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Research Article



Coupled Thermal–Electrical Performance in Hybrid Energy Systems: A Review of PV–TEG–PCM Integration, Modeling, and Waste-Heat Recovery

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Abstract: Photovoltaic (PV) systems, thermoelectric generators (TEGs), and phase-change materials (PCMs) offer complementary approaches to electricity generation, thermal management, and energy storage. Their integration can improve the utilization of available thermal energy, but the resulting performance depends on interactions among photovoltaic temperature, thermoelectric temperature difference, PCM charging and discharging, heat-transfer characteristics, and auxiliary energy consumption. This thematic narrative review examines the fundamental principles, material characteristics, system architectures, and numerical modeling approaches associated with PV–TEG–PCM integration and thermoelectric waste-heat recovery. Applications involving fuel cells, automotive exhausts, and industrial heat sources are considered alongside hybrid photovoltaic configurations. A comparative analysis of previous studies highlights the influence of thermal interfaces, heat-exchanger geometry, transient operating conditions, and performance evaluation methods. The reviewed evidence indicates that improvements in individual components do not necessarily produce corresponding gains in net system energy, particularly when additional thermal resistance, hydraulic losses, or auxiliary power requirements are introduced. The analysis also identifies limitations arising from inconsistent reference configurations, incomplete transient assessment, and insufficient consideration of long-term reliability. Future progress requires reproducible experimental protocols, validated coupled models, robust multi-objective optimization, and performance evaluation under representative operating conditions. Overall, the review emphasizes that the practical value of integrated thermoelectric systems should be established through measurable net-energy benefits and system-level assessments rather than peak component performance alone.

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Nomenclature

Symbol	Definition	SI unit
A	Active area of the photovoltaic module	m^2
c_p	Effective specific heat capacity of the PCM	J kg^{-1} K^{-1}
E_{TEG}	Electrical energy generated by the TEG over a specified time interval	J
f_l	Liquid fraction of the PCM	–
G	Incident solar irradiance	W m^{-2}
$g_ι$	Inequality constraint in the optimization problem	Depends on formulation
h_j	Equality constraint in the optimization problem	Depends on formulation
I	Electrical current	A
J	Electrical current density	A m^{-2}
J	Objective function in the optimization problem	Depends on objective
L	Latent heat of the PCM	J kg^{-1}
m	Mass of the PCM	kg
P	Electrical power	W
P_{aux}	Auxiliary power consumption	W
P_{gross}	Gross electrical power generated by the PV–TEG system	W
P_{net}	Net electrical power after subtracting auxiliary consumption	W
P_{PV}	Photovoltaic electrical power	W
P_{TEG}	Thermoelectric generator electrical power	W
P_{max}	Maximum electrical power under the specified circuit conditions	W
Q_{PCM}	Thermal energy stored in or released by the PCM	J
Q_h	Heat-transfer rate entering the hot side of the TEG	W
q	Heat-flux density	W m^{-2}
R^{int}	Internal electrical resistance of the TEG	O
R_L	External electrical load resistance	O
$R_{th,total}$	Total thermal resistance between the heat source and heat sink	K W^{-1}
R_{TEG}	Thermal resistance of the thermoelectric module	K W^{-1}
S	Seebeck coefficient	V K^{-1}
S_{eff}	Effective Seebeck coefficient of the thermoelectric module	V K^{-1}
T	Absolute temperature	K
T_{cell}	PV cell temperature	K
T_h	Hot-side temperature of the TEG	K
T_c	Cold-side temperature of the TEG	K
T_{ref}	Reference temperature in the PCM enthalpy expression	K
ΔT	Temperature difference across the TEG, \(T_h-T_c\)	K
t	Time	s
t_0	Initial time of the energy-generation interval	s
t_f	Final time of the energy-generation interval	s
V	Electrical voltage or electric potential, depending on context	V
V_{oc}	Open-circuit voltage	V
x	Vector of design variables in the optimization problem	Depends on variable
X_{hybrid}	Performance metric of the hybrid system	Depends on metric
$X_{reference}$	Performance metric of the reference system	Depends on metric
ZT	Dimensionless thermoelectric figure of merit	–
$η_{PV}$	Effective photovoltaic conversion efficiency	–
$η_{TEG}$	Thermoelectric conversion efficiency	–
κ	Total thermal conductivity	W m^{-1} K^{-1}
Π	Peltier coefficient	V
σ	Electrical conductivity	S m^{-1}

Abbreviation	Definition
CFD	Computational fluid dynamics
FEM	Finite element method
PCM	Phase-change material
PEM	Proton exchange membrane
PV	Photovoltaic
PVT	Photovoltaic–thermal
TEG	Thermoelectric generator
CPV	Concentrated photovoltaic
ZT	Dimensionless thermoelectric figure of merit

INTRODUCTION

The demand for more efficient energy conversion has sustained interest in technologies that recover thermal energy otherwise rejected by energy-conversion and industrial processes. Thermoelectric generators are attractive in this context because they convert a temperature difference directly into electricity without moving mechanical components. Their compact construction can be useful where conventional heat engines are impractical, although achievable output is constrained by material properties and by the thermal conditions maintained across the device. Early work on thermoelectric-coupled photovoltaic systems explored whether a TEG could recover part of the heat associated with PV operation, while reviews of PV thermal management and solar thermoelectric cogeneration established the wider context for such hybrid designs[1,2]. The motivation for hybridization is not simply to add another electricity-producing component. A PV module absorbs solar radiation, converts a portion to electrical power, and dissipates the remaining energy through thermal pathways. A TEG placed in that pathway may convert part of the heat flow into electricity, but it also introduces thermal resistance and changes the module's heat-rejection conditions. Work on renewable-energy harvesting and numerical PV–TEG/PCM integration has therefore examined the combined response rather than treating the components as independent devices[3,4]. PCM integration introduces a temporal dimension. During melting, a PCM absorbs latent heat; during solidification, it releases stored heat. This behavior can moderate temperature fluctuations or extend heat availability beyond the period of direct input, but the benefit depends on the transition temperature, latent heat, conductivity, geometry, and cycle duration. Studies of PV–TEG hybrid systems and TEGs coupled with PCM show why storage and conversion must be assessed together: a higher storage capacity does not necessarily mean higher instantaneous power or a larger net energy yield[5,6]. Research on TEG–PCM coupling and broader thermal-storage technologies has examined both the potential and limitations of latent-heat storage, while theoretical analyses of hybrid solar thermoelectric–photovoltaic generators have shown that predicted benefits depend on the assumed operating conditions and reference technology[7,8]. The device geometry and the thermal pathway also matter. Variable thermoelectric-leg geometries and theoretical PV–TEG studies indicate that component design can alter the balance between heat transfer, electrical resistance, and temperature difference[9,10]. TEGs are also studied for recovering heat from fuel cells, vehicle exhausts, and industrial heat exchangers. Such applications broaden the design space but introduce different constraints: fuel-cell systems must preserve the primary stack's thermal requirements; vehicle systems face transient load, vibration, packaging, and backpressure; and heat-exchanger systems must balance heat transfer against flow resistance. Fuel-cell recovery studies illustrate the importance of source-side flow and the integration of thermoelectric modules with the surrounding thermal system[11,12]. These application-specific constraints provide the basis for examining thermoelectric conversion as part of a coupled energy system rather than as an isolated device. The following sections establish the physical principles and governing equations, then assess how thermal storage, heat-exchanger design, and source variability influence the performance of PV–TEG–PCM systems. Figure 1 presents the conceptual architecture used to organize this discussion[13].

Scope and Review Approach: This study adopts a thematic narrative review approach to examine the integration of thermoelectric generators TEGs with PV systems, PCMs and waste-heat recovery technologies. The review addresses four interconnected research areas: thermoelectric conversion and device modeling, PCM-assisted thermal management, PV–TEG hybrid configurations, and thermoelectric recovery of waste heat from fuel cells, automotive exhausts, and industrial processes. Rather than examining these technologies independently, the review considers their interactions within a common thermal–electrical framework, with particular attention to the factors governing overall system performance. The literature is synthesized according to the engineering questions addressed by the studies, including the influence of material properties, thermal coupling, heat-exchanger configuration, PCM placement, operating conditions, and numerical modeling assumptions. Experimental investigations, analytical formulations, and numerical studies are considered as complementary sources of evidence. Their findings are interpreted in relation to the physical configurations and operating conditions reported in the respective publications. Particular emphasis is placed on studies that help explain the relationships between thermal management, temperature distribution, thermoelectric output, and system-level energy recovery. To support the comparative discussion, the reviewed investigations are examined in terms of their application, system configuration, research method, reported performance, and principal limitations. This framework

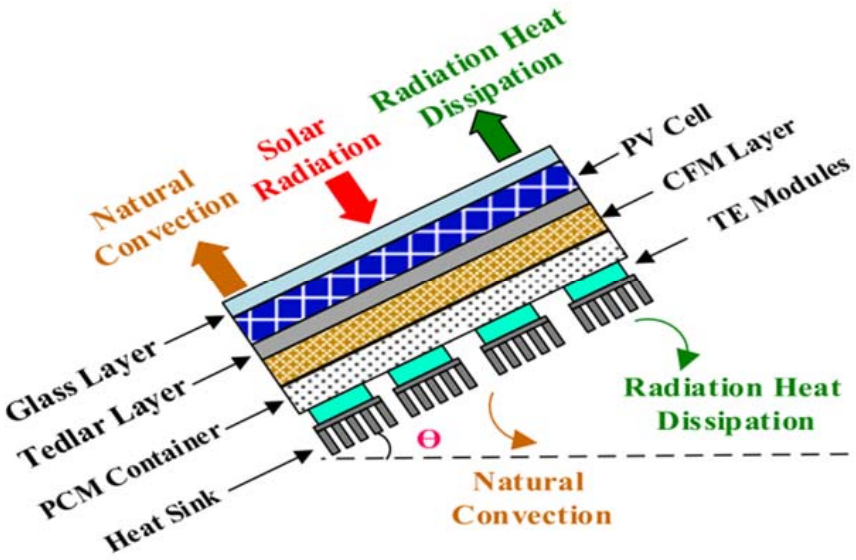


Figure 1: Conceptual architecture of an integrated PV–TEG–PCM system

is reflected in the comparison of previous studies presented in Section 8. Quantitative findings are retained in their original contexts, including the operating conditions, reference configurations, and performance indicators under which they were obtained. Because the available studies differ in their experimental arrangements, heat-source characteristics, thermal boundaries, and evaluation metrics, their numerical improvements are not treated as directly interchangeable. Instead, the comparison emphasizes the mechanisms responsible for the reported outcomes and the limitations affecting their interpretation. A central consideration throughout the review is the distinction between component-level improvements and net system-level benefits. Accordingly, electrical power, accumulated energy generation, thermal-storage behavior, heat-transfer enhancement, and auxiliary energy requirements are considered as different, but interconnected, aspects of performance. This distinction is particularly important for PCM-assisted configurations and systems exposed to variable heat sources, where improvements in peak output or heat-transfer rate do not necessarily correspond to greater electrical energy recovery over a complete operating cycle. The synthesis is qualitative and application-oriented, rather than a systematic review or statistical meta-analysis. It does not assume that results obtained under different operating conditions can be combined into a single quantitative performance estimate. Instead, recurring findings, engineering trade-offs, methodological limitations, and differences between reported outcomes are examined to identify areas of agreement and unresolved questions. The resulting assessment provides the basis for the cross-cutting synthesis in Section 9 and the future research priorities developed in Section 10.

