CIVILIAN POWER FROM SPACE IN THE EARLY 21ST CENTURY: Technologies, Paths and Implications

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Opinions expressed herein are – at most – those of the authors only.
WHY-&-HOW DO YOU GET POWER-FROM-SPACE?

♦ WHY?
  – Because you don’t like getting it from terrestrial sources
    • Generation and/or transport ‘side-effects’ are deemed tedious
  – Because space-derived power looks more attractive
    • A presently-preferred profile of the various cost-types
      – “The grass is always greener…” syndrome?
  – There’s lots of it out there – and it’s all free, forever
    • We only use \(~10^{-4}\) of the sunlight falling right on the Earth

♦ HOW?
  – With a long extension cord – made of ‘jiggled ether’…
    • Electromagnetic radiation beams – shafts of polarized vacuum
  – …connecting Earthside loads to…
    • Power stations-in-Earth orbit!
      – Getting their energy from…
        • Nuclear (fission, now; fusion, later) reactors?
        • Solar photovoltaic arrays (PVAs)? [Peter Glaser, ~1978]
WHY NOT?

- After all, the basic idea’s a quarter-century old…
  …and we’ve been orbiting things for a half-century..
  …and technology has never been advancing faster…
  …and we’ve never been as wealthy as at present…

- **BUT** the proposed classic ‘first step’ is a dilly
  - $> 10 \text{ km}^2$ arrays of microwave radiators in GEO
  - $> 10 \text{ km}^2$ arrays of microwave rectennae Earthside
  - Multi-GWe stations are smallest-economically-practical
  - *Proponent*-estimated “switch-on cost” of $N \times 10^{10}$, $N \gg 1$
    - These are “Only really big-&-rich governments need apply” scales

- U.S. Government becomes ever-more-modest about its abilities to **accomplish** any big new things in space
  - “He’s a modest man, with much to be modest about.”

- Thus, ~25 years later, this remains “a bridge too far”
  - No key feature is becoming easier, cheaper, safer,…
WHAT’S TO BE DONE?

- Replace the thus-far-show-stopping features
  - Systematically re-engineer all problematic features
  - Too big-&-costly? Trim by required factors!
    - E.g., by invoking physics-&-technology alternatives
    - E.g., by leveraging new, mass-market technologies
      - E.g., GPS, Internet/GDN, automated transaction-clearing,…
  - USG hesitancy? Make attractive to private sector!
    - Has to happen eventually (at least in the U.S.A.)
      - USG didn’t elect to pursue the TVA & BPA models
        - Current policy-trend is to fully-liberalize energy markets
          - Why not sooner-than-later?
  - Figure out if the ‘minimum Governmental lead-in’ can be stretched to meet what the USG may do anyway
    - E.g., can technology-legacies of mil-space efforts be re-engineered to “do the job” re power-station-prototyping?
    - Can future USG requirements be met with space power station capabilities to telling extents?
      - USG as ‘anchor tenant’ of nascent space power station(s) or ‘salvage buyer’ of their (surplus) outputs?
HOW’S THIS TO BE DONE? I.

- Modernize PVA choice: Slash prime-mover’s mass
  - *Mass*-in-space is *cost*-in-space, for very nearly everything
  - Crystalline Si was baselined – “That was then;…”
    - 4-mil slabs – 100 µm thickness of Si
  - But now-COTS a-Si is *far* more mass- (hence cost-)efficient
    - 0.3 µm a-Si, on 5 µm plastic-film (40X lower areal mass)
      - a-Si is now the Earthside *market*-dominating COTS solar PVA technology
    - >0.5 the sunlight-to-DC conversion efficiency:>20X power-to-mass
      - Space-performance-proven on MIR’s *Kvant* module, for 18 months
    - Mass- & dollar-budget-gains are of *logjam-breaking magnitudes*

- Shrink the transmitter/receiver sizes – *drastically*
  - Chop projected beam’s wavelength: the *only* (physics) alternative
    - Go from *λ* of 2-12 cm (µwave) to <0.0001 cm (near-optical)
  - T/R antennae areas *each* shrink by *λ*-ratio: ~10⁵ X (!!!)
    - 10 square kilometers ⇒ 100 square meters (if T&R are symmetric)
    - Pick in-GEO transmitter area of 10,000 m²: receiver’s is ~1 m² (!!)
  - Improvements in T/R areas are of *fundamental* importance
    - Associated cost reductions are crucial enough
    - But scale-size reduction is enabling for getting *there* from *here!*
HOW’S THIS TO BE DONE? II.

