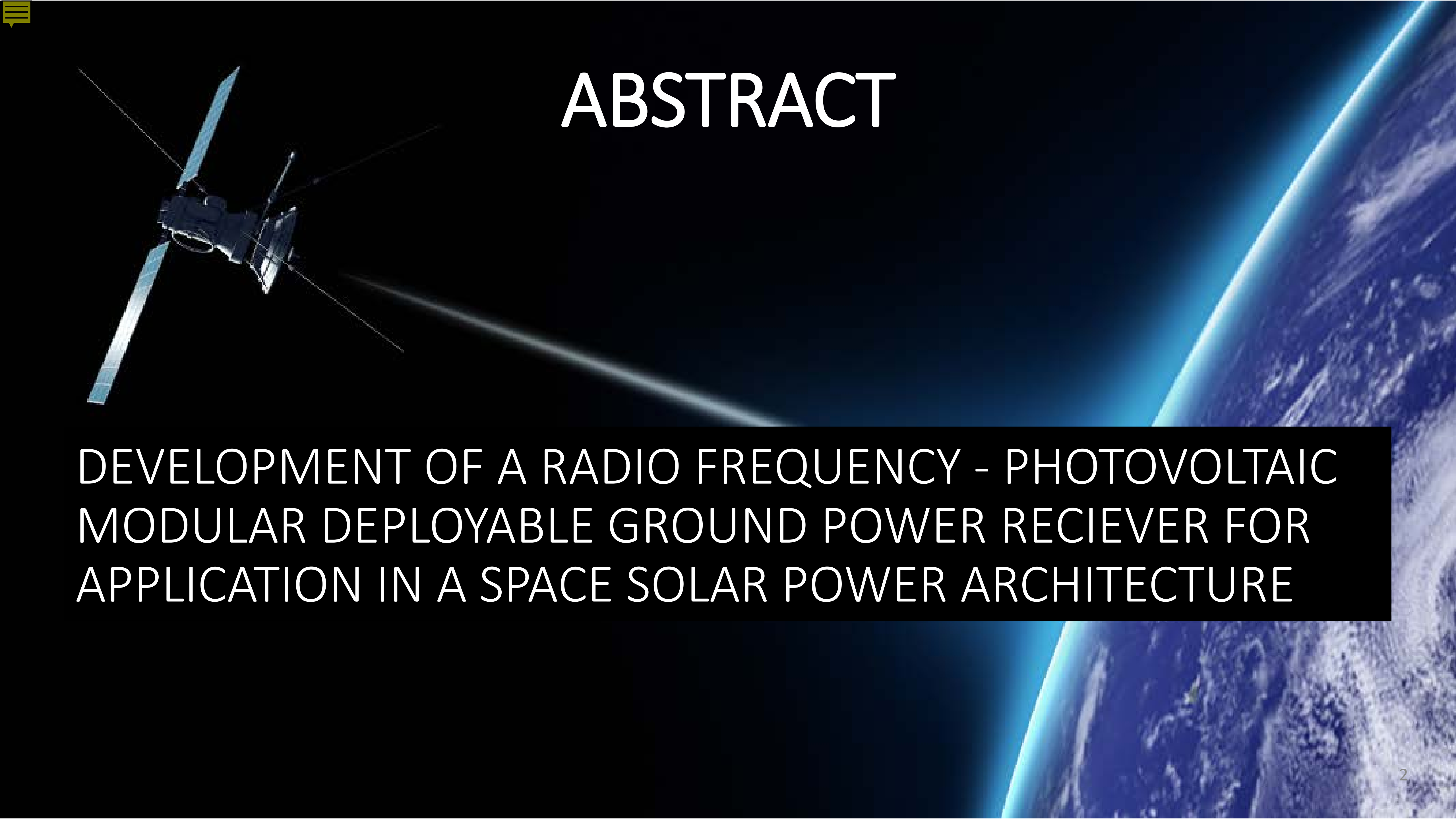
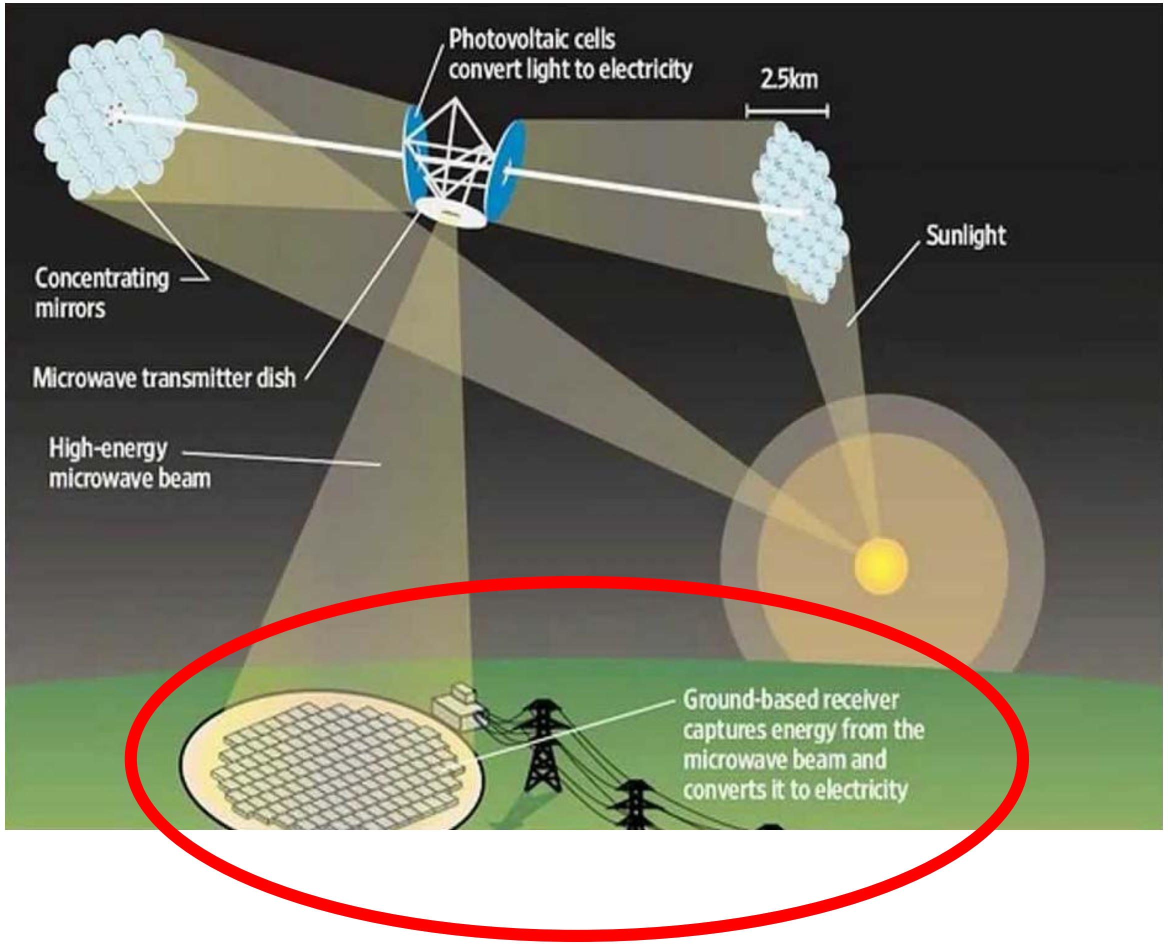
Advised By: Dr. Pablo Rangel (TAMUCC) & Dr. Paul Jaffe (Informal Capacity)


ABSTRACT
DEVELOPMENT OF A RADIO FREQUENCY - PHOTOVOLTAIC MODULAR DEPLOYABLE GROUND POWER RECIEVER FOR APPLICATION IN A SPACE SOLAR POWER ARCHITECTURE



- With space solar, unfiltered, continuous sunlight is collected and converted into DC power through photovoltaics by large satellites in space.
- This power is then used to drive a power beaming system, transmitting a microwave beam to receivers on the Earth.
- Receivers then collect the beamed energy and convert it back to useable electricity for use on a grid.

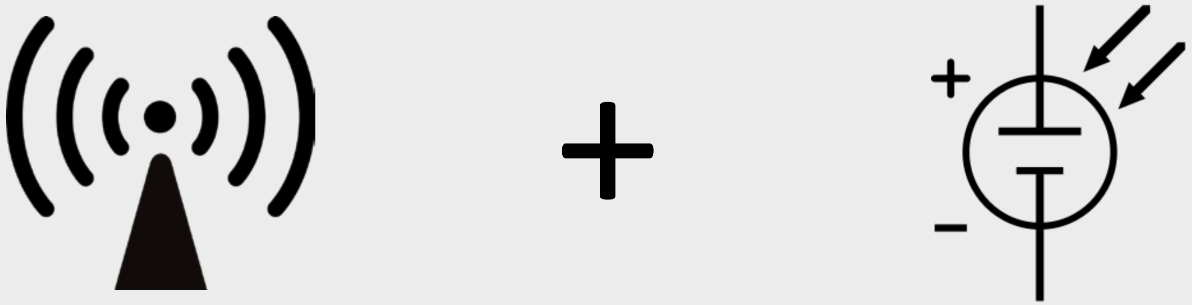
Space Solar System Architecture

Problem

Both defense and disaster recovery applications of space solar would almost certainly require the development of a tactically deployable power receiver to satisfy operational and transport requirements in theatre, no work has been done in this area to date.

Objective

In a novel approach to wireless power reception in a space solar power system, a modular deployable ground power receiver (MDGPR) architecture will be developed, integrating both microwave energy (RF) and solar energy (PV) collection and conversion elements.



Why RF & PV?

- The goal is to maximize to collection of available energy using multiple renewable sources to eliminate a single point of failure in power generation
- Our solution utilizes unused area within the satellite receiving aperture on top of containers
- It's a modular integrated solution that can grow with demand

Applications Considered

Defense and Energy Security

- The need to reduce logistics burdens and minimize energy resupply risks
- The transition to autonomous systems and crewless facilities
- The need to increase energy architecture flexibility

Disaster Response and Recovery

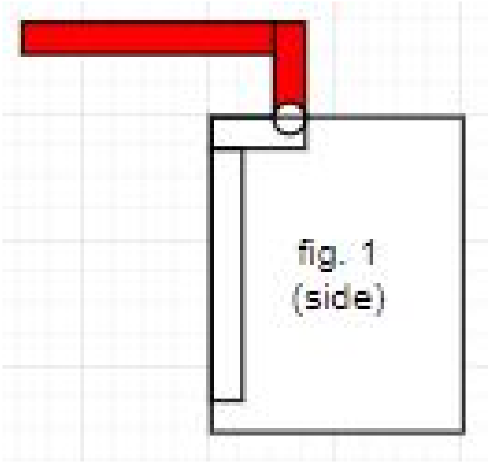
- Quickly restore electricity to critical infrastructure and recovery operations.
- Resilient, reliable power distribution day or night in any weather condition.
- Deployable and scalable power output to bring increasing power restoration during a period of need.

