From Nano to Impact: Designing Materials Across Scales

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ELECTRO INTRUSION

Workshop on Nanostructured Materials and Quantum Technologies

European Innovation Council

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FERRARIAE UNIVERSITAS 13 91 EX LABORE FRUCTUS

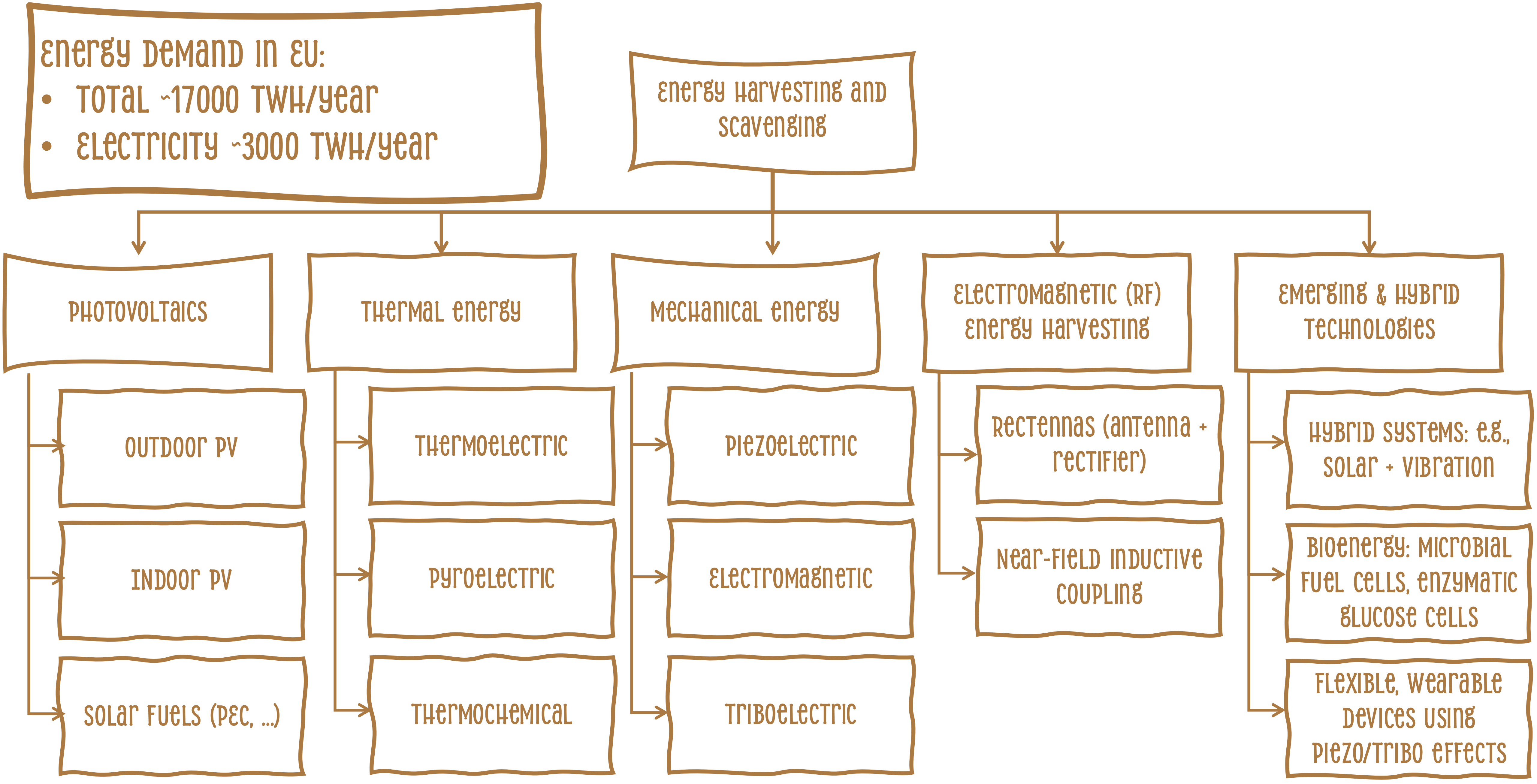
Taxonomy of Energy Harvesting and Scavenging

Energy demand in EU:

- Total ~17000 TWh/year
- Electricity ~3000 TWh/year

Sector	Share of Total Energy	Notes
Industry	~25%	High thermal demand (process heat)
Transport	~30%	Mostly fossil fuels, growing EV share
Residential	~25%	Heating, cooling, appliances
Commercial/Public	~10%	Offices, services
Agriculture	~5%	Machinery, heating, drying

Taxonomy of Energy Harvesting and Scavenging



Solar (Photovoltaic) Energy Harvesting

Electricity demand in EU ~3000 TWh/year

Mechanism:

- Converts light (usually sunlight) into electricity using photovoltaic (PV) cells.

Technologies:

- **Crystalline Silicon PV** – High efficiency, widely used.
- **Thin-Film PV** – Lightweight, flexible, lower efficiency.
- **Organic & Perovskite PV** – Emerging materials for wearables and indoor use.

Pros:

- High energy density in sunlight.
- Mature technology with scalable manufacturing.

Cons:

- Dependent on light availability.
- Efficiency drops indoors or in shaded environments.

Applications:

- Outdoor sensors, solar-powered wearables, building-integrated photovoltaics.

Alternative ways to store solar energy

- Solar fuels (PEC and more)

Energy harvesting/scavenging opportunities: PV

Electricity demand in EU ~3000 TWh/year

1. Rooftop Potential

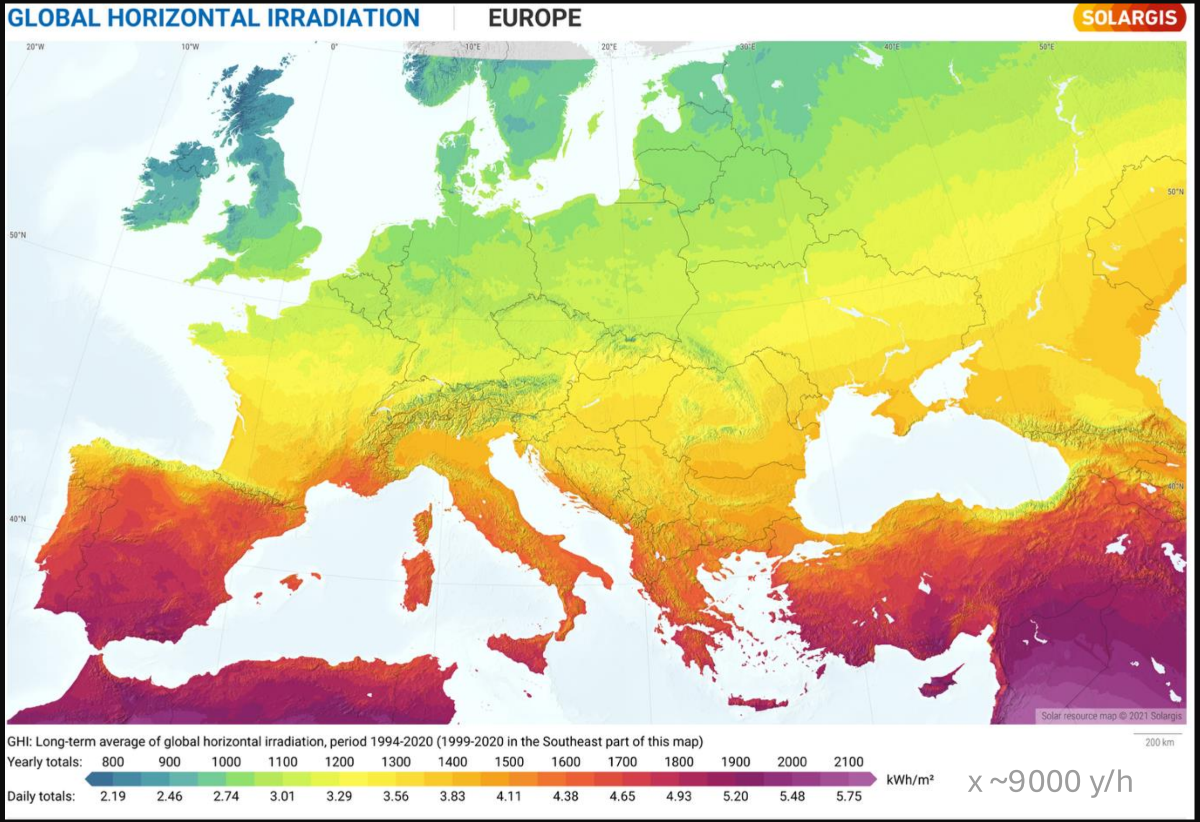
- EU rooftops alone could host **up to 1,000 GW** of solar capacity.
- That's **~5,000–6,500 km^2** of panels, > **0.15%** of EU.

