National Aeronautics and Space Administration

OPERATIONS MODELING OF ISRU LUNAR BASE ARCHITECTURES

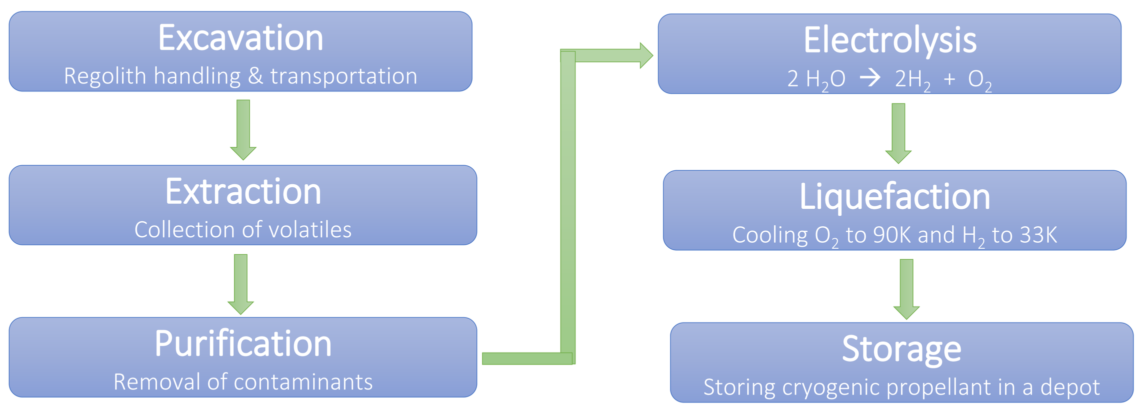
J. O. Elliott[1], A. Austin[1], P. Metzger[2], B. Sherwood[1] and M. Smith[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, [2]University of Central Florida

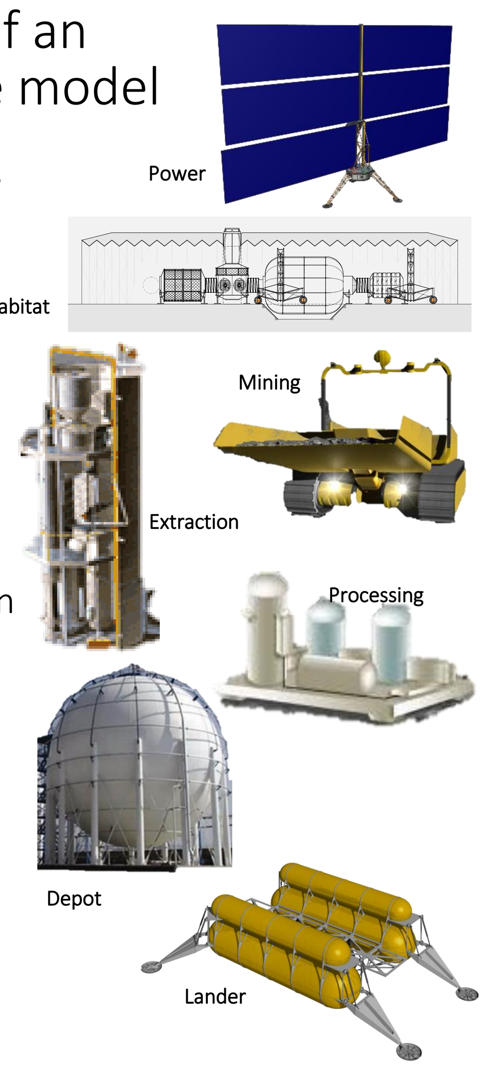
(jelliott@jpl.nasa.gov)

Model Based on Conceptual Designs for Robotically Assembled and Operated Base

Functional decomposition of ice-based propellant ISRU Led to design of minimal set of base elements