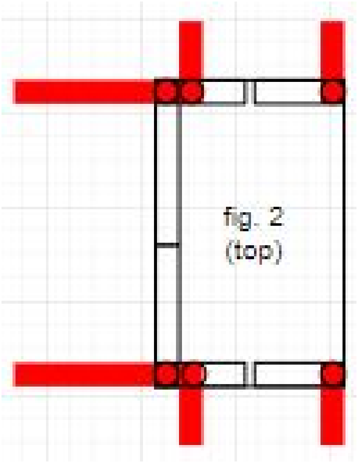
Requirements Summary

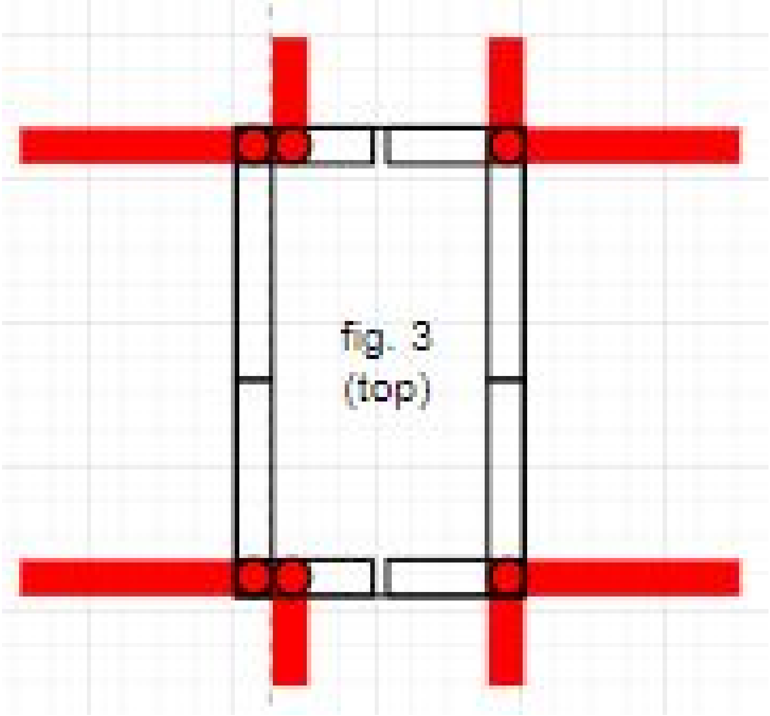
- Stakeholder (Defense Logistics Agency, DoD, Red Cross)
  - System setup deployment by no more than 5 personnel
  - Receiver shall operate in remote desert/tropical environment as well as mitigate obstacles and changes in elevation.
  - Modules shall be maneuvered by military helicopter, forklift, and flatbed loader
  - System shall have a protected perimeter with access control
- Project (MDGPR)
  - Convert RF energy at 5.8GHz and solar energy to DC power at 60Hz
  - Store the power within the module (container) for 12-hrs usage at 50% normal load
  - Output power of building block system (10 containers) shall be no less than 200kW (100 person – small forward operating base)
  - Each module shall be packaged in a standard 20-ft ISO shipping container
  - Receiver shall self-package without human intervention (self-retract)

Concepts Considered & Criteria

- All 20’ ISO Standard Shipping Containers
- Commercially Available Containers
  - One side of container opens vertically (fig. 1) (custom des.)
  - One side of container opens horizontally w/front and rear doors (fig. 2)
  - Both sides of container open horizontally w/ front and rear doors (fig. 3)

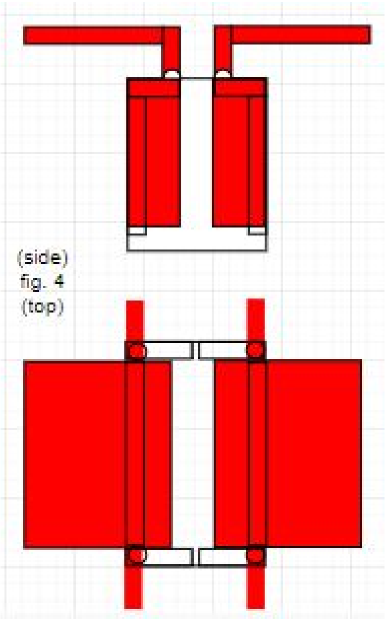


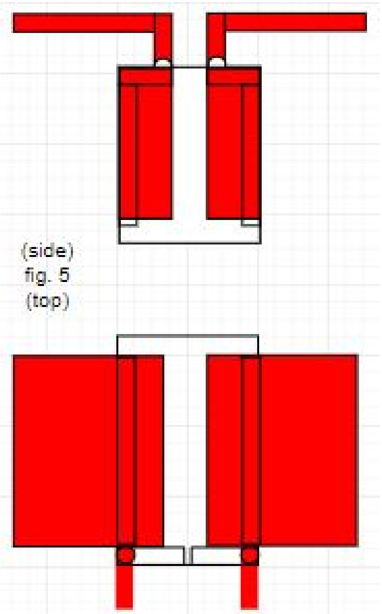


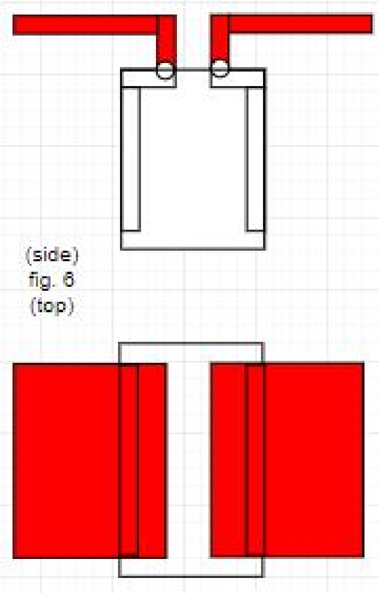


Concepts Considered & Criteria

- All 20’ ISO Standard Shipping Containers
- Custom Built Containers
  - “Gullwing” container w/front and rear doors (fig. 4)
  - “Gullwing” container w/front and no rear door (fig. 5)
  - “Gullwing” container without front and rear doors (fig. 6)







Design Criteria

Modularity

- Since they are all shipping containers, the modularity is largely consistent, however, commercially available (non-custom) containers score more favorably.

Design Complexity

- More structural design changes score less favorably.

Rapid Deployability

- All containers would be setup in equal time, this largely depends on the receiver deployment.

Cost

- Custom solutions (more parts) increase cost and score less favorably.

Stability

- Containers with large open surfaces can act as a lift device and score less favorably.

Temperature Control

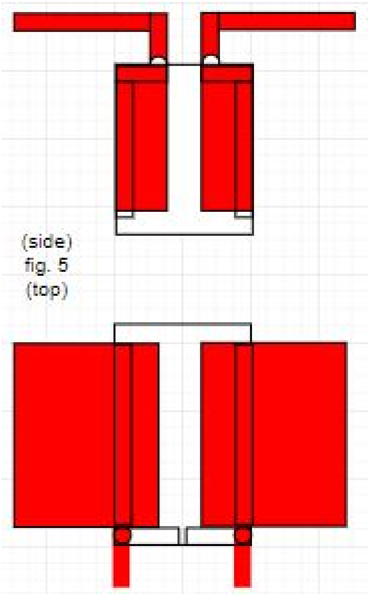
- Important passive cooling for batteries and therefore scores more favorably.

PV Panel Integration

- A large part of this project is to integrate two sources of renewable energy into one system and therefore scores significantly higher.

Selected Concept

- “Gullwing” container w/front and no rear door (fig. 5)



Reasons:

- Maximum PV collection area
- Front door access allows for access without the need for a large area
- Through container passive cooling
- Possible spin-off applications

Structural Modifications Needed:

- Roof frame
- Gullwing door
- Gullwing door PV sub-frame
- Integrated battery pack mounts

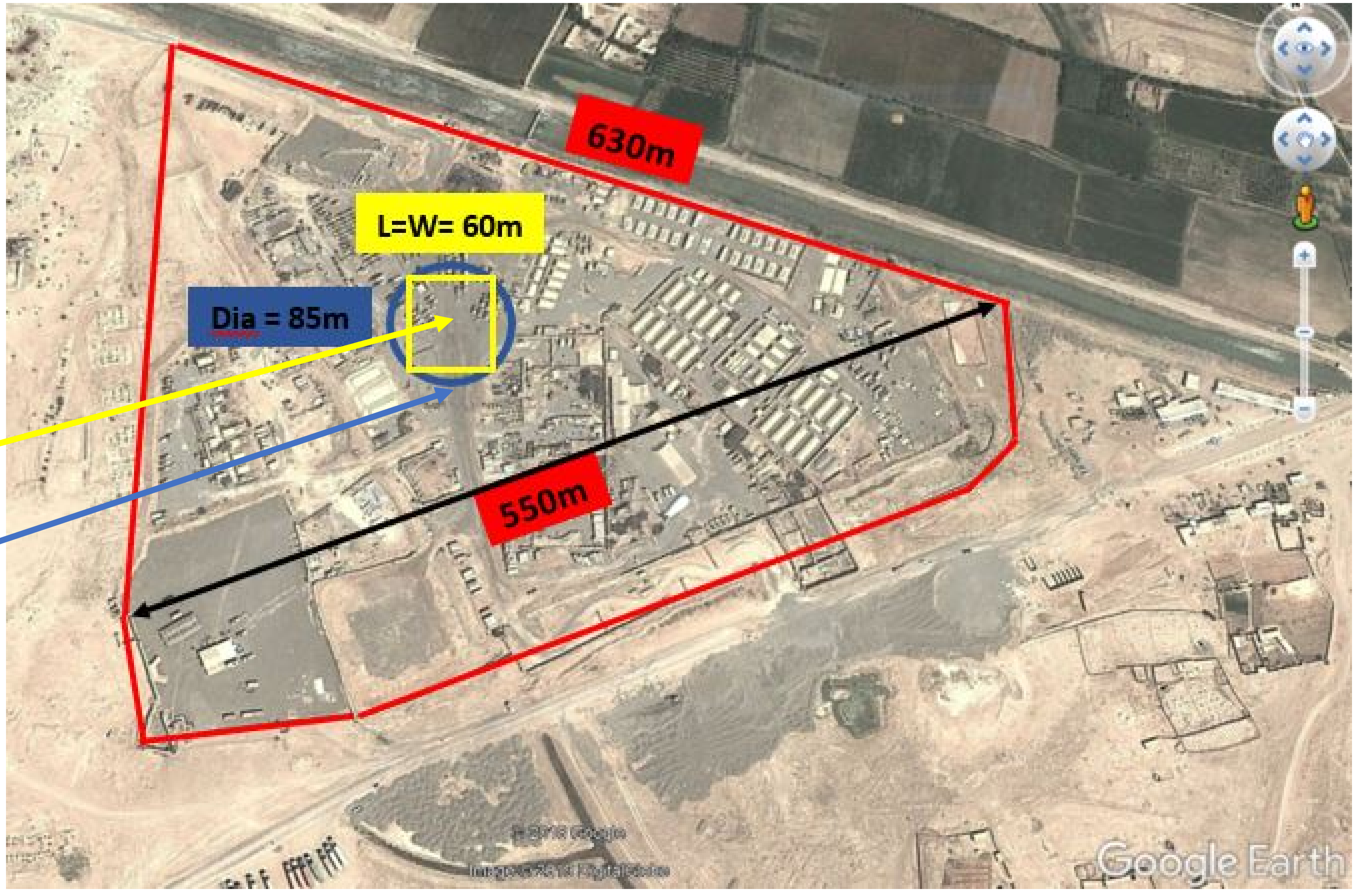
Assumptions

- Rectenna PCB panel is flexible and can be spooled on a 6” diameter shaft
- Maximum intercepted power density of 80W/m^2
- Average intercepted power density of 50W/m^2
- Each container has a receiver area of 4.5m x 100m (450m^2)
- 22,500W power output per container (50W/m^2)
  - 10 Containers = 225KW