This approach is intended to clarify the conditions under which integrated thermoelectric systems may provide meaningful benefits, while recognizing the limitations of comparisons across different technologies and applications. By connecting physical mechanisms, system architectures, modeling practices, and reported experimental outcomes, the review aims to provide a coherent basis for evaluating the practical potential of PV–TEG–PCM integration and thermoelectric waste-heat recovery.

THERMOELECTRIC CONVERSION: PRINCIPLES, MATERIALS, AND EQUATIONS

Historical development and physical effects: The modern field of thermoelectricity grew from observations that temperature differences can produce electrical effects and that electrical current can transport heat. Seebeck's experiments established the temperature-induced voltage effect, while Peltier identified heating or cooling associated with current at a junction. Later work on the Thomson effect and irreversible thermodynamics helped place these observations within a unified framework for coupled heat and charge transport[14,15]. These effects are not separate curiosities in a practical TEG. The Seebeck effect supplies the useful voltage; the Peltier effect describes reversible heat transport associated with current at

material junctions; the Thomson effect accounts for distributed reversible heating or cooling in a conductor with a temperature gradient; and Joule heating represents irreversible electrical dissipation. Their relative importance depends on geometry, current, material properties, and the temperature field. The thermoelectric handbook and foundational analyses of reciprocal and irreversible processes provide the theoretical background for treating these mechanisms consistently[16,17]. Onsager reciprocity and subsequent thermodynamic formulations are important because thermoelectric heat and charge transport are coupled. In practical device modeling, the constitutive relations must use compatible sign conventions for current, voltage, heat flux, and Seebeck coefficient. A sign inconsistency may leave a model numerically solvable while reversing the predicted direction of heat transport or electrical output. The thermodynamic treatment of thermoelectricity and modern materials reviews provide the basis for a consistent device-level description[18,19]. The physical mechanisms underlying thermoelectric conversion are summarized in Figure 2.

Governing equations for a thermoelectric element: At device level, the electrical response depends on the Seebeck coefficient S, electrical conductivity σ, thermal conductivity κ, absolute temperature T, and imposed temperature difference. A common dimensionless material indicator is the figure of merit ZT. It provides a useful first screening measure, but it cannot replace a device-level analysis because electrical contact resistance, thermal interfaces, heat-exchanger performance, and load matching influence the usable output. Modern reviews of thermoelectric materials discuss the relationships among these transport properties and their role in heat-to-electricity conversion[20,21].

$$ZT = \frac{S^2 \sigma T}{\kappa}$$

Here, S is the Seebeck coefficient (V K ^{1}), σ is electrical conductivity (S m ^{1}), T is absolute temperature (K), and κ is total thermal conductivity (W m ^{1} K ^{1}). A high ZT generally requires a favorable combination of large Seebeck coefficient, high electrical conductivity, and low thermal conductivity. These variables are coupled in real materials, so maximizing one property independently may not maximize the final figure of merit. For an effective element with approximately constant S across the operating range, the open-circuit voltage can be approximated by the product of the Seebeck coefficient and the temperature difference. For a module containing multiple p-type and n-type legs, the net voltage depends on the effective Seebeck contributions and the electrical interconnection.

$$V_{\mathrm{oc}} \approx S_{\mathrm{eff}}(T_h - T_c) = S_{\mathrm{eff}} \Delta T$$

When the module is connected to a load, electrical power is P = VI. In a simplified circuit with internal resistance R_{int} and load resistance R_L, the current is determined by the total circuit resistance, and maximum power is approached when load resistance is matched to internal resistance. This familiar result is an idealized starting point; temperature-dependent material properties and the feedback between current and heat flow can shift the optimum in a fully coupled model.

$$P = VI$$

$$I \approx \frac{V_{\mathrm{oc}}}{R_{\mathrm{int}} +}$$

$$P_{\max} \approx \frac{V_{\mathrm{oc}}^2}{4R_{\mathrm{int}}}, \qquad R_L = R_{\mathrm{int}}$$

The energy equation must account for heat conduction, thermoelectric heat transport, and internal heat generation. In a one-dimensional idealized leg, the conductive heat flux follows Fourier's law, while the electrical constitutive relation contains both the electric-potential gradient and the Seebeck contribution. In multidimensional simulation, these terms are expressed in vector form and solved together with charge conservation.

$$\mathbf{q} = -\kappa \nabla T + \Pi \mathbf{J}$$

$$\mathbf{J} = \sigma(-\nabla V - S \nabla T)$$

In these relations, q is heat-flux density, Π is the Peltier coefficient, J is current density, and V is electric potential. With consistent sign conventions, Π and S are linked by the Kelvin relation Π = ST. The precise governing equations implemented in a solver may be written in alternative equivalent forms; the important requirement is consistency between constitutive equations, boundary conditions, and material-property definitions. A material-

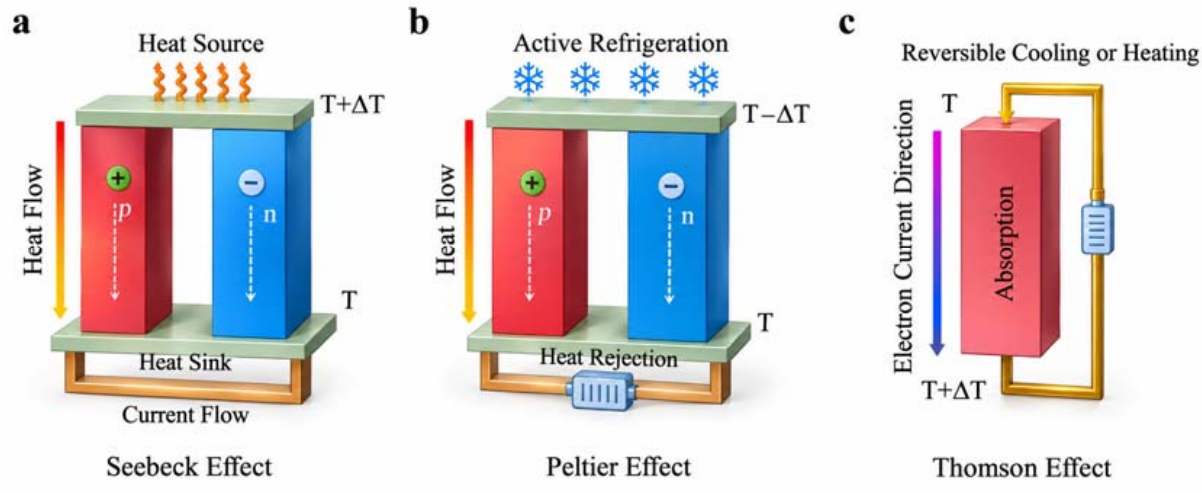


Figure 2. Schematic illustration of the principal thermoelectric effects: (a) Seebeck effect, (b) Peltier effect, and (c) Thomson effect.

level model often prescribes T_h and T_c, but a system-level model should calculate them from the heat source, thermal contacts, heat exchangers, and cooling environment. This distinction is central for PV–TEG–PCM configurations, where the TEG changes the heat path and the PCM changes the transient boundary conditions. At the module scale, thermoelectric performance depends on both the semiconductor legs and the arrangement of the electrical and thermal connections. The p-type and n-type legs are connected electrically in series and thermally in parallel, while the ceramic plates provide electrical insulation and support heat transfer between the external surfaces and the thermoelectric elements. Figure 3 illustrates these structural features and the interfaces through which heat enters and leaves the module[20,21].

Classification of thermoelectric materials: Thermoelectric materials are selected according to the temperature range, chemical stability, mechanical requirements, manufacturability, and cost of the intended application. No material family is universally optimal. Bismuth telluride-based materials are widely associated with near-room-temperature operation; lead telluride and related compounds are used in intermediate-temperature contexts but raise toxicity and environmental concerns; skutterudites and half-Heusler compounds are investigated for higher-temperature applications; silicon–germanium materials have been used in high-temperature environments; and oxide or polymer-based materials may offer advantages in stability, availability, flexibility, or processing, depending on the design.

As Table 1 indicates, the choice of thermoelectric material should follow the source temperature and the intended duty cycle rather than a single ranking of ZT. In a PV–TEG system, the operating temperature difference may be modest, and module-level contact resistance can be comparable in importance to intrinsic material performance. In automotive exhaust recovery, higher temperatures may be available but thermal cycling, vibration, and packaging can dominate long-term reliability. Reviews of thermoelectric conversion and materials processing emphasize that the practical module is a composite assembly whose performance depends on both active materials and their interfaces[20,21].

Photovoltaic temperature response and hybrid coupling: Photovoltaic modules convert incident radiation into electrical energy, but their output is influenced by cell temperature. For conventional crystalline-silicon modules, rising temperature typically reduces open-circuit voltage and maximum power, even though short-circuit current may increase slightly. The net response depends on the cell technology and module construction. Research on cooling photovoltaic cells under concentrated illumination and passive PV cooling

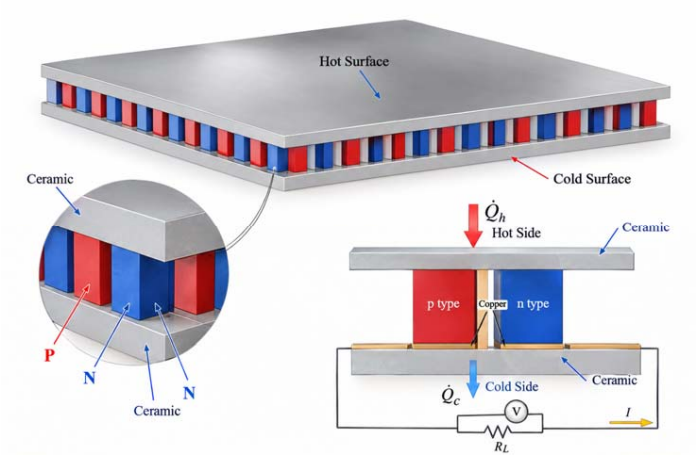


Figure 3. Structural configuration of a thermoelectric generator module, illustrating the p-type and n-type thermoelectric legs, ceramic plates, metallic interconnects, and the principal heat-transfer and electrical pathways.

provides a basis for treating temperature management as an integral part of system design[22,23].

$$P_{\mathrm{PV}} = \eta_{\mathrm{PV}}(T_{\mathrm{cell}}, G)AG$$

In this expression, P_{PV} is PV electrical power, η_{PV} is the effective conversion efficiency, T_{cell} is cell temperature, G is incident irradiance, and A is the active area. The expression is a system-level representation rather than a complete semiconductor model. A coupled energy balance must also account for absorbed radiation, electrical conversion, convection, radiation, conduction through the module, and heat transferred to any attached TEG or PCM.

A PV–TEG arrangement can increase gross electrical output if the TEG converts part of the thermal flow into useful power. Yet integration may introduce thermal resistance that changes the PV cell temperature, and the TEG needs a cold-side heat sink to maintain ΔT. Therefore, total power should be evaluated as a sum of PV and TEG contributions at a consistent boundary, with auxiliary consumption subtracted when net performance is reported.

$$P_{\mathrm{gross}} = P_{\mathrm{PV}} + P_{\mathrm{TEG}}$$

$$P_{\mathrm{net}} = P_{\mathrm{PV}} + P_{\mathrm{TEG}} - P_{\mathrm{aux}}$$

The temperature response of a PV module is closely connected to its electrical output and to the thermal conditions imposed by an attached TEG. Heat extraction may support additional thermoelectric generation, but the added thermal resistance and the capacity of the cold-side heat sink determine whether the overall arrangement is beneficial. Figure 4 compares the experimentally measured front-surface temperature of a PV module operating with and without an integrated TEG. The results illustrate the temperature response of the PV module under the reported outdoor operating conditions and show how integrating a TEG can influence its thermal behavior[24].