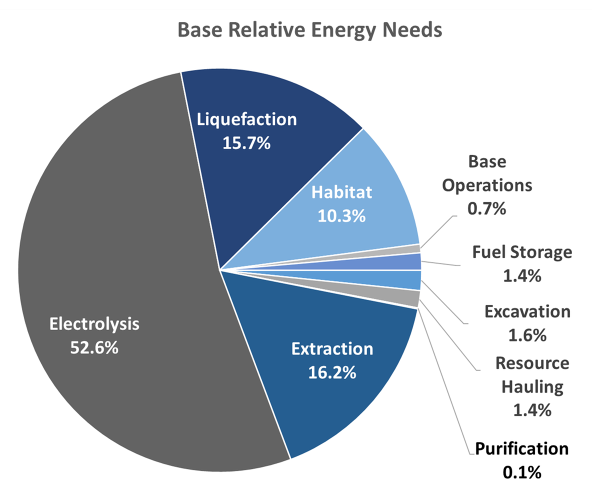
Conceptual designs for major elements of an ISRU base provide a starting point for the model



- **Power System** – 500 kW capacity, near-100% duty cycle, modular units landed intact, then connected via cables or laser WPT
- **Habitat System** – Minimal functions, 30-d visits: hab, logistics, workshop, EVA, regolith-shield superstructure
- **ISRU Mining System** – Mobile robots that reach, excavate, beneficiate, and transport lunar regolith (or extract resource onboard and transport it)
- **ISRU Extraction System** – Processor that separates frozen volatiles from lunar regolith
- **ISRU Volatiles Processing System** – Plant that separates water from other volatiles, and cracks it into H_2 and O_2
- **ISRU Depot System** – Plant that liquefies, cryogenically stores, and distributes cryogenic propellant to reusable landers
- **Lander System** – Reusable, refuelable lander, reusable landing pad, and ground support systems

Water mining needs flow from assumptions on self-sustaining lander fueling (LOx/LH2) capability

- Lander flights per year: 4
- Propellant required per flight: 40,000 kg
- Water required per flight: 51,500 kg (6:1 engine ratio vs. 8:1 water mass ratio)
- Water need: 206,000 kg/yr (=1,130 kg/d @ half-time operations)



Resource need

- Type 1: 0.15 m^3 (~210 kg) per kg of H_2O yield
- Type 2: 0.40 m^3 (~600 kg) per kg of H_2O yield

Regolith need

- Type 1: 240,000 kg/d @ half-time
- Type 2: 680,000 kg/d @ half-time

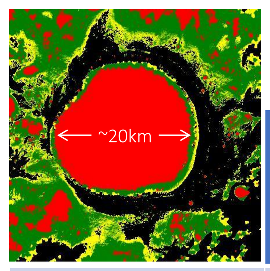
Total base energy need for 206,000 kg of H2O per year: > 600 kW (not including power losses) driven primarily by the processing of regolith into propellant (extraction, electrolysis, liquefaction)

Emergent Findings

- Nuclear power useful for production-scale ISRU would have to be MWe class
- "Best" ice resource and location may not be in a PSR
- Potential competitive roles for commercial actors
  - Power providers, extraction rovers
- Empirical knowledge gaps with high leverage
  - Vertical distribution at m scale – wt% of ice as a function of depth
  - Horizontal distribution at km scale – patchiness of resource "field"
  - Geotechnical properties – "coffee grounds and sugar" or cryo-permafrost
  - Diffusion rate – trapping vs losing the resource from heating in situ
  - Agitation loss coefficient – losing the resource from handling it

Three Base/ISRU Siting Options (Using Shackleton as Example) Considered to Exercise Model with Variety of Resource Assumptions

