

Fundamental Limitations of Thermoradiative Energy Conversion

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Understanding the fundamental limits of various energy conversion approaches is essential for assessing their efficiency and power output. In this work, we derive general performance bounds for thermoradiative heat engines that exchange heat radiatively with a cold sink, establishing power-versus-efficiency thermodynamic bounds for several configurations. We find that the performance of these engines is always bounded by that of radiative engines, which harness the thermal radiation emitted by a hot source, making thermoradiative engines inherently less favorable for energy conversion. By unifying the results of radiative and thermoradiative engines within a common thermodynamic framework, which also encompasses dual-engine configurations that combine both features, this work provides a comprehensive understanding of the thermodynamic limits of radiative energy conversion. Our framework offers general metrics for evaluating specific devices and raises critical questions regarding the relevance of thermoradiative cells for energy production.

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I. INTRODUCTION

The efficiency of a heat engine operating between a hot source at temperature T_H and a cold sink at temperature T_C is bounded by the Carnot limit, $\eta_C = 1 - T_C/T_H$. Unfortunately, except for very specific cases [1–3], operating close to Carnot efficiency leads to vanishing power output. Conversely, operating at maximum power output leads to significantly degraded efficiencies [4,5], imposing a trade-off between both metrics. While universal trade-off relationships between power and efficiency have been identified [1,6], they do not provide specific answers for given classes of heat engines. Due to the increasing importance of developing energy converters across diverse environments, determining the performance bounds of different technologies is essential for evaluating their potential.

Radiative heat engines are nonlinear engines that exchange heat in the form of thermal radiation. Conventional radiative heat engines [7] convert radiation from a hot emitter (e.g., the Sun), while thermoradiative heat

engines [8] generate power by radiating heat away towards a cold sink (e.g., deep space). Dual systems that combine both types of engines can also be considered [3,9,10].

A photovoltaic cell is the canonical example of a conventional radiative heat engine. Its thermoradiative counterpart is known as a *thermoradiative cell*, which aims to extract energy from the heat radiated by a hot object towards a colder environment. Thermoradiative cells are mainly envisioned in the context of nighttime power generation, whereby an object can be cooled below ambient temperature by radiating towards cold outer space at night, enabling nighttime photovoltaic power generation [11,12]. As with solar cells, nighttime thermoradiative cells take advantage of a thermal bath as a “free” heat source. For solar cells, the heat source is the Sun itself, whereas in the case of nighttime thermoradiative cells, it is the Earth’s ambient temperature.

For both solar cells and nighttime thermoradiative cells, performance can be characterized by a single metric: electrical power generated per unit area. However, in applications where energy must be expended to establish and maintain the temperature difference between the thermal reservoirs—such as thermal energy storage [13] or waste heat recovery [14]—not only *power output* but also *efficiency* must be taken into account. In such cases, the trade-off between the two figures of merit is a key consideration in the design and operation of radiative heat engines.

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The first experimental demonstration of power generation using a thermoradiative cell was achieved in 2016 [15], followed in 2019 by a demonstration using outer space as the cold sink [16]. More recent experiments have demonstrated significantly larger power densities [17] and considered rectenna-based devices [18]. However, their performance to date has remained very limited, especially when compared to their thermophotovoltaic counterparts [19–21]. Indeed, all thermoradiative experiments required lock-in detection to generate a measurable signal.

The performance limits of single- and multijunction thermoradiative devices have been highlighted in Refs. [8,22,23], both in terms of power and efficiency. At the same time, the thermodynamic power output limits associated with heat engines radiating heat towards deep space have been addressed extensively in Refs. [2,9]. However, universal power-versus-efficiency trade-off relationships for thermoradiative energy conversion, as we previously reported for conventional radiative heat engines [7], are currently unknown. As a result, it remains an open question whether radiative, thermoradiative, or dual (i.e., a combination of both) approaches offer universally superior performance bounds.