PCM-BASED THERMAL STORAGE AND INTEGRATED SYSTEMS

Latent-heat storage and material selection: Phase-change materials store thermal energy by absorbing or releasing latent heat during a phase transition. Compared with sensible storage, latent storage can accommodate substantial energy transfer over a relatively narrow temperature interval. Its usefulness depends on matching the transition range to the actual operating conditions, as well as on latent heat capacity, thermal conductivity, density, compatibility with containment, cycling stability, and cost. Reviews of PCM thermal management and storage describe a wide range of applications but also emphasize material and system limitations[25,26].

$$Q_{PCM} = m\left[c_p\left(T - T_{ref}\right) + f_l L\right]$$

Here, m is PCM mass, c_p is the effective specific heat, L is latent heat, and f_l is the liquid fraction, which varies from 0 to 1 through the phase transition. This simplified enthalpy representation is useful for describing the energy stored as sensible and latent contributions[27].Real PCM behavior may require a temperature-dependent

Table 1: Major thermoelectric material families and design considerations. Ranges are qualitative and should be specified numerically for a particular material composition.

Material family	Typical application range or context	Advantages	Key limitations / selection issues
Bi Te -based alloys	Near-room-temperature and moderate-temperature modules	Established module technology; useful performance near ambient conditions	Tellurium cost/availability; brittleness; interface and contact reliability
PbTe-based compounds	Intermediate-temperature heat recovery	Useful thermoelectric performance in appropriate temperature ranges	Lead toxicity and environmental management; operating-temperature constraints
Skutterudites	Intermediate-to-high temperature research and recovery systems	Composition can be tuned to reduce lattice thermal conductivity	Processing complexity; stability and contact engineering
Half-Heusler compounds	Medium-to-high temperature applications	Mechanical robustness and potential for higher-temperature operation	Relatively high thermal conductivity in some compositions; cost and optimization
SiGe alloys	High-temperature applications	Thermal stability at elevated temperatures	Material and processing cost; lower suitability for low-temperature systems
Oxide thermoelectrics	Oxidizing/high-temperature environments	Potential chemical and thermal stability	Often lower electrical performance than than leading chalcogenides
Conducting polymers / composites emerging devices	Flexible, low-temperature or	Low density, flexibility, potentially low-cost processing	Environmental stability and generally lower power factor
Nanostructured / composite systems	Research across multiple temperature ranges	Microstructure can modify carrier transport and phonon scattering	Reproducibility, scale-up, interface effects, and long-term stability

Table 2: Common PCM heat-transfer enhancement strategies and the trade-offs that should be assessed.

Enhancement strategy	Potential benefit	Trade-off to report
Extended fins	Shorter conduction path and larger heat-transfer area	Added mass, manufacturing complexity, reduced PCM volume
Metal or graphite foam	Higher effective conductivity and distributed heat paths	Pressure/contact issues, material cost reduced latent-storage fraction
Conductive PCM composite	Improved thermal response within the PCM volume	Possible reduction in latent heat per unit mass; compatibility and stability
Heat pipe / thermal spreader	Redistribution of heat to remote regions	Cost, orientation or operating limits, added interfaces may
Optimized PCM geometry	Better match between storage volume and thermal boundary	complicate manufacture and maintenance

liquid fraction and a phase-change interval rather than a single melting temperature. The charging and discharging response of a PCM can be described by tracking its liquid fraction over time[28]. During charging, the liquid fraction increases as the material melts and absorbs latent heat; during discharging, it decreases as the stored heat is released and the material solidifies. The rate of either process depends on the thermal pathway and heat-transfer area, so the response should be interpreted for the geometry and boundary conditions used in the original study. Figure 5 presents a published example of these charging and discharging trends for a latent-heat storage unit with uniform fins. The data illustrate PCM behavior in a thermal-storage system; they are not direct measurements of a PV–TEG–PCM assembly. In an integrated PV–TEG system, the same phase-change processes may affect the temperature difference available to the TEG, but that effect must be evaluated under the relevant system operating conditions[29].

PCM–TEG integration and transient output: When a PCM is coupled to a TEG, the stored thermal energy can sustain heat transfer after the external heat input decreases. This may extend the period of power generation or reduce rapid temperature fluctuations. The benefit depends on how much of the stored energy is available at a useful temperature difference, not simply on the total latent heat. Reviews of TE–PCM systems and hybrid photovoltaic/thermal/PCM/thermoelectric concepts identify this coupling as promising while noting that geometry and thermal pathways remain central design variables[30,31]. Experimental investigations have considered PCM as a means of protecting TEGs from transient temperature changes, while further studies have examined heat-transfer mechanisms and structural design to improve device performance. These studies motivate reporting the complete transient response: hot-side and cold-side temperatures, PCM phase state, voltage, current, power, and total energy over the cycle [32,33]. Automotive TEG studies have investigated PCM integration as a means of managing fluctuations in exhaust heat during transient operation. Although thermal storage may moderate these variations, its contribution to electrical generation depends on the source-temperature history, PCM properties, and thermal coupling with the TEG[34,35]. The location of the PCM within the thermal pathway is particularly important. When positioned on the cold side, the PCM

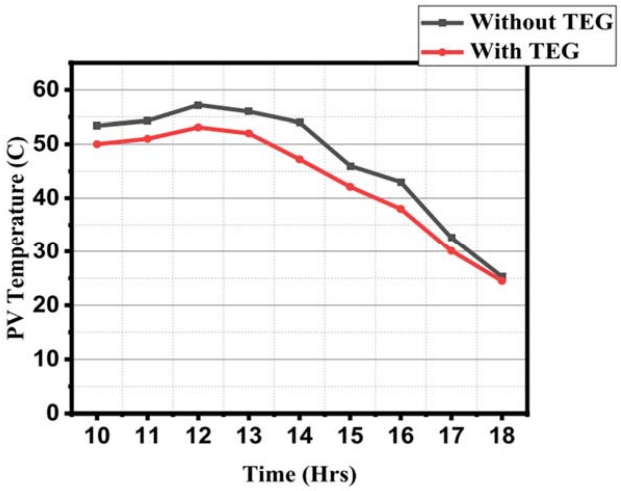


Figure 4: Experimental variation in photovoltaic front-surface temperature with and without an integrated thermoelectric generator.

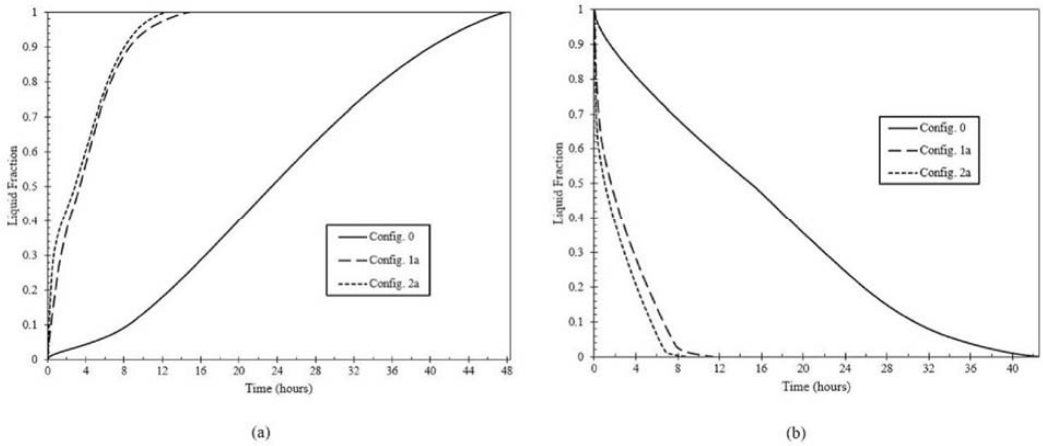


Figure 5: Evolution of PCM liquid fraction during (a) charging and (b) discharging for the no-fin reference and two uniform-fin configurations.

can absorb heat and delay the temperature rise at the cold junction, helping to maintain the temperature difference across the thermoelectric module. Incorporating a conductive porous structure, such as copper foam, can further improve heat transfer within the storage medium. However, the effectiveness of this arrangement depends on the PCM's charging and discharging characteristics and its ability to reject stored heat to the surroundings. Figure 6 shows an experimental cold-side PCM–TEG assembly incorporating porous copper foam[36].

Heat-transfer enhancement in PCM: The thermal conductivity of many PCMs is insufficient to charge or discharge a large storage volume rapidly. Fins, metal foams, graphite-based structures, heat pipes, and conductive composites are therefore used to shorten heat-transfer paths or increase effective conductivity. These methods impose trade-offs: fins and porous structures add material and may displace PCM; conductive fillers can change latent heat per unit mass; and heat pipes add cost and packaging constraints. The design objective should be a useful storage rate over the full cycle rather than maximum conductivity in isolation. In a TEG-integrated configuration, enhanced PCM conductivity can improve the thermal response but may also reduce the temperature gradient if it spreads heat into regions that were previously cooler. The correct evaluation depends on where the PCM sits relative to the hot side, cold side, and ambient environment. A

comparison should report both storage utilization and electrical output, along with geometry and boundary conditions.

The strategies summarized in Table 2 differ in how conductive structures are distributed within the PCM and how they influence the thermal response of the storage unit. Among these approaches, copper foam fins provide additional conduction pathways whose geometry and spatial arrangement can affect melting and solidification behavior. Meng et al.[37] investigated different copper foam fin configurations, demonstrating the importance of structural design in PCM thermal management. Figure 7 illustrates the investigated configurations and highlights the geometric variations considered in the study.

Integrated PV–TEG–PCM system behavior: In a fully integrated system, PV electrical output, TEG generation, and PCM storage interact through a common thermal field. During high irradiance, the PV module absorbs energy and its temperature rises. Depending on the configuration, some heat may pass through the TEG, be stored in the PCM, or be rejected to the environment. When irradiance falls, the PCM may release heat and maintain a temperature difference across the TEG, but the available output will decline as the storage temperature approaches the cold-side temperature. The thermal and electrical performance of integrated photovoltaic systems depends strongly on how the PV module, thermal-storage unit, thermoelectric generator, and heat-transfer components are arranged. Li et al.[38] experimentally compared five configurations: PV, PV/T, PV/T–PCM, PV/T–PCM–TEG, and PV/2T–PCM–TEG. These architectures illustrate different levels of integration between photovoltaic conversion, thermal management, latent-heat storage, and thermoelectric generation. Figure 8 presents a conceptual comparison of the five configurations considered in that study. Their relative performance should be interpreted in relation to the original operating conditions, thermal pathways, and system boundaries, rather than assuming that the addition of individual components necessarily improves net electrical output.

THERMOELECTRIC WASTE-HEAT RECOVERY APPLICATIONS

Fuel-cell systems: Fuel-cell systems reject heat through the stack, exhaust, and associated balance-of-plant components. A TEG may recover part of this thermal energy, but the heat exchanger must be integrated without compromising stack temperature management or adding excessive pressure drop. Studies of fuel-cell vehicle waste-heat temperatures and cruising speed, as well as validation work on a 1 kW PEM fuel-cell recovery model, show that source temperature and operating state are key variables in predicting output[39,40]. Fuel-cell waste-heat recovery can involve several forms of energy utilization, including thermoelectric generation, thermal preheating, and cooling. The integration of these functions requires a consistent energy balance to avoid double-counting recovered energy and to ensure that the fuel-cell operating requirements are maintained. Studies of combined fuel-cell systems and integrated vehicle recovery arrangements highlight the importance of selecting a suitable thermal configuration and accounting for application-specific constraints[41,42]. In water-cooled fuel-cell systems, the circulating coolant provides an opportunity to transfer waste heat to a thermoelectric generator through an intermediate heat-exchange assembly. The available electrical output depends on the temperature difference established across the thermoelectric modules and the effectiveness of cold-side heat rejection. Figure 9 illustrates a representative fuel-cell thermal-management system and its modification through the integration of thermoelectric modules, including the associated heat-transfer and cooling arrangements[43].