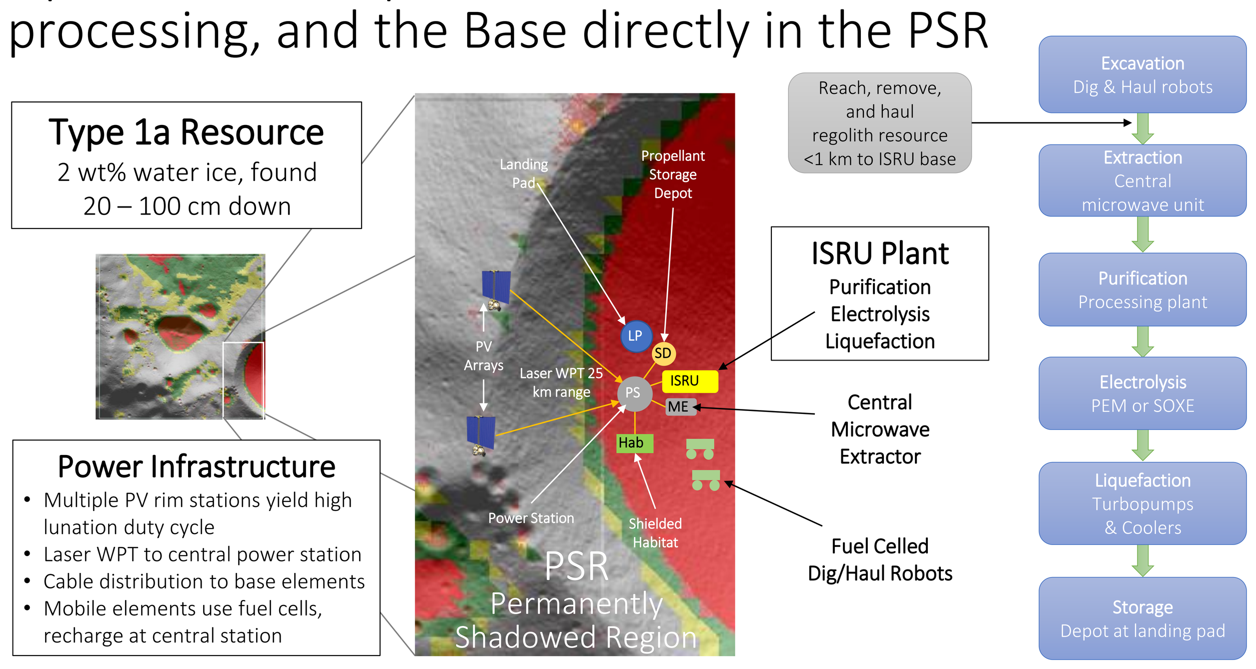
Polar ice resource assumptions



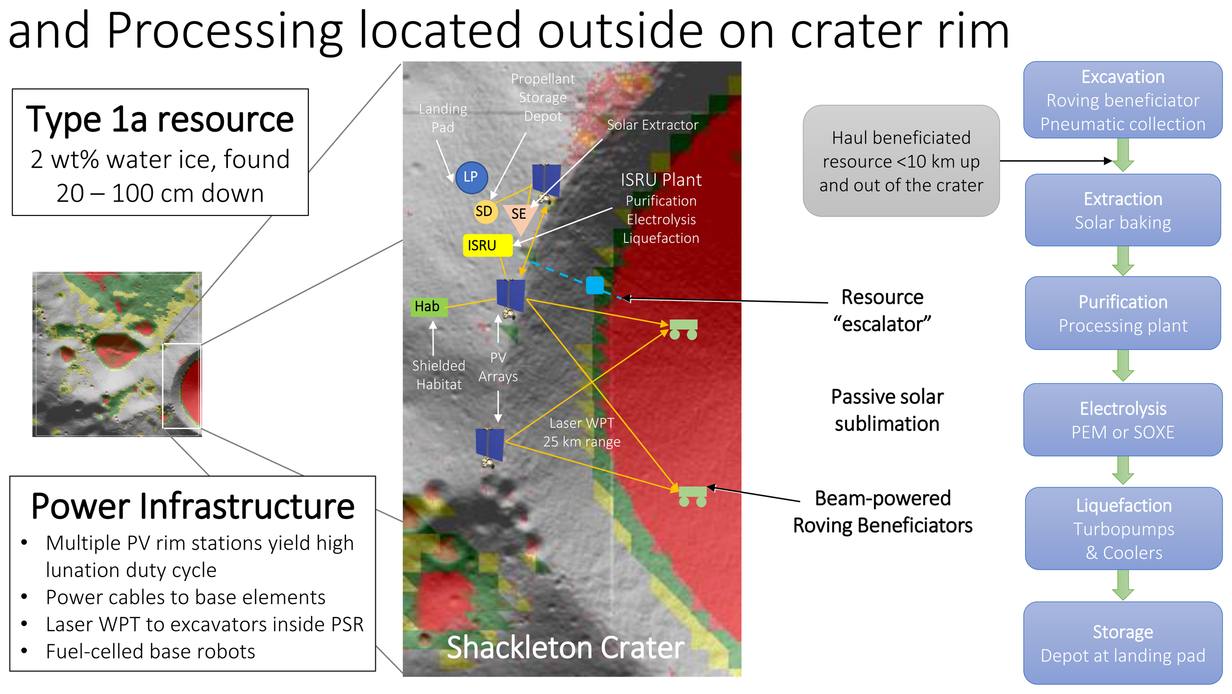
- Bin by water-stability depth into four terrain types
- Map areas that have 20-m DEM and high-res thermal models
- Illustrated: Hermite-A crater, lunar north pole