COP Hanson: Case Study

Deployed Receiver

Power Beam/
Protected Perimeter



Average power density assumption: 50W/m^2

10 Containers

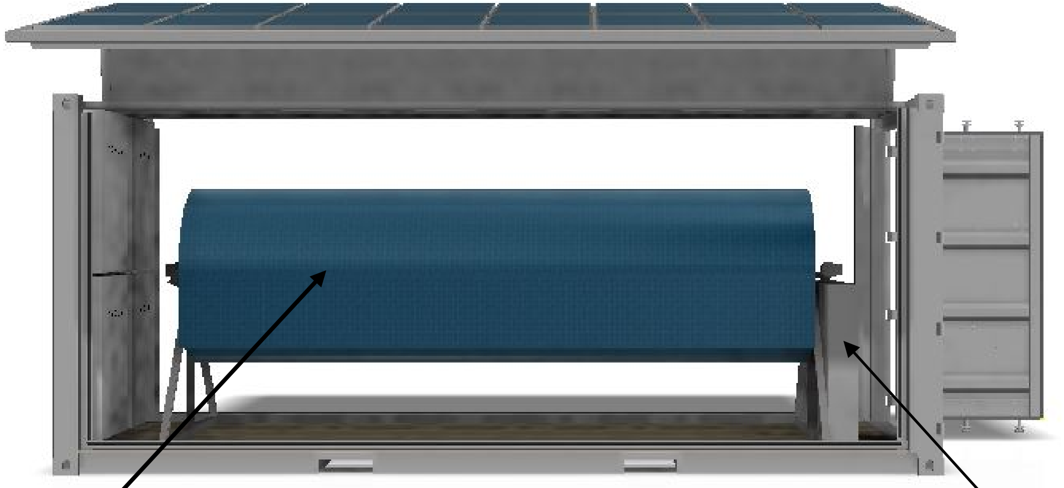
60m Deployed Receiver, 4.5m wide

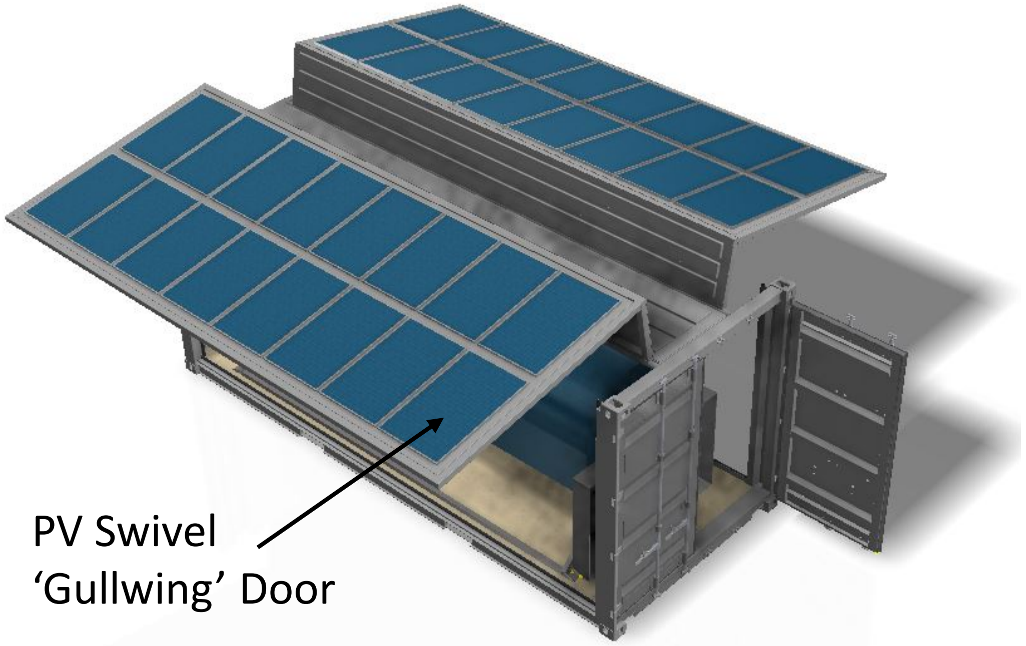
13,500W per container

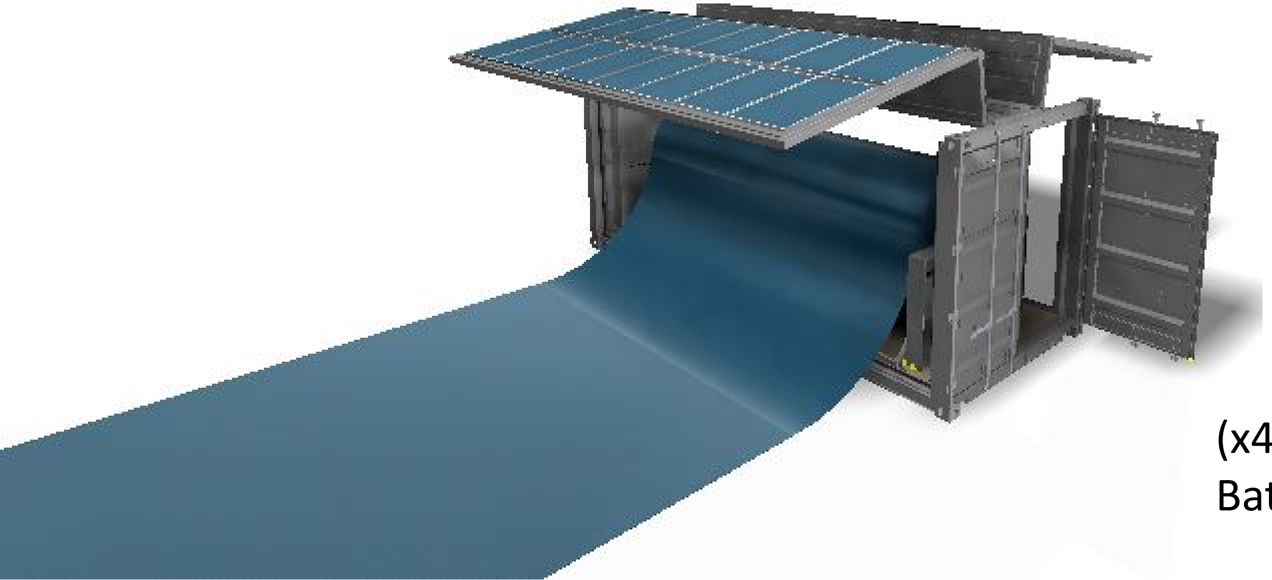
135,000W for this system

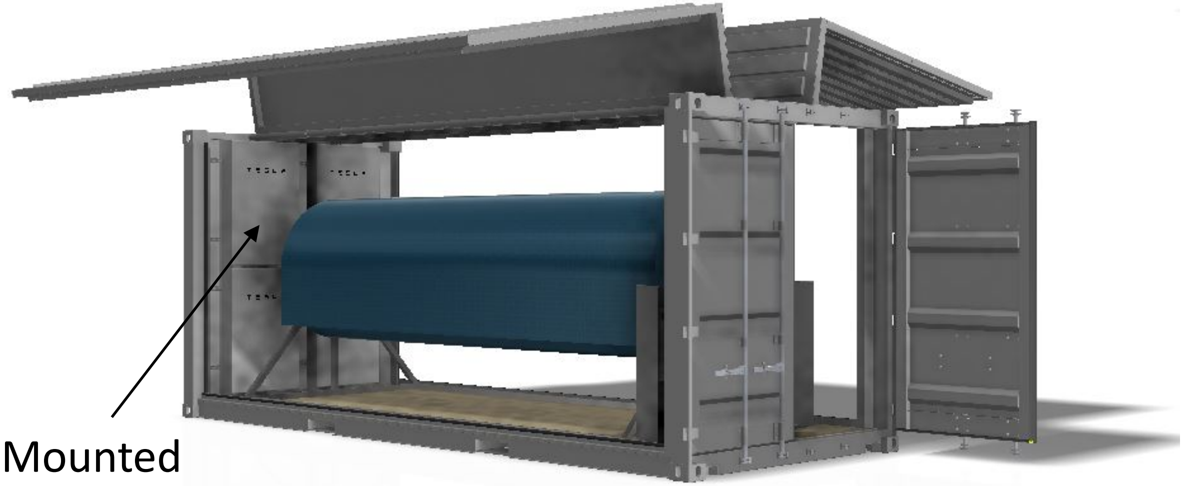
Publicly Available Information, Decommissioned Base