Heat exchangers and industrial waste heat:
Heat exchangers determine how effectively the source heat reaches the TEG and how uniformly the hot-side temperature is distributed. Cross-flow optimization studies have long considered the balance between heat transfer, pressure drop, and available surface area. Dynamic TEG models further show why transient source conditions should be represented when the application is not steady-state[44,45]. Compact printed-circuit heat exchangers and newer modular heat-exchanger designs seek to increase heat-transfer effectiveness while meeting restrictions on size and flow resistance. The reported performance of a TEG system depends not only on the exchanger's heat-transfer coefficient but also on the module arrangement, thermal interfaces, coolant conditions, and electrical load. Recent optimization work on high-performance heat exchangers for low-grade heat recovery extends this design problem to modular systems[46,47]. The arrangement of the heat exchanger influences how thermal energy is delivered to and

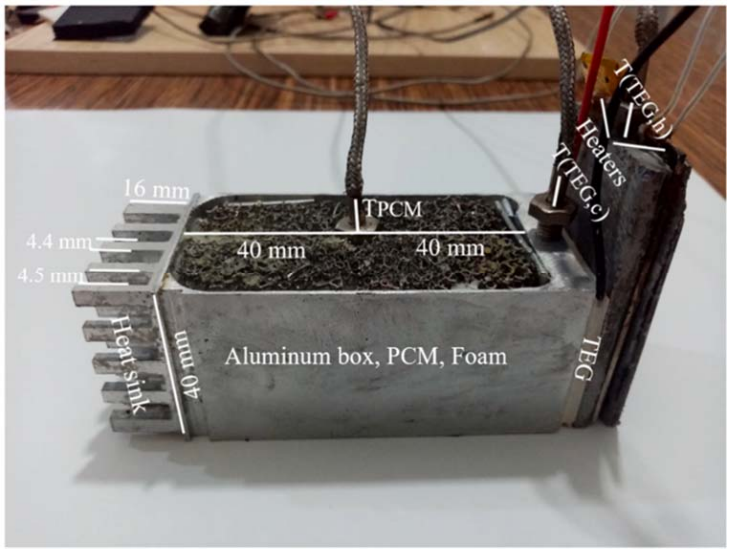


Figure 6: Experimental assembly of a thermoelectric generator integrated with a cold-side phase-change-material heat sink containing porous copper foam.

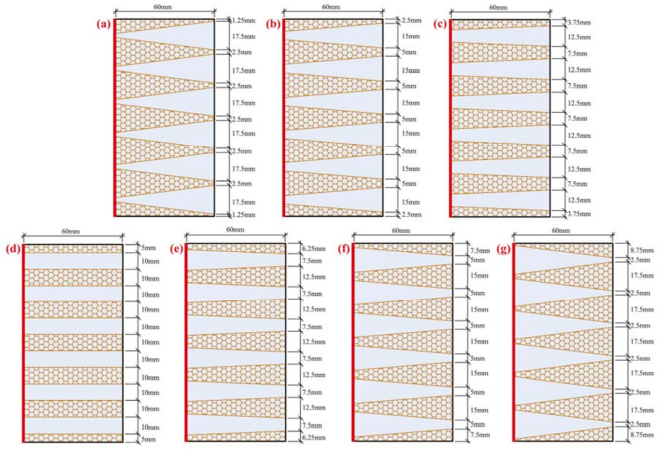


Figure 7: Representative copper foam fin (CFF) configurations investigated for enhancing heat transfer in PCM thermal energy storage systems.

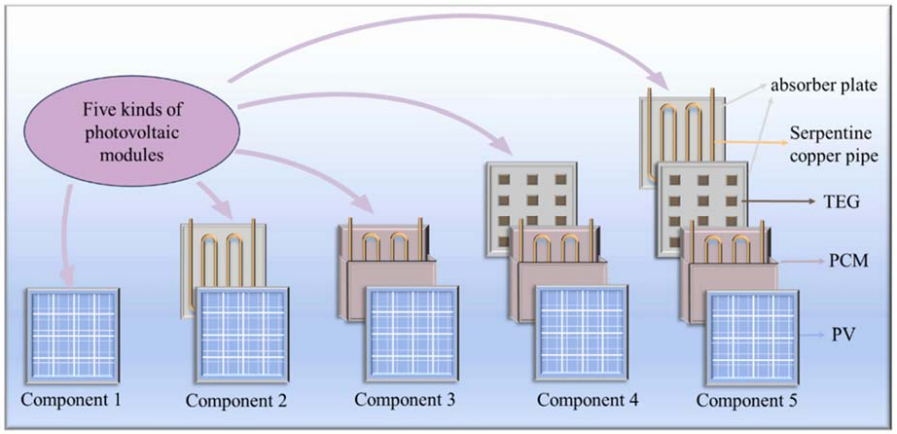


Figure 8: Schematic comparison of five photovoltaic-based configurations incorporating thermal management and thermoelectric generation

removed from the thermoelectric module. Li et al.[48] investigated two heat-exchanger configurations, providing a basis for examining the relationship between exchanger geometry and the thermal conditions experienced by the TEG. As illustrated in Figure 10, the tube-type and finned configurations represent

alternative approaches to thermal coupling and cold-side heat removal. These arrangements highlight the need to consider heat-transfer performance together with the flow characteristics of the exchanger when evaluating thermoelectric recovery systems.

Automotive exhaust recovery: Automotive exhaust is a variable heat source. Exhaust temperature and mass flow change with engine speed, load, and driving cycle, while the TEG's cold-side conditions also vary. A steady-state design may therefore overestimate the energy recovered over real driving conditions. Dynamic models and studies of fuel economy provide a basis for evaluating the device at vehicle level rather than at a single engine operating point[49,50].

Thermal resistance and contact behavior also influence automotive systems. Models that explicitly consider contact resistance, asymmetric device geometry, and alternative theoretical formulations help explain why a module's nominal material performance does not directly determine installed output[51,52]. These details become more important when the heat source changes rapidly or when module dimensions are optimized for packaging. Comparisons between theoretical modeling approaches and analytical models for thermoelectric-generator dimensions show that model selection affects predicted performance and design variables. Three-dimensional models can represent nonuniform fields in greater detail, while simplified models can support rapid parameter screening. Neither should be accepted without checks against conservation requirements and suitable measurements[53,54]. Automotive exhaust thermoelectric generators recover part of the thermal energy carried by exhaust gases through a hot-side heat exchanger coupled to thermoelectric modules. As illustrated in Figure 11(a), the system incorporates a muffler, guide fins, a hot-side heat exchanger, thermoelectric modules, and a cold-side heat exchanger. The heat-exchanger geometry and fin arrangement influence the heat-transfer pathway between the exhaust stream and the thermoelectric modules, while the cold-side temperature affects the temperature difference available for power generation. Figure 11(b) presents the geometric configuration and principal dimensions of the heat-exchanger structure, whereas Figure 11(c) shows the variation in matched-load output power with hot-side temperature under different cold-side temperature conditions. These results highlight the importance of both hot- and cold-side thermal management when evaluating the electrical performance of automotive exhaust TEG systems[55].

Modeling vehicle-level benefit and heat-transfer enhancement: Three-dimensional analytical models and fuel-economy assessment methods broaden the evaluation beyond module voltage. A useful vehicle-level assessment must consider total recovered energy, conversion electronics, auxiliary cooling or pumping, added mass, exhaust backpressure, and the engine's response. This is why output reported under a laboratory heat source cannot be transferred directly to a vehicle without accounting for its duty cycle[56,57]. Flow-channel inserts and longitudinal vortex generators (LVGs) have been investigated as methods for enhancing heat transfer in thermoelectric generator systems. By disturbing the fluid flow and promoting secondary vortices, these structures can improve thermal exchange between the working fluid and the heat-transfer surfaces. However, the resulting enhancement may be accompanied by increased flow resistance and auxiliary power requirements. Consequently, their effectiveness should be assessed through coupled thermal–hydraulic and electrical analyses rather than heat-transfer performance alone. Numerical investigations of plate-fin heat exchangers and transient automotive exhaust systems demonstrate the importance of accounting for these interacting effects under the specified operating conditions[58,59]. Figure 12 illustrates a representative plate-fin heat-exchanger configuration incorporating longitudinal vortex generator[60].

NUMERICAL MODELING AND SIMULATION

Thermal and electrical models: A thermal–electrical model describes how heat flow, temperature distribution, and electrical generation interact within a thermoelectric device. Its physical representation should account for the temperature difference across the active thermoelectric legs, heat losses through surrounding components, and the thermal resistance of the interfaces connecting the module to the heat source and sink. These factors determine the effective operating conditions of the TEG and provide the basis for

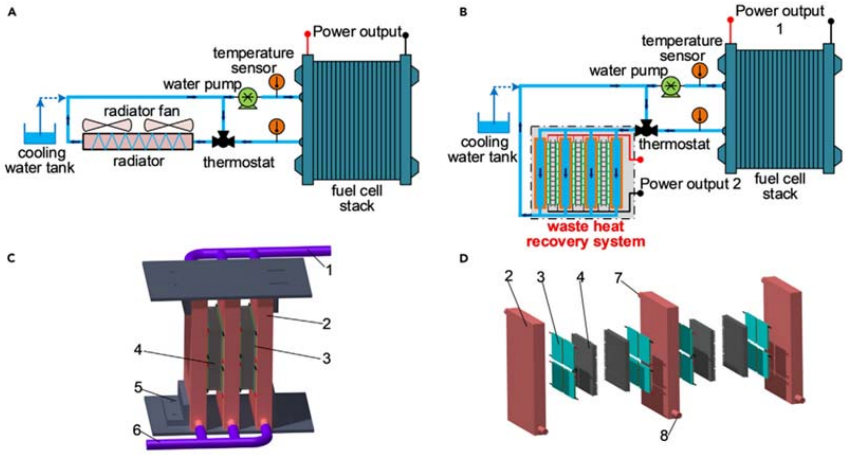


Figure 9. Conventional and modified fuel-cell thermal-management systems: (A) conventional cooling circuit, (B) modified configuration incorporating thermoelectric waste-heat recovery, and (C–D) structural arrangements of the hot-water sinks, thermoelectric modules, and cooling assembly.

