

High-Efficiency Solid-State Waste Heat Recovery for Iron and Steelmaking

IEDO

Dr. Brendan Kayes, Antora Energy

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Abstract

Antora Energy is developing a cost-effective thermophotovoltaic (TPV) system capable of directly converting radiant waste heat into electricity. In combination with a chemically-stable barrier/emitter, this could be suitable for use in processes such as iron and steelmaking. This technology has the modular and scalable form factor of a solar panel, allowing it to scavenge heat from sources that are completely inaccessible to mechanical heat engines and recuperators. Just as the modularity, simplicity, robustness, and minimal operations & maintenance (O&M) costs of solar photovoltaics have revolutionized the electricity sector, these same key attributes in our TPV-based waste heat recovery (WHR) system have the potential to transform American heavy industry. The compactness, safety, and durability of this approach has attracted the interest of multiple major steelmakers, including Gerdau, EVRAZ, voestalpine, and ArcelorMittal. This project focuses exclusively on technologies that have a demonstrated ability to be manufactured at scale, and will culminate in a field test of a >1 kW heat-to-electricity conversion system at a temperature relevant to steelmaking.

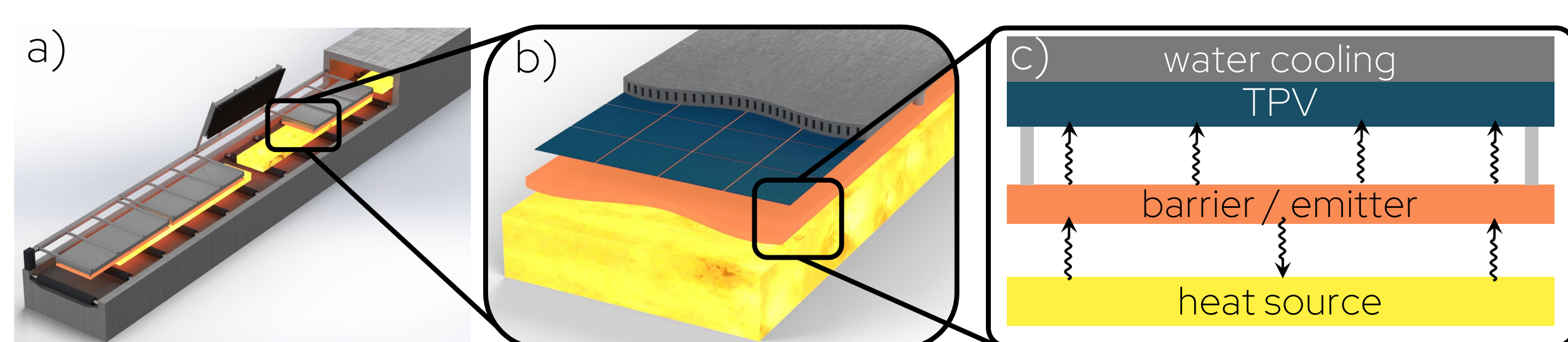


Fig. 1 Overview of thermophotovoltaic (TPV) waste heat recovery (WHR) technology. a) Example application in a hot mill. b) Inset showing layers of TPV WHR system. c) Inset showing exchange of photons between the hot steel, the barrier/emitter, and TPV cells.

Alignment with Office Mission

Iron and steelmaking are carbon-intensive industries in need of decarbonization, to align with the goals of the Department of Energy. Waste heat recovery (WHR) is a compelling piece of the solution, by increasing operational efficiency.

Challenges and Impact

By reducing the amount of heat energy wasted in multiple parts of the iron and steelmaking processes, TPV WHR can save nearly 400 kWh of primary energy per tonne of steel, yielding a >10% reduction in on-site energy consumption. This increased efficiency translates directly to a 6.3% reduction in operating costs, yielding over \$2B in economic value and increased profit margins for US steel manufacturers relative to overseas competitors while reducing lifecycle energy and resource impacts of domestically-manufactured steel.