The Shipping Container

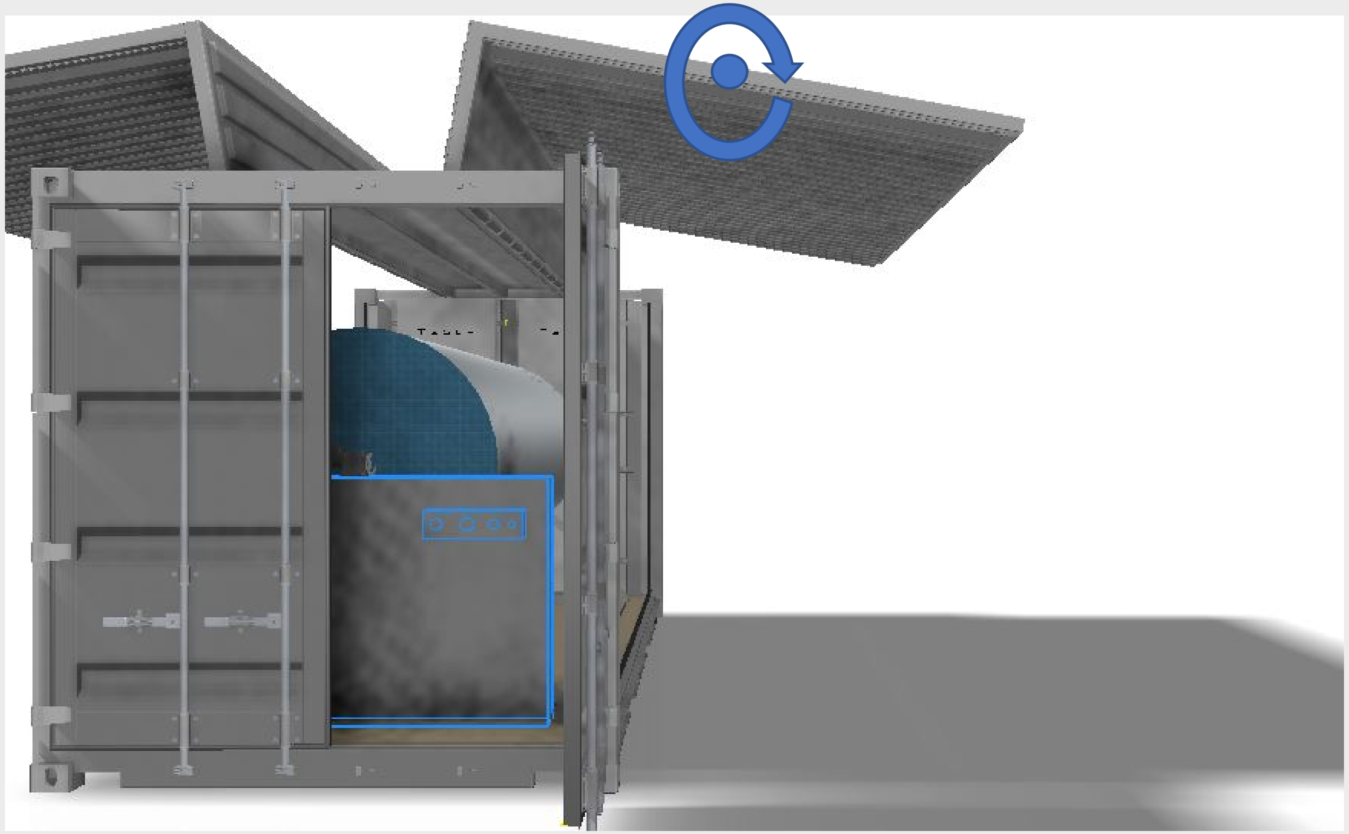

Rectenna on Spool
Receiver Spool
Controls Box

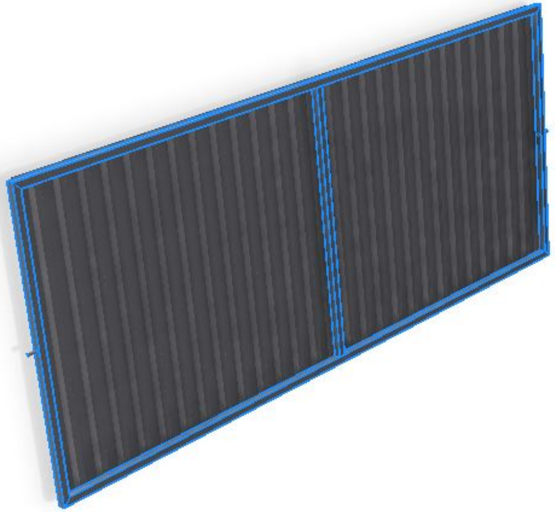

PV Swivel
'Gullwing' Door

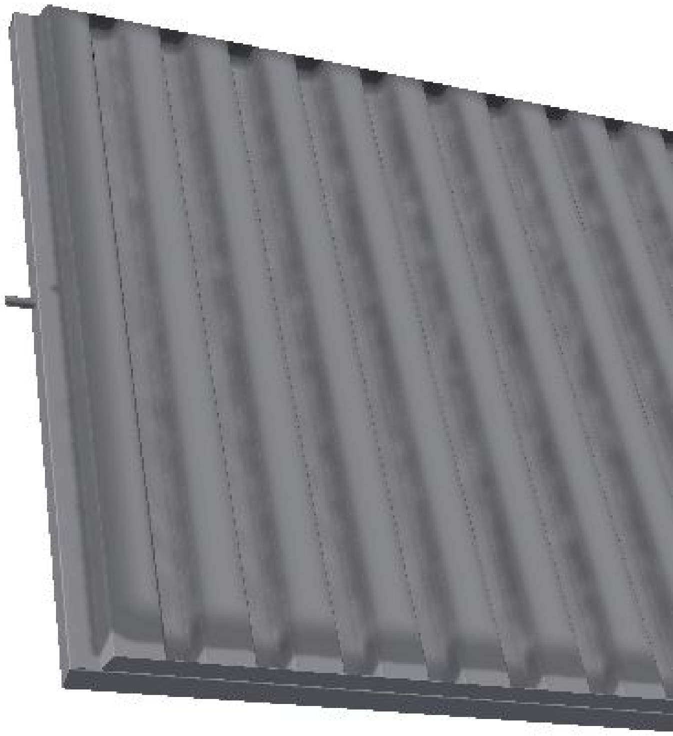



(x4) Mounted
Batteries

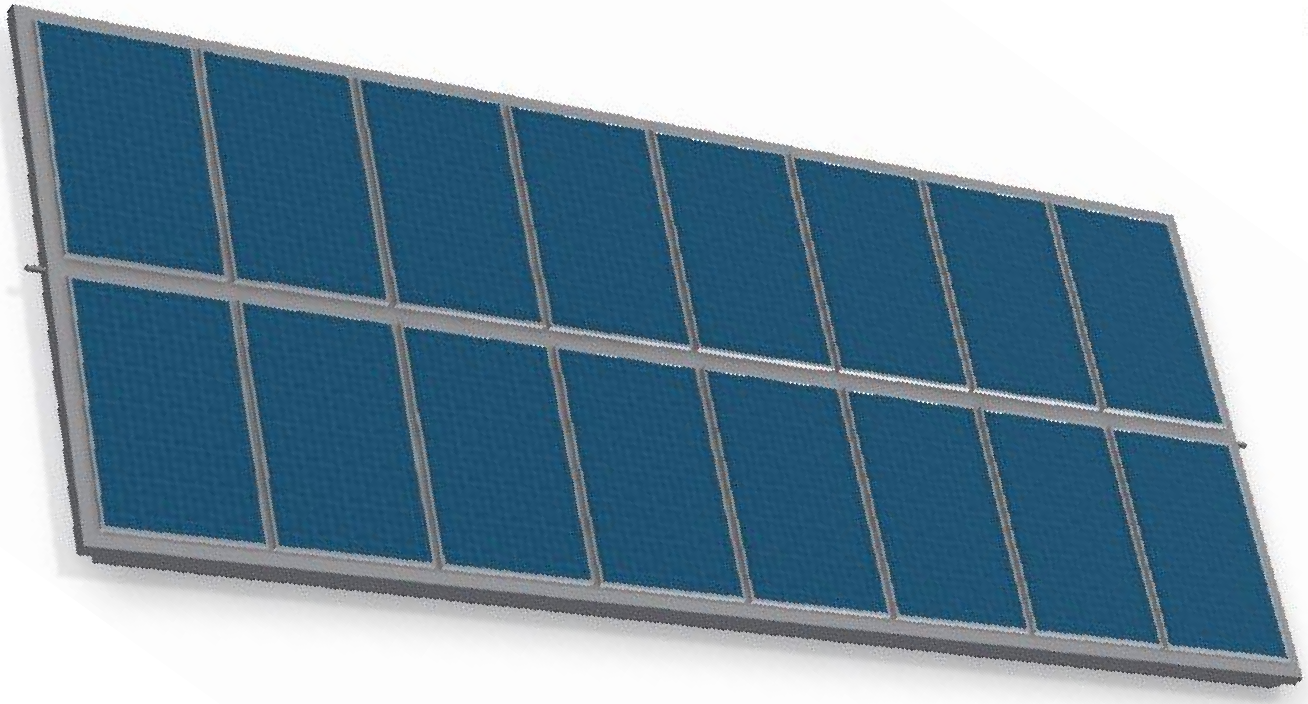
The PV Swivel 'Gullwing' Doors



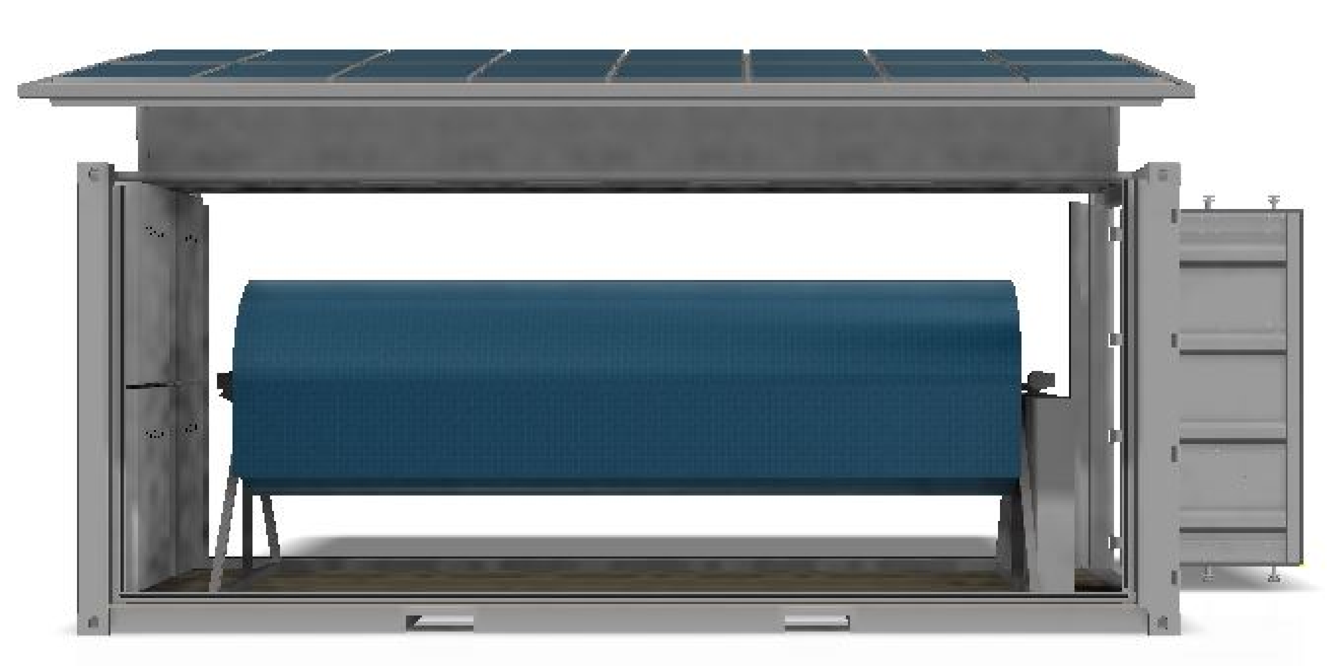


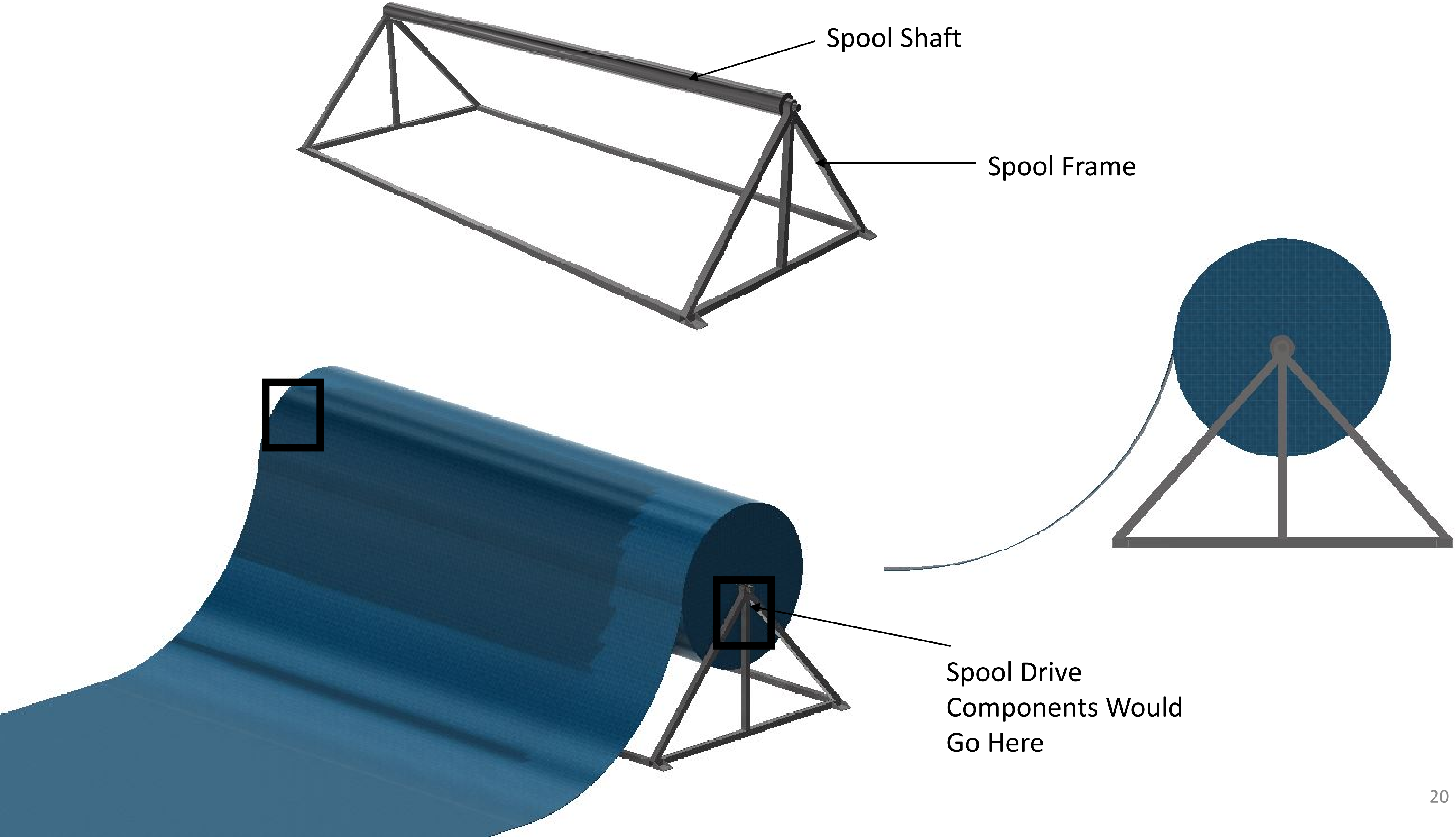


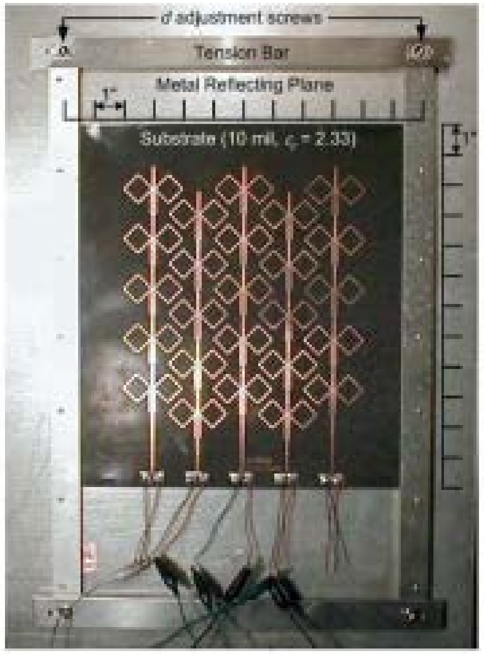
Approximately 1500W of Power Generation Per Door
(x2) Doors = 3kW Per Container
10 Containers = 30kW Added Power To System



The Receiver Spool




Spool Shaft
Spool Frame
Spool Drive
Components Would
Go Here



Tested rectenna array by Strassner and Chang

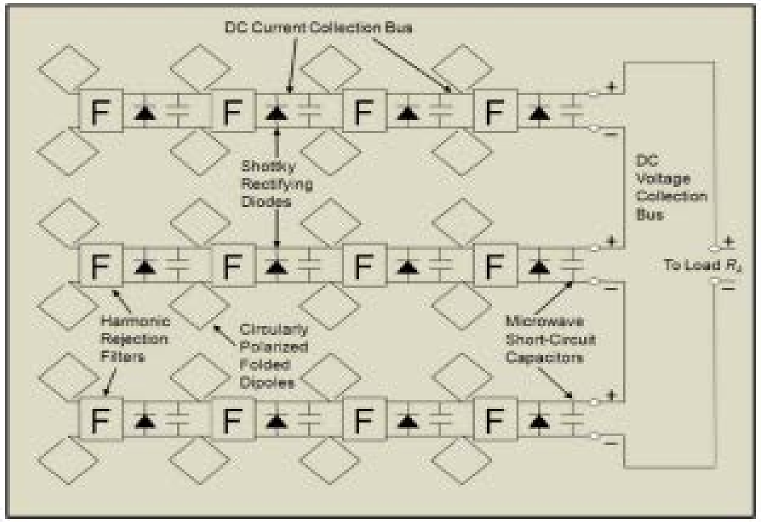


Fig. 15. *Array consisting of 12 individual rectennas.*

Printed Rectenna Array

- Determined that circularly polarized folded dipoles should be used
- Circular polarity of receiving antennas in a space solar application is critical, since the power will be transmitted from an orbiting satellite above