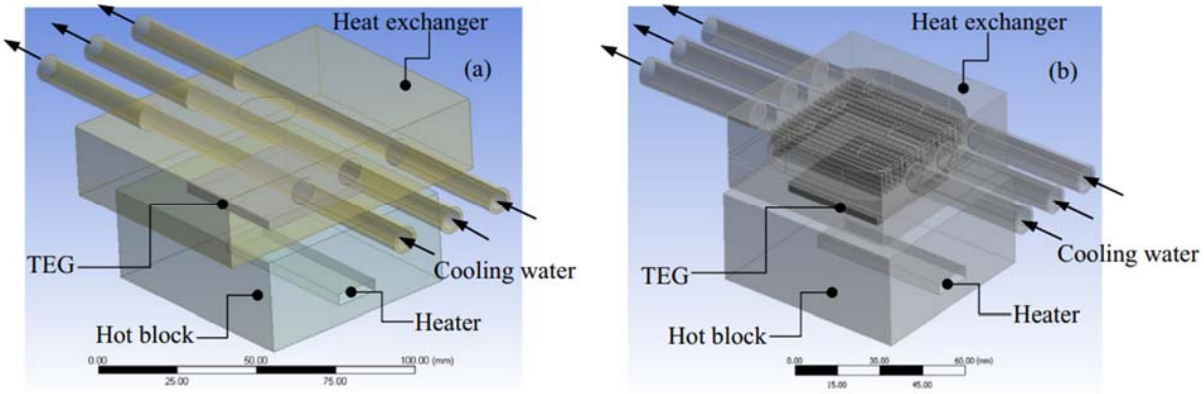


Figure 10. Three-dimensional configurations of two heat exchangers investigated for thermoelectric generator applications: (a) tube-type heat exchanger and (b) finned heat exchanger.

evaluating its electrical output. Analytical modeling of contact resistance and response-surface experimental analysis show that the interfaces and effective thermal resistance can be as important as the active thermoelectric material. These factors should be distinguished from intrinsic material properties when comparing designs[49,50]. Thermal-resistance models and parametric studies of asymmetric thermoelectric devices provide alternative ways to represent the relationship between geometry, heat flow, and electrical output. A model that assumes symmetry may miss a design advantage or disadvantage when the hot and cold sides have different boundary conditions[51 52].

$$R_{th,total} = R_{conv,h} + R_{HX,h} + R_{contact,h} + R_{TEG} + R_{contact,c} + R_{HX,c} + R_{conv,h}$$

Equation (12) represents a simplified series thermal-resistance network connecting the heat source to the ambient sink. Along this pathway, temperature drops occur across the hot-side heat exchanger, thermal contact interfaces, thermoelectric module, and cold-side heat-rejection assembly. Consequently, only part of the overall source-to-sink temperature difference is established across the TEG, directly affecting the thermal

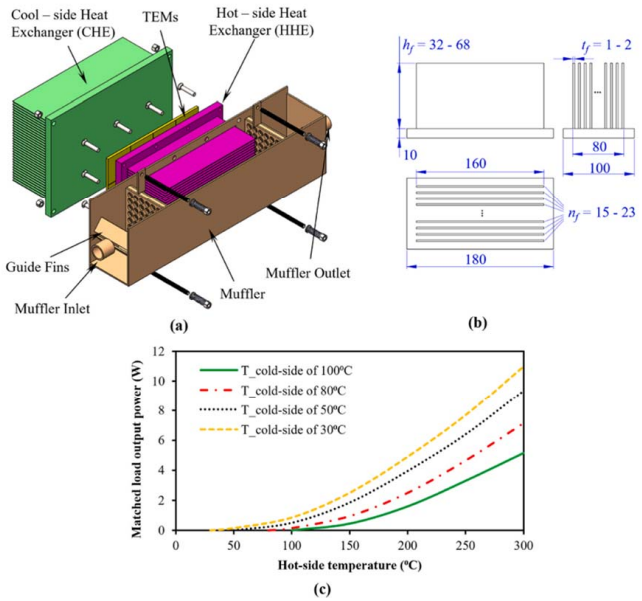


Figure 11. Configuration and thermal–electrical performance of a motorcycle exhaust thermoelectric generator: (a) exploded view of the exhaust and heat-exchanger assembly, (b) geometry and principal dimensions of the heat exchanger, and (c) matched-load electrical power as a function of hot-side temperature for different cold-side temperatures

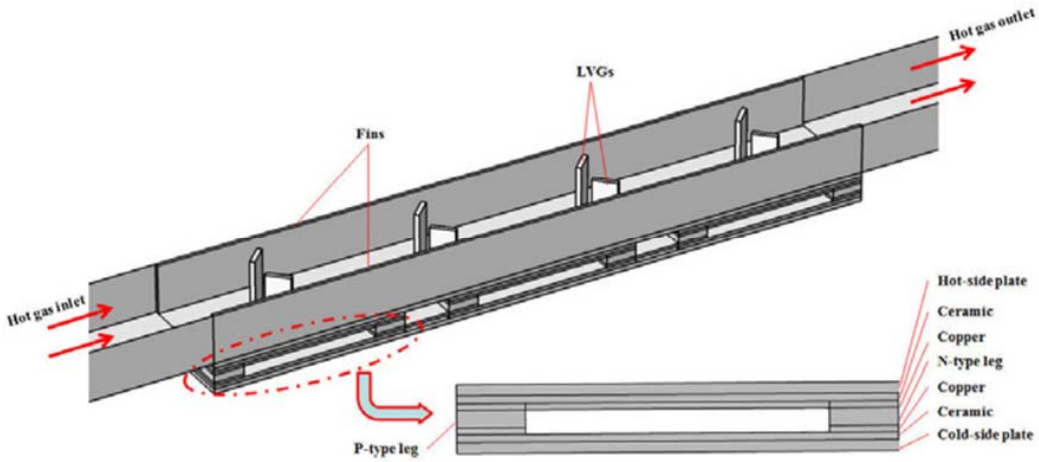


Figure 12. Physical configuration of a plate-fin thermoelectric generator incorporating longitudinal vortex generators (LVGs) for heat-transfer enhancement.

conditions available for electrical generation.

The total thermal resistance includes the convective, conductive, and interfacial contributions along the simplified source-to-sink pathway, as illustrated in Figure 13. This series representation neglects parallel heat-loss paths and multidimensional spreading effects, which may require a more detailed thermal-network or numerical model.

Finite-element, CFD, and coupled Multiphysics methods: The finite-element method discretizes a domain into elements and solves the governing equations over the mesh. It is well suited to complex geometry, multiple materials, and coupled domains. CFD

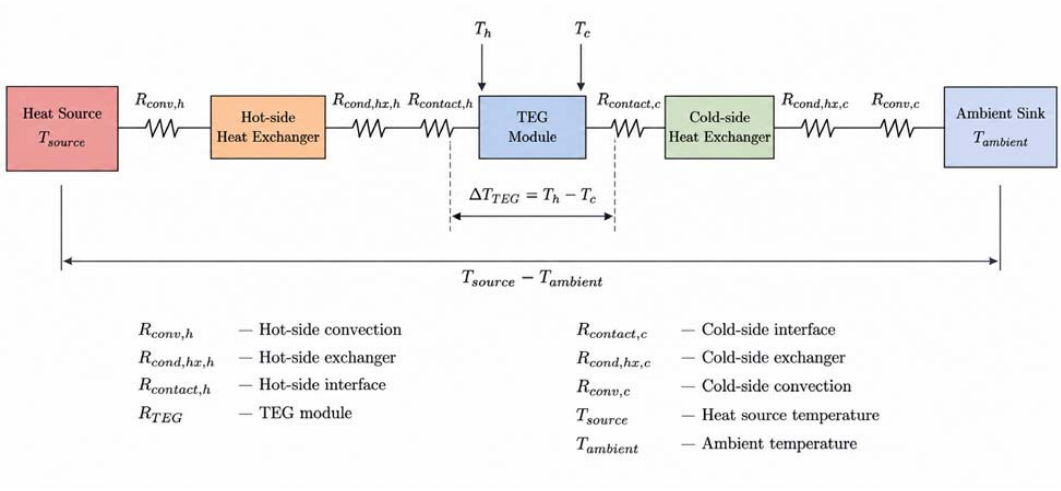


Figure 13: Conceptual thermal-resistance network of a thermoelectric generator system, illustrating the heat source, hot-side and cold-side heat exchangers, thermal contact interfaces, thermoelectric module, and ambient heat sink. The network distinguishes the overall source-to-sink temperature difference from the effective temperature difference across the TEG.

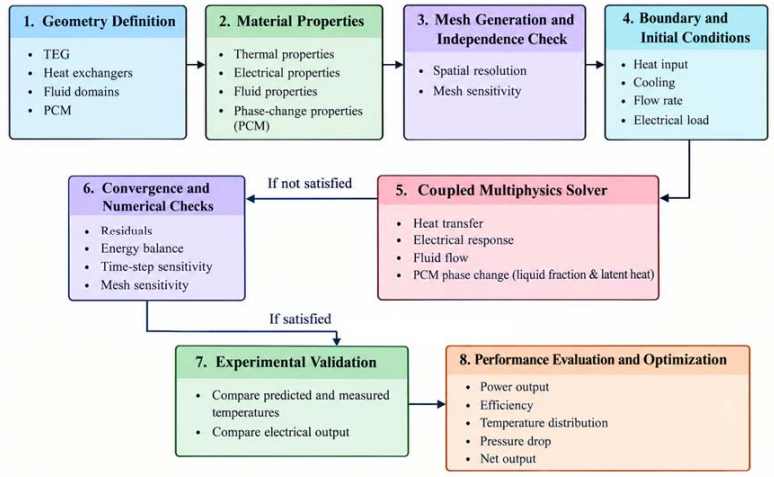


Figure 14: Proposed Multiphysics modeling workflow for thermoelectric energy-conversion systems, including geometry definition, material characterization, mesh generation, boundary-condition specification, coupled numerical solution, verification, experimental validation, and performance optimization.

resolves fluid flow and convective heat transfer, but the additional equations and fine spatial resolution can increase computational cost. Coupled models exchange temperatures, heat fluxes, or source terms between the fluid and solid domains, and their accuracy depends on consistent interfaces and boundary conditions.

Comparisons of theoretical modeling approaches and compact analytical models provide a useful check on computational results. A three-dimensional analytical model can serve as a benchmark for a numerical implementation when assumptions align, while experiments are needed to establish whether the physical model captures the real device. Model choice should therefore be justified by the output of interest, not simply by the availability of software[53,54]. A reliable Multiphysics modeling workflow requires consistent treatment of the thermal, electrical, and, where applicable, fluid-flow processes within a thermoelectric

energy-conversion system. The procedure begins with geometry definition and material-property assignment, followed by mesh generation and specification of the initial and boundary conditions. The coupled solver then resolves the interactions among heat transfer, electrical response, fluid flow, and phase change. Numerical reliability should be assessed through convergence monitoring, energy-balance checks, and mesh- and time-step-sensitivity analyses. If the numerical criteria are not satisfied, the solver settings or discretization should be revised and the calculations repeated. Once numerical reliability has been established, experimental validation can be performed by comparing predicted temperatures and electrical output with measured values. Figure 14 summarizes this workflow and identifies the principal verification and validation steps required before simulation results are used for performance evaluation and design optimization.

Transient modeling and model validation: Transient models are essential when source temperature, load, or PCM phase fraction changes over time. Automotive exhaust TEGs are exposed to driving cycles, while PV–TEG–PCM systems experience day–night irradiance variation and storage charging/discharging. A steady-state calculation cannot describe the full cycle or establish how much energy is generated over a defined period. The transient numerical study of automotive exhaust recovery provides a relevant example of why time-dependent boundary conditions matter[59]. Validation should be distinguished from verification. Verification checks whether the numerical equations are solved and implemented consistently, using mesh refinement, time-step sensitivity, and conservation checks. Validation compares the model with independent measurements. Agreement between two simulations is not experimental validation, and a benchmark comparison should state which variables and operating conditions were matched. For a PCM model, the mesh should resolve the region where phase change occurs, and the time step should be small enough to capture meaningful changes in temperature and liquid fraction. Sensitivity should be tested for latent heat, transition interval, conductivity, and contact resistance. Where convection in the PCM is neglected, the assumption should be justified by geometry and operating conditions rather than carried over automatically from a conduction-dominated source model.

The modeling record should report geometry, material properties, heat-source profile, cold-side boundary condition, electrical load, solver settings, mesh and time-step studies, and the uncertainty in measurements used for validation. These details are required to reproduce the result and determine whether a reported gain is caused by the physical design or by a modeling assumption.

