Nexus of solar and thermal photovoltaic technology could help solve the energy storage problem

by: Andrej Lenert*[1], Stephen R. Forrest[2]

Departments of Chemical Engineering[1], Electrical Engineering and Computer Science[2], and Physics[2]
University of Michigan, Ann Arbor, MI 48109
*alenert@umich.edu

Writing recently in *Nature*,[1] LaPotin and colleagues introduce a tandem photovoltaic cell that converts thermal radiation into electricity with efficiencies exceeding 40%, clearly surpassing the thermoelectric efficiency of steam turbines. The cell blurs the lines between solar and thermal photovoltaic technology and could help make solar energy more dispatchable.

MAIN TEXT

Greater adoption of renewable energy on the electrical grid is essential to decreasing carbon emissions and achieving carbon neutrality. With the price of renewable electricity decreasing significantly over the past decade to prices as low as US$0.01/kWh-e, the greatest barrier to achieving high penetration of intermittent renewables (*e.g.,* wind and solar) has become the deployment of adequate energy storage. The existing capacity in stationary energy storage is dominated by pumped-storage hydropower (PH), while new projects are generally based on lithium-ion (Li-ion) batteries.[2] Neither of these technologies, however, satisfies the growing unmet need for inexpensive, long-duration stationary energy storage that is based on earth-abundant materials and can be implemented virtually anywhere in the world. Solutions to this problem need a cost of ~US$20/kWh-e to enable deep decarbonization of the grid.[3]

To address this energy storage problem, several research groups and startups are developing ultra-low-cost versions of the thermal battery concept. These systems pair thermophotovoltaic (TPV) cells with inexpensive thermal energy storage (TES) in the form of ceramic or graphite blocks. At times of low electrical demand, these systems resistively heat the medium to a higher temperature and store the energy in well-insulated tanks. When demand is high, the stored energy is emitted as light (thermal radiation) that the TPV cells absorb and convert into electricity. The outcome is an approach to stationary energy storage that, despite a lower round-trip efficiency, could offer significant advantages over other storage technologies. These include low cost (like PH), no geographical requirements (unlike PH), use of earth-abundant storage materials that do not require energy-costly and environmentally damaging extraction (unlike Li-ion), and short response time, on the order of seconds (unlike turbomachinery-based storage). The latter is particularly advantageous for regulating the supply of intermittent renewables like wind and solar.

Though promising, thermal batteries require high-efficiency TPV cells to be feasible because the cells govern their round-trip efficiency (RTE). Some estimates suggest that an RTE > 36% is required to generate revenue from arbitrage on a representative U.S. grid (2007 PJM).[4] Meanwhile, performance in TPVs has been limited to efficiencies to below 30% for decades,[5] ever since the pioneering work of R. M. Swanson. Only recently have reported efficiencies surpassed Swanson's record (see Figure 1a), mainly through the use of III-V thin-film cells that are supported by highly reflective substrates.[6–8]

Now, writing in *Nature*, the team from the Massachusetts Institute of Technology (MIT) and the National Renewable Energy Laboratory (NREL) report a maximum efficiency of around 41% using gallium arsenide-based tandem cells.[1] This impressive efficiency clearly surpasses the performance of steam turbines and is high enough to enable use with thermal batteries. The cells integrate a number of key features that allow them to navigate the tradeoffs between carrier management and spectral utilization, including relatively large bandgap materials, a tandem architecture, very hot emitters, and a highly reflective back mirror.

With respect to carrier management, the design relies on large bandgap materials and a tandem architecture to mitigate losses such as non-radiative recombination and series resistance. The efficiency of large bandgap materials suffers a smaller penalty from recombination of photogenerated carriers because it lowers the output voltage by 0.3–0.4 V regardless of the bandgap. To this end, the team's best-performing cell features a 1.4eV GaAs top cell and a 1.2eV GaInAs bottom cell as shown in Figure 1b. Growth of these specific bandgaps is enabled by high-quality metamorphic epitaxy. The combination of large bandgap subcells and a tandem architecture also increases the operating voltage and lowers the current density, which mitigates the impact of series resistance — another major loss pathway in TPVs.

Although larger bandgaps greatly improve carrier management, they typically introduce significant spectral losses because they convert a narrower band of the incident spectrum, such that a greater portion of the black body spectrum is emitted at energies below the bandgap (out of band). For this reason, the bandgaps of Si and GaAs have been considered too large to convert heat with acceptable efficiency. The team addresses this issue by (1) increasing the temperature of the thermal emitter to as high as 2,400°C, which shifts the incident spectrum to higher photon energies, and (2) introducing a gold back mirror that reflects a large fraction (~93%) of out-of-band radiation back to the heat source. The use of two absorbers further improves spectral utilization by lowering hot carrier thermalization losses. Overall, this approach allows one to increase the bandgap, which greatly improves carrier management as mentioned above, while maintaining a high spectral utilization. The result is a record high efficiency for TPVs.