	Total Fractional Area (%)	Water concentration (wt%)	Depth beneath the surface (cm)	Water-containing column (cm)	Total water excavated (kg/m^3)	Extraction area for 10 t of water (m^2), @30% patchy
Type 1a PSR regolith	9	2	20-100	80	7.2	1,400
Type 1b PSR surface frost	9	100	0 - 0.002	0.002	0.006	> 1.5M
Type 2 PLR buried regolith	28	1	40-100	60	2.7	3,700
Type 3 PLR deeper regolith	7	0.5	60-100	40	0.9	12,000
Type 4 Lunation-lit regolith	56	0	--	0	0	n/a

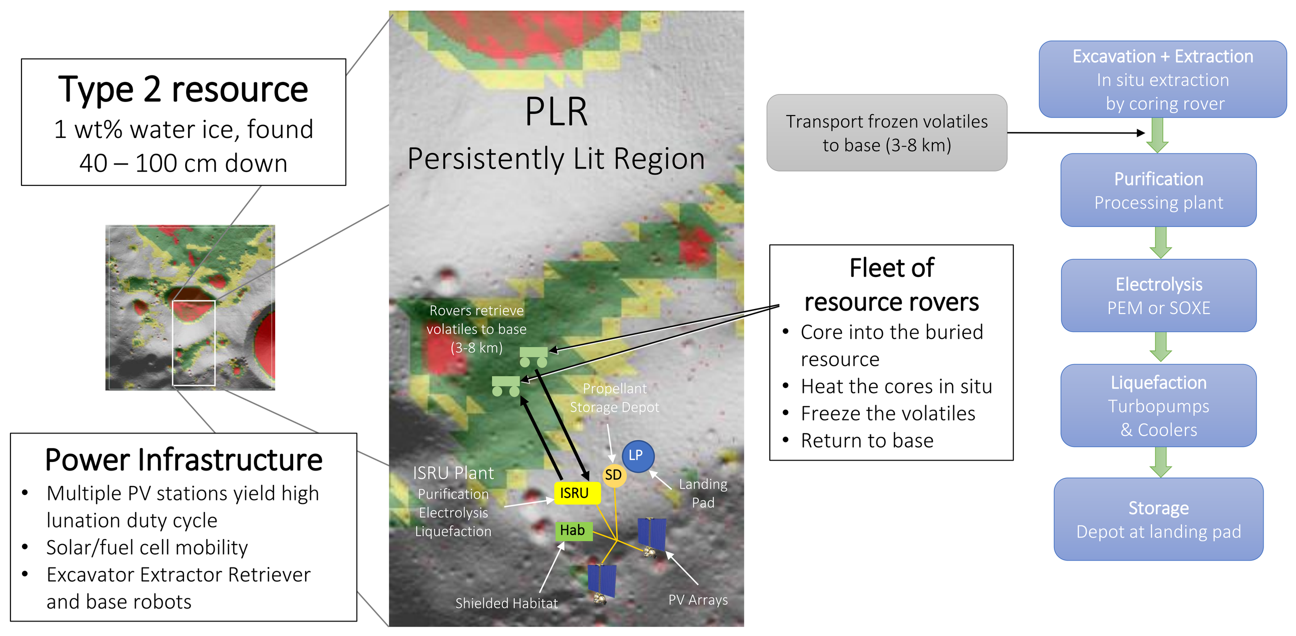
Option 1 would place resource collection and processing, and the Base directly in the PSR



Option 2 assumes excavation in the PSR, with Base and Processing located outside on crater rim