2. Agrivoltaics & Dual Use

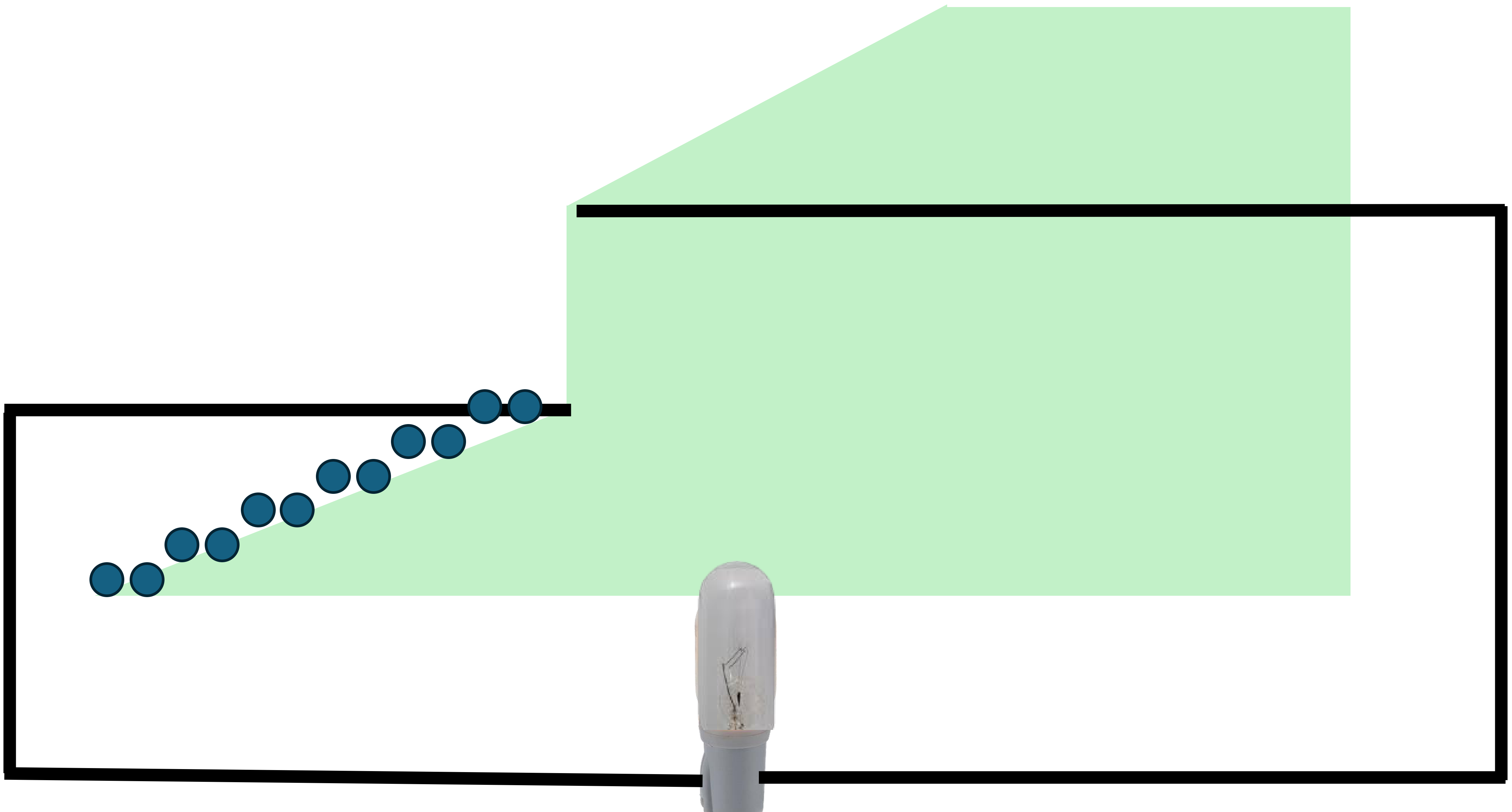
- Farmland with elevated panels: crops + energy co-production.
- Could > **100 GW** without displacing agriculture.

3. Brownfields & Infrastructure

- Solar on highways, rail corridors, parking lots, and industrial zones.
- Adds capacity without competing for pristine land.



Quantum Cartoon: I principi del fotovoltaico



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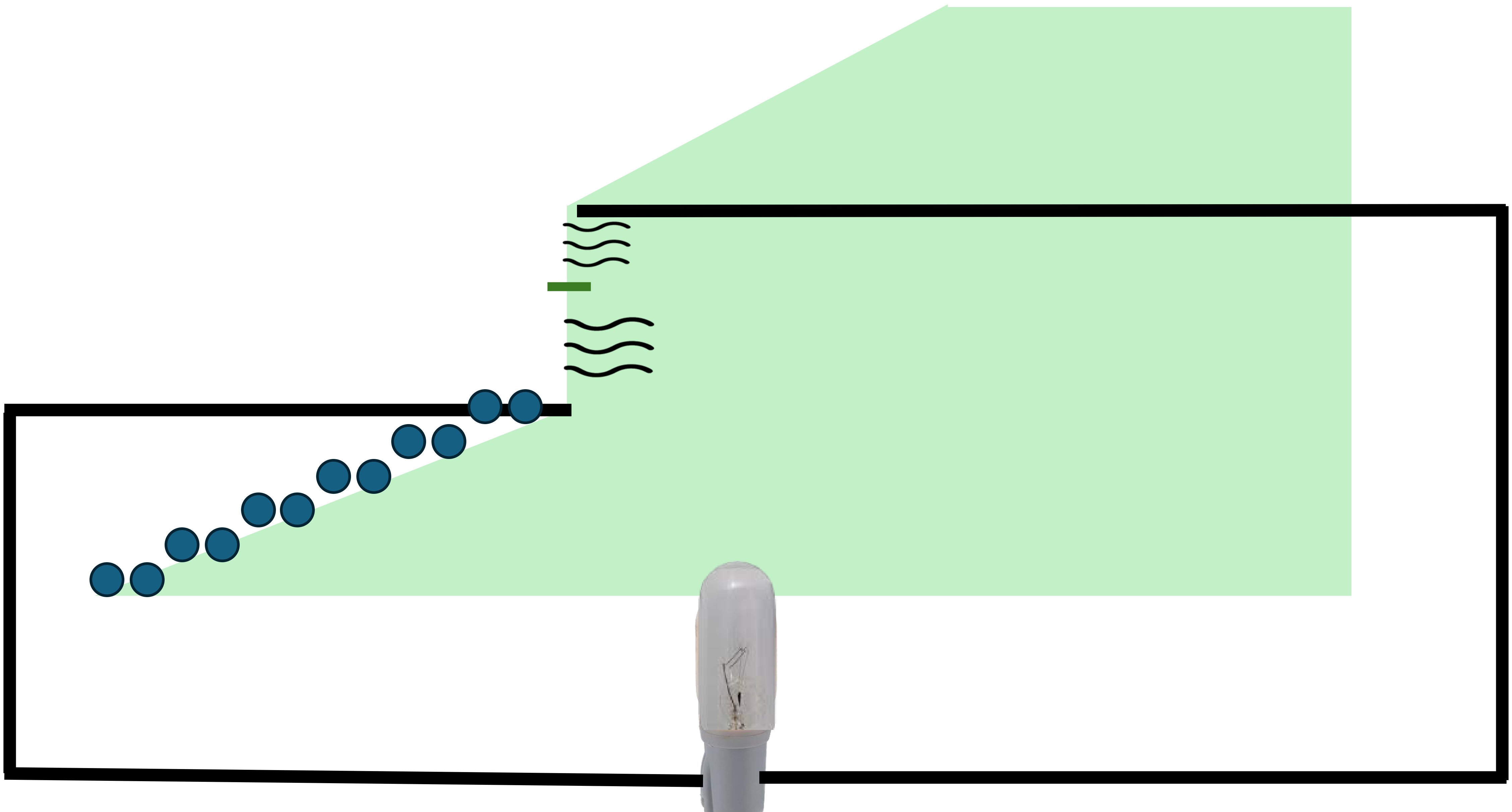
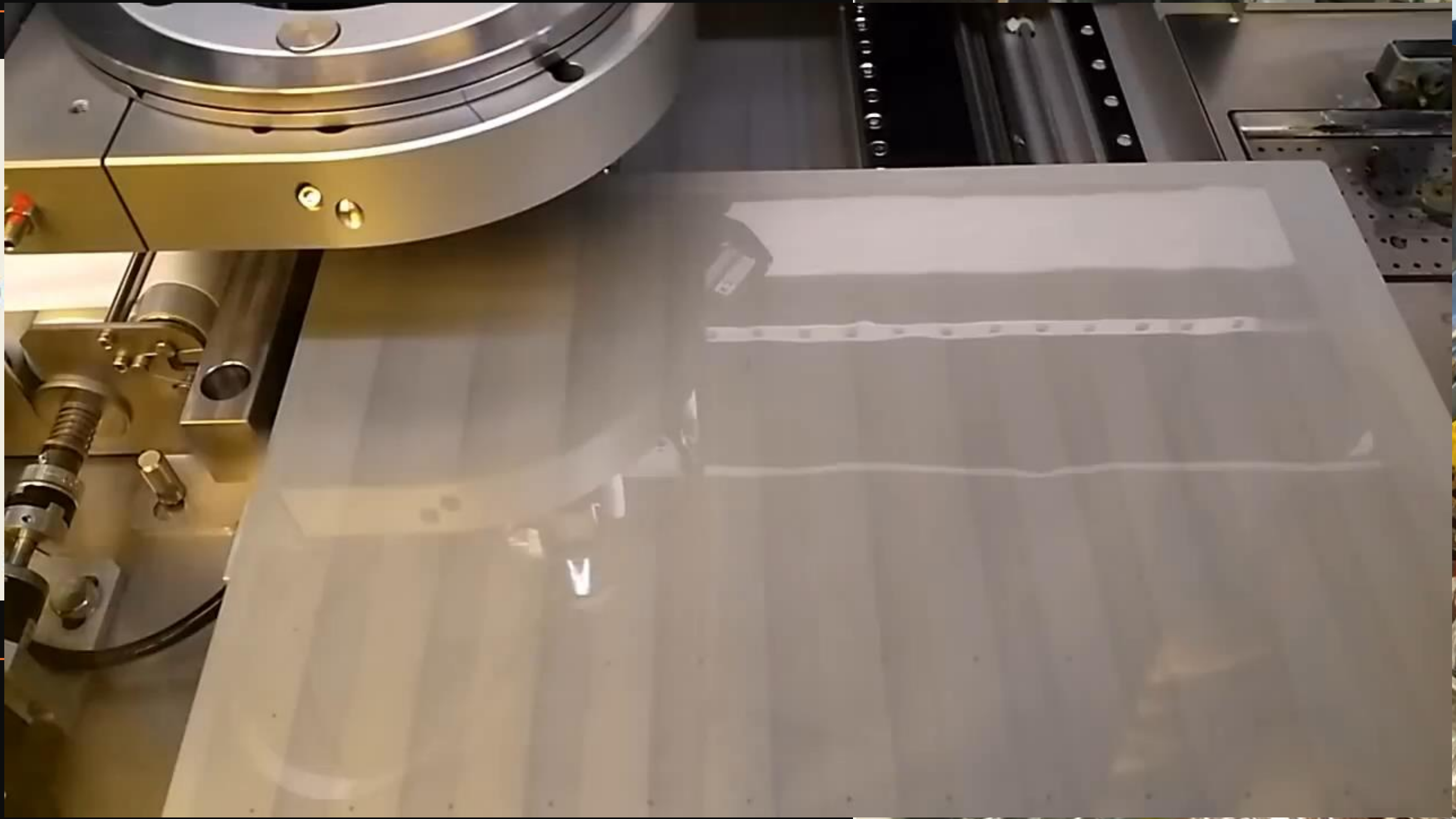