Though the advances are notable, 2,400°C is a very high temperature (even for the TPV community), which naturally raises the question: how practical is thermal energy storage at nearly half the temperature of the Sun? That question remains to be fully addressed; however, the MIT team points to initial experiments that support the feasibility of the TES at ~2000°C, and suggest that higher temperatures are realistic.[4] For decades, research in TPVs has focused on low-bandgap, InGaAs- and GaSb-based cells. Now, thermal batteries can leverage resistive heating to access much higher temperatures[1,4,9] and, in turn, allow the use of larger bandgap cells (>1 eV). At these emitter temperatures, many of the boundaries between solar and thermal PV technology disappear, opening the door for materials that were previously considered suitable only for solar applications, including Si, perovskites, CdTe, and others. This could allow TPVs to take advantage of far lower costs than that of cells based on lower bandgap semiconductors.

Even if temperatures >2,000°C prove to be impractical, the future of TPV remains bright, with materials traditionally used for solar PV having a large role to play. A colder emitter radiates more power at longer wavelengths, which means that an improved out-of-band reflection is needed to maintain efficiency. Recent work using patterned dielectric[10] and air-bridge[7] back-reflectors has pushed the out-of-band reflectance as high as 99%, providing a way of raising efficiency at lower emitter temperatures. Lower temperatures also decrease the current density and therefore mitigate the need for very low contact and series resistances, which otherwise remains a challenge. Furthermore, if 98% out-of-band reflectance is combined with the advancements made by the MIT/NREL team, efficiencies are predicted to reach >56% at 2,250 °C, or >51% averaged over a 1,900–2,400 °C temperature range.[1] The importance of the latter is that high out-of-band reflectance can extend the range of temperatures over which the storage medium can be charged/discharged.

These are promising avenues for the future of both solar and thermal PV technology. For TPV, the synergy with solar PV provides many potential benefits, including access to lower cost semiconductors and established manufacturing capacity which could allow TPV to meet its global potential. Meanwhile, thermal batteries can serve as a solution to the grid storage problem, which could convert solar PV into an on-demand energy resource and ultimately reduce global CO_2 emissions by 25-40%.

ACKNOWLEDGEMENTS

This work is supported by the National Science Foundation under Grant No. 2018572, 2140694, and 2144662, and by the Army Research Office (ARO) under award number W911NF-19-1-0279. The authors acknowledge Tobias Burger for the efficiency timeline figure and table.

DECLARATION OF INTERESTS

The authors have filed a patent application related to this work. A.L. is a scientific advisory board member of Antora Energy.

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FIGURES

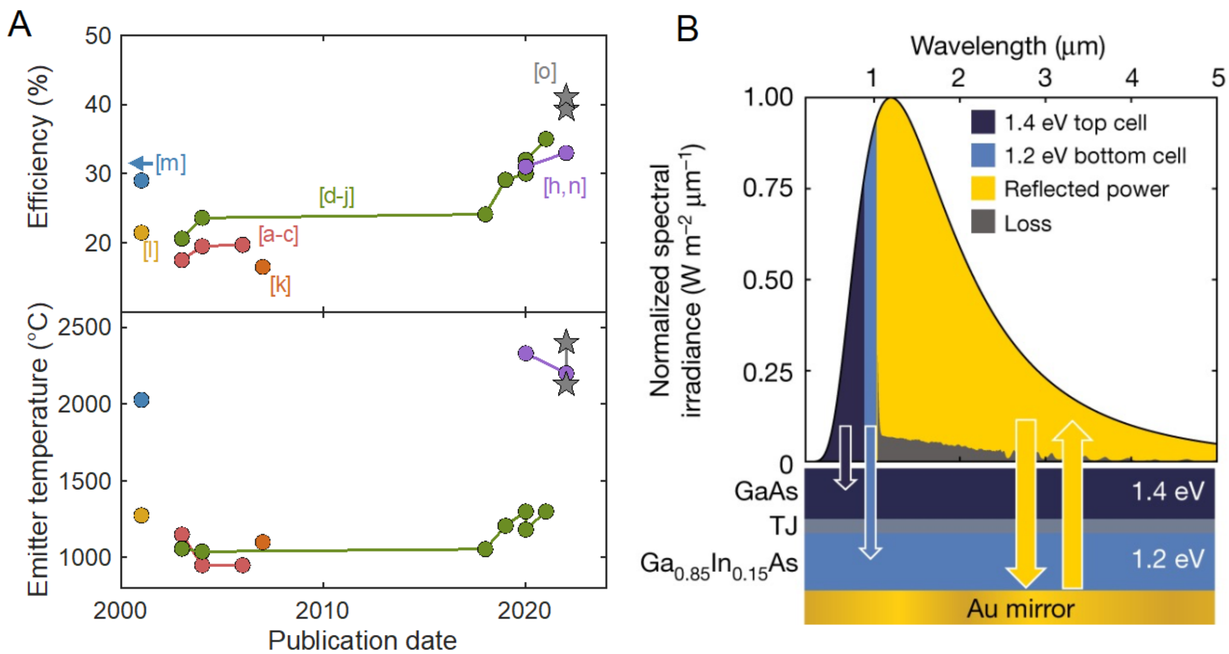

Figure 1. MIT/NREL tandem sets a record-high efficiency for TPVs. (a) Timeline of TPV efficiencies, with corresponding emitter temperatures (lower panel), showing the MIT/NREL tandems (stars) and previous records (see *TPV Efficiency Table* for references). (b) Spectral utilization in the MIT/NREL GaAs-based tandem that achieved a record-high TPV efficiency of ~41% (adapted from Ref. 1).