- This design allows for the number of rectifying antennas required in a given area to be reduced by half when compared to a linearly polarized (LP) system.
- This printed array will make up the deployable receiver panel.

MECHANICAL SPECIFICATIONS

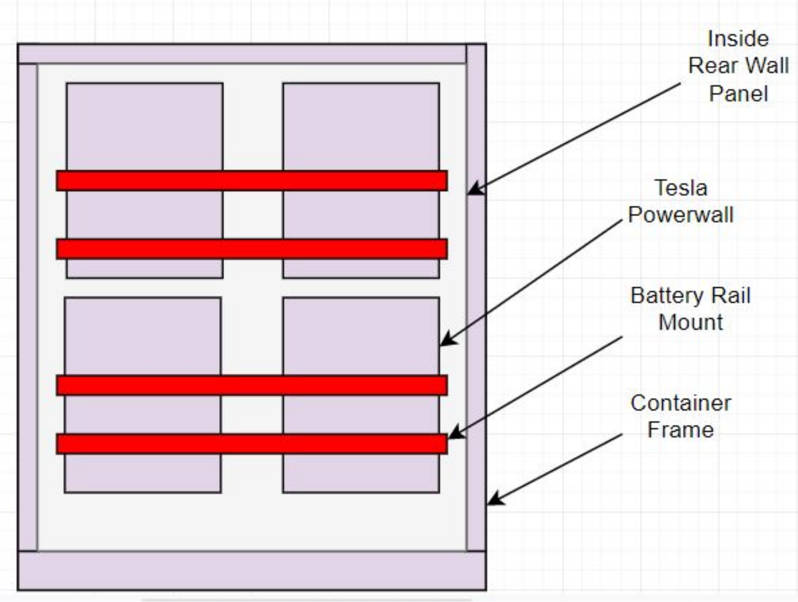
Dimensions	1150 mm x 755 mm x 155 mm (45.3 in x 29.7 in x 6.1 in)
Weight	125 kg (276 lbs)
Mounting options	Floor or wall mount

ENVIRONMENTAL SPECIFICATIONS

Operating Temperature	–20°C to 50°C (–4°F to 122°F)
Optimum Temperature	0°C to 30°C (32°F to 86°F)
Operating Humidity (RH)	Up to 100%, condensing
Storage Conditions	–20°C to 30°C (–4°F to 86°F) Up to 95% RH, non-condensing State of Energy (SoE): 25% initial
Maximum Elevation	3000 m (9843 ft)
Environment	Indoor and outdoor rated

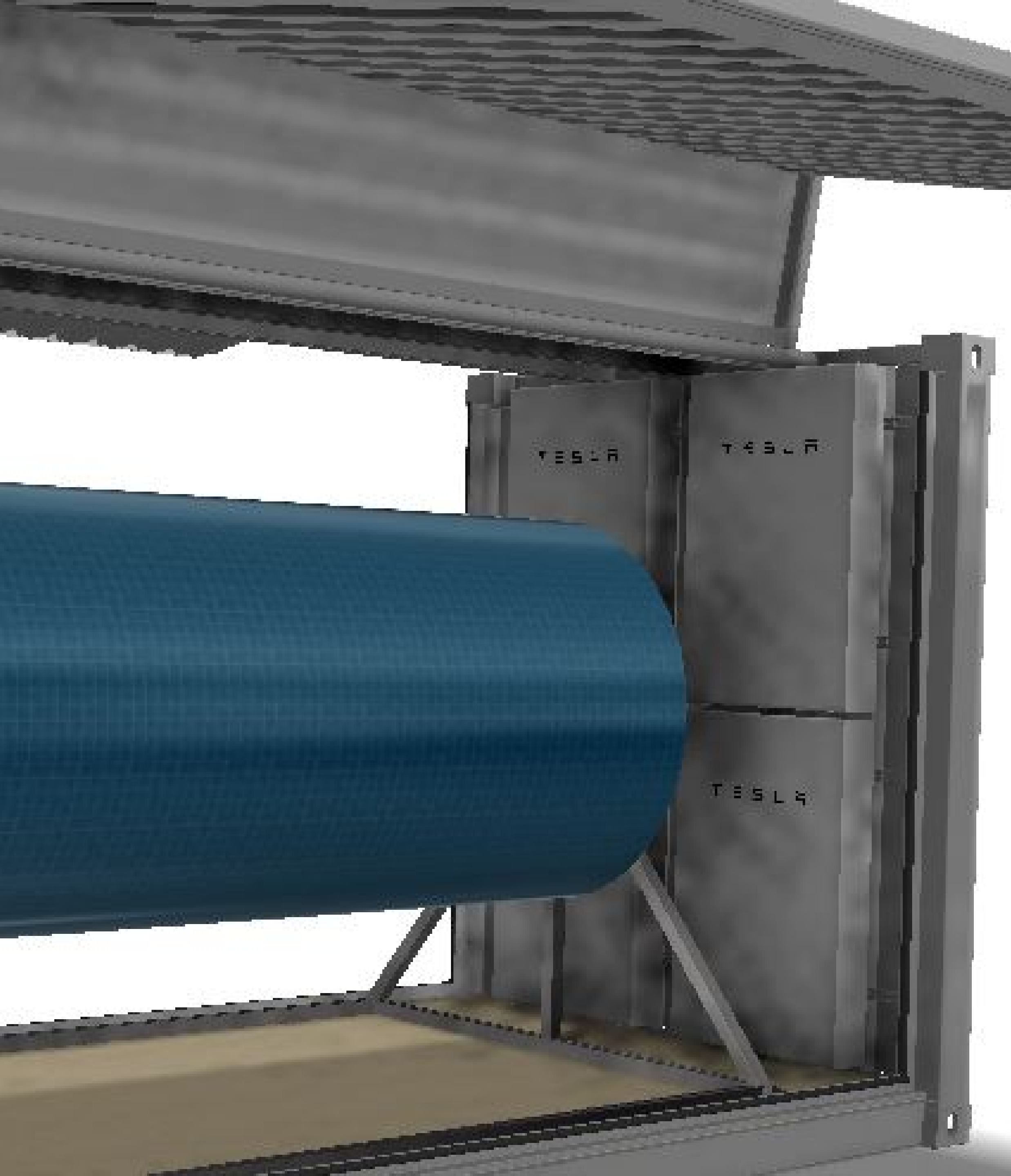
PERFORMANCE SPECIFICATIONS

AC Voltage (Nominal)	120/240 V
Feed-In Type	Split Phase
Grid Frequency	60 Hz
Total Energy[1]	14 kWh
Usable Energy[1]	13.5 kWh
Real Power, max continuous[2]	5 kW (charge and discharge)