Project Outline

Innovation: A cost-effective thermophotovoltaic (TPV) system capable of directly converting radiant waste heat into electricity.

Project Lead: Dr. Brendan Kayes

Project Partners: N/A

Timeline: 08/01/2021 – 07/31/2024, 70% progress

Budget: \$2,499,974 total

	FY21 Costs	FY22 Costs	FY23 Costs	Total Planned Funding
DOE Funded	\$1,143,734	\$856,240		\$1,999,974
Project Cost Share	\$286,000	\$214,00		\$500,000

End of Project Goal: Build and test a water-cooled TPV module, and demonstrate at least 1 kW of electrical power when exposed to a 1400 °C thermal emitter

Background

- Thermophotovoltaics (TPVs) are a promising technology for waste heat recovery (WHR), exhibiting advantages over incumbent WHR approaches in terms of safety, CapEx, scalability, reliability, operations and maintenance, uptime, standardization, and heat source accessibility.
- Until recently, TPV cell efficiencies were < 30%, and power levels < 1 kW
- Here we demonstrate a population of cells with efficiency > 30%, and a TPV module that produces > 300 W of electrical power when exposed to a 1400 °C thermal source.

Results

- We quantified TPV efficiency > 30% under 1400 °C emitter for 21 cells, and we have many more such cells for building into modules (Fig. 2).
- We built an individual module that is a prototype for the modules that will go into the module array to be tested later this year, and it generated 309 W of electrical power in a 1400 °C furnace (Fig. 3, Table 1).