In this work, we derive the thermodynamic performance limits of thermoradiative heat engines, expressed as a trade-off between power and efficiency. We consider the nonreciprocal and reciprocal bounds, as well as the endoreversible model, and derive simple analytical expressions when available. We show that the performance of thermoradiative heat engines is fundamentally bounded by that of conventional radiative heat engines. This is especially evident for large temperature differences between the hot and cold baths, while the limits approach each other when the temperatures of the hot and cold baths are similar. Finally, we extend our results to dual engines to provide a complete performance assessment of radiative heat engines.

II. FRAMEWORK

We consider a heat source at temperature T_H and a heat sink at temperature T_C exchanging power through a heat engine at steady state. The heat source and the converter are in thermal contact, while the converter and the sink exchange heat in the form of thermal radiation. We call P_E and P_C the power densities emitted by the engine and the sink, respectively. The heat engine receives a heat flux Q_H from the source and generates an output power density W . The system is schematically represented in Fig. 1(a). In the following, we do not consider near-field effects. We also assume that all photons emitted by the heat engine reach the sink, and vice versa, such that we only need to consider exchanged power *densities* (i.e., power per unit area).

To compare with radiative engines, where the engine is in thermal contact with the cold bath [7], we define a

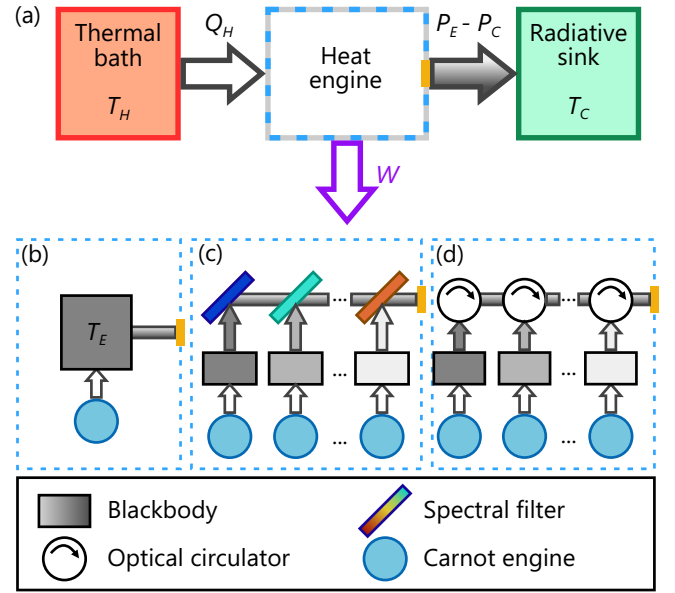


FIG. 1. (a) General representation of a thermoradiative heat engine. (b)–(d) Different heat engine models considered. (b) Blackbody coupled to a Carnot engine. (c) Infinite nonreciprocal engine for isentropic conversion. (d) Infinite reciprocal engine.

first figure of merit, ρ , as the output power density normalized to the power density emitted by a blackbody emitter at source temperature T_H :

$$\rho = \frac{W}{\sigma T_H^4}, \quad (1)$$

where σ is the Stefan-Boltzmann constant. Meanwhile, the second figure of merit is the thermodynamic efficiency, η , for which the power density is normalized to the net heat flux received from the source:

$$\eta = \frac{W}{Q_H}. \quad (2)$$

We note that a thermoradiative engine can be viewed as a radiative engine for which the source and sink temperatures have been exchanged ($T_H < T_C$). Therefore, the work produced by a thermoradiative engine can be calculated from the formulas for conventional radiative energy conversion [7] by swapping T_C and T_H . Nonetheless, the definitions for ρ and η should then be modified to reflect the reversed direction of heat flow.