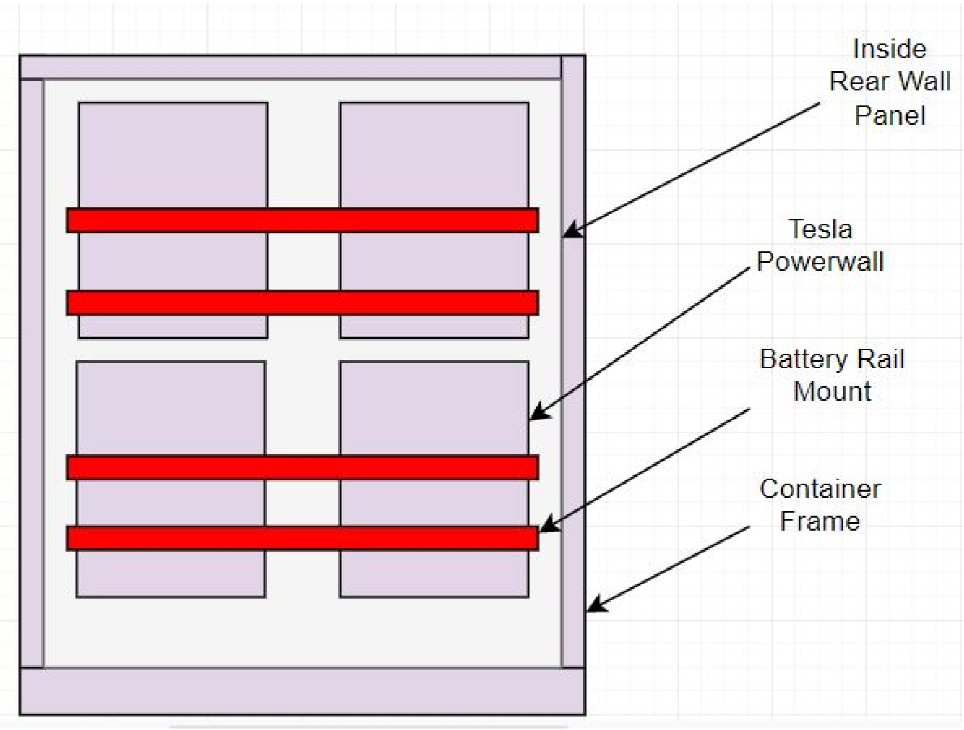


Integrated Battery Power Storage

https://www.tesla.com/powerwall



(x4) – 13.5kW Batteries
= 54 kW Total Usable Energy Per Container
(x10) Containers Building Block = 540kW

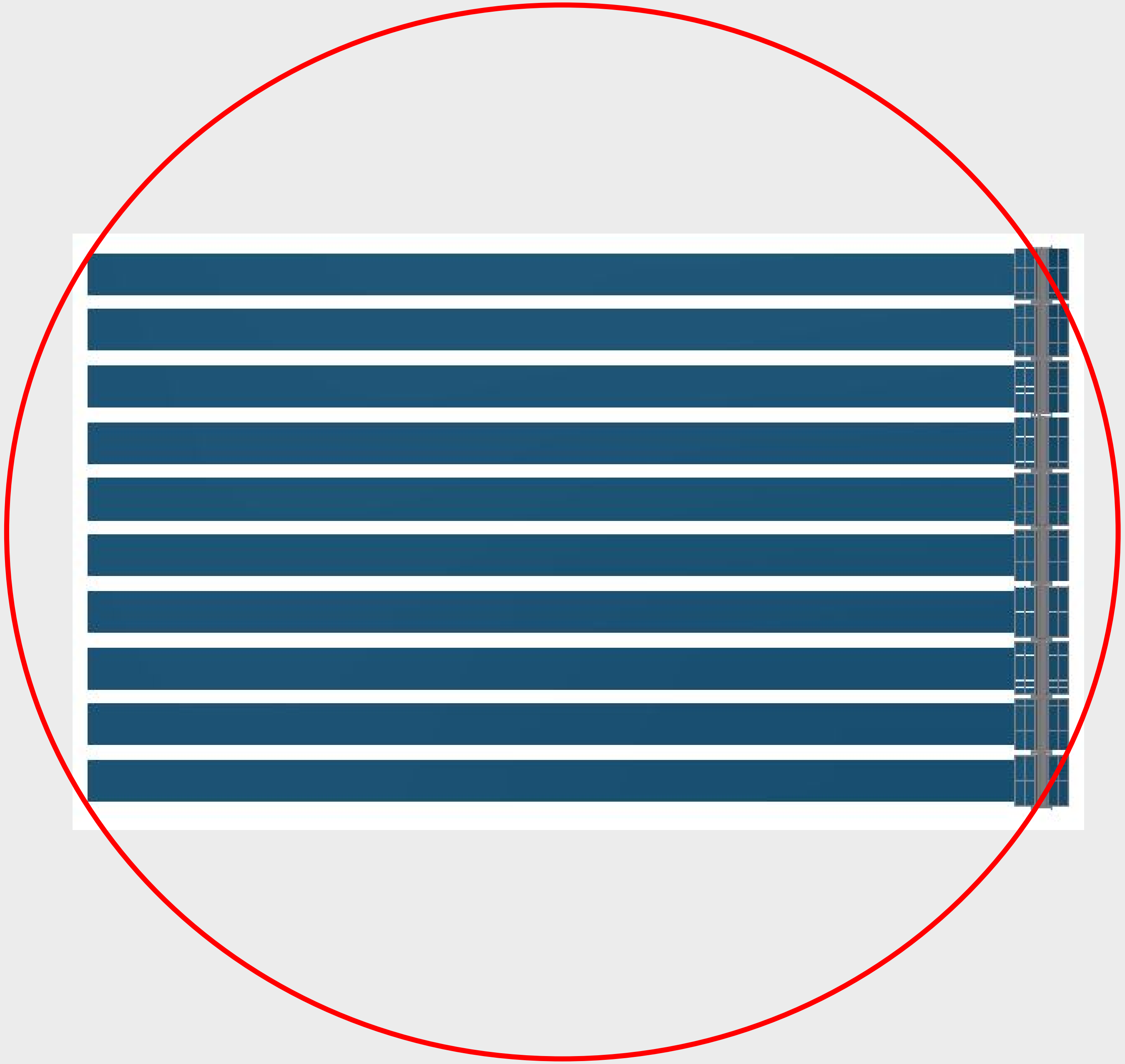


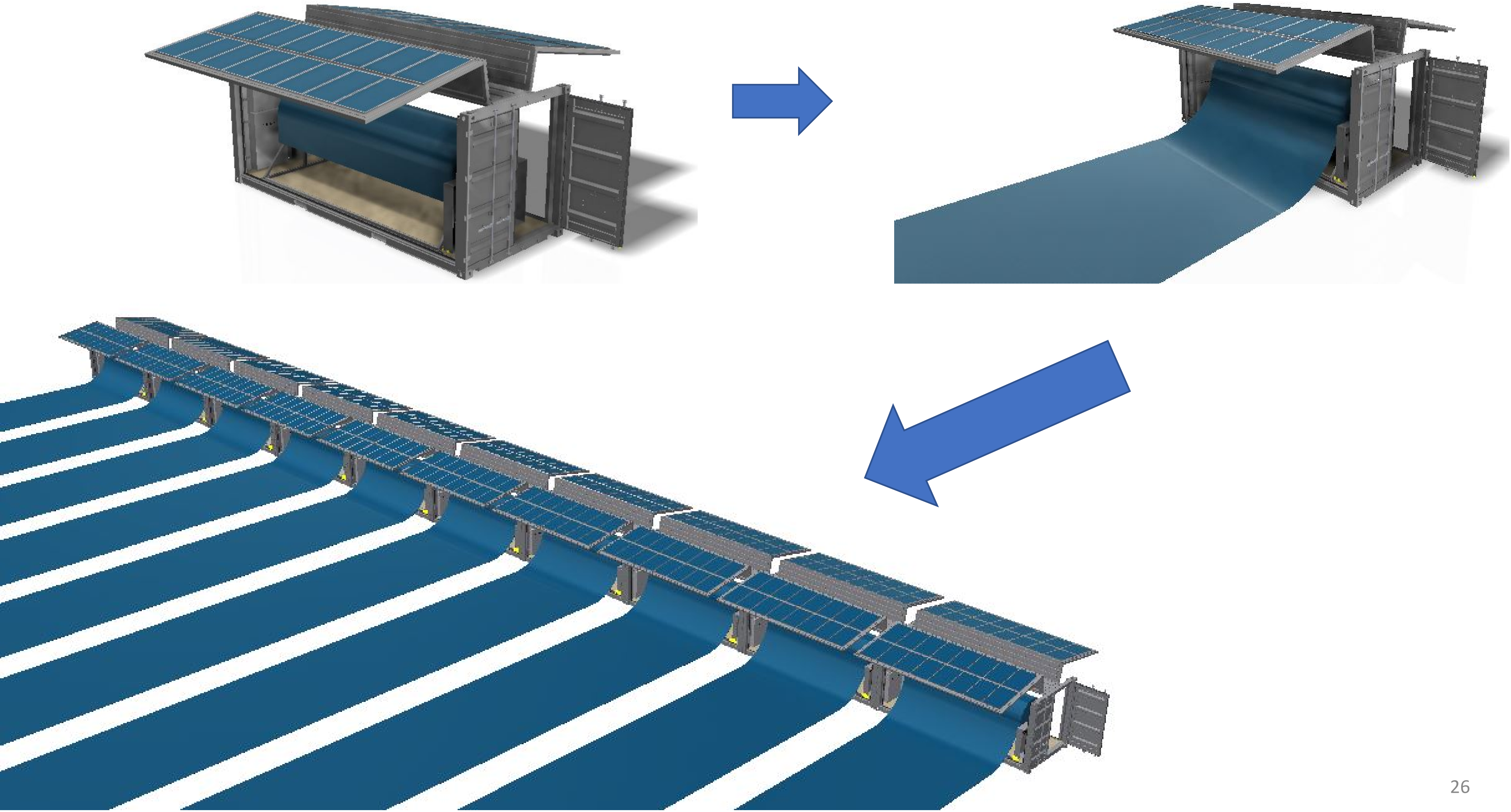
Container Cost Estimate

- Custom Container: $5,000 (base) + $5,000 (mods) = $10,000
- 4 Batteries: $15,000 each = $30,000
- Spool Frame: $5,000
- Spool Drive System: $2,000
- Total: $47,000
- 10 Container Cost: $470,000 – equivalent to 94,000 gallons of fuel at $5/gallon

- **Rectenna cost not included

System Configuration





System Deployment

1. Deployment site is scanned by small UAS, and cleared of major debris
2. Containers are airlifted or unloaded to the pre-determined location
3. Gullwing doors are unlocked and opened
4. Center of container is located and marked
5. A line 90 degrees to container side is marked out a pre-determined length
6. ATV hooks-up to the receiver and drives down the line.

Project Deliverables

- A concept of operation and requirements study.
- 2D drawings, 3D modeling, flowcharts, and system diagrams of a selected design.
- A 1/4th scale receiver prototype will be produced to demonstrate its modularity and deployment functionality.
- A wireless power transmission, table-top demo, will be produced to demonstrate the concept of SSP and wireless power transmission.
- A printed circuit board (PCB) rectenna array will be designed, manufactured, and demonstrated on the table-top demo.