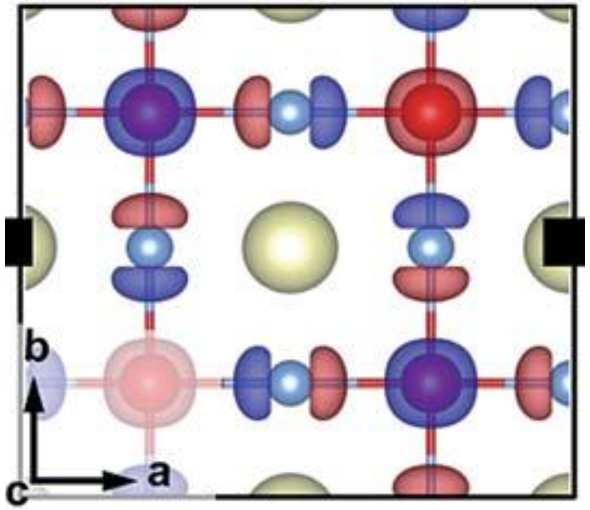
Energy harvesting/scavenging opportunities: PV

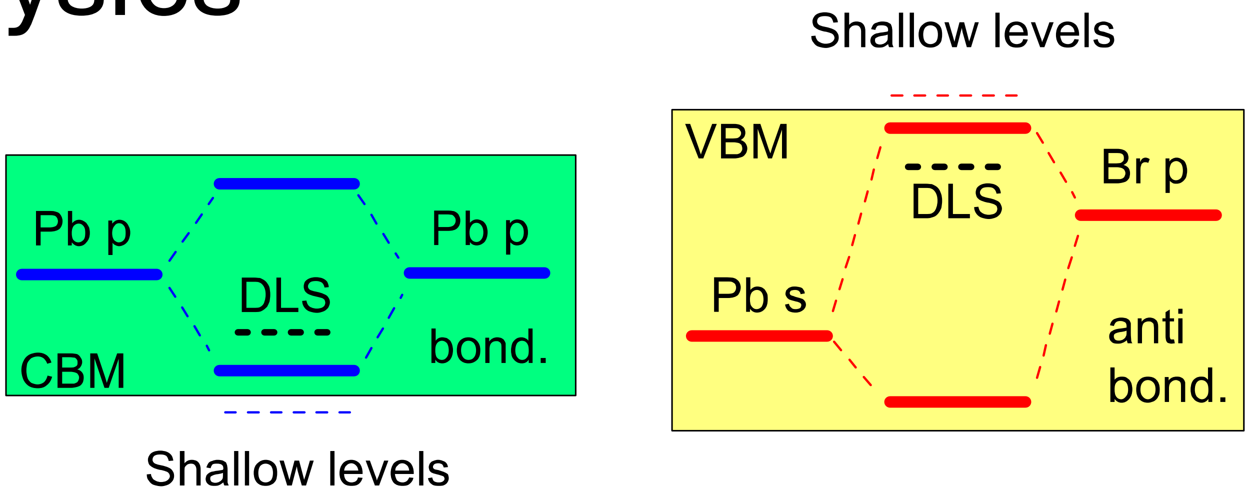


Nga Phung

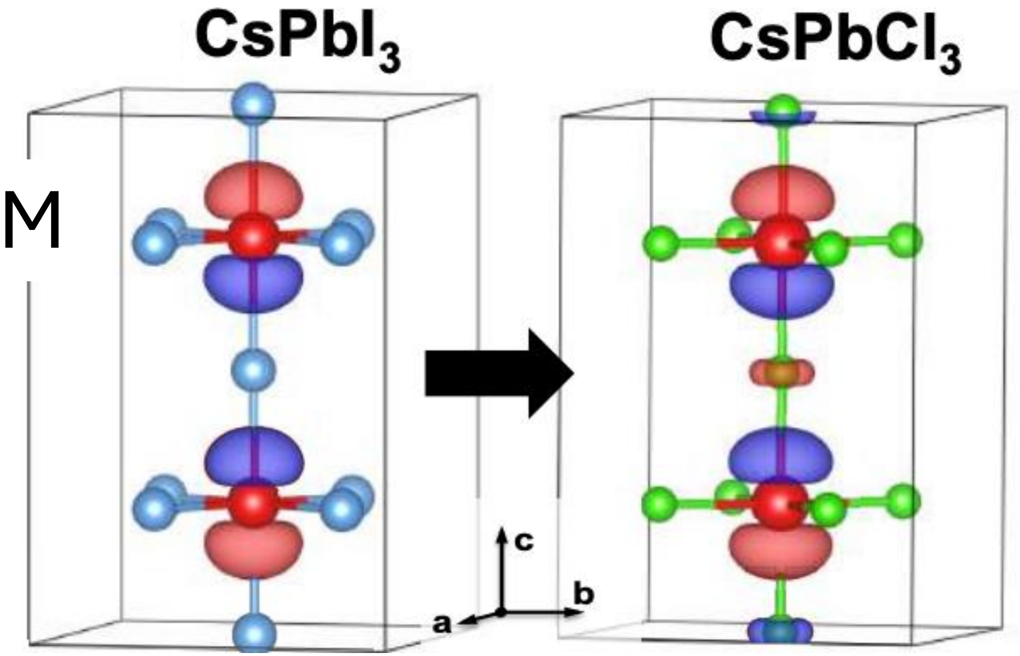
Unusual electronic structure: game changes in defect physics