III. ANALYTICAL RESULTS

We start by describing a simple endoreversible engine, which consists of a blackbody at temperature T_E coupled to a Carnot engine [Fig. 1(b)]. The normalized power output

and efficiency, respectively, are given by [24,25]

$$\rho_E = \left[\frac{T_E^4 - T_C^4}{T_H^4} \right] \left[\frac{T_H}{T_E} - 1 \right], \quad (3)$$

$$\eta_E = 1 - \frac{T_E}{T_H}. \quad (4)$$

By varying the converter temperature, T_E , from T_C to T_H , Eqs. (3) and (4) give the *endoreversible model* for thermoradiative heat engines. At the limit $T_E \rightarrow T_H$, the efficiency approaches the Carnot limit, yielding zero power output. The maximum power, $\bar{\rho}_E$, is obtained for an engine temperature, T_E , which satisfies $4T_E^5 - 3T_C T_E^4 - T_C T_H^4 = 0$. Interestingly, this is the same condition as that for radiative endoreversible engines [7].

Endoreversible thermoradiative engines have a strict power bound, $\rho_E \leq 3^3/4^4 \approx 0.11$, approached for $T_C/T_H \rightarrow 0$. When considering radiation from the Earth ($T_H = 300$ K) into outer space ($T_C = 3$ K), we find $W_B \approx 48.4 \text{ W m}^{-2}$, in accordance with Ref. [2]. A closed-form relationship between ρ_E and η_E can be derived that is independent of T_E and depends only on the temperature ratio, T_C/T_H :

$$\rho_E = \frac{\eta_E}{1 - \eta_E} \left[(1 - \eta_E)^4 - \left(\frac{T_C}{T_H} \right)^4 \right]. \quad (5)$$

This endoreversible model is not an upper bound for thermoradiative energy conversion. The *reciprocal bound* for thermoradiative heat engines, i.e., the upper bound assuming time-reversal symmetry, is obtained in the limit of an infinite number of endoreversible subengines, each converting an infinitesimal part of the incident radiation [Fig. 1(c)]. However, the difference between these two bounds is marginal, so the simple endoreversible model is an appropriate approximation of the reciprocal bound, as detailed in the Supplemental Material [26]. The *nonreciprocal bound* for thermoradiative heat engines, which is the absolute limit for thermoradiative energy conversion, is presented below.

We consider a thermoradiative heat engine performing *isentropic* energy conversion, similar to the approach considered by Landsberg for solar energy conversion [25,27]. We consider that the heat engine is at temperature T_E , emitting power density $P_E = \sigma T_E^4$. To approach an isentropic conversion process, the converter must combine an infinite number of endoreversible subengines coupled via nonreciprocal optical elements, using either optical circulators [28] or nonreciprocal emitters that break Kirchhoff's law of thermal radiation [29]. In that configuration, each subengine receives radiation from the colder subengines (to the right) and emits towards the hotter subengines (to the left) [2,28,30] [see Fig. 1(d)]. The heat and power flux

can be calculated from power and entropy conservation:

$$Q_H = \frac{4}{3} \sigma T_H (T_E^3 - T_C^3), \quad (6)$$

$$W = \frac{4}{3} \sigma T_H (T_E^3 - T_C^3) - \sigma (T_E^4 - T_C^4), \quad (7)$$

leading to the following figures of merit:

$$\rho_N = \frac{4}{3} \left(\frac{T_C}{T_H} \right)^3 \left[\left(\frac{T_E}{T_C} \right)^3 - 1 \right] - \left(\frac{T_C}{T_H} \right)^4 \left[\left(\frac{T_E}{T_C} \right)^4 - 1 \right], \quad (8)$$

$$\eta_N = 1 - \frac{3 T_C \left(\frac{T_E}{T_C} \right)^4 - 1}{4 T_H \left(\frac{T_E}{T_C} \right)^3 - 1}. \quad (9)$$

By adjusting the engine temperature, $T_E > T_C$, such that η_N is varied from 0 to η_C , the power-efficiency relationship can be determined from Eqs. (8) and (9), leading to the *nonreciprocal bound* for thermoradiative heat engines. In the Supplemental Material [26], we present a closed-form expression (independent of T_E) relating η_N and ρ_N and justify why the relationship is only a function of the temperature ratio, T_C/T_H .

