Unorthodox and Exciting Applications of Solar Energy Research

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1) Solar-driven synthesis of novel nano-materials
2) Ultra-high algal bioproductivity
3) Solar electricity for private commercial space missions
Solar Paradigms: Mature, affordable, large-scale (GW)

1) **Solar thermal** for *electricity* production.
Concentrate sunlight → generate steam → drive turbines.

Yearly-average conversion efficiency ≈ 16%
Admits gas backup heating *and* thermal storage
   (temperatures of 350-550°C) → dispatchability
Avoided capacity for utilities— not just energy savings

2) **Photovoltaics**: Direct conversion to electricity
Mainly Silicon technology.
Inexpensive, ~20% efficient *modules*.
Stable, robust, modular, growing rapidly.
But electrical storage technologies are (still) inadequate.

Today we’ll be exploring novel, unorthodox uses of solar energy:
Aspiring to futuristic applications rather than just implementing mature technologies.
Blaustein Institutes for Desert Research: An interdisciplinary Faculty in desert science, exploring fundamental and applied scientific issues (founded 1977)
David Ben-Gurion, Israel’s founding premier, deeply appreciated the importance of excellence in academia.
Maps drawn to same scale.
1) A new and distinct solar paradigm:

Synthesizing singular nanomaterials at the service of human technology, via concentrated solar (instead of using solar to supply heat, electricity or fuels)

Examples: \( \text{MoS}_2, \text{Cs}_2\text{O}, \text{SiO}_2, \text{SiC}, \text{WS}_2, \text{WSe}_2, \text{MoSe}_2 \)

Practical motivation: Remarkable lubricating, optical, thermal, catalytic, electronic or adhesive properties

In collaboration with Reshef Tenne’s group at the Weizmann Institute (Rehovot, Israel)

Our BGU group: Daniel Feuermann, Eugene A. Katz, JG

Advantages relative to the key alternatives of pulsed laser ablation and chemical vapor deposition:

1. Safer (no toxic reagents)
2. Far faster (minutes rather than hours)
3. Scalable – hence the potential of commercialization
R. Tenne (1992): Fullerene-like and nanotube structures should not be restricted to Carbon: they should be realizable from layered compounds, e.g., MoS$_2$, MoSe$_2$, WS$_2$, WSe$_2$, GaS, ... (and none of their nano-structures, so far, appear to pose occupational health hazards).

Sobering realities:

a) Carbon nanotubes were found to be carcinogenic to humans

b) No rational synthesis found for C$_{60}$ - only by arc-discharge chambers → exorbitant costs, problematic scalability
Examples of layered materials:

Strong in-plane covalent bonds ↔ but weak inter-layer van der Waals bonds
Chronological promenade through our solar concentrators

Generation 1: Solar fiber-optic mini-dish

Target irradiance $\approx 4,000$ suns

$D_{\text{aperture}} = 200\, \text{mm}$

Optical fiber core diameter $= 1.0\, \text{mm}$

1st effort: Cs$_2$O - used to tailor photo-detector and photo-emitter coatings, but violently reactive upon exposure to air $\rightarrow$ expensive photonic-device preparation

Fullerene-like nano-structures (if producible) should mitigate that reactivity.
Inexpensive, photo-thermal process for synthesizing fullerene-like Cs$_2$O with concentrated sunlight: confirmed with materials characterization tools: TEM, High-Resolution TEM, Energy Dispersive x-ray Spectroscopy (EDS), Electron Energy Loss Spectroscopy (EELS) and stable upon exposure to air

WIS + BGU teams, *Advanced Materials* 18, 2993-2996
SiO$_2$ nanofibers and nanospheres (for the nano-photonics industry)

First production of SiO$_2$ nanostructures directly from (pure) quartz

Apparent key to success: creating a naturally ultra-hot, continuous, extensive annealing region conducive to the requisite molecular rearrangements
Pure Silicon nanorods and nanofibers, from pure SiO: \[ 2 \text{SiO} \rightarrow \text{Si} + \text{SiO}_2 \]
Generation 2: solar furnace that can attain $\sim 15,000$ suns

Higher temperatures permit access to more metastable (and hence more remarkable) nanostructures
Nature’s true inorganic fullerenes: MoS$_2$ nano-octahedra, the basic smallness limit

Previously found: far larger, hollow, multi-wall, quasi-spherical MoS$_2$

Practicality: super-lubricant and super-catalyst (but yields were sparse)

Can *hybrid* nano-structures (nano-octahedral core and quasi-spherical shells) exist?