PV–TEG INTEGRATION: CONFIGURATIONS AND DESIGN TRADE-OFFS

Configuration families: PV–TEG systems can differ in the location of the TEG relative to the PV module, the type of heat exchanger, the presence of a glass cover, the use of concentration optics, and the integration of a PCM. Each arrangement produces a different thermal resistance network and different operating temperatures. Reviews of building-integrated PV/thermal systems and experimental CPV/TEG studies provide examples of how the optical and thermal configuration affects the available heat and electrical response [61, 62].

PV–TEG architectures can be grouped according to the way solar radiation is delivered to the PV component and how the resulting heat is transferred to the thermoelectric generator. In a non-concentrating configuration, the PV module receives incident solar radiation directly, and the TEG recovers part of the heat conducted through the module or an attached thermal structure. Concentrating configurations use optical elements, such as Fresnel lenses, to increase the incident solar flux over a smaller PV-cell area, making effective thermal management particularly important. Hybrid arrangements may also incorporate heat exchangers, phase-change materials, or enhanced cooling channels to regulate the temperature of the PV component and maintain a useful temperature difference across the TEG. Figure 15 presents a conceptual comparison of these configuration families, emphasizing their different heat-transfer pathways and cooling requirements. Performance comparisons should account for irradiance, concentration ratio, aperture area, and auxiliary cooling demand rather than relying on total electrical output alone[61–64].

Topology and module optimization: Optimization can involve the geometry of the TEG legs, number and arrangement of couples, heat exchanger shape, thermal

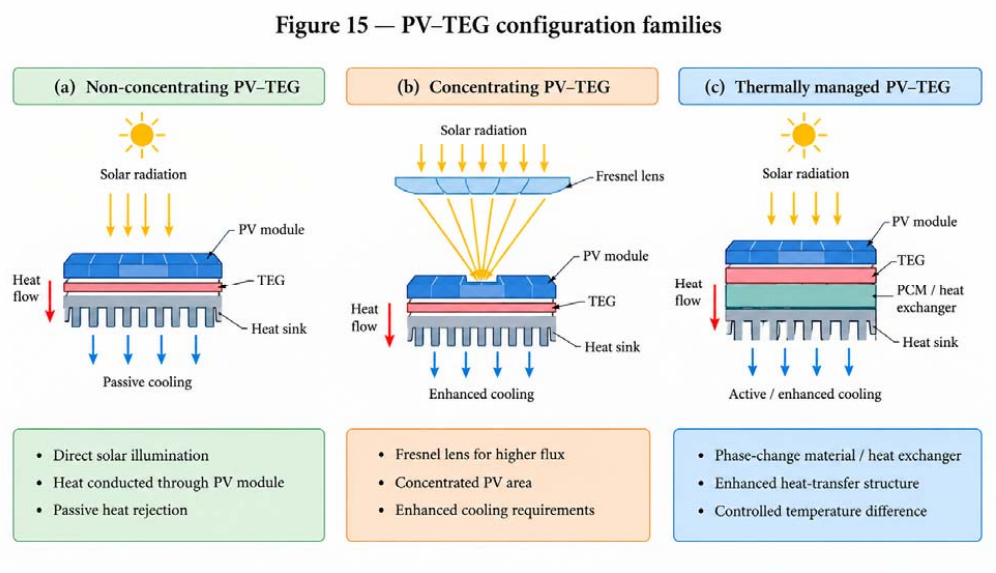


Figure 15. Conceptual comparison of three photovoltaic–thermoelectric generator configurations: (a) non-concentrating PV–TEG with passive cooling, (b) concentrating PV–TEG with enhanced heat rejection, and (c) thermally managed PV–TEG incorporating phase-change storage or an enhanced heat-transfer arrangement.

interfaces, PCM placement, and electrical load. A concentrated PV–PCM–TEG topology-optimization study is an example of treating the arrangement as a system-level design problem rather than optimizing only the thermoelectric material[65].

The choice of topology should follow the design objective. If the goal is maximum instantaneous power, the optimum may differ from the design that maximizes daily energy or minimizes PV temperature. If the system is intended to operate after solar input falls, PCM discharge duration becomes an important metric. If it is intended for an industrial heat stream, pressure drop and operating stability may dominate. Optimization objectives should therefore be explicit and should include constraints that reflect practical use.

$$\max_{\mathbf{x}} \mathcal{J}(\mathbf{x}) \quad \text{subject to} \quad g_i(\mathbf{x}) \leq 0, \quad h_j(\mathbf{x}) = 0$$

Here, x represents design variables such as leg dimensions, exchanger geometry, PCM mass, or flow rate; J is the chosen objective; and g_i and h_j represent inequality and equality constraints. This formulation is generic, but it emphasizes that an optimization result is only meaningful when the objective and constraints are reported. A design optimized for gross TEG power may not maximize net system energy after auxiliary consumption.

PERFORMANCE METRICS AND COMPARISON OF PREVIOUS STUDIES

Electrical power, energy, and efficiency: The instantaneous electrical output of a TEG is P_{TEG} = VI. The total energy generated over an operating interval is the time integral of power, . Peak power and total energy answer different questions: a short peak may have little impact on daily yield, while a lower output maintained for longer can produce more energy. This distinction is especially important for PCM-assisted systems and variable automotive heat sources.

$$E_{TEG} = \int_0^{t_f} P_{TEG}\,(t)\,dt$$

A common thermal efficiency definition is , where $\dot{Q}_h$ is the heat-transfer rate entering the hot side. The boundary must be stated because heat available in the source stream is not necessarily the same as heat that reaches the module. A hybrid-system metric can report gross output as the sum of PV and TEG power, but net output should subtract relevant auxiliary demand and conversion losses.

$$\eta_{TEG} = \frac{P_{TEG}}{\dot{Q}_h} \qquad P_{net} = P_{PV} + P_{TEG} - P_{aux}$$

Table 3: Framework for comparing previous TEG studies across application classes.

Study focus	Design variable or condition	What should be compared	Interpretation caution
Module optimization	Leg geometry, dimensions, load	Power, temperature difference, material properties	Peak output may not equal maximum energy
Automotive integration	Driving cycle, exhaust temperature, Coolant	Net energy, fuel economy, pressure drop	Steady-state results may not represent road operation
Fuel-cell recovery	Stack/exhaust temperature and flow	Recovered power, stack thermal conditions	Avoid double counting of co-generated heat or power
Heat-exchanger enhancement	Fins, vortex generators, compact geometry	Heat transfer, pressure loss, auxiliary demand	Higher heat-transfer coefficient can carry a a hydraulic penalty
PCM-assisted generation	PCM mass, transition temperature, placement	Charging/discharging, cycle energy, temperature history	Storage capacity is not identical to useful electrical Energy

When reporting percentage improvement, the reference configuration and the performance metric must be stated explicitly. Comparisons are meaningful only when the baseline, operating conditions, and system boundaries are sufficiently compatible. For this reason, reported gains from different studies should be interpreted in their original context rather than ranked directly.

$$\text{Improvement}(\%) = \frac{X_{hybrid} - X_{reference}}{X_{reference}} \times 100$$

Energy and exergy analysis should also be distinguished. Energy analysis accounts for energy quantities; exergy analysis evaluates the useful-work potential relative to a defined environment and highlights irreversibilities. Economic and environmental measures require still other boundaries, including investment cost, lifetime, maintenance, and material impacts.

Evidence from TEG optimization and automotive studies: Studies of thermoelectric module optimization and converging TEG configurations have investigated how geometry and flow arrangement influence output.

These studies support the general conclusion that the module should be optimized together with its thermal environment rather than selected only from a material-level figure of merit[66,67]. Automotive TEG optimization has examined the effect of design on hybrid vehicles, exhaust recovery, fuel economy, and emissions. Nanofluid coolants and novel cylindrical or polygonal generator geometries have also been investigated. Such work illustrates the range of design variables but should be compared using a common basis: source temperature and flow, vehicle duty cycle, net power, pressure drop, and electrical load[68,69]. Further automotive studies have examined coolant selection, cylindrical designs, transient driving cycles, and split-fin structures. The results are most useful when they report both thermal enhancement and the penalties associated with it. A high heat-transfer rate alone does not establish a net gain if pumping demand, backpressure, or mass increases substantially[70,71]. Recent transient models and split-fin designs reinforce the need for operating-cycle analysis. In real use, the temperature gradient changes with driving conditions, and an optimized structure may perform differently at low and high engine loads. Experimental and numerical findings should be reported separately and combined only when their assumptions and metrics are compatible[72,73].

The comparison framework in Table 3 provides a common basis for interpreting the studies reviewed in the following subsections. The discussion now turns to fuel-cell applications, where the available temperature gradient and the interaction between thermoelectric recovery and the primary energy-conversion system are central to performance assessment.

Fuel-cell and heat-exchanger evidence: Fuel-cell TEG studies have considered low-grade waste heat, different stack temperatures, and multistage arrangements. Experimental and theoretical work on ultra-low-temperature PEM fuel-cell vehicles and methods for exploiting waste heat in PEM fuel-cell systems indicate that the usable thermal gradient can be a limiting factor [74,75]. Two-stage TEGs for solid-oxide fuel-cell waste heat and hybrid fuel-cell–TEG–absorption-chiller systems

Table 4. Comparative analysis of previous studies on PV–TEG integration, PCM-assisted thermal management, and waste-heat recovery

Ref.	System / research focus	Method	Main findings reported in the study	Critical assessment / limitation
[1]	Thermoelectric-coupled solar PV in microgrids	System-level analysis	Examines the potential benefits of coupling thermoelectric generation with solar PV and the challenges associated with integrating renewable energy resources.	The system-level benefit depends on thermal integration and the operating conditions of the PV and TEG subsystems.
[6]	PV–TE hybrid system with and without a glass cover	Theoretical thermal–electrical modeling modeling	The study indicates that a glazed configuration can be competitive with or superior to an unglazed system under suitable conditions involving the figure of merit, concentration ratio, glass transmissivity, wind speed, and nanofluid flow rate.	A glass cover does not provide a universal benefit; the conclusion depends on the combined optical and thermal conditions
[11]	Low-grade waste-heat recovery from a fuel cell using swirl flows .	Numerical and system-Level performance analysis	The study investigates swirl-assisted heat transfer for a TEG utilizing low -temperature PEM fuel-cell waste heat The abstract reports an increase in maximum output power from 200 μW under a non-swirl condition to 3056 μW at a swirl strength of 1.6. However, the reported improvement depends on the specified thermal and flow conditions, which should be considered when interpreting the performance comparison.	The reported gain is configuration-specific; the effects of flow resistance and the complete system energy balance must be considered.
[32]	PCM-based thermal protection and management of a TEG	Experimental investigation	Three PCMs were tested using arrangements on the hot side, cold side, and both sides. Hot -side PCM extended voltage generation after removal of the external heat source and helped protect the module under high thermal input	The outcome depends on PCM location, heat-source history, and the thermal conditions on both sides of the TEG.
[33]	PCM heat-transfer mechanisms and structural design for TEG performance	Coupled mathematical modeling supported by experimental data	The study examines hot-side, cold-side, and dual-sided PCM arrangements, finned PCM, and the response to unstable heat sources. The dual-sided arrangement is identified as a promising practical configuration.	Performance depends on storage geometry, heat -transfer enhancement, and the stability of the thermal source.
[44]	Cross-flow heat exchangers for thermoelectric waste -heat recovery	Numerical modeling and optimization validated against experimental data	The study shows that heat-exchanger optimization must account for the electrical output of the TEG together with fan and pump power losses.	The optimum flow conditions represent a compromise between heat transfer and auxiliary power consumption.
[46]	Compact TEG using printed-circuit heat exchangers	Three-dimensional CFD analysis and experimental investigation	A compact heat-exchanger architecture was developed, and experimental results were reported for a 200 W TEG implementation The design targets compactness, high power density, and reduced flow requirements.	The performance must be assessed alongside pressure drop, heat-source conditions, and the practical requirements of scale-up.
[58]	Plate-fin TEG heat exchanger with longitudinal vortex generators	Coupled fluid-thermal–electrical numerical modeling	The introduction of longitudinal vortex generators produced three-dimensional flow structures and improved heat transfer and electrical performance compared with the configuration without vortex generators.	Heat-transfer enhancement must be evaluated together with pressure drop and the net power balance.
[59]	Automotive exhaust TEG under transient driving conditions	Transient Multiphysics numerical simulation	The study developed a transient fluid-thermal–electrical model for an automotive exhaust TEG, incorporating variations in exhaust temperature, mass flow rate, and temperature-dependent material properties. Under the investigated driving-cycle conditions, the steady-state simulation predicted an electrical output power 12.6% higher than the transient simulation. The findings also revealed a delayed electrical response to change in	Steady-state modeling may overestimate output when exhaust conditions vary during driving.