For $T_E \rightarrow T_C$, the efficiency tends to the Carnot limit, η_C , as the power density vanishes. By contrast, for $T_E = T_H$, the power output is maximized, leading to

$$\bar{\rho}_N = \frac{1}{3} - \left(\frac{T_C}{T_H} \right)^3 \left[\frac{4}{3} - \frac{T_C}{T_H} \right], \quad (10)$$

$$\bar{\eta}_N = \frac{1}{4} - \frac{3 \left(\frac{T_C}{T_H} \right)^3}{1 + \frac{T_C}{T_H} + \left(\frac{T_C}{T_H} \right)^2}. \quad (11)$$

Introducing nonreciprocity, the power that can be generated through radiation from the Earth (300 K) into cold outer space (3 K) is $W_N \approx 153 \text{ W m}^{-2}$, as calculated by Buddhiraju *et al.* [2]. While operating at $T_E > T_H$ may lead to positive power output, it is always suboptimal, as both efficiency and power density are lower than those for $T_E = T_H$. Interestingly, from Eq. (10), there is an absolute limit, $\bar{\rho}_N \leq 1/3$, on the normalized power output, corresponding to an efficiency at maximum power, $\bar{\eta}_N \leq 1/4$. The equality condition is approached as $T_C/T_H \rightarrow 0$. This power limit can be understood as the free energy or exergy of radiation into space (related to the $4/3$ factor in the entropy of radiation). It was first identified by Wülfel, although he initially presented it as a paradox violating the second law of thermodynamics [31].

Linear approximations of the endoreversible model and nonreciprocal bound close to the Carnot limit ($T_E \rightarrow T_C$),

detailed in Eqs. S10–S13 within the Supplemental Material [26], lead to

$$\rho_E \approx 4 \left(\frac{T_C}{T_H} \right)^2 \eta_C (\eta_C - \eta_E), \quad (12)$$

$$\rho_N \approx 8 \left(\frac{T_C}{T_H} \right)^2 \eta_C (\eta_C - \eta_N). \quad (13)$$

Furthermore, as $T_C/T_H \rightarrow 1$, a second-order expansion in η leads to

$$\rho_E \approx 4\eta_E(\eta_C - \eta_E), \quad (14)$$

$$\rho_N \approx 8\eta_N(\eta_C - \eta_N). \quad (15)$$

These expressions are identical to those found for conventional radiative heat engines [7]. This generalizes the previous observation (both theoretical [22] and experimental [17]) that radiative and thermoradiative cells tend to offer similar performances for small temperature differences.

IV. POWER-EFFICIENCY BOUNDS

We present in Fig. 2 the power-efficiency relationship for the nonreciprocal [Eqs. (8)–(9)] and reciprocal (see the Supplemental Material [26]) bounds, as well as the endoreversible model [Eqs. (3)–(4)], for a temperature ratio $T_C/T_H = 0.5$. The reciprocal limit and endoreversible