**Motivation:** simultaneous presence of *both* metallic (nano-octahedra) *and* semi-conducting (quasi-spherical structure) properties in a *single* nano-particle.

The question had never been asked, and no experimental results had ever shown this, until ...

Deciphering reaction pathways via irradiation of variable duration ("snapshots")
30,000-sun solar furnace

$D_{\text{aperture}} = 508 \text{ mm}$

Highest measured solar concentration (in air/vacuum) to date

Rapid, high-yield, safe synthesis of SiC nanowires

*Nanotechnology* 24, 335603

In progress: Graphene in *high yield.*
Boron nitride (BN) fullerenes (nano-onions)
Aim: Dramatic increases in algal bioproductivity.

New predictive capability now *confirmed experimentally*.

Strategy: Find the optimal synchronization of (1) biological, and (2) photonic time scales.

Do algae have a built-in potential for far higher bioproductivity than found in nature?

*Key degree of freedom: light-dark cycles – prior studies were plagued by misguided choices*

Ultra-high bioproductivity from algae
(Collaboration: Yair Zarmi of our department, Reliance Industries Ltd., Mumbai, India)
What are the key rate-limiting processes for bioproductivity?
How simple a biophysical picture can suffice?
A physicist’s approach:

minimum complexity and maximum physical insight

Assume a spherical cow of uniform density.
1 photon → 1 electron (very short time scale)

2 photons are needed to produce 1 PQ

→ pivotal role of photon arrival statistics

If the PQ pool is full and photons keep generating PQs, then “clogging” occurs (a waste of photonic input).

Motivates synchronizing pulsed light input to surmount the bottleneck.
Let’s make a coarse prediction based on simple photon arithmetic:

Rate of photon input = (intensity $I$) $\times$ (antenna cross-section $A$)

e.g., $A \approx 1 \text{ nm}^2$ and $I = 1,000 \ \mu\text{mol}/(\text{s-m}^2) \rightarrow 600 \ \text{photons/s}$

For perspective: peak solar input $\approx 2,000 \ \mu\text{mol}/(\text{s-m}^2)$

(referring to Photosynthetically Active Radiation, PAR, only)

2 photons are needed to generate 1 PQ $\rightarrow$ 1 PQ generated every 3.3 ms

For continuous irradiation: With a “crossing time” of $\sim 10$ ms, only 1 PQ can be harvested every 10 ms.
But there are 3 PQs generated every 10 ms → potential improvement of ~3X if we apply judicious light pulsing (at this particular light intensity).

Let’s try: a 10 ms pulse at $I = 1,000 \mu\text{mol/(s-m}^2\text{)}$, which generates 3 PQs (PQ pool capacity $\approx 7$), after which we provide a longer dark time to harvest them → ~3X in photon efficiency.

Now, let’s do the experiments (at Reliance Industries Ltd, India)
Dark time = 0 means continuous irradiation

Specific growth rate per photon normalized to continuous irradiation

$t_{\text{irradiation}} = 10 \text{ ms}$

Light intensity = $1,000 \ \mu\text{mol}/(\text{s-m}^2)$

~3-3.5X
and basic photon statistics predict how this enhancement lessens with light intensity (consistent with the data)

Specific growth rate (per photon) as a function of light intensity (white LEDs):
(a) continuous irradiation, (b) 300 ms cycle with $t_{\text{irradiation}} = 10$ ms, $t_{\text{dark}} = 290$ ms
Basic prediction: For continuous irradiation, at what intensity should bioproductivity “saturate”?

Do the arithmetic based on “clogging” of the PQ channel → ~330 μmol/(s-m²).

And then do the experiment:

![Graph showing specific rate vs. light intensity](image-url)
The ~3X enhancement is in photon efficiency.

But the longer dark time means time-averaged bioproductivity is low.

How do we translate this advance into a 3X enhancement in bioproductivity?

Two pathways: (1) Outdoor solar reactors – via innovative opto-mechanics
(2) Indoor pulsed-LED systems - decoupling solar and photon delivery, and we can tailor spectrum, intensity and pulsing protocols (a proposal that is rational provided the electricity comes from renewables, e.g., solar, wind, hydroelectric)

• Challenges and realizations reserved for our future reunions.

Exciting prospect/prediction: Higher light intensity and/or longer pulse time could yield photon-efficiency enhancements exceeding 10X.