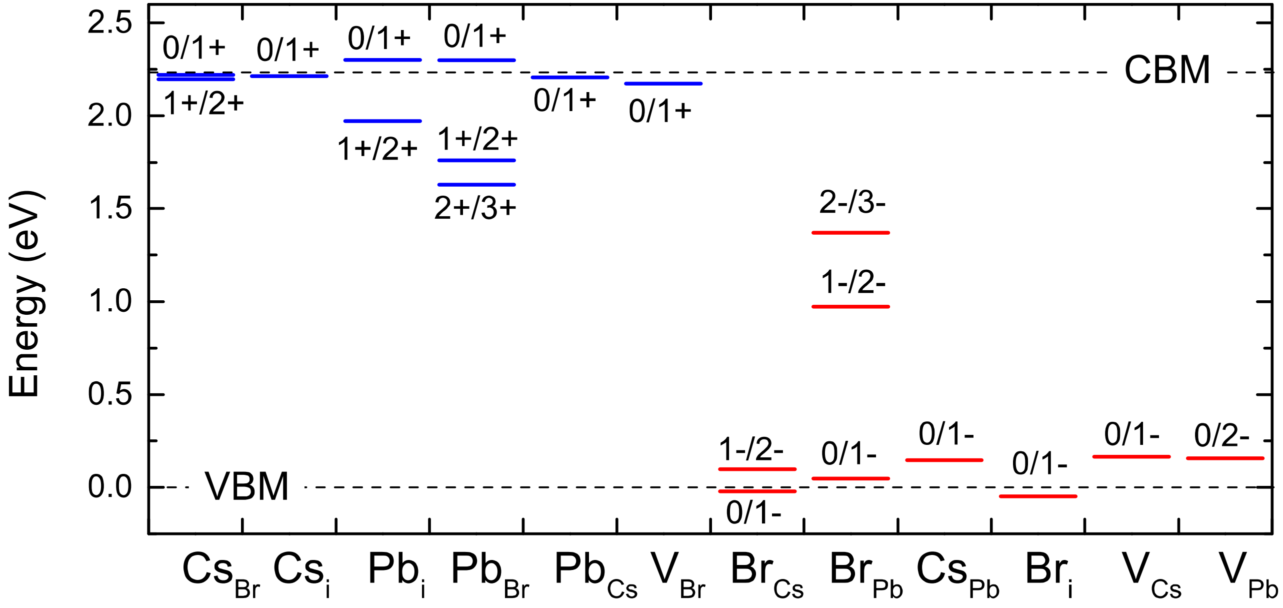
VBM





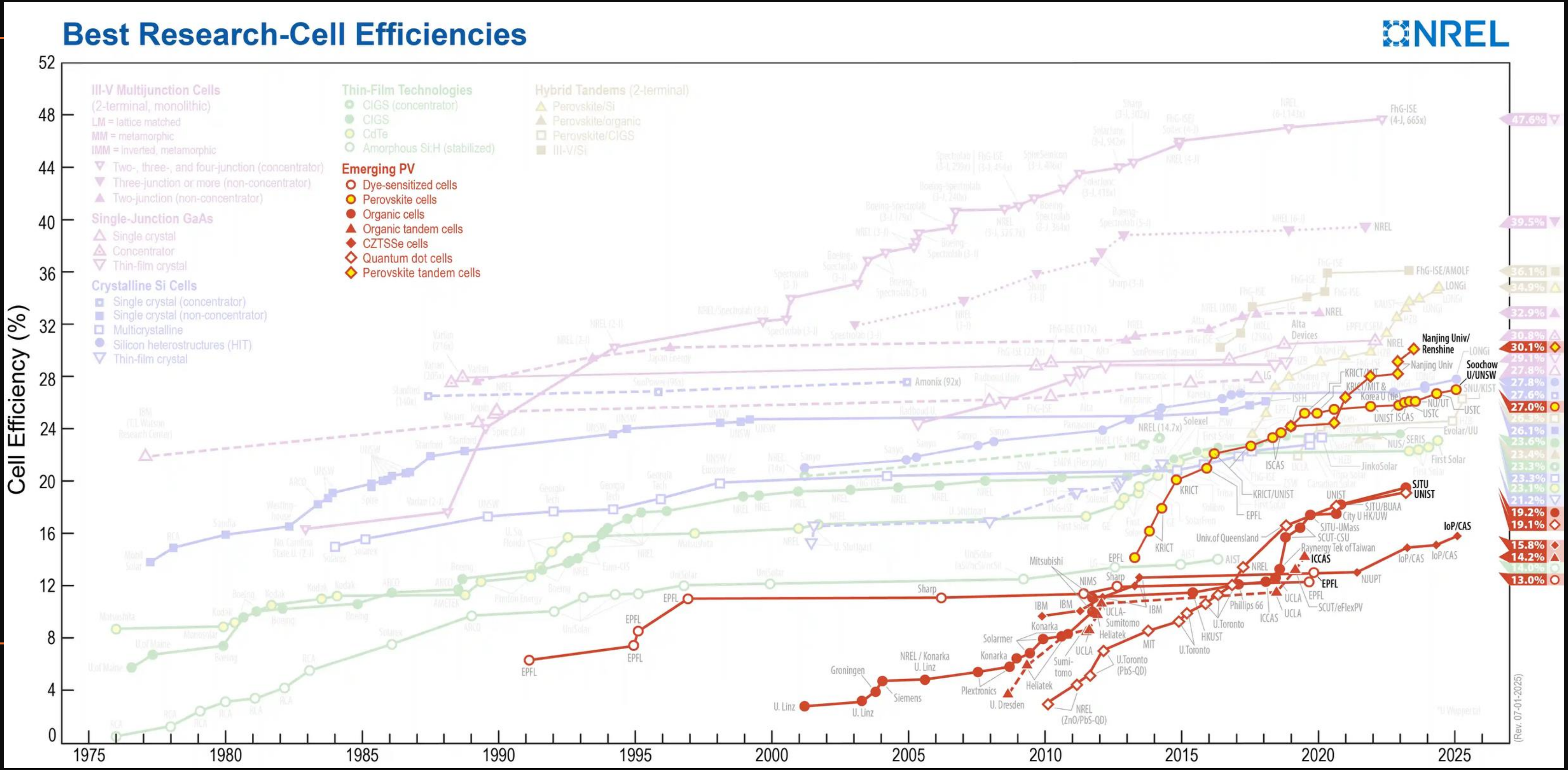
CBM





J. Mat. Chem. A 4, 15997, 2016; Nano Lett. 14, 888. 2014

Energy harvesting/scavenging opportunities: PV



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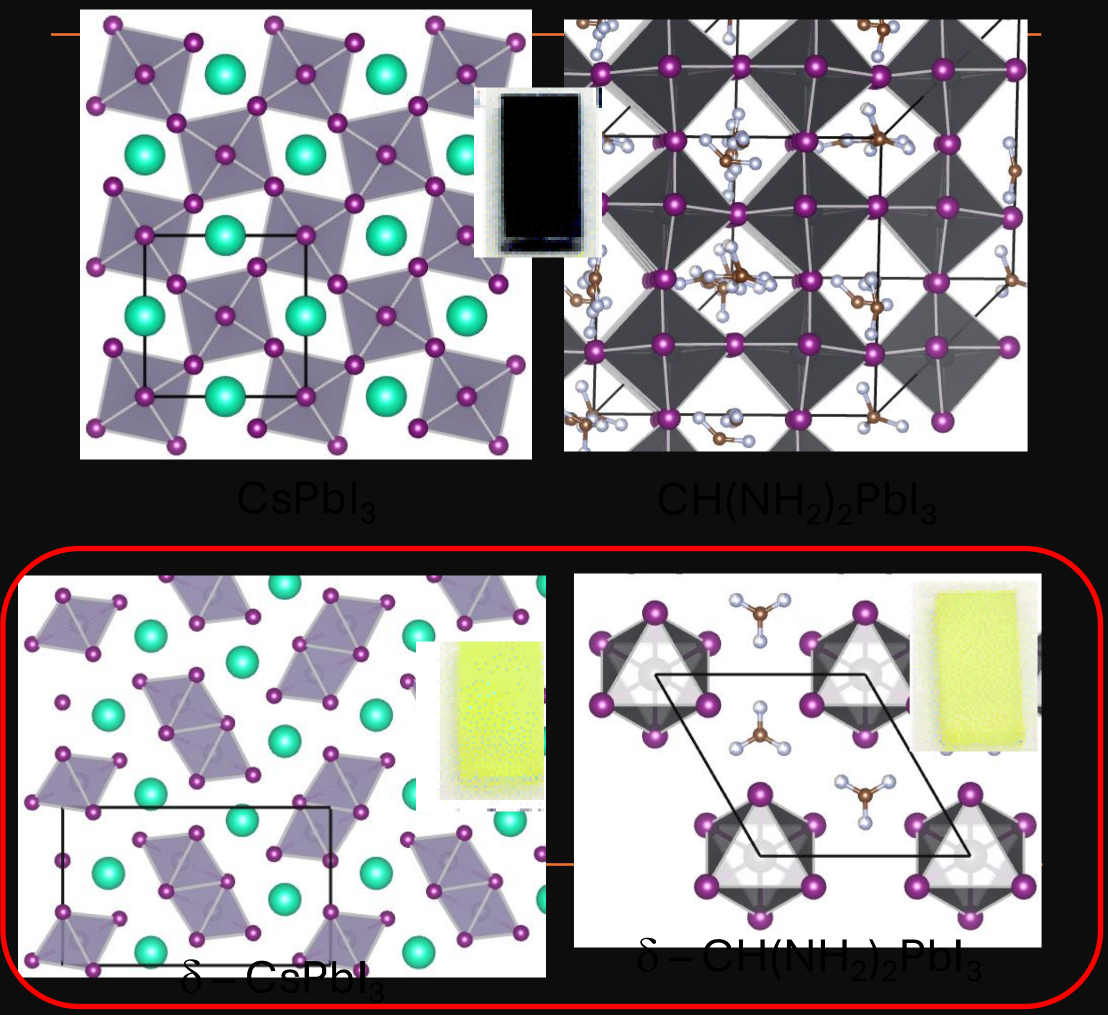
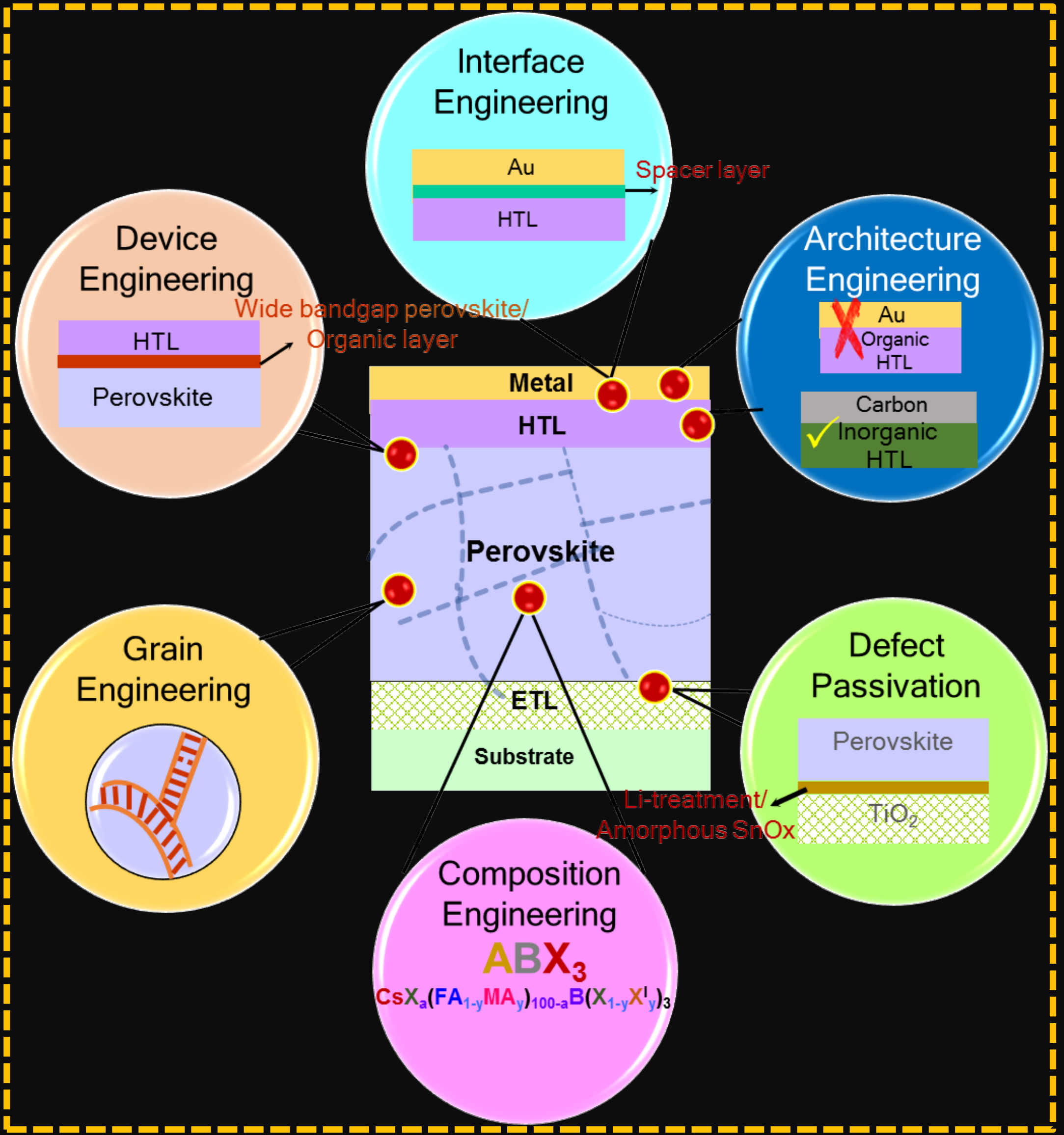




Thermal energy sources and capacity

Energy demand in EU:
- Total ~17000 TWh/year
- Electricity ~3000 TWh/year

Temperature Range	Typical Sources	Harvesting Technologies	Estimated Potential
< 100°C	Ambient heat, building HVAC, low-grade waste	Thermoelectric (low ΔT), Pyroelectric	Very large, but low efficiency
100–250°C	Industrial exhaust, district heating	Thermoelectric (mid ΔT), ORC (low-temp)	~60–80 TWh/year (recoverable)
250–500°C	Metal processing, chemical plants	Thermochemical, ORC (mid-temp)	~40–60 TWh/year (recoverable)
> 500°C	Cement, glass, steel industries	Thermochemical, advanced ORC	~50–70 TWh/year (recoverable)

Thermal Energy Harvesting

Mechanisms:

- **Thermoelectric**: Converts temperature gradients into voltage via the Seebeck effect.
- **Pyroelectric**: Generates charge from time-varying temperature changes.
- **Thermochemical and sorption**: absorb and release heat, which is stored under the form of chemical energy

Technologies:

- **Bismuth Telluride (Bi_2Te_3)** for thermoelectric modules.
- **Lead Zirconate Titanate (PZT)** for pyroelectric films.
- **$MgSO_4 \cdot nH_2O$-based composite** for hydration/de-hydration.