Work Yet To Be Completed

- Complete project documentation including CONOPs flowchart
- Finalize design and modeling
- Fabricate and assemble the ¼ scale prototype

Strength and Weaknesses

- S- Gullwing PV swivel door design is novel and could have spin-off applications (festivals, events)
- S- The power collection area can be changed easily to supply the demand
- W- PV integration provides little added benefit to the power capacity, more PV area would be necessary
- W- Integration with a power management system has not been considered
- W- A spool receiver may not be a reliable solution due to variances in the deployment process, unmanned systems may be more useful
- W- Manufacturing a (very) large flexible PCB rectenna has never been done
- W- A MW size receiver would likely have to be a permanent solution requiring a different design

Challenges with Developing the Ground Component

- No significant development or manufacturing activity done to date
- Prototyping costs could be high
- System needs to flexible enough to satisfy many different applications to be viewed favorably amongst stakeholders
- Power demand varies significantly with application and may not be suitable for some

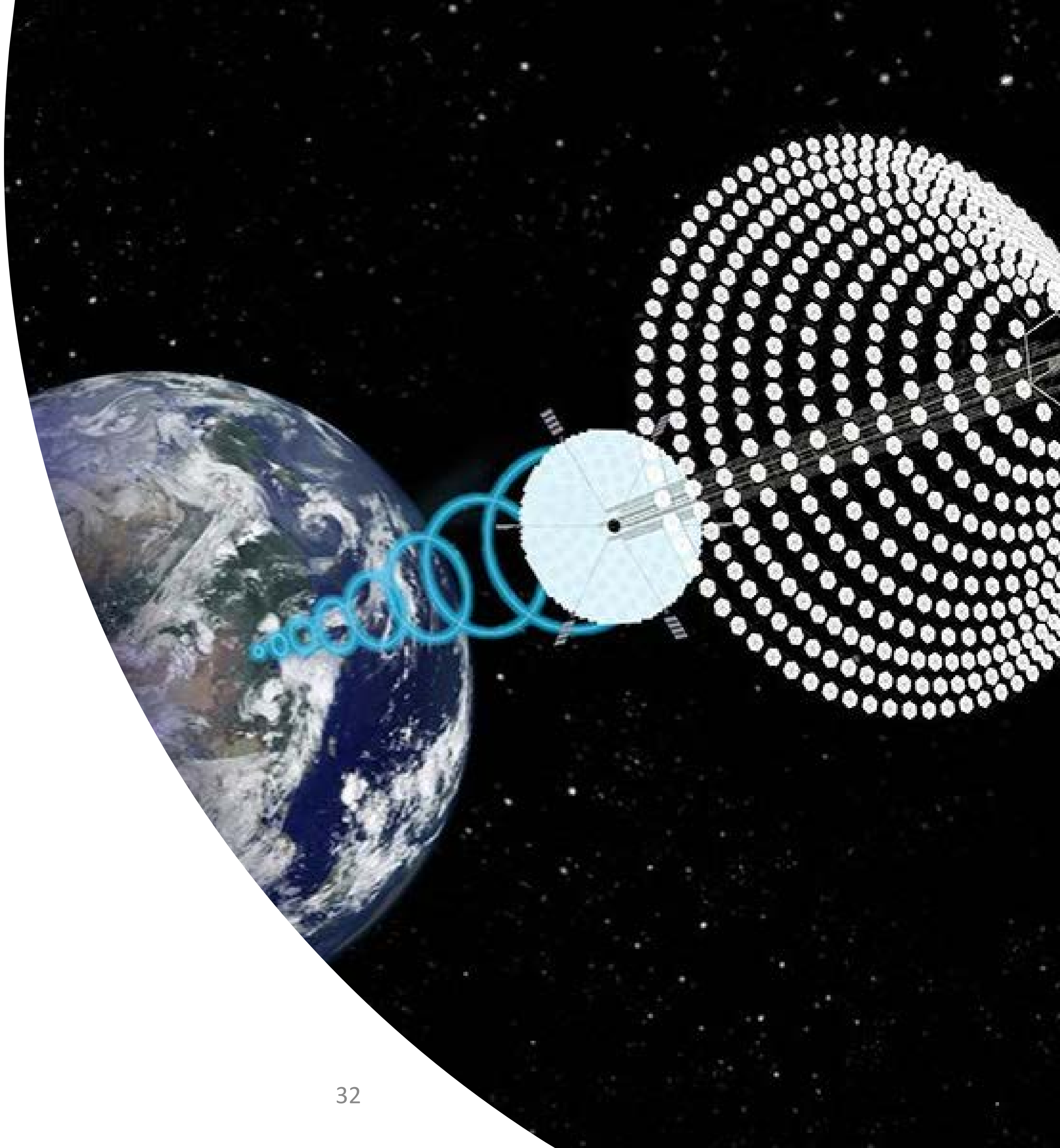
Any Questions?

Visit our project website at…

www.sspdevelopmentgroup.com

On Facebook and LinkedIn
@sspdevelopmentgroup

https://www.gofundme.com/space-solar-power-development-group



BACKUP

Useable Volume In Shipping Container For Reciever							
	m	ft	in		m³	ft³	in³
Length	4.50	14.76	177.17	Volume	20.19	713.13	1,232,296
Width	2.01	6.58	78.95				
Height (avail)	2.24	7.34	88.10				

$$D_o = \sqrt{\frac{4Lt}{\pi} + D_i^2}$$

Input Diameter of Shaft and Deployed Length Desired				
	m	ft	in	
Diameter (spool) D	2.24	7.35	88.19	*max available (height)
Diameter (shaft) D_i	0.10	0.33	4.00	*subject to change
Length (deployed) L	100	328.10	3937.20	*max 310

$$t = \frac{\pi(D_o^2 - D_i^2)}{4L}$$

	in	
Thickness (panel)	1.55	(max possible)

Input Desired Panel Thickness			
	in	ft	m
Desired Panel Thickness	0.50	0.04	0.01

Panel Material Mass per m² (kg):

Total Mass or Reciever Panel:

Input Power Requirement							
Power Received (Required)	Power Transmitted (Output)	Area of Transmitter	Wavelength	Far Field Distance	Area of Reciever	Diameter of Receiver	Diameter of Transmitter
P_r (GW)	P_t (GW)	A_t (km²)	λ (mm)	D (km)	A_r (km²)	d_r (km)	d_t (m)
0.0002	1.3	143.9	51.8	7066.7	1.44	0.04	428
P_r (kW)	P_t (kW)	A_t (m²)	λ (m)	D (m)	A_r (m²)	d_r (m)	
200	1,300,000	143872.4	0.0518	7066738.7	143.53	42.47	

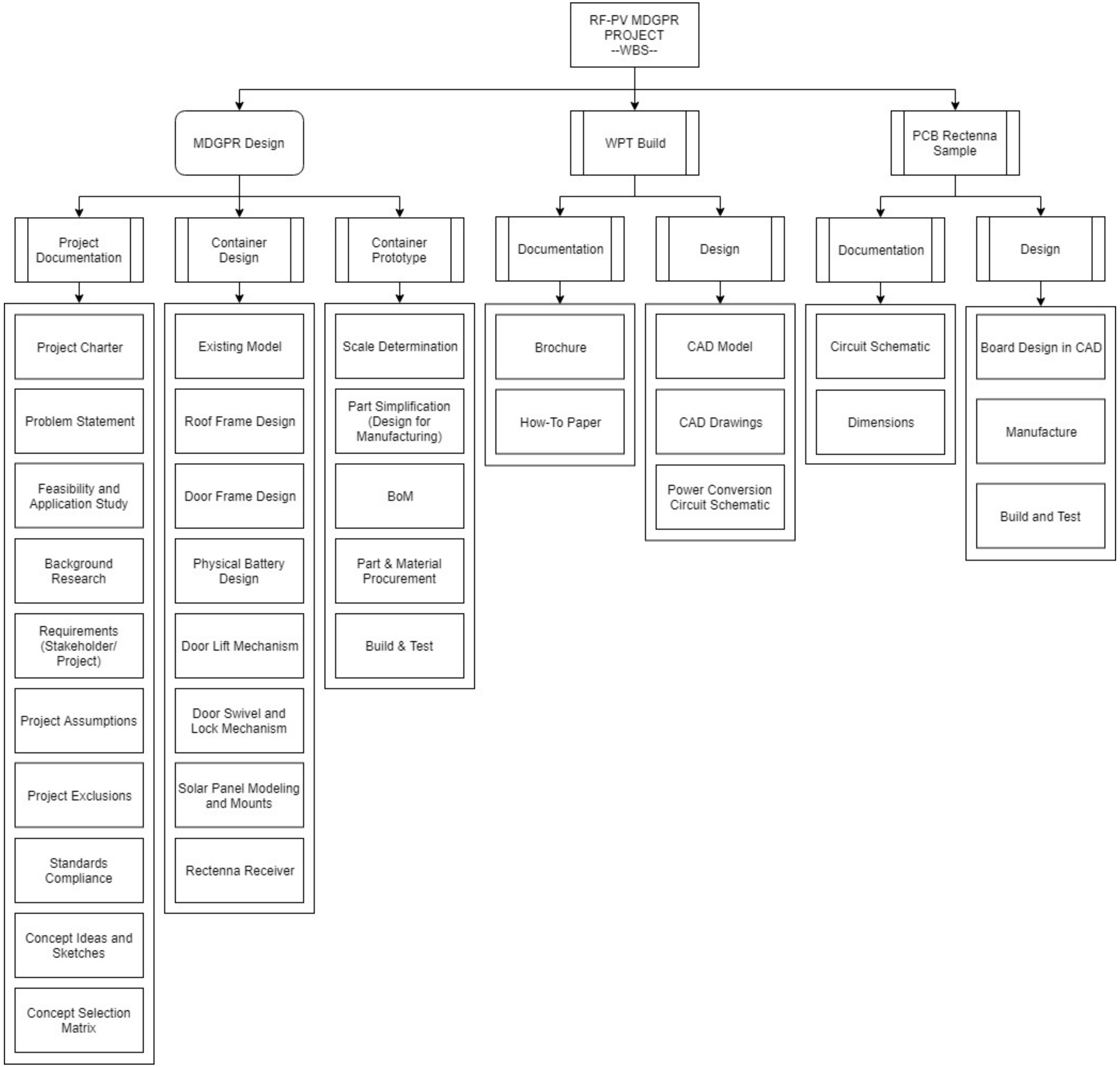
	m2
Area Required	143.5

$$P_r = \frac{P_t A_t A_r}{\lambda^2 D^2} \quad where\ D > \frac{2d^2}{\lambda}$$

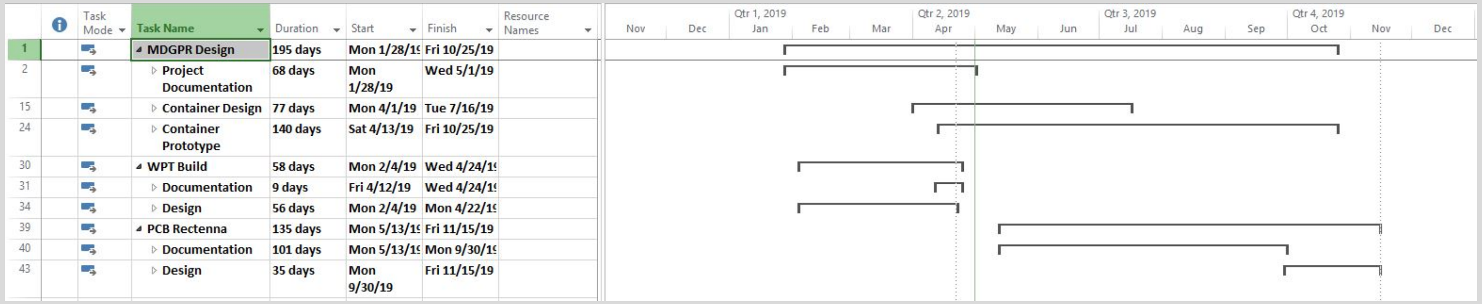
$$A_r = \frac{P_r \lambda^2 D^2}{P_t A_t} \quad where\ D > \frac{2d^2}{\lambda}$$