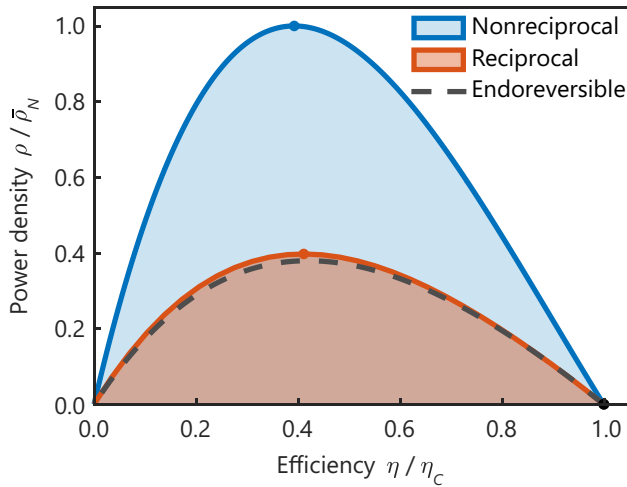


FIG. 2. Thermodynamic performance limits of thermoradiative energy conversion: maximum power output, ρ (normalized to the nonreciprocal power limit, $\bar{\rho}_N$), as a function of efficiency, η (normalized to the Carnot efficiency η_C), for the nonreciprocal bound (blue area), reciprocal bound (red area), and endoreversible model (dashed black line). Heat source temperature is $T_H = 600$ K and sink temperature is $T_C = 300$ K.

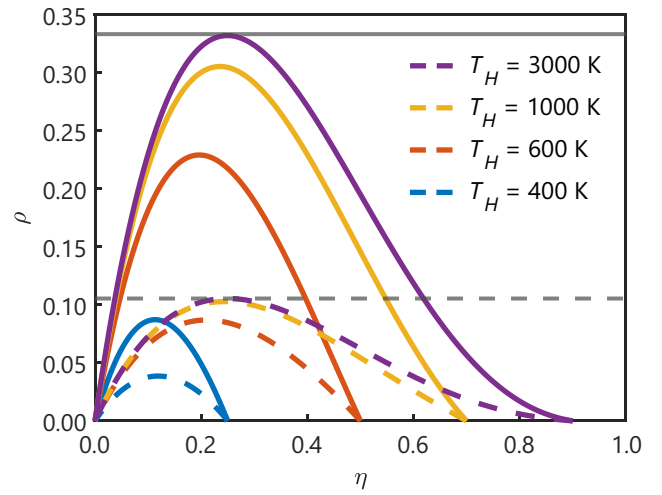


FIG. 3. Maximum power, ρ , as a function of efficiency, η , for different temperature ratios for the nonreciprocal bound (solid lines) and the endoreversible model (dashed lines). Absolute maximum achievable output power for each paradigm is indicated by gray lines.

model are similar, although we note that they are not as close as in the case of conventional radiative heat engines [7]. At the same time, a significant performance improvement can be achieved by breaking reciprocity. Indeed, for any given efficiency η and temperature ratio T_C/T_H , the power output limit of nonreciprocal systems is always at least twice as large as for reciprocal systems, as justified in the Supplemental Material [26].

Next, we show in Fig. 3 the power-efficiency relationship derived for different temperature ratios, focusing on the endoreversible and nonreciprocal cases. As $T_H \gg T_C$, the performance progressively approaches the maximum achievable power (discussed earlier), shown by dashed and solid gray lines, respectively. We also observe that $\partial\rho/\partial\eta \rightarrow 0$ close to the Carnot limit, a feature we can infer from Eqs. (12) and (13). Finally, we note that the results reported in Ref. [23] for multijunction thermoradiative devices converge, as expected, to our limits as the number of junctions increases.

V. COMPARISON WITH RADIATIVE AND DUAL HEAT ENGINES

So far, we have presented the performance of thermoradiative heat engines where the engine is in contact with the hot source. In our previous work [7], we considered the performance limits of radiative heat engines, where the engine was in contact with the cold sink. To complete this framework, here, we also consider the possibility of implementing dual radiative heat engines that generate power on both the hot and cold sides, as previously considered in Refs. [3,9,10]. With respect to Fig. 4, we consider a dual engine with a left engine at temperature T_L (hot side),

generating work W_L , and a right engine at temperature T_R (cold side), generating work W_R . We impose the inequalities $T_H \geq T_L \geq T_R \geq T_C$ such that W_L and W_R are both positive. The total power output is $W = W_L + W_R$. With these notations, the definitions of normalized power and efficiency of Eqs. (1) and (2) remain identical for dual engines. In analogy with the previous sections, we consider two cases: the endoreversible model, which considers blackbodies coupled to Carnot engines, and the nonreciprocal bound, assuming no entropy generation on either side. The formulas are obtained by combining the results of thermoradiative engines derived in this paper with those of conventional radiative heat engines from Ref. [7].