Pros:

- Useful in environments with waste heat.
- No moving parts—long lifespan.

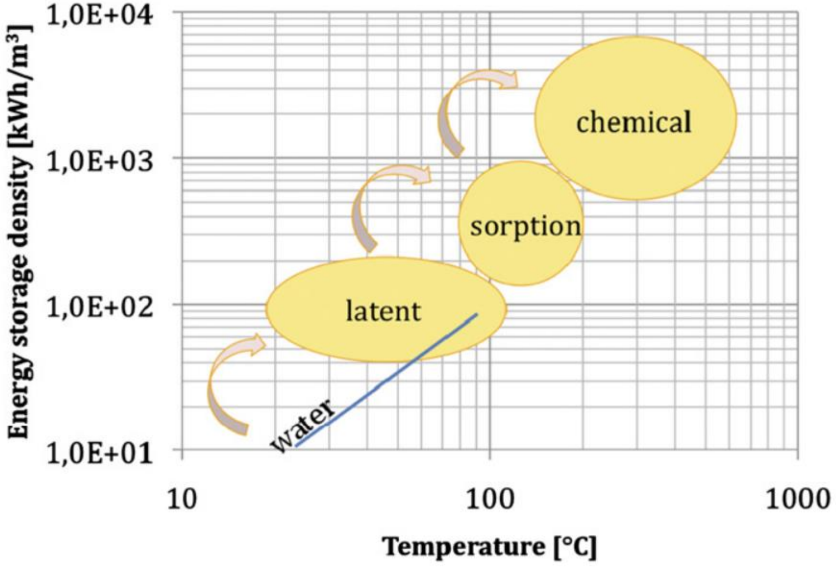
Cons:

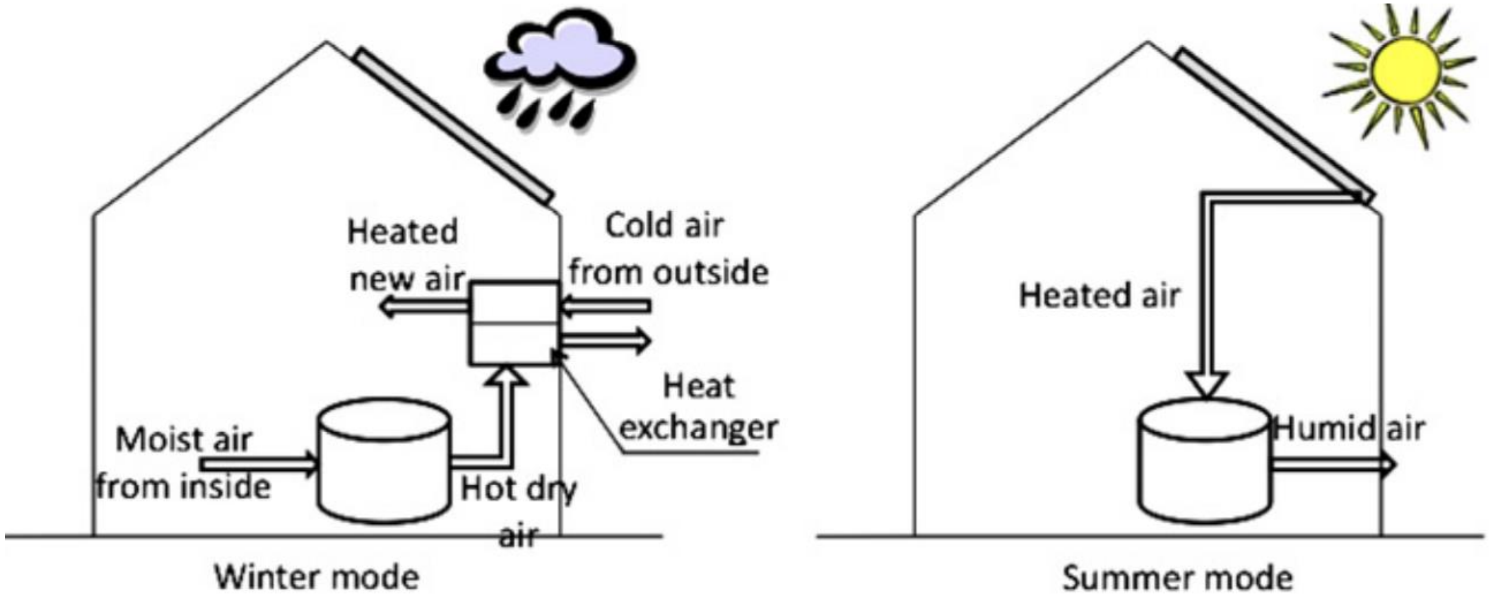
- Low conversion efficiency.
- Requires significant temperature gradients.

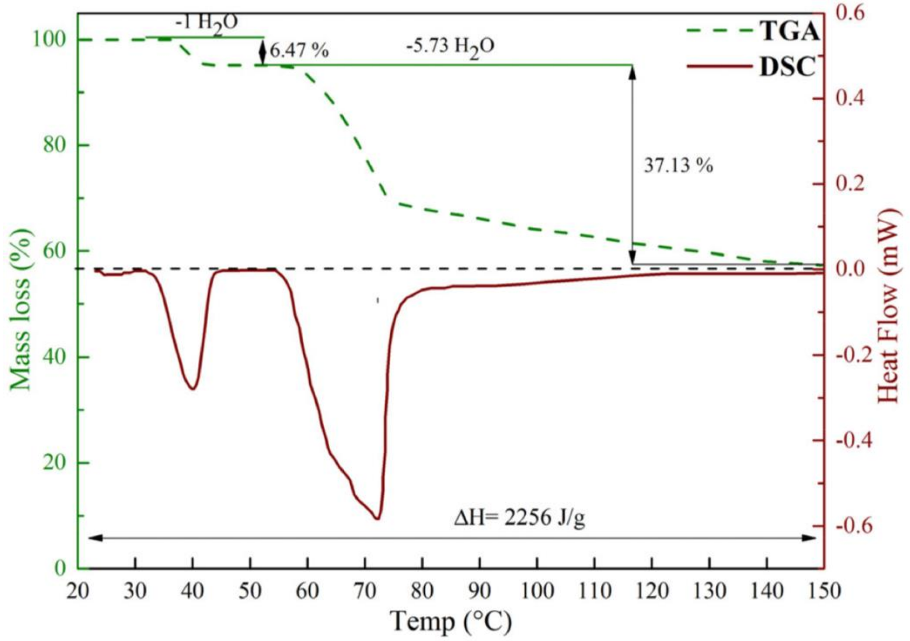
Applications:

- Industrial machinery, body heat-powered wearables, automotive exhaust systems.