Summary of determined dimensions				
	m	mm	ft	in
D_{rolled}	1.28	1,275.64	4.19	50.22
D_{shaft}	0.10	101.60	0.33	4.00
Panel	0.01	12.70	0.04	0.50
Deployed Panel Length	100.00	100,000.00	382.10	4,585.20
Deployed Area (m²) [per	m² 450.00		Power Density Selection 50	Output per Container: 22,500.00
Weight of Rectenna on Spool (kg) [2kg/m²]:	900.00		Power Desired (W)[see input power req table]:	200,000
Weight of Shipping Container (kg) [empty w/	4000		Required Number of Shipping	9
Gross Weight of Container w/Array (kg)[subj. to change]:	4900			

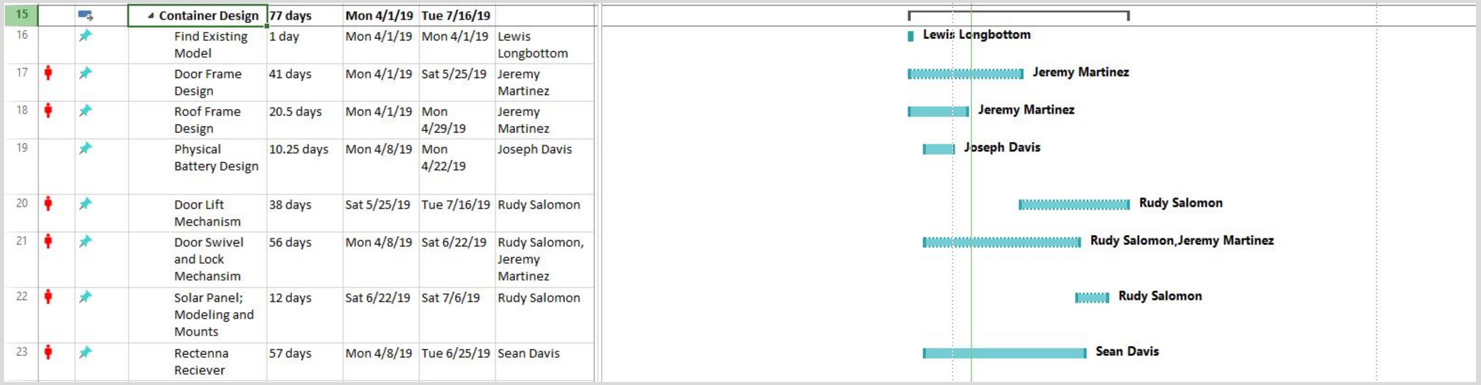
Work Breakdown Structure



Gantt Chart



		Task Mode	Task Name	Duration	Start	Finish	Resource Names
1			MDGPR Design	195 days	Mon 1/28/1!	Fri 10/25/19	
2			Project Documentation	68 days	Mon 1/28/19	Wed 5/1/19	
15			Container Design	77 days	Mon 4/1/19	Tue 7/16/19	
24			Container Prototype	140 days	Sat 4/13/19	Fri 10/25/19	
30			WPT Build	58 days	Mon 2/4/19	Wed 4/24/1!	
31			Documentation	9 days	Fri 4/12/19	Wed 4/24/1!	
34			Design	56 days	Mon 2/4/19	Mon 4/22/1!	
39			PCB Rectenna	135 days	Mon 5/13/1!	Fri 11/15/19	
40			Documentation	101 days	Mon 5/13/1!	Mon 9/30/1!	
43			Design	35 days	Mon 9/30/19	Fri 11/15/19	



15			Container Design	77 days	Mon 4/1/19	Tue 7/16/19	
16			Find Existing Model	1 day	Mon 4/1/19	Mon 4/1/19	Lewis Longbottom
17			Door Frame Design	41 days	Mon 4/1/19	Sat 5/25/19	Jeremy Martinez
18			Roof Frame Design	20.5 days	Mon 4/1/19	Mon 4/29/19	Jeremy Martinez
19			Physical Battery Design	10.25 days	Mon 4/8/19	Mon 4/22/19	Joseph Davis
20			Door Lift Mechanism	38 days	Sat 5/25/19	Tue 7/16/19	Rudy Salomon
21			Door Swivel and Lock Mechansim	56 days	Mon 4/8/19	Sat 6/22/19	Rudy Salomon, Jeremy Martinez
22			Solar Panel; Modeling and Mounts	12 days	Sat 6/22/19	Sat 7/6/19	Rudy Salomon
23			Rectenna Reciever	57 days	Mon 4/8/19	Tue 6/25/19	Sean Davis

30			WPT Build	58 days	Mon 2/4/19	Wed 4/24/1!	
31			Documentation	9 days	Fri 4/12/19	Wed 4/24/1!	
32			Brochure	9 days	Fri 4/12/19	Wed 4/24/1!	Kristopher Lowr
33			How-To Paper	9 days	Fri 4/12/19	Wed 4/24/1!	Kristopher Lowr
34			Design	56 days	Mon 2/4/19	Mon 4/22/1!	
35			CAD Model	46 days	Mon 2/18/1!	Mon 4/22/1!	Kristopher Lowr
36			CAD Drawings	2 days	Fri 3/1/19	Sat 3/2/19	Lewis Longbotto
37			Machining	1 day	Mon 2/4/19	Mon 2/4/19	
38			Power Conversion Circuit Schematic	7 days	Fri 4/12/19	Mon 4/22/19	Kristopher Lowry

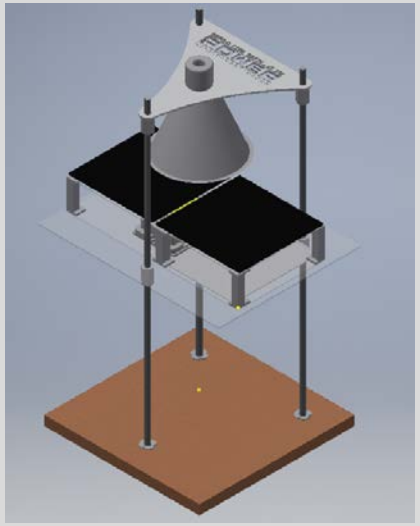
Budget

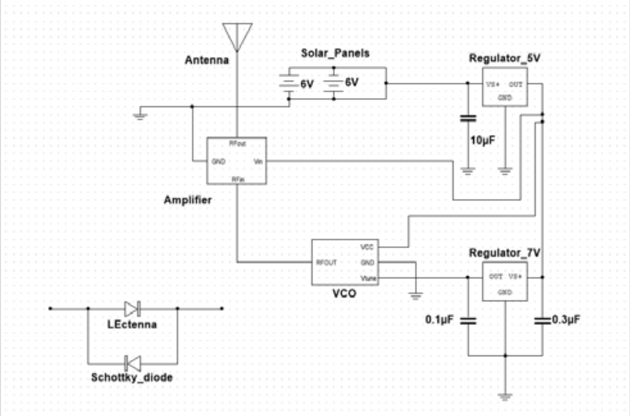
Available Funds: $2000

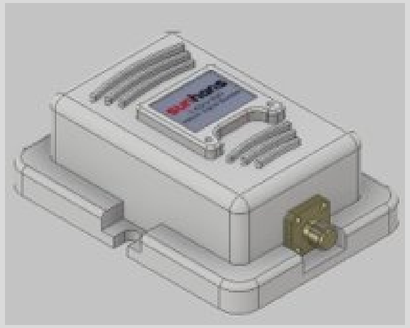
Project Expenses		Cost	Quantity	Total	Description
WPT Demo		$400.00	1	$400.00	Table-top demo, incl. storage case
Container Prototype Module					
	4'x8'x18 Guage Steel	$58.66	4	$234.64	Federal Iron Quote
	1"x1"x72"x1/16" Steel Tube	$13.16	6	$78.96	https://www.metalsdepot.com/steel-products/steel-square-tube
	1/2"x72" Steel Round Bar	$8.20	2	$16.40	https://www.metalsdepot.com/steel-products/steel-round-bar
	3/4"ODx1/16" Round Steel Tube	$10.52	1	$10.52	https://www.metalsdepot.com/steel-products/steel-round-tube-welded
	Gas Struts	$18.21	4	$72.84	https://www.mcmaster.com/4138t56
	Spool Shaft Motor	$35.99	1	$35.99	https://www.vexrobotics.com/vexpro/motors-electronics/775pro.html
	Victor SPX Motor Controller	$49.99	1	$49.99	https://www.vexrobotics.com/217-9191.html
	VersaPlanetary 180 Drive Gearbox	$67.95	1	$67.95	https://www.vexrobotics.com/vp-180.html
	VersaPlanetary Integrated Encoder	$49.99	1	$49.99	https://www.vexrobotics.com/vexpro/motors-electronics/encoders/217-5046.html
	Voltage Regulator Module	$44.99	1	$44.99	https://www.vexrobotics.com/217-4245.html
	Battery	$30.00	1	$30.00	
Hardware		$100.00	1	$100.00	Miscellaneous
3D Printing Expenses		$100.00	1	$100.00	
PCB Expenses		$100.00	1	$100.00	
Transportation and Storage Equipment		$100.00	1	$100.00	
Presentation/ Marketing Materials		$100.00	1	$100.00	
			Total:	$ 1,592.27	

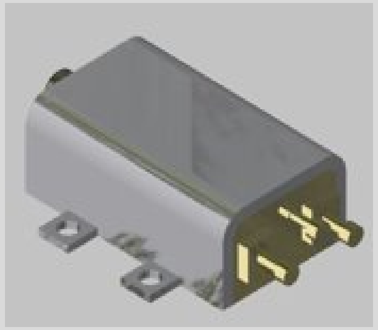
Wireless Power Transmission Demo

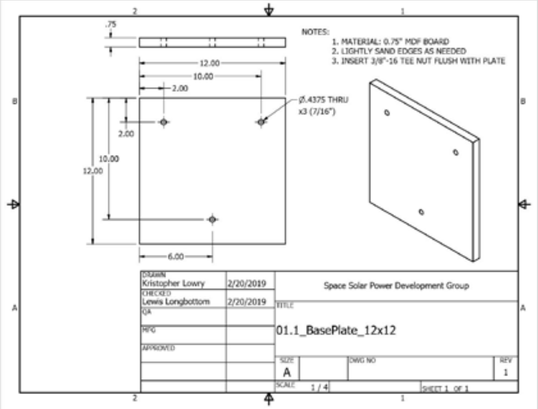
Purpose: A table-top demonstration of wireless power transmission and reception.











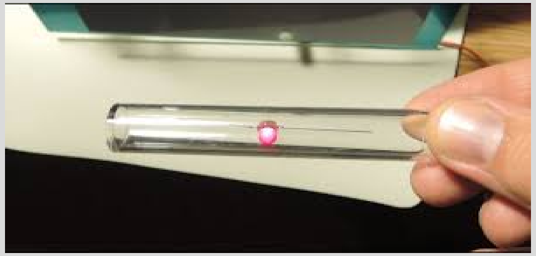


Image References

- Slide 23: https://www.tesla.com/powerwall
- Rectenna Array Design: https://images.app.goo.gl/VNuUbSv5RH4B1aU4A
- Paul Jaffe Presentation: https://www.youtube.com/watch?v=V5SMF9p-4Q0