For the endoreversible case, the power and efficiency of dual engines are given by

$$\rho_E^d = \left(\frac{T_R}{T_H}\right)^3 \left[\left(\frac{T_L}{T_R}\right)^4 - 1 \right] \left[\frac{T_R}{T_L} - \frac{T_C}{T_H} \right], \quad (16)$$

$$\eta_E^d = 1 - \frac{T_L}{T_R} \frac{T_C}{T_H}. \quad (17)$$

We verify $\eta_E^d \leq \eta_C$ from the constraint $T_L \geq T_R$. For a given efficiency, from Eq. (17), the ratio T_L/T_R is fixed; hence, the power output is an increasing function of T_R [see Eq. (16)]. Therefore, the optimal configuration leads to

$$T_L = T_H, \quad (18)$$

$$\eta_E^d = 1 - \frac{T_C}{T_R}. \quad (19)$$

These expressions coincide with the endoreversible model for conventional radiative engines ($W_L = 0$). Thereby, adding a thermoradiative engine on the hot side yields no performance improvement in the endoreversible case. We argue that this conclusion extends to the reciprocal bound, for the following reasons. First, the argument

derived for a single engine can be made on a per-photon-energy basis. Second, the results obtained for the endoreversible model are almost identical to those of reciprocal dual engines presented by Park *et al.* in Ref. [3], Fig. 3(d), when considering the same temperature conditions.

As a result, *the performance of any reciprocal system is practically bounded by the endoreversible model for conventional radiative engines.* This implies that employing thermoradiative cells in place of—or even in addition to—thermophotovoltaic cells cannot be justified from a performance standpoint, and therefore, requires additional motivation, such as economic considerations (e.g., reduced area to convert a given radiative power). In this context, we believe that efforts are better directed towards approaching the endoreversible limit through a combination of multijunction thermophotovoltaic cells [19] and minimized sub-band-gap heat transfer [20].

We note that the performance could be substantially enhanced by allowing $W_L < 0$. This regime corresponds to thermophotonics, where the hot-side engine operates as a light-emitting diode (LED) rather than a thermoradiative cell [10]. However, this configuration remains experimentally challenging due to the exceptionally high radiative efficiency required of the LED, and no conclusive demonstration has been reported to date.

Next, we consider the case of nonreciprocal dual engines, where the performance bounds are

$$\rho_N^d = \frac{4}{3} \left[1 - \frac{T_C}{T_H} \right] \left[\left(\frac{T_L}{T_H}\right)^3 - \left(\frac{T_R}{T_H}\right)^3 \right], \quad (20)$$

$$\eta_N^d = \eta_C. \quad (21)$$

This nonreciprocal dual case was previously investigated in Refs. [2,3], demonstrating the peculiar fact that a nonreciprocal dual engine can produce finite power at Carnot efficiency. In this idealized case, there is therefore no trade-off between power and efficiency. This has been shown to be compatible with thermodynamic principles, although it implies diverging fluctuations [6]. Assuming

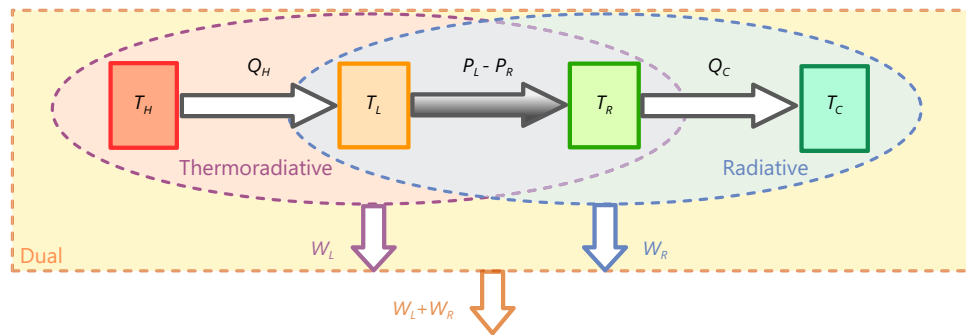


FIG. 4. Illustration of a dual radiative engine and its decomposition into radiative and thermoradiative subparts.