Thermochemical and sorption energy harvesting/storage





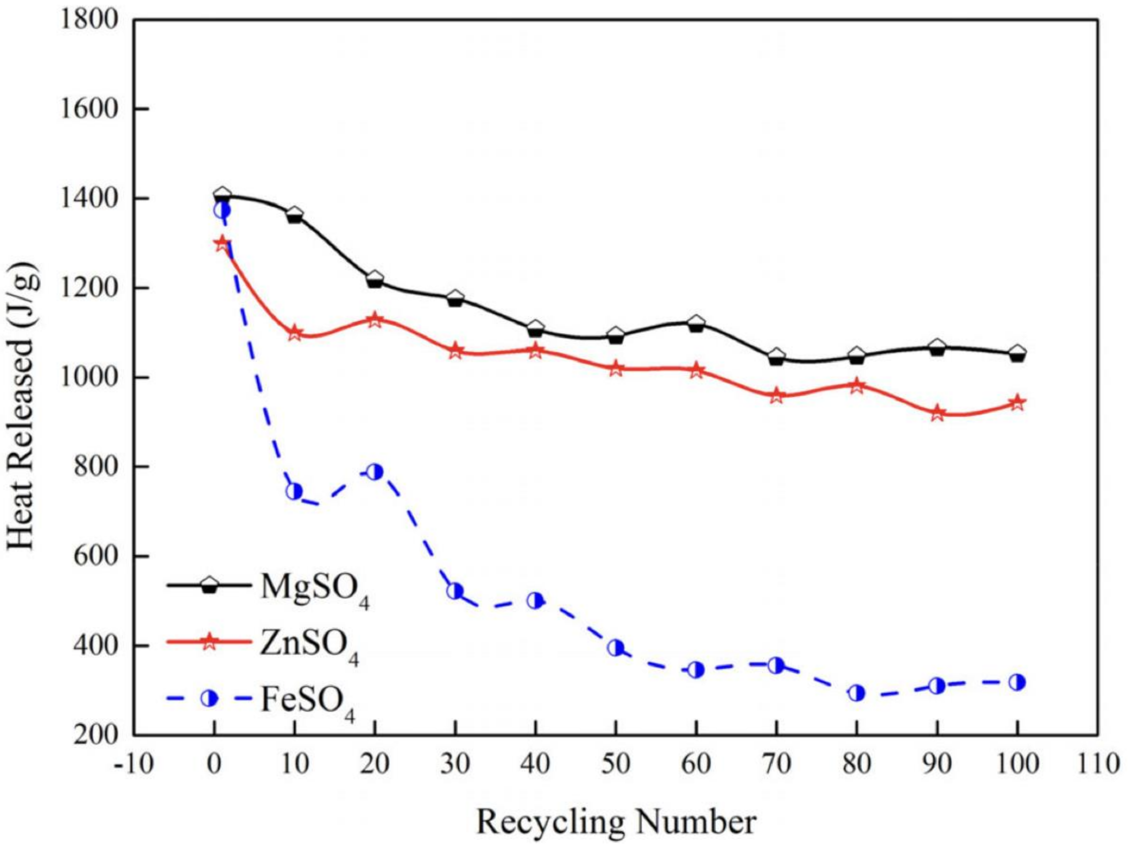


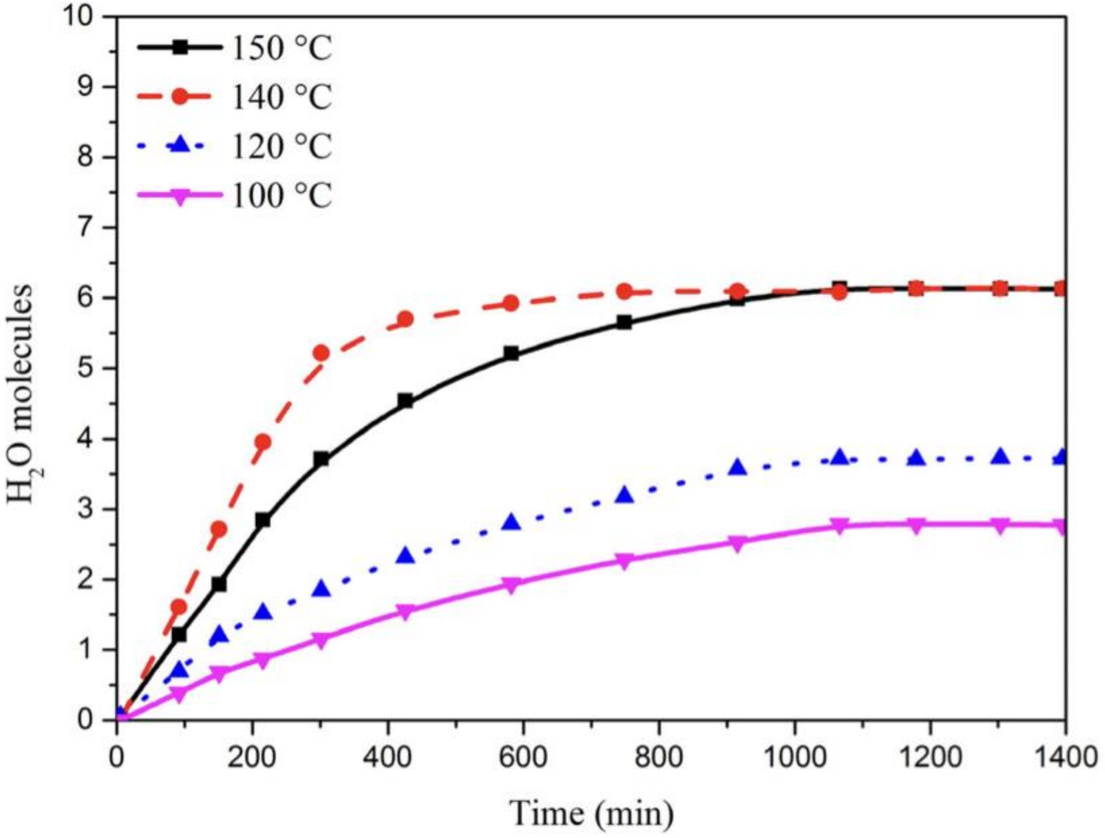
$$MgSO_4 \cdot nH_2O \underset{\text{humidity}}{\overset{\text{heat}}{\rightleftarrows}} MgSO_4 + n\,H_2O$$

Solar Ener. Mat. & Solar Cells 95 (2011), 1831

Int. J. Ener. Research 44 (2020), 6981

Thermochemical and sorption energy harvesting/storage





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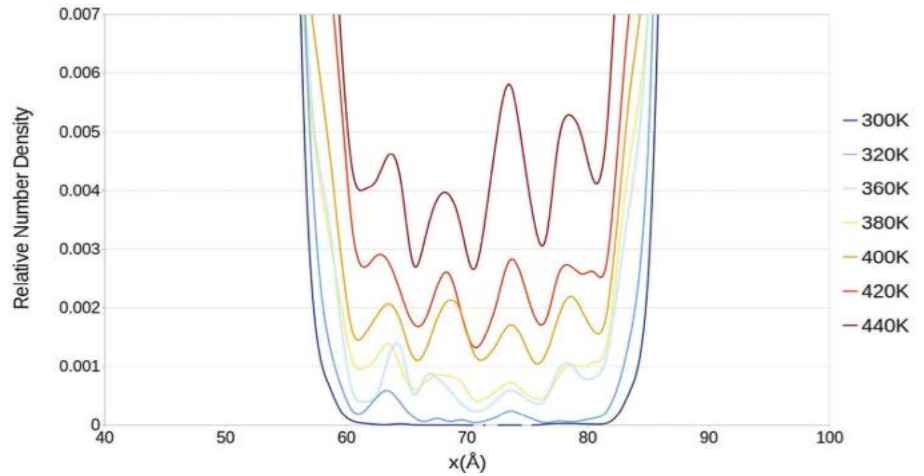
Thermochemical and sorption energy harvesting/storage

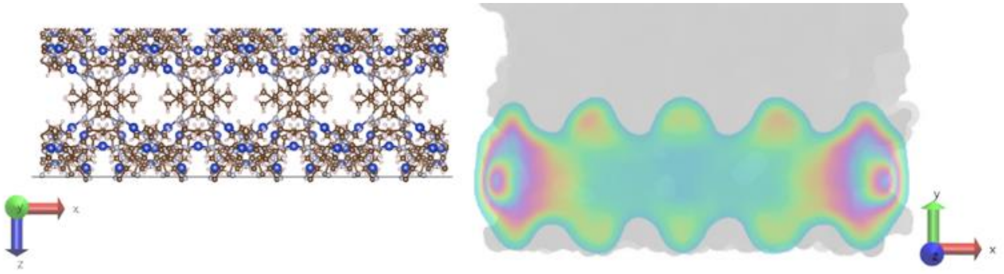
- **$MgSO_4 \cdot nH_2O$ composites to improve stability**
  - **%p: amount of active matter on the overall mass**
  - **Kinetics of diffusion of vapor in and out**
  - **Thermal transport**
  - **Kinetics of phase transition**
  - **…**

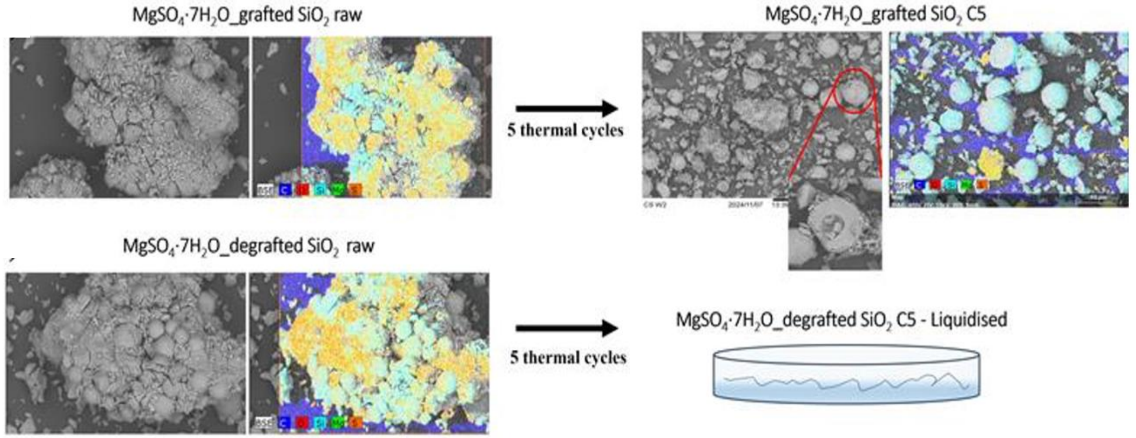
Material System	%	E	C	Key Observations
Bennici et al. 2022. $MgSO_4$ @ Activated carbon	30	~1324	8	Structure degradation; no long-term tests
Nguyen et al. 2022. $MgSO_4$ @ Activated carbon	7.6	~920	10	Low salt loading; fair stability; limited testing
Liu et al. 2022. $MgSO_4$ @ Mesoporous silica	50	N/A	1	High kinetics; weak structure; no cycling data
Xu et al. 2018. $MgSO_4$ @ Zeolite 13X	35	~492	5	Short-term stable; poor >50 °C; no long-term tests
Yang et al. 2024. $MgSO_4$ @ Silica Gel	20	~380	15-30	Scalable system test; gradual performance decline after 30 cycles.
Miao et al. 2021. $MgSO_4$ @ Expanded graphite	60	~576	1	High thermal conductivity; no durability data
Zhang et al. 2021. $MgSO_4$ @ Diatomite	60	~773	20	Better than pure $MgSO_4$; ~10 % capacity fade

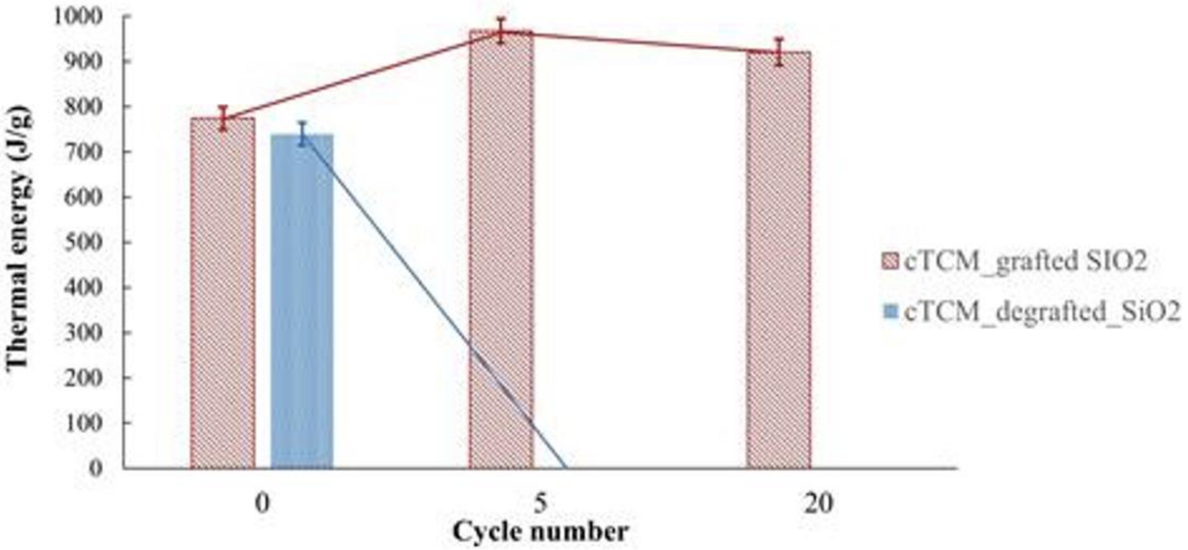
Humidity management

- Hydrophobic material for preparing the composite
  - Prevents formation of liquid water
  - Counterintuitive:
    - how this favors entrance of vapor in the composite?
    - How does this allow to control loading/discharging kinetics









J. Colloid Interf. Sci. 693 (2025), 137605

J. Am. Chem. Soc. 146 (2024), 13236

Mechanical Energy Harvesting

Mechanisms:

- **Piezoelectric**: Converts mechanical stress into electrical charge.
- **Electromagnetic**: Relative motion induces current in coils.
- **Triboelectric**: Generates electricity from friction/contact between materials.