• Latest update: experimental evidence of the 10X improvement!
Payoffs:

• Hundreds of percent higher bioproductivity.

• With LEDs: Indoors, avoid contamination, 24 hr/day, control: spectrum (more efficient with red LEDs), intensity, pulse times and temperature.

• Much smaller footprint for vertical reactors.

• Scalable

• Direct adaptability to products more lucrative than biofuels, e.g., antibody generation / pharmaceuticals.
Explosive growth of *private, commercial* space missions.

Dramatically alters specs for on-board solar electricity generation

Creates the need for novel concentrators and solar cells. Why?

Military and government space programs: Cost is no object.

Private space vehicles: Cost is paramount (subject to reliability).

PV cells on past satellites were ultra-efficient but ultra-expensive

Concentrating (by ~100 X) vastly diminishes the photovoltaic (PV) contribution to system cost: replacing 99% of exorbitant PVs by inexpensive optics.

**Our program:** In collaboration with Penn State U. and the U.S. Air Force
A few examples of the private commercial companies involved:

- SpaceX
- Boeing
- Blue Origin
- Rocket Lab
- Orbital Sciences
- Sierra Nevada Corp.
- Virgin Galactic
- XCOR Aerospace
- Made in Space
- Ad Astra Rocket
- Planetary Resources
- ARCA Space
- OneSpace
- PLD Space
- Nanoracks ...

Market for on-board solar electricity production:

~10 MW today.

At ~US$100/W (in space) → one billion US$

(and projected to increase rapidly with time).
Launch costs are falling rapidly

→ solar power is a sizable fraction of satellite cost

→ $/W becomes pivotal

→ affordable max. specific power (W/kg) is crucial: room for improvement relative to today’s best solutions >4X (via innovative optics)

3-pronged strategy beyond the basic virtue of concentration:

(a) Benefit from the PV efficiency boost at high concentration

(measured)
3-pronged strategy beyond the basic virtue of concentration:

(b) Reduce PV cells to sub-mm dimensions (system volume $\propto L^3$), and hence shrink the concentrator to mm dimensions.
3-pronged strategy beyond the basic virtue of concentration:

(c) Advanced multi-junction PV cells exploit the full solar spectrum

5-junction cells now in fabrication

Near-term aim: 50% efficiency under concentration

Full experimental characterization scheduled in our BGU solar lab → results will guide the next generations of suitable PV cells
Concentration requires accurate tracking: always aimed at the sun.

Laws of optics $\rightarrow$ basic relation between max. concentration $C$ and optical tolerance angle $\theta$ (max. permitted misalignment): $\theta \propto 1/\sqrt{C}$

Quantify: $\theta = \pm 5^\circ$ is achievable and realistic for private satellites (USAF tests) $\rightarrow$ feasible concentration $C \leq 100$

These are new, demanding constraints

very low mass – ultra-high efficiency – high tolerance

for designing suitable optics.
Our 1st prototype: Simple optic for 0.65 $\times$ 0.65 mm$^2$ cells.

Each hexagon’s diagonal = 5 mm.

The 10 black hexagons have the solar cell installed.
Challenges in highly-constrained optical design

Example of an ultra-compact glass-filled, dual-mirror concentrator

Why glass-filled? (1) attainable optical tolerance $\propto$ refractive index (1.5 for glass) (2) ease of fabrication and internal alignment by glass molding
Second generation: accommodate a “fail-safe” option

Ability to provide some power (affordably) even if solar aiming fails

Highly challenging: optics that are both compact and high-performance for the fail-safe option.
Key value for distant missions (e.g., Jupiter, Saturn):
Concentration compensates for poor cell performance at low irradiance

Earth: 1 A.U.  
Jupiter: 5.2 A.U.  
Saturn: 9.5 A.U.

Irradiance $\propto \frac{1}{(\text{distance})^2}$  
Jupiter: 0.037 (1/27)  
Saturn: 0.011 (1/90)

Concentration of $\sim$100 “restores” efficiency losses inherent to low irradiance.
Australian Space Agency – established 1 July 2018

Launch center: RAAF Woomera Range Complex (latitude = 31°S)

“... engaging with companies nationwide ... already signed Strategic Statements of Intent and Cooperation with 3 industry partners, all with investments in South Australia, including Airbus, Sitael and Nova Systems. Fleet Space Technologies and Myriota, both South-Australian start-ups, have launched satellites and a payload that can help farmers and other industries.”
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