			exhaust conditions.	
[62]	Concentrated photovoltaic-TEG hybrid system	Experimental and numerical investigation	The study compares the electrical and thermal behavior of a concentrated PV-TEG arrangement using experimental observations and simulation.	Results should be interpreted in relation to concentration conditions, thermal interfaces, and the chosen reference configuration.
[63]	Two concentrated PV/thermal–TEG configurations	Comparative system analysis	The study compares systems with and without a gravity-driven heat pipe. The reported findings distinguish the stronger thermal and overall performance of one arrangement from the electrical performance of the alternative.	System ranking depends on whether thermal, electrical, or comprehensive performance is used as the comparison criterion.
[65]	Concentrated PV–PCM –TEG system with topology-optimized fins	Coupled transient numerical modeling and topology optimization	Relative to straight fins, optimized fins reduced CPV temperature by 15.6K, increased CPV output power by 10.52%, increased TEG output power by 4.56%, and improved total output work over the simulated period by 3.08%.	The optimized structure performed less effectively during the period without solar radiation, showing that the benefit depends on the operating phase.
[67]	Converging TEG for waste-heat recovery	Multiphysics numerical modeling supported by experimental validation	The converging heat-exchanger configuration produced higher electrical output, a more uniform temperature distribution, and lower backpressure-related power losses than the conventional design. At an inlet air temperature of 550 K and a mass flow rate of 60 g/s, the predicted output power increased by approximately 5.9%. The maximum deviation between numerical and maximum deviation between numerical was 2.4%, supporting the reliability of the model under the investigated conditions.	The reported gain is associated with the specified inlet conditions and geometry and should not be generalized to all TEG systems.
[82]	Modular TEG with a compact heat exchanger for low-grade heat recovery	Experimental investigation	A five-module unit achieved 1.64% thermoelectric conversion efficiency at a temperature difference of 96.4 °C and a volumetric power density of 86.4KW/m^3 Auxiliary power consumption was 0.64% of total output power.	The findings demonstrate the potential of compact modular design, but performance at other flow rates and temperature differences requires separate assessment.
[83]	Industrial gas-phase waste-heat recovery	Finite-time thermodynamic modeling	Using a finite-time thermodynamic model, the study predicted an electrical power output of approximately 1.47 kW/m² and a conversion efficiency of 4.5% for exhaust gas at 350 °C. The analysis also examined the effects of heat-transfer coefficients and thermoelectric-element length. Improving gas-side heat transfer increased electrical power but did not necessarily improve conversion efficiency, highlighting the importance of distinguishing these performance indicators.	The reported output and efficiency are specific to the modeled thermal conditions and assumptions.
[84]	TEG with a non-uniform hot-side heat exchanger	Experimental investigation	Under matched electrical load conditions, the uniform and non-uniform winglet heat exchangers improved the average total and net electrical power relative to the smooth -channel reference. The non-uniform configuration achieved average increases of 189.1% in total power and 177.4% in net power. These gains were obtained under the investigated inlet-temperature and flow conditions.	The improvement applies to the tested heat-exchanger geometry and operating conditions; it is not a universal performance gain.

extend the concept toward combined energy services. Such configurations require clear accounting of each output and the heat allocated to each subsystem. Compact plate-fin heat exchangers and optimization of TEG subsystems for high-temperature PEM fuel-cell exhaust illustrate the role of thermal design in these integrated systems[76,77]. Additional studies of compact heat exchangers, subsystem optimization, and integrated recovery designs broaden the evidence base for fuel-cell applications. The system should be evaluated against the primary fuel-cell output and auxiliary loads, not just the electricity generated by the TEG. This is necessary to determine whether integration improves total performance under the stated operating condition[78, 79]. The studies in this section cover several distinct recovery environments, from fuel-cell exhaust to industrial heat streams[80,81].

Industrial gases, heat exchangers, and source variability: Experimental investigations of compact heat exchangers for low-grade thermal energy recovery have reported the importance of exchanger design, while industrial gas-phase waste-heat studies address a different source profile from automotive exhaust. These systems should not be compared by module power alone because source flow, temperature, available surface area, and operating hours differ[82,83]. Non-uniform hot-side heat exchangers and comparisons of heat-exchange technologies have examined how spatially varying heat input changes TEG performance. A uniform boundary may be a convenient modeling assumption, but it can hide local hot spots and underutilized module regions. Experimental and numerical studies of different heat-exchanger design therefore support reporting temperature distribution and not just mean inlet/outlet values[84,85]. Heat exchangers for billet-casting processes and plate-heat-exchanger-based TEG systems provide further examples of industrial integration. These applications involve process-specific temperatures and operating schedules. A reliable economic comparison should account for the fraction of time heat is available and whether the recovered energy can be used locally[86,87]. Recent experimental studies that combine thermoelectric performance, exergy analysis, and economic assessment represent a useful direction because they evaluate more than gross power. Broader energy-system context and distributed-energy analyses can help situate the technology within the host process, but the final benefit still depends on source-specific conditions and system boundaries[88,89].

To compare the evidence across different thermoelectric applications, selected studies were examined in terms of their system configuration, research method, reported outcomes, and principal limitations. The studies do not share identical operating conditions or performance metrics, so their reported improvements should not be interpreted as a direct ranking of technologies. Instead, the comparison identifies the design variables that influence performance and the evidence needed to establish whether a proposed enhancement provides a practical system-level benefit.

The comparison in Table 4 highlights the importance of evaluating thermoelectric systems at the level of the complete thermal and electrical configuration. In PV–TEG systems, the glass cover, concentration ratio, and heat-transfer arrangement influence the balance between photovoltaic output and thermoelectric generation [6, 63]. PCM-assisted configurations introduce an additional temporal effect because stored heat can extend the availability of a temperature difference, although the outcome depends on the placement and geometry of the storage material[32,33]. Heat-exchanger design is another major determinant of performance. Vortex generators and non-uniform heat-transfer surfaces can increase electrical output, but their value should be assessed against pressure drop and auxiliary consumption[58,84]. Similarly, the transient automotive results demonstrate that a steady-state model may overestimate power when the heat source changes during operation[59]. The reported numerical improvements therefore represent different physical effects and reference conditions rather than a common ranking of technologies. Taken together, these findings suggest that the selection of a promising TEG configuration should be guided by the dominant thermal constraints of the intended application. For systems with intermittent heat availability, transient response and energy generated over the operating cycle are particularly important. In applications involving continuous fluid flow, heat-exchanger effectiveness, hydraulic losses, and net electrical output become more decisive. This application-dependent perspective provides a basis for identifying suitable design strategies without treating improvements reported under different experimental or numerical conditions as directly equivalent.

Economic, environmental, and lifecycle considerations: The economic feasibility of thermoelectric energy recovery depends on the relationship between lifetime

electrical generation and the additional costs associated with thermoelectric modules, heat exchangers, thermal interfaces, power electronics, installation, and maintenance. Although techno-economic investigations of large-scale photovoltaic installations provide useful examples of evaluating energy yield against project costs [90], their conclusions cannot be directly transferred to integrated TEG systems. Furthermore, analyses of energy-loss mechanisms in photovoltaic cells demonstrate that the available thermal energy is linked to the underlying conversion and loss processes[91]. Consequently, the economic assessment of a PV–TEG configuration should consider both the achievable additional electrical generation and any changes in photovoltaic performance.

The feasibility of hybrid PV–TEG systems is also influenced by their configuration and operating conditions. Reviews of concentrated photovoltaic–thermoelectric arrangements demonstrate the diversity of possible integration strategies[92], while analyses of the constraints governing efficient PV–TEG operation emphasize the importance of thermal coupling and system design[93]. A meaningful comparison should therefore use consistent assumptions regarding irradiance, concentration ratio, heat rejection, and electrical output. Improvements reported under different operating conditions should not be interpreted as directly transferable economic or technical advantages. Material selection and long-term stability introduce further considerations, particularly in PCM-assisted systems. Reviews of PCM-based thermal storage identify challenges associated with material properties, storage design, and practical implementation[94]. Investigations of phase-change materials for energy conversion and storage also illustrate the diversity of material approaches and their application-specific requirements [95]. For integrated PV–TEG–PCM systems, these considerations suggest that thermal-storage performance should be evaluated alongside material compatibility, cycling stability, and the additional complexity introduced by storage components. The durability of thermoelectric modules is another important factor in lifecycle performance. Repeated thermal cycling can affect mechanical integrity and effective device performance, while the properties of electrical contacts influence the reliability of the assembled module. Studies of thermoelectric degradation under thermal cycling[96] and contact fabrication for thermoelectric generators[97] demonstrate why interface quality and long-term stability should be considered when assessing practical deployment. An initially favorable electrical output may offer limited lifetime benefit if degradation or replacement requirements substantially increase operating costs. Application-specific design choices can also influence the balance between performance improvements and system complexity. Research on nanofluid cooling in automotive thermoelectric generators illustrates the role of coolant selection in thermal management[98], whereas investigations of cascaded thermoelectric arrangements in railway vehicles address a different approach to recovering available waste heat[99]. These studies highlight the need to evaluate auxiliary requirements, integration constraints, and operating conditions for each application rather than assuming that improvements observed in one recovery system will be equally beneficial in another.

Environmental assessment introduces an additional system-level requirement. Studies examining the environmental impacts of photovoltaic systems emphasize the importance of considering impacts beyond the electricity-generation stage[100]. Research on future photovoltaic waste management further identifies end-of-life treatment and material recovery as relevant considerations for long-term deployment[101]. Accordingly, lifecycle assessments of integrated PV–TEG–PCM systems should define a consistent functional unit and system boundary, accounting for manufacturing, operation, maintenance, component replacement, and end-of-life management. The additional environmental burdens associated with thermoelectric modules and thermal-storage components should ultimately be evaluated against the lifetime energy benefits achieved by the integrated system.

Synthesis of prior research and unresolved questions: The previous literature can be understood as progressing through several connected themes. Early work established the physical basis of thermoelectric conversion and the feasibility of coupling thermoelectric modules with solar or waste-heat sources. Later studies focused on practical integration, thermal resistance, heat-exchanger geometry, and the use of PCM to manage transient conditions. More recent work increasingly examines system-level optimization, Multiphysics simulation, driving-cycle behavior, and economic or environmental performance. This progression is reflected in earlier investigations of PV–TEG feasibility and comparative analyses of hybrid photovoltaic–thermoelectric configurations[6,102]. Automotive reviews have emphasized the gap between laboratory demonstrations and practical vehicle deployment. The major issues include the variable

Table 5: Cross-cutting synthesis of prior research and unresolved needs.