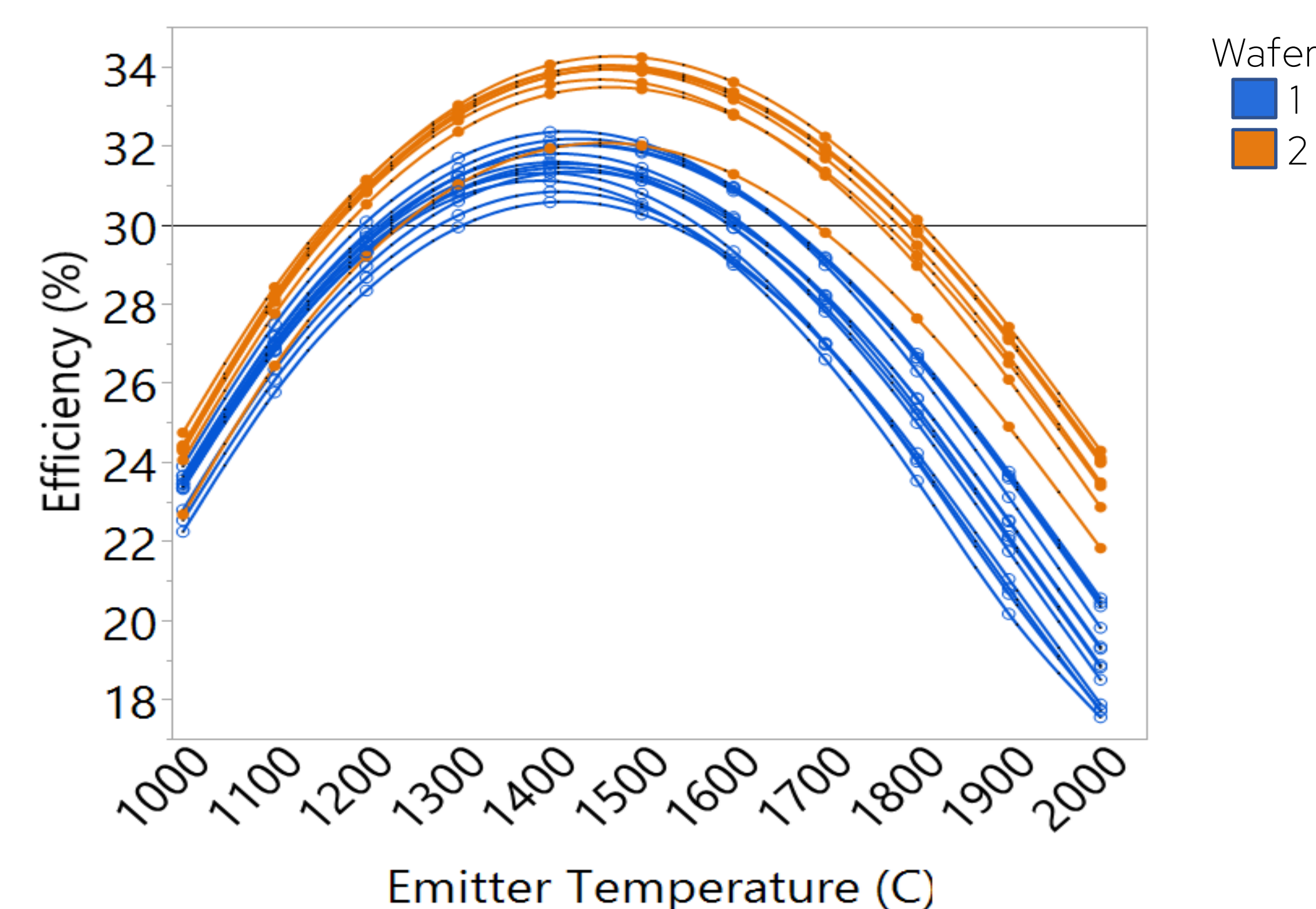


Fig. 2 Heat-to-electricity conversion efficiency vs. emitter temperature for subset of cells characterized for this project. Multiple cells are shown from two different wafers.