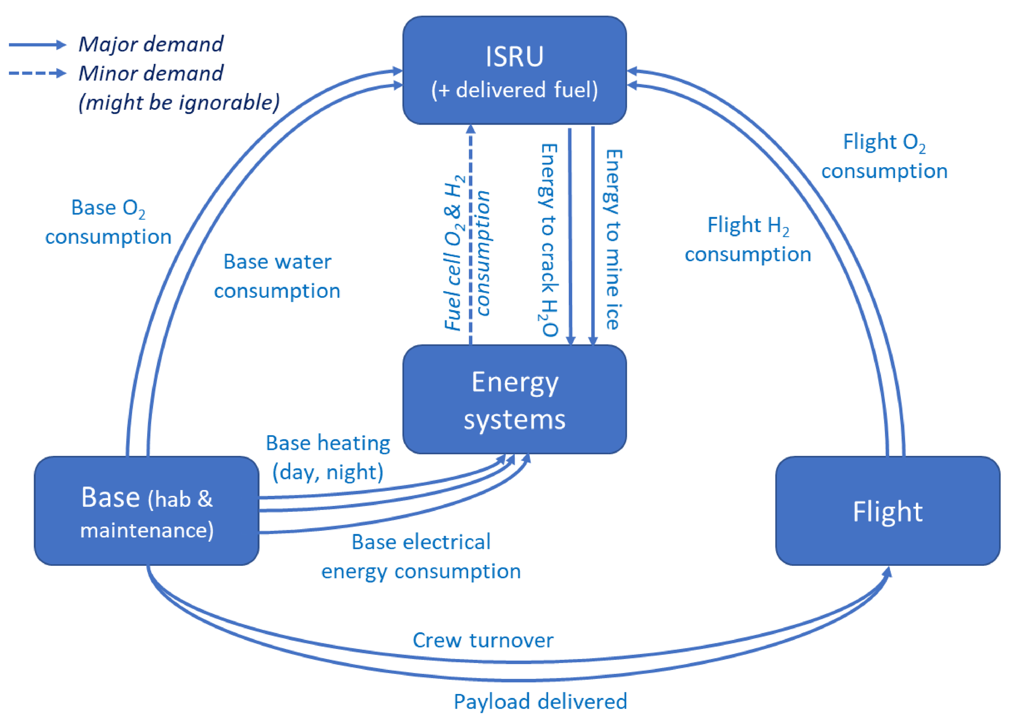
Option 3 Looks at gathering resources from Type 2 areas with Base and Processing located in PLR



Base Model in Development. Example Given for Base Power Trades

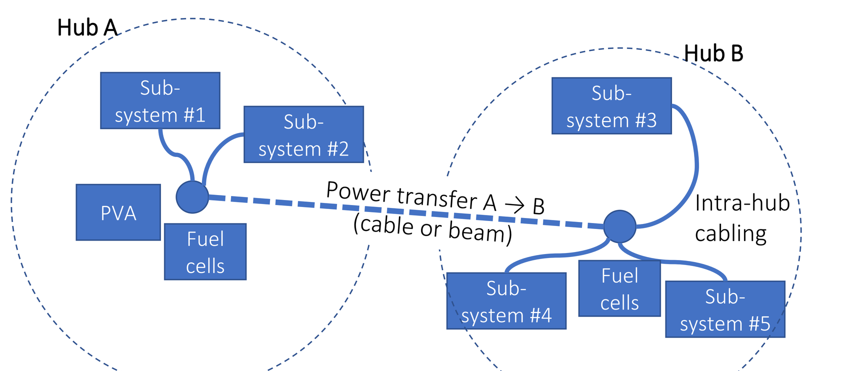
Overview of model – steady state system

- The integrated model seeks to gracefully handle the interconnected aspects of the lunar base in order to size the entire base system



Example energy system model shows basic energy production and distribution architecture

- Solar for primary production, fuel cells for mobile units and overnight



Constant	value	units
cable_resistance_per_length	3.71e-5	Ohms/m
cable_mass_per_length	2.0	kg/m
PVA_power_per_kg	47	W/kg
FC_energy_per_kg	300	Wh/kg
FC_recharge_efficiency	50%	%
mass_hub_with_beaming	500	kg
mass_hub_no_beaming	200	kg
beaming_efficiency	20%	%
local_transmission_volltage	240	V
AtoB_transmission_voltage	1000	V
power margin policy	30%	%