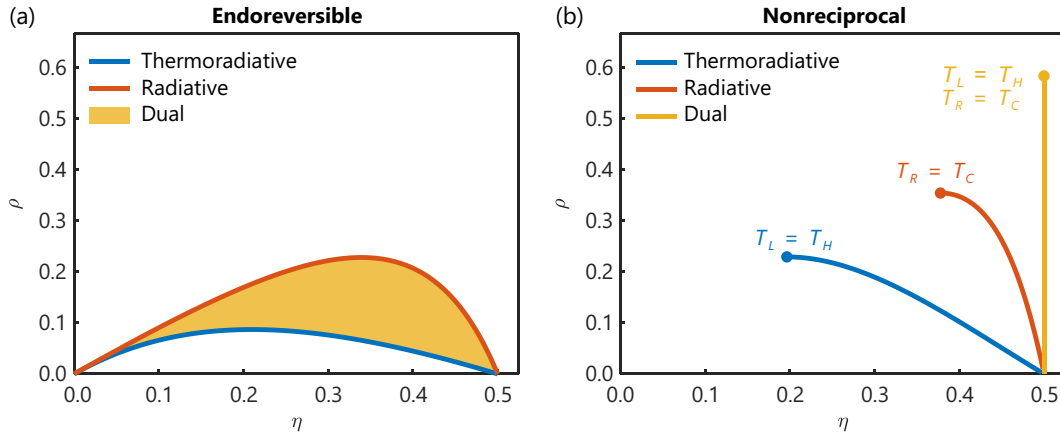


FIG. 5. Power-versus-efficiency characteristics of (a) endoreversible and (b) nonreciprocal heat engines when considering engines exclusively on the hot side (thermoradiative) in blue, on the cold side (radiative) in red, or on both sides (dual) in yellow, for a temperature ratio $T_C/T_H = 0.5$.

both engines generate positive work, maximizing power yields $T_L = T_H$ and $T_R = T_C$, leading to

$$\rho_{N,\max}^d = \frac{4}{3} \left[1 - \frac{T_C}{T_H} \right] \left[1 - \left(\frac{T_C}{T_H} \right)^3 \right], \quad (22)$$

which is the sum of the maximum power generated by nonreciprocal radiative and thermoradiative engines. Since a dual nonreciprocal heat engine simultaneously harvests radiation from both the hot and cold reservoirs, it can extract more available work than either engine alone. Notably, the maximum normalized power output, $\rho_{N,\max}^d$, can exceed unity, approaching 4/3 for $T_C/T_H \rightarrow 0$, in accordance with the exergy of thermal radiation.

All aforementioned results are summarized in Table I, and the performance is illustrated in Fig. 5 for the endoreversible (panel a) and nonreciprocal (panel b) cases, for $T_C/T_H = 0.5$. In the Supplemental Material [26], we also consider the cases $T_C/T_H = 0.1$ and $T_C/T_H = 0.9$. Since

in the case of endoreversible dual engines, T_L and T_R can be varied independently, the dual results in panel (a) cover an area instead of being a curve.

As stated above, in the endoreversible model, there is no benefit to operating a dual engine compared to a purely radiative one. Accordingly, assuming reciprocal heat transfer, implementing thermoradiative cells provides no advantage. By contrast, as shown in panel (b) and inferred from Eqs. (21) and (22), nonreciprocal radiative engines benefit strongly from dual-engine operation, enabling finite power generation, even at the Carnot efficiency limit.