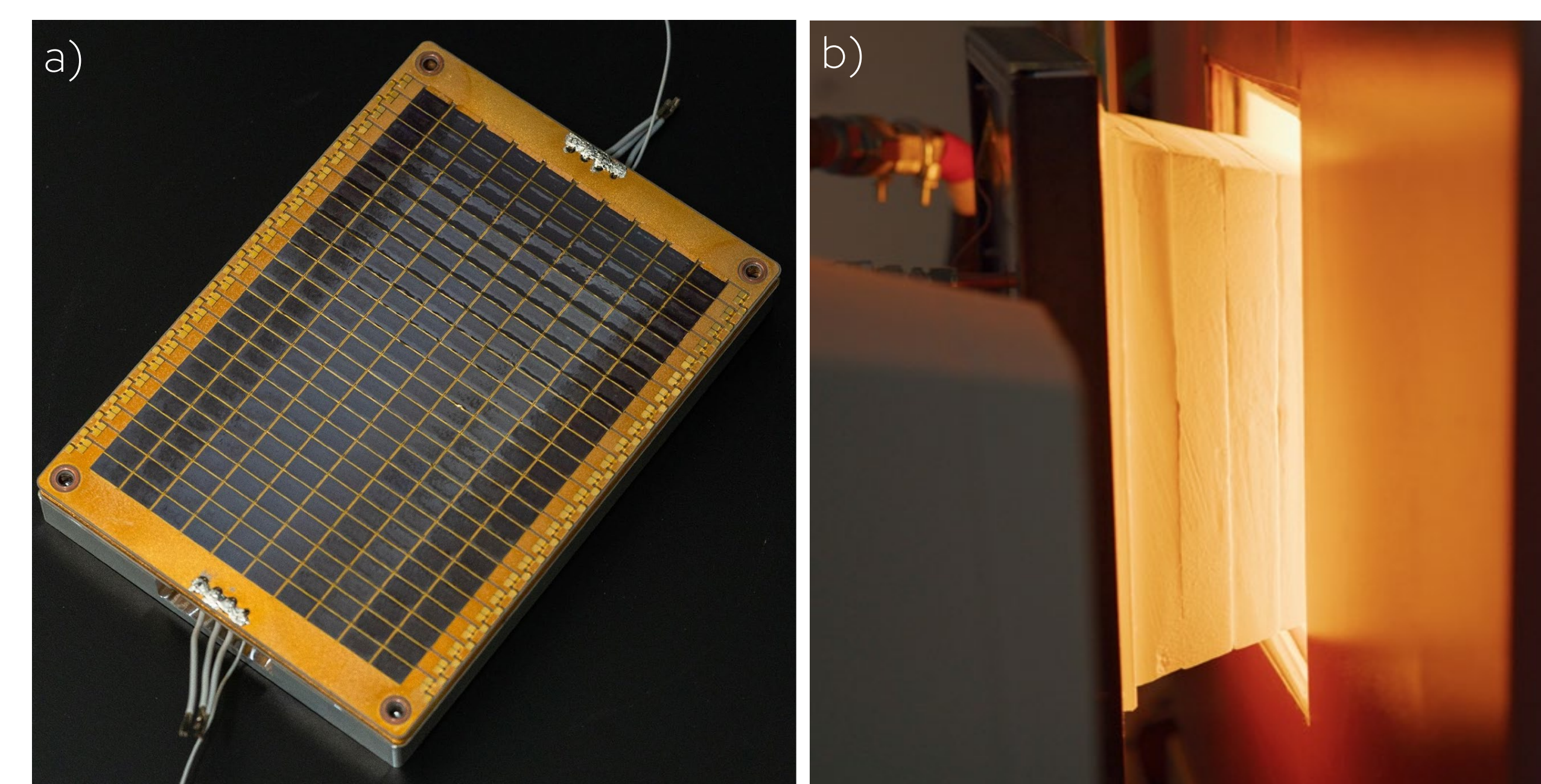


Fig. 3 a) Photograph of our prototype module. b) Photograph of our module characterization furnace, partially opened to show the glow of the thermal emitter.

Emitter Temp. (°C)	Module Temp. (°C)	Voltage @ Max. Power (V)	Current @ Max. Power (A)	Max. Power (W)
1400	22	10.327	29.954	309.3

Table 1. Results of testing our prototype module in our TPV characterization furnace.

Conclusions

These results demonstrate the potential of modular thermophotovoltaics (TPVs), and set the stage for the use of TPVs in a variety of applications, including waste heat recovery (WHR) in iron and steelmaking.

We believe that further work on scaling the TPV supply chain, understanding the cost sensitivity of the target applications relative to the costs that are achievable for TPV, and investigating the bespoke requirements for the use of TPV in particular applications (for example, chemical compatibility of the emitter in harsh environments), could unlock a variety of very compelling use cases for WHR using TPV in heavy industry.

Key Achievements

In this work, we have demonstrated:

- a scalable method of manufacturing TPV cells with efficiencies above 30%,
- a densely-packed module built from these cells, and
- > 300 W of electrical power from the module when exposed to our characterization furnace at 1400 °C.

These are important milestones towards our ultimate project goal of demonstrating > 1000 W of electrical power at a 1400 °C emitter temperature.

Future Work

Within 2023 we will demonstrate > 1 kW of electrical power from interconnected TPV modules exposed to a 1400 °C thermal emitter. We meet semiannually with our Industrial Advisory Board (IAB), and we are engaging them for ideas about how to do a larger demonstration even more directly relevant to their application in iron and steelmaking.

Technology Transfer

The work described here will be continue to be complemented by ongoing semiannual meetings with our IAB to discuss the significance of our results, and how they could be incorporated into real applications in iron and steelmaking for maximum impact. Beyond this application, we are always looking for new ways to utilize TPV. To this end, we participate in many industry councils, where we present on many of our technical results. Finally, in the future we intend to submit a manuscript describing the technology we've developed here to a peer-reviewed journal.

References

- Tervo, E. J. et al. (2022). Efficient and scalable GaInAs thermophotovoltaic devices. *Joule*, 6(11), 2566.
- Narayan, T. C. et al. (2020). World record demonstration of > 30% thermophotovoltaic conversion efficiency. *Proceedings of 47th IEEE Photovoltaic Specialists Conference (PVSC)*, 1792.

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