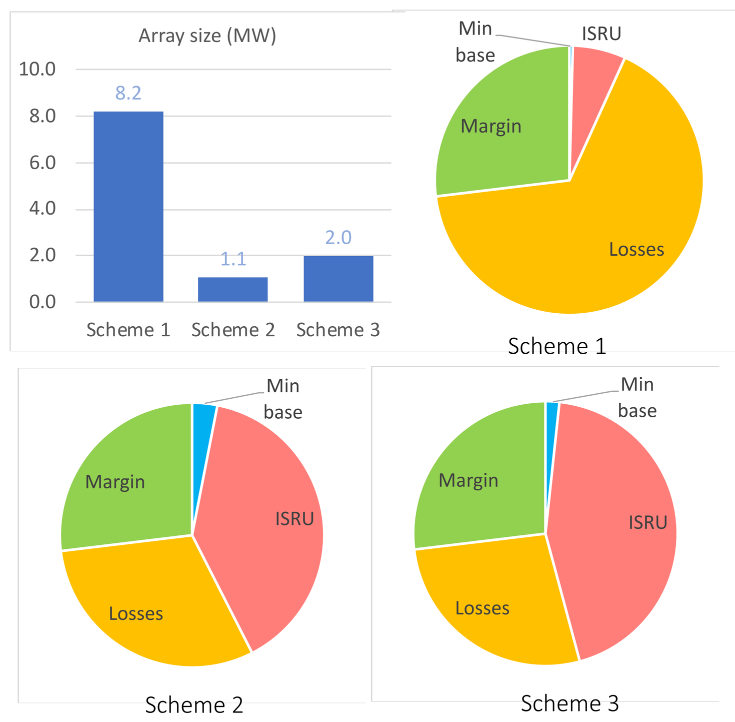
Architecture	PVA hub	Base hub	Mining hub	distance A->B (m)	power A->B	habitat cables (m)	flight cables (m)	ISRU cables at base (m)	ISRU cables at mine (m)	array <cosine>	Longest night (hrs)	Recharge time (hrs)	FC hub	FC Cables (m)
Scheme 1	A	B	B	10000	beam	50	200	100	0	0.95	350	720	B	200
Scheme 2	A	A	B	10000	beam	200	350	250	0	0.95	350	720	A	350
Scheme 3	A	B	B	3000	cable	50	200	100	0	0.95	350	720	B	200

"base" = habitat, flight, most ISRU processing; "mining" = excavation and any in situ processing

Preliminary results illustrate model output

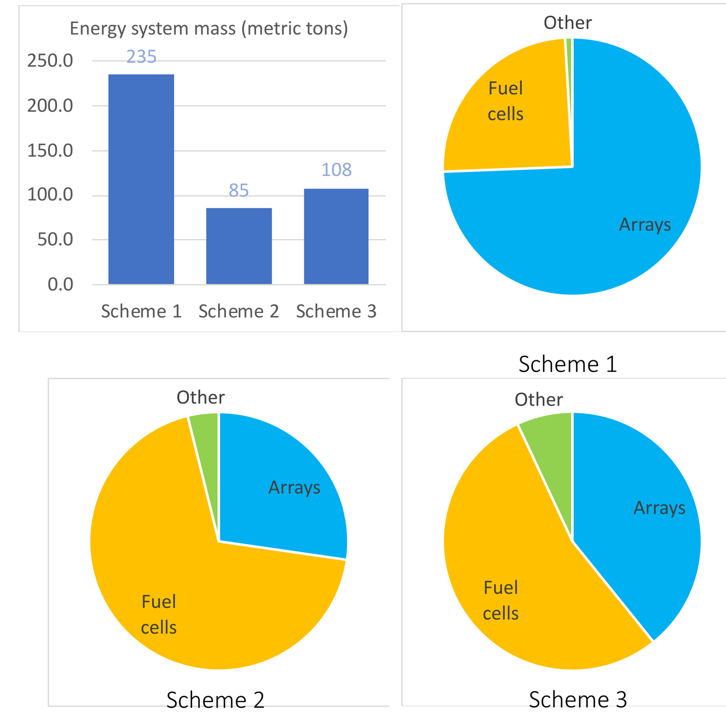
Array size

- Minimum base (habitat + flight) power need is approximately the same for each architecture
- ISRU dominates power need over minimum base
- Cable and beaming losses are a substantial fraction of the power budget in all cases
- Scheme 1 suffers significantly higher losses because the energy-expensive processing is a long way from the power source



Energy system mass

- Current assumptions require significant RFC mass to survive the longest night
- Scheme 1 has significantly more array mass due to beaming losses
- The increased mass for scheme 1 might be offset by savings elsewhere (e.g. transportation infrastructure)



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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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