Overall, the most crucial observation is that *for any given temperature ratio and efficiency, conventional radiative heat engines consistently yield higher power output than thermoradiative ones*. The difference is particularly striking for large temperature differences, whereas for $T_C/T_H \rightarrow 1$, heat transfer becomes linear with temperature such that both models converge towards the same parabolic behavior [see Eqs. (14)–(15)].

TABLE I. Summary of the power-efficiency relationships for different kinds of radiative engines, considering the endoreversible model and the nonreciprocal limit.

	Endoreversible	Nonreciprocal
Radiative	$\rho_E = \left[1 - \left(\frac{T_E}{T_H} \right)^4 \right] \left[1 - \frac{T_C}{T_E} \right]$ $\eta_E = 1 - \frac{T_C}{T_E}$	$\rho_N = 1 - \frac{4}{3} \frac{T_C}{T_H} - \left(\frac{T_E}{T_H} \right)^4 \left[1 - \frac{4}{3} \frac{T_C}{T_E} \right]$ $\eta_N = \frac{\rho_N}{1 - \left(\frac{T_E}{T_H} \right)^4}$
Thermoradiative	$\rho_E = \left[\frac{T_E^4 - T_C^4}{T_H^4} \right] \left[\frac{T_H}{T_E} - 1 \right]$ $\eta_E = 1 - \frac{T_E}{T_H}$	$\rho_N = \frac{4}{3} \left(\frac{T_C}{T_H} \right)^3 \left[\left(\frac{T_E}{T_C} \right)^3 - 1 \right] - \left(\frac{T_C}{T_H} \right)^4 \left[\left(\frac{T_E}{T_C} \right)^4 - 1 \right]$ $\eta_N = 1 - \frac{3}{4} \frac{T_C}{T_H} \frac{\left(\frac{T_E}{T_C} \right)^4 - 1}{\left(\frac{T_E}{T_C} \right)^3 - 1}$
Dual	$\rho_E = \left(\frac{T_R}{T_H} \right)^3 \left[\left(\frac{T_L}{T_R} \right)^4 - 1 \right] \left[\frac{T_L}{T_L} - \frac{T_C}{T_H} \right]$ $\eta_E = 1 - \frac{T_L}{T_R} \frac{T_C}{T_H}$	$\rho_N = \frac{4}{3} \left[1 - \frac{T_C}{T_H} \right] \left[\left(\frac{T_L}{T_H} \right)^3 - \left(\frac{T_R}{T_H} \right)^3 \right]$ $\eta_N = \eta_C$

VI. CONCLUSION

In this work, we derived performance bounds for thermoradiative energy conversion, expressed in terms of the maximum power density achievable at a given efficiency. We demonstrated that, for any efficiency, radiative energy converters consistently generate more power when the engine operates on the cold side. In practical terms, this implies that *optimal thermophotovoltaic devices will always outperform optimal thermoradiative devices*. This conclusion holds, even before considering that thermoradiative cells operate on the *hot* side, where elevated temperatures exacerbate nonradiative processes, thereby further limiting efficiency.

For small temperature differences between hot and cold reservoirs, radiative and thermoradiative energy conversion exhibit similar performance limits. However, in this regime, thermoelectric devices are typically more suitable than radiative heat engines [32]. As the temperature difference increases, thermoradiative performance saturates and becomes dominated by that of radiative engines. Introducing a combination of engines on the hot and cold sides offers potential gains, but only when nonreciprocal elements are introduced. In that regard, promising results have been obtained by breaking Kirchhoff's law of thermal radiation [29]. Still, this remains to be translated into developments on nonreciprocal energy converters, which require extremely efficient implementations of nonreciprocity for specific spectral and angular ranges. As a result, *all practical radiative engines can be considered bounded by the radiative endoreversible model*, which therefore serves as a critical reference point for evaluating device performance [21]. Besides nonreciprocity, the only ways to surpass this limit involve super-Planckian radiative exchange, for example, using thermophotonics [33], near-field effects [34,35], or a combination of both [36].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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