♦ Issues-&-alternatives

– Minimize power-station’s $/W: the fundamental FoM
  • Optical-vs.-μwave ~ 2X inferiority in DC ⇒ AC is minor concern
  • More than offset by
    – a-Si’s >20X advantage in power/mass efficiency
    – Huge T/R area-reductions enabled by optical waveband transmission

– Minimize the initial power-station size
  • Big beam-projectors are ~ N meters diameter, N the transmitter-receiver range in thousands of km
    – 1-2 meters is the practical range for LEO power stations
  • Thus may have LEO constellations of sub-tonne power-stations

– Generate and project optical-wavelength photon beams
  • Use laser diodes to optically pump fiber-lasers
    – Leverages 2 decades’ advances in huge telecommunications tech-base
    – Allows areally-distributed (not point-concentrated) entropy rejection
  • Use large-area Fresnel lens main beam-projectors
    – Low areal-mass technology: Lens is thin, flat, polyimide film
      • ~10 gm/m² asymptotic mass-budgets
    – Far looser tolerances than reflectors: e.g., tolerates ~10⁴X surface errors
HOW’S THIS TO BE DONE? III.

- Issues-&-alternatives, cont’d
  - (Finely) partition the power station’s transmitted beam
    - Radiate many lower-beams through one shared primary projector
      - More leveraging of far-shorter transmission wavelength
      - Servicing many small customers, rather than just one mega-customer
    - Readily done: PVA’s optical fiber ‘power-harvesting’ network
  - Send these myriad beams in different directions all over the field-of-regard, each to a distinct Earthside receiver
    - Thereby servicing a continent-sized area of receivers…
      - Eliminating all transmission and distribution costs of POES (cf. ‘POTS’)
    - ..at different power levels, for different dwell-durations,…
      - Leveraging the differentially-pumped laser-diode modules on PVA…
      - …as well as individually-steered beamlet-lensette modules in the focal plane of the station’s primary projector
    - ~3-30X sunlight intensities likely hit ‘sweet spot’ of mass markets
      - ~2.5-25 kWe/m² of customer’s receiver (≥60% receive-efficiency)
    - Beams’ ‘soft edges’ and real-time closed power-loops assure safety
      - Beams’ perimeter intensity-meters & ‘coding’ foil defeat-attempts
  - ..energizing myriad loads, just-as-ordered: **spacetime beam-agility**
    - Purchasing done in real-time, via the Internet/Global Digital Network
      - Tiny comm-&-Xaction costs: c < $10⁻¹⁰/bit, world-wide; -c’>2X/yr.
    - To GPS-cued \{x,v,a,θ,ϕ\} precision locations/motions/orientations
      - Thus enabling precision servicing of moving customer-receivers
      - *No* major prime mover-type goes unserviced by space powerbeams!
Typical Values

\[ \lambda: \quad 0.0000008 \text{ m} \]
\[ R: \quad 4,000,000 \text{ m} \]
\[ L: \quad 35,000,000 \text{ m} \]
\[ D_T: \quad 300 \text{ m} \]
\[ D_R: \quad 0.4 \text{ m} \]
\[ \text{F.L.:} \quad 3,000 \text{ m} \]

\[ D_T D_R \geq 4 \lambda L \]
\[ A_T A_R \geq \pi^2 \lambda^2 L^2 \]
\[ R \sim 0.1 L \]
\[ \frac{r}{R} = \frac{\text{F.L.}}{L} \]
HOW’S THIS TO BE DONE? IV.

† Issues-&-alternatives, cont’d.
  – Leverage upcoming advances in space-transport costs
    • ‘Space tugs’ using big solar PVAs and COTS plasma-jet engines
      – ‘Motor around’ cislunar space at milligee acceleration-levels
        • “From anywhere to anywhere” in a matter of weeks
    • No more expensive to transit from Earthside-to-GEO than from Earthside-to-LEO
      – ‘Overhead’: 5-10% of payload mass, used as 7000-3500 sec $I_{sp}$ jet-mass
      – Vs. ~3-4X more expensive ‘classically’: GTO-insertion-&-apogee-kick
    • Big economic ‘win’
      – On top of ~2X gain in costs-to-LEO (current space-launch ‘glut’)
  – Maximize use of lunar materials-as-available
    • Likely 3-10X cheaper-in-GEO than Earth-sourced equivalents
      – For Mg, Al, Si, Ti, Fe – and O; possibly for H, C & N, as well
    • Feedstocks for in-orbit robotic manufacturing plants
      – E.g., for making PVAs; low-fractional-mass ‘smarts’ come up from Earthside
WHY NOT PROCEED? I.