Technologies:

- **Piezoelectric ceramics (PZT, PVDF)**.
- **Microgenerators with magnets and coils**.
- **Triboelectric nanogenerators (TENGs)**.

Pros:

- Ideal for vibration-rich environments.
- Scalable from macro to micro devices.

Cons:

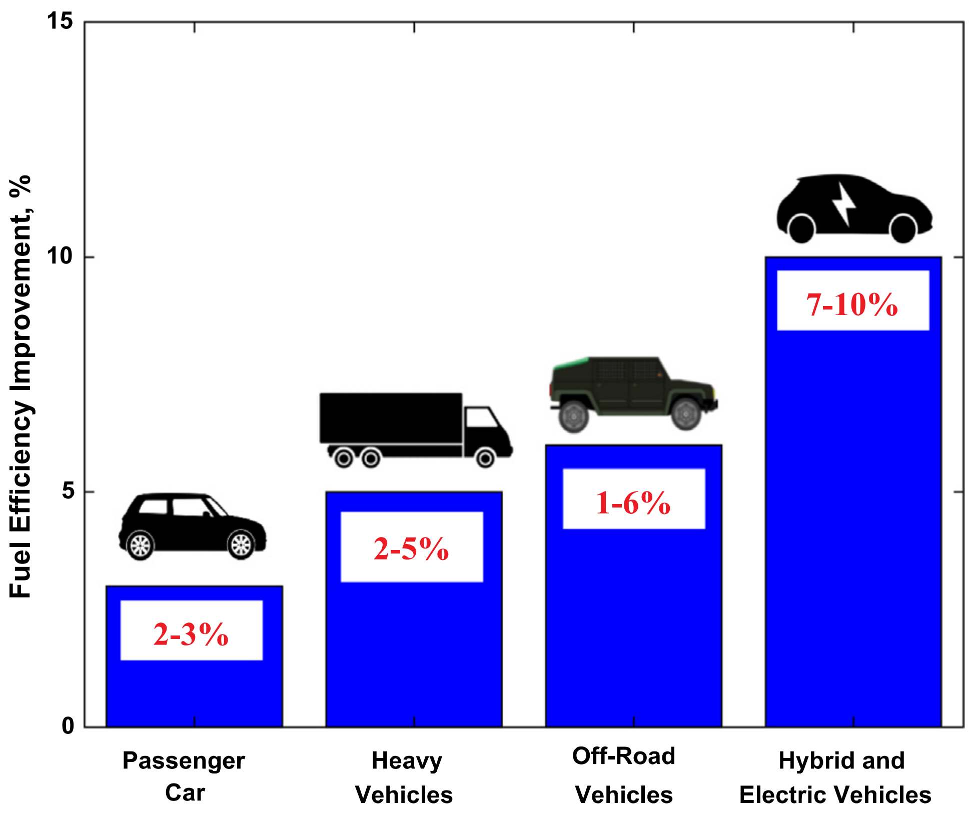
- Output is intermittent and often low.
- Requires mechanical movement or vibration.

Applications:

- Structural health monitoring, footstep-powered devices, wearable motion sensors.

Mechanical Energy Harvesting

Sector	Estimated Dissipated "Mechanical" Energy (EU)
Shock absorbers/Suspension damping (road vehicles)	~ 75 TWh/year (note: very approximate)
Vehicle braking (non-regenerative)	~ 700 TWh/year (non-recoverable in many ICE vehicles)
Industrial mechanical losses (friction, transmissions, damping)	Hard to isolate; part of "other losses" in industry, 20-50% total input energy wasted : mechanical fraction small but non-negligible
Other mechanical dissipation (e.g., in buildings: doors, HVAC dampers, etc.)	Likely much smaller, no good data found



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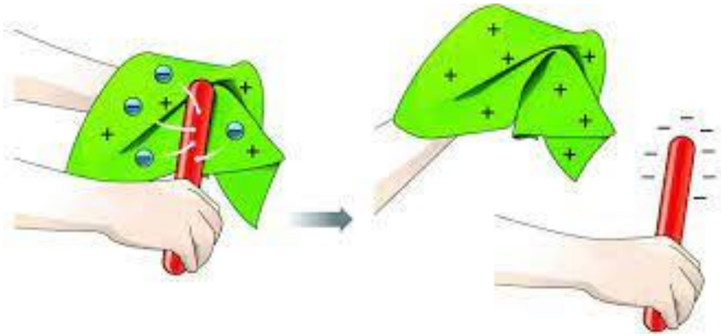
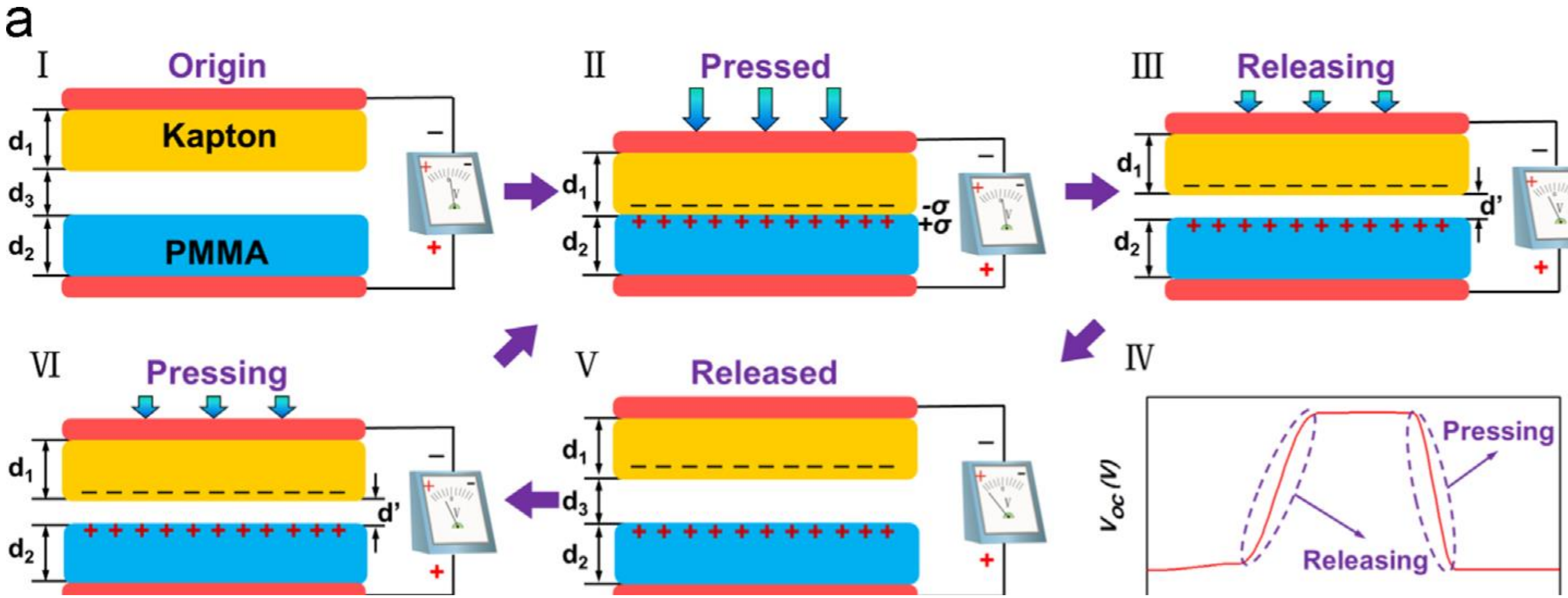
Triboelectric nanogenerators (TENGs)