Research theme	Established understanding	Remaining need
Thermoelectric materials	Material properties determine potential conversion performance	Device-level assessment including interfaces, contact resistance, and durability
PV–TEG integration	Thermal coupling may add electricity but alters PV temperature	Consistent baseline and full-cycle net energy measurements
PCM-assisted systems	Latent storage can buffer heat and alter transient output	Evidence that storage improves net energy under realistic cycles
Heat exchangers	Geometry and flow affect heat transfer and pressure drop	Joint thermal-hydraulic-electrical optimization
Numerical simulation	FEM, CFD, and Multiphysics models reslove coupled behavior	Reproducible boundary conditions, mesh/time-step checks, independent validation
Techno-economics and lifecycle	Cost and durability influence feasibility	Comparable lifecycle boundaries and real operating profiles

exhaust source, system mass, backpressure, durability, and the need to compare recovered energy with any change in fuel consumption. These constraints show why the highest reported module power is not sufficient evidence of commercial readiness[103 104]. Reviews of automotive exhaust TEGs identify material performance, heat-exchanger design, thermal cycling, and integration as continuing challenges. PCM-assisted thermoelectric modules for low-power devices provide a different application context, where output requirements and thermal duty may be much smaller. The comparison underscores that successful design depends on matching the architecture to the source and load rather than applying a single configuration universally[105,106]. Multiphysics simulation and optimization studies of converging TEGs and automotive baffle geometry show that numerical optimization is increasingly used to explore design spaces that would be difficult to investigate experimentally in full. Nevertheless, optimized results remain conditional on the governing model, objective function, boundary conditions, and validation data. These methods should be used to guide experiments and design decisions, not as substitutes for independent validation[107,108].

Table 5 shows that the main unresolved issues extend across material performance, thermal integration, transient storage, numerical reliability, and lifecycle assessment. These challenges are interconnected: improvements at the component level do not necessarily translate into better performance of the complete system. The following section translates these research gaps into practical priorities for experimental design, coupled optimization, and long-term assessment.

FUTURE RESEARCH PRIORITIES

The studies reviewed in this article highlight several unresolved challenges in translating component-level improvements into reliable system-level benefits. Although considerable progress has been made in thermoelectric materials, heat-exchanger design, PCM-assisted thermal management, and multiphysics modeling, the reported performance gains remain strongly dependent on operating conditions and system configuration. Building on the limitations identified in Table 5, future research should prioritize reproducible performance assessment, robust system optimization, long-term reliability, and validation under realistic operating conditions. These priorities are discussed below, with particular emphasis on establishing measurable improvements in net electrical energy rather than isolated gains in individual components.

Standardized Experimental Protocols and Performance Assessment: One of the main challenges in the existing literature is the limited comparability of experimental results. Studies often use different thermal inputs, electrical loads, reference configurations, and evaluation periods. Consequently, improvements in peak power, conversion efficiency, or thermal-storage performance cannot always be interpreted as equivalent indicators of system effectiveness. Future investigations should establish consistent reporting practices that include source temperature, irradiance where applicable, mass flow rate, module temperatures, electrical loading, ambient conditions, and auxiliary energy consumption. Particular attention should be given to selecting an appropriate reference configuration and maintaining comparable operating conditions throughout the assessment. For PCM-assisted systems, the evaluation should extend beyond the period of maximum heat input to include charging, discharging, and the subsequent decline in stored thermal energy. This distinction is important because changes in the timing or duration of thermoelectric generation do not necessarily indicate an increase in total energy production. Reporting both instantaneous power and accumulated net electrical

energy would provide a stronger basis for determining whether PCM integration offers a meaningful advantage over conventional thermal-management arrangements[29,32].

Multi-Objective Optimization and Uncertainty Quantification: Future optimization studies should move beyond maximizing thermoelectric power under a single set of operating conditions. The reviewed investigations demonstrate that modifications intended to improve heat transfer can introduce competing effects, including increased pressure drop, additional cooling demand, reduced PCM volume, or greater structural complexity. These interactions make it difficult to identify a universally optimal configuration. A more useful approach is to evaluate several performance objectives simultaneously, including net electrical energy, PV temperature regulation, thermal-storage utilization, hydraulic losses, and system cost. Multi-objective optimization can help identify configurations that balance these requirements rather than maximizing one indicator at the expense of others. Previous investigations involving optimized PCM structures, heat exchangers, and thermoelectric geometries provide a basis for extending this approach to integrated systems [65,66]. Uncertainty quantification should also become a more consistent part of the optimization process. Temperature-dependent material properties, contact resistance, heat-transfer coefficients, PCM transition characteristics, and variable heat-source conditions can affect the predicted performance. Sensitivity analyses should therefore determine which parameters have the greatest influence on system behavior and whether the preferred design remains effective when these parameters vary within plausible ranges. Such assessments would improve confidence in the robustness of numerical optimization results.

Long-Term Reliability and Lifecycle Performance: The practical deployment of integrated TEG systems requires greater attention to performance degradation during prolonged operation. Thermal cycling can introduce mechanical stresses and changes in electrical or thermal contact resistance, potentially reducing the effectiveness of the thermoelectric module over time. Experimental evidence concerning thermoelectric degradation and contact fabrication indicates that interface stability is an important aspect of long-term performance[96,97]. Future studies should investigate how repeated operating cycles affect electrical output, contact integrity, and the structural stability of integrated assemblies. For PCM-assisted configurations, these assessments should also consider containment reliability, material compatibility, and changes in thermal-storage behavior after repeated melting and solidification. Beyond technical durability, the added complexity of an integrated system should be justified by its lifetime performance. Techno-economic and environmental assessments should therefore compare the additional manufacturing, maintenance, replacement, and auxiliary energy requirements against the electrical and thermal benefits achieved over the intended service life. This would provide a more realistic basis for evaluating whether integrated PV–TEG–PCM systems offer advantages over simpler alternatives, while maintaining consistency with the lifecycle considerations discussed in Section 8.5[94,100].

Reliable Transient Modeling and Independent Validation: Further development of numerical models should focus on their predictive reliability under changing operating conditions rather than solely on increasing model complexity. As discussed in Section 6, analytical and multiphysics approaches can provide valuable information about coupled thermal and electrical processes. However, their applicability depends on the treatment of boundary conditions, material properties, thermal interfaces, and time-dependent behavior. A particularly important direction is the development of validated transient models capable of representing variable thermal inputs, temperature-dependent thermoelectric properties, and PCM phase transitions within a consistent computational framework. Studies of automotive exhaust recovery demonstrate that transient operating conditions can influence predicted power generation and may lead to differences from steady-state estimates[59]. Future investigations should clearly separate numerical verification from physical validation. Mesh independence, time-step sensitivity, and conservation checks are necessary to establish numerical reliability, while comparison with independent experimental measurements is needed to assess predictive accuracy. Where discrepancies arise, their origins should be examined through targeted sensitivity analyses rather than relying exclusively on adjustments that improve agreement with a particular dataset. Improved reporting of model assumptions, uncertainty, and validation conditions would make numerical predictions more reproducible and support their use in the design of integrated systems.

Performance under Realistic Operating Conditions: A remaining gap between laboratory investigations and practical deployment is the limited evidence available for

net-energy improvements under representative operating profiles. Many configurations are evaluated at selected temperatures, flow rates, or irradiance levels, whereas actual thermal sources vary over time and may impose additional operational constraints. For PV–TEG and concentrated PV–TEG systems, future studies should account for changes in solar irradiance, PV operating temperature, cooling effectiveness, and optical concentration. PCM-assisted configurations should additionally be evaluated under successive thermal cycles to determine whether stored heat provides a sustained electrical benefit. In automotive applications, representative driving conditions and their associated exhaust-temperature and flow variations should be considered together with system mass, pressure drop, and auxiliary power requirements. The central objective should be to determine whether an integrated configuration produces a repeatable net-energy advantage over a clearly defined reference system. Experimental and numerical assessments that combine realistic operating profiles with consistent system boundaries would help identify the conditions under which additional thermal-management or heat-recovery components are justified. This approach would also provide a clearer connection between laboratory-scale performance improvements and practical energy-recovery potential.

An Integrated Framework for Future Investigations: The preceding priorities suggest the need for a coordinated research framework in which system design, numerical prediction, experimental validation, and practical assessment inform one another. Future investigations should begin by characterizing the available heat source and defining the required electrical or thermal output. Candidate architectures should then be assessed using consistent operating boundaries and performance objectives. Numerical optimization should guide the selection of promising configurations, while independent experiments should establish whether the predicted improvements can be reproduced. Designs that demonstrate favorable performance should subsequently be examined under variable operating conditions and evaluated in terms of durability, auxiliary consumption, and lifecycle implications. This framework would provide a more direct connection between advances in thermoelectric materials, thermal-storage enhancement, and heat-exchanger design and their practical contribution to integrated energy systems. The principal research challenge is no longer limited to demonstrating that additional electrical power can be generated, but extends to establishing when that power represents a reliable, reproducible, and worthwhile improvement in overall system performance.

CONCLUSIONS

Thermoelectric generation offers a solid-state route for converting part of an available temperature difference into electrical energy. Its practical value, however, depends on more than the intrinsic properties of the thermoelectric material. The findings reviewed in this article show that electrical output emerges from the interaction between material performance, module configuration, thermal interfaces, heat-exchanger design, source-temperature variability, cold-side heat rejection, and electrical loading. Consequently, the performance of an integrated thermoelectric system should be assessed at the system level rather than inferred from the material figure of merit or peak power alone. The fundamental thermoelectric effects provide the basis for understanding this behavior. The Seebeck effect enables voltage generation in response to a temperature difference, while Peltier and Thomson heat transfer, Joule heating, and thermal conduction influence the temperature field and the resulting electrical output. Although the dimensionless figure of merit, (ZT), is useful for comparing thermoelectric materials, it does not independently determine the performance of a complete energy-recovery system. Contact resistance, the temperature dependence of material properties, the distribution of temperature drops across the thermal pathway, and the external electrical load can all alter the operating conditions experienced by the active thermoelectric legs. Material selection and device-level optimization should therefore be considered alongside the design of the surrounding thermal system. The integration of thermoelectric generators with photovoltaic systems provides an opportunity to recover part of the heat associated with photovoltaic operation. Nevertheless, the benefits of PV–TEG integration depend on how heat is transferred to the thermoelectric module and how effectively the remaining heat is rejected. Concentration conditions, irradiance, photovoltaic operating temperature, thermal contact, and cooling requirements can change the balance between photovoltaic and thermoelectric output. A configuration that improves TEG generation does not necessarily maximize the combined electrical output, particularly when additional cooling or flow-management equipment is required. Comparisons between PV–TEG architectures must therefore distinguish the performance of individual components from the overall electrical benefit of the integrated system. Phase-change materials introduce an additional degree of thermal control by storing and releasing latent heat. Their integration with thermoelectric generators can modify transient

temperature conditions and, under suitable operating circumstances, maintain a useful temperature difference after the external heat input has declined. The effectiveness of this strategy depends on the PCM melting range, latent heat, thermal conductivity, storage geometry, charging and discharging rates, and the thermal contact between the storage material and the TEG. Hot-side, cold-side, and dual-sided arrangements influence the thermal pathway differently, so their relative performance cannot be established independently of the heat-source profile and heat-rejection conditions. Greater storage capacity or a longer period of thermal response should not automatically be interpreted as an increase in total electrical energy. The decisive metric is the energy generated over the complete operating cycle under clearly defined conditions. Heat-exchanger design is equally important in waste-heat recovery from fuel cells, vehicle exhausts, industrial gas streams, and other thermal sources. Compact exchangers, extended surfaces, vortex generators, and modified flow passages can improve heat transfer and alter the temperature distribution across a thermoelectric module. These improvements, however, may be accompanied by higher pressure drop, increased pumping or fan power, or additional cooling requirements. Their practical value must