- Economics are daunting
  - Start-up ones are completely show-stopping
    • Huge amounts of technology development/demonstration required
    • USG is only likely performer
      – But may well perform, for its own purposes, in the coming decade
  - Initial system economics are sharply challenging
    • Market-required ROIs are huge: 30-40% per annum
      – Risk discounts are necessarily huge
    • Limits on initial capital investment dictates system/orbital design
      – Place power-stations in LEO, not GEO
        • Shorter range permits smaller, 1st-generation transmitters
        • Need constellation of power-stations to assure customer coverage
      – Start with small (sub-tonne) power-stations: Servicing few customers
        • More (or larger) power-stations are added as customer-base grows
  - Full-sized, mature system economics ‘look sweet’
    • But so did the “square miles of microwave antennae” ones
    • Maturity and scale advantages are huge
      – Customers are ‘always there’
      – Capital market-required ROIs are down to ~10-15% per year
  - Crucial issue: how to survive ‘infant’ & ‘youth’ periods
    • It’s simply idle to “wish them away”
    • Must be able to survive ‘birth’ and bootstrap up to ‘adulthood’
WHY NOT PROCEED? II.

- Meteorology?
  - Water droplets (fog, clouds, rain) get in the beam’s way
    - All beam-types; some suffer more than others…
  - Classic responses
    - Beam-around patchy obscuration (many stations in all skies)
    - Punch-through thin, wall-to-wall obscuration ($\tau \leq 3$)
    - Work-around really thick, wall-to-wall stuff (ground reserves)
      - Thunderstorm-centers: ~10 hours/year, in most (U.S.) places
      - Live with such outages: Like ‘standard’ electrical utilities do
        - E.g., rely on Earthside ‘baseload’ system, via price-rationing

- Safety?
  - Ground-level issues
    - Injuries precluded by intensity-sensors on receivers’ perimeters
      - Leveraging physics features of beams’ “soft edges”
      - Receiver’s computer must be ‘happy’ at all times, re all conditions
        - Ditto for power-station’s computer, re each-&-every powerbeam
        - Receiver must ‘echo unknown song’ encoded on its power-beam to the power-station, continually – or the beam goes off instantly
      - System fails-safe by design if beam-control loop isn’t actively closed
        - E.g., any comm failure cuts beam’s power at lightspeed: 0.2 sec.
  - Issues at altitude
    - Injuries precluded by varying-intensity sensors at beam’s receiver
      - ‘Fast flyers’ pass through highest-intensity beams ‘without knowing it’
      - Birds not burned by any time-intensity flight-history
**EXEMPLARY SYSTEMS**

- **Near-term (first-generation)**
  - Customers
    - Small set (100s at any time) willing to pay premium (~$10/kW-hr)
    - Each needs small (≤10 kW) amounts of power, but located far off-grid
  - LEO-based system
    - Short-range dictated by use of small (~2 meter) beam-projectors
    - LEO constellation of ~250 power-stations
      - Each uses 50 kWe from 300 m² PVAs to project single 20 kW beams
      - Constellation of ~80 kg power-stations launched on single EELV
  - Economics
    - Deliver 0.62 MWe at ~$10/kW-hr: generate ~$55 M/yr. of revenue
    - 30% annual return on $180 M investment ($90 M launch; $90 M fab)

- **Far-term (a few decades out)**
  - Customers
    - Large set (50 M) paying low rates (~$0.05/kW-hr)
    - Need small (~10 kW) amounts of power, delivered wherever they are
  - GEO-based system
    - Long-range demands use of large (~300 meter) beam-projector
    - Constellation of ~1000 power-stations to service a continent
      - Each uses 5 GWe, 20 km² PVAs to project many beams (~50,000 @ 40 kW each)
      - Each station has ~1500 ton (mostly PVA) mass; ~90% from lunar materials
  - Economics
    - Each station delivers 1 GWe at $0.05/kW-hr: ~300 M$/yr of net revenue
    - 15% annual return on $2 B investment ($0.5 B launch; $1.5 B fab)
SUMMARY

- **Big** changes are required, in order to ‘move out’ on large-scale power supply from space
  - Basic challenge is economic: must make commercial sense
    - Eventual, mature system-set looks great
      - Provides non-hydrocarbon-based energy from GEO directly to users
        - Wherewhen & as-much-as desired: ubiquitous utility-grade power
      - Economically viable: Service large, non-baseload market
        - Locally-delivered (mobile!) energy commands price-premium
        - Mature systems/technologies attract low ROI-demanding investors
    - Getting **there** from **here** (i.e., zero) remains the crucial challenge
      - First-step capital-investment must be affordable: 10s of B$ are not!
      - New system/technology is risky: investors always demand high ROIs
      - Start by servicing small set of high $/kW-hr customers; then bootstrap up

- Recent technology advances offer titanic leverage, e.g.,
  - High W/gm a-Si PVAs: greatly cuts system mass (cost)
    - Allows system to sell power at economically-viable $/kW-hr
  - Optical power transmission: drastically cuts T/R sizes
    - Allows smaller-scale power-stations (cutting initial investments)
    - Allows sales to small (mobile!) end-users: not just mega-users

- Near-term USG programs **may** provide crucial tech-bases
  - In-space tech-demos/uses; technology legacies “for free”?

- Hydrocarbon energy economy **may** recede ‘naturally’
  - *Technology-enabled market forces* – vs. government decrees