G. Zhu et al, Nano Energy 14, 126, 2015

ELECTRO INTRUSION

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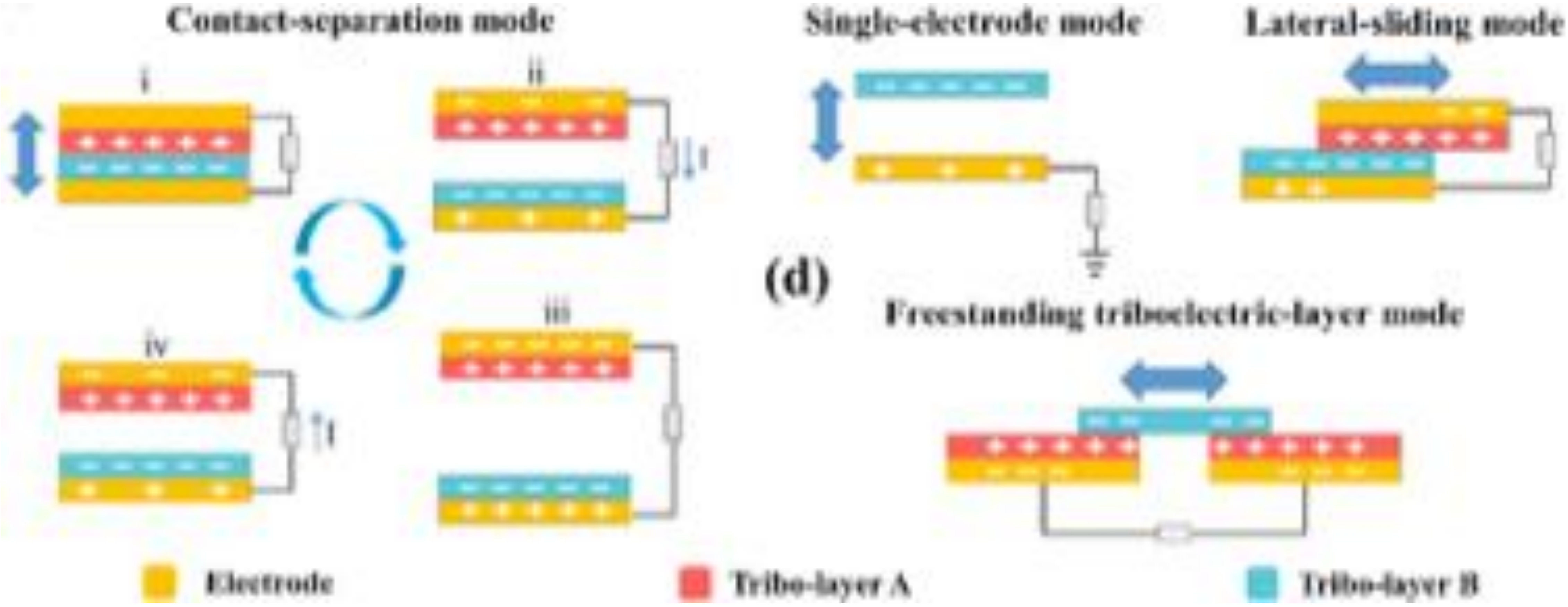
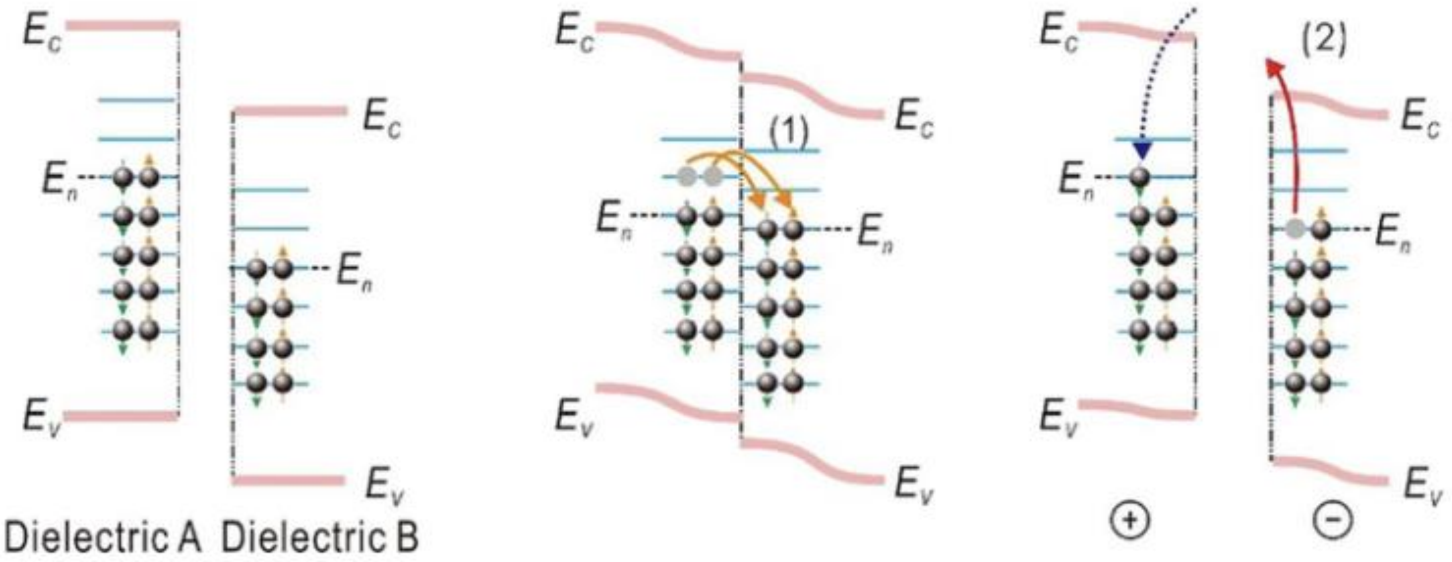
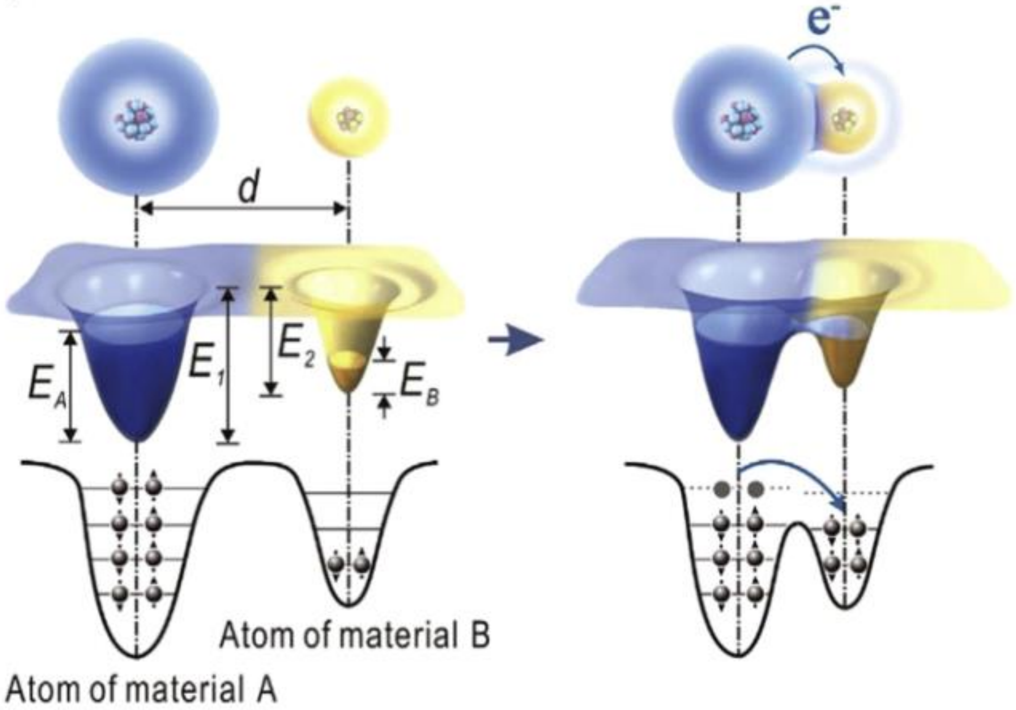


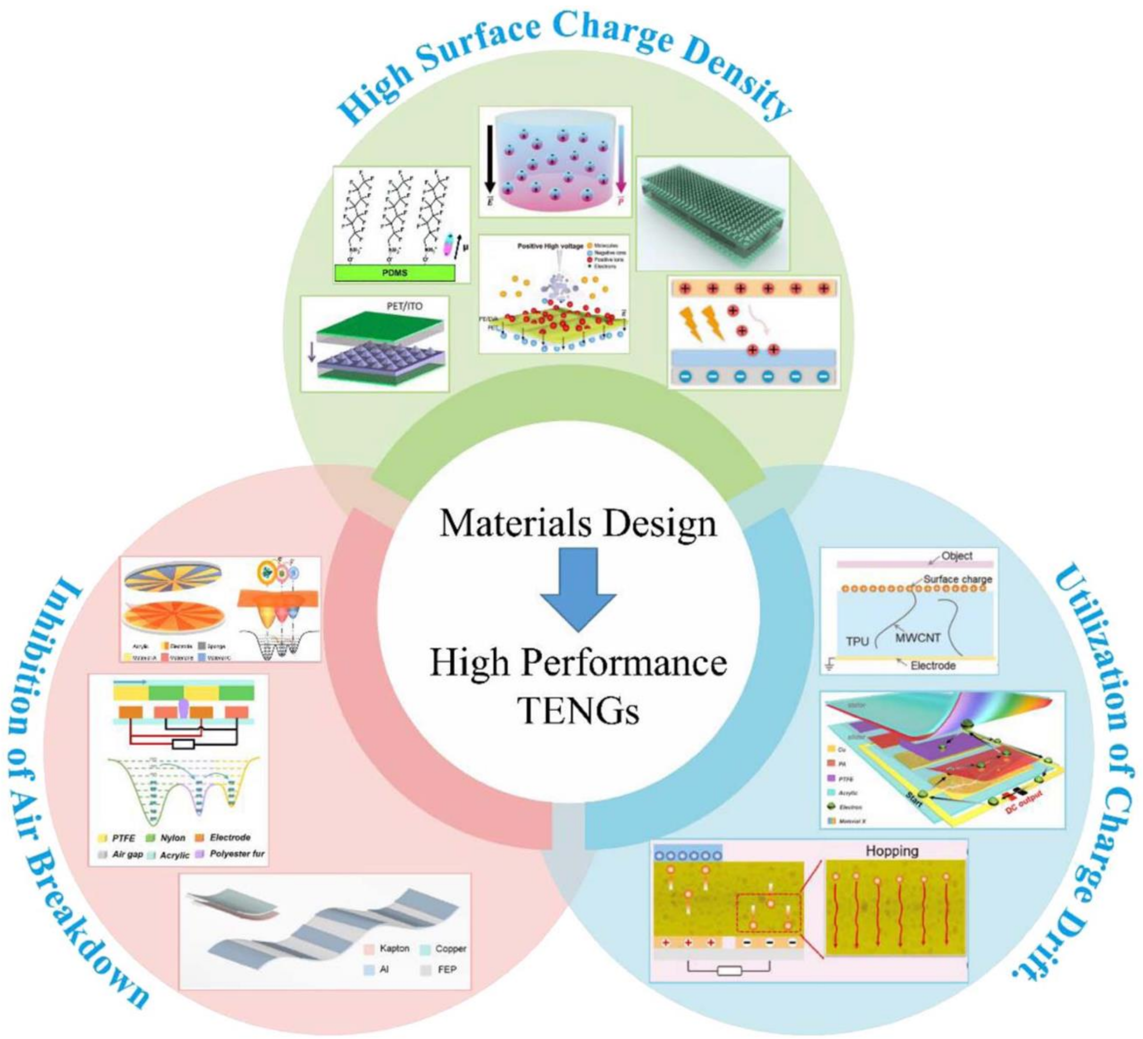
Fundamental mechanism





Materials Today 30 (2019), 34
Nano Energy 52 (2018) 517

Key questions and improvements



Nanoscale Adv. 4 (2024) 4522

Conclusions

- Multiple energy source to be harvested, some are primary, other are not.
- I used three cases, starting from the better-known PV case to the more exotic TENG one, to illustrate the challenges in the field.
- This requires understanding fundamental phenomena occurring at the nanoscale to be converted in technology.
- Often experiments do no have direct access to these info, one can only infer the origin of a measurement.
- Simulations, *in silico* experiments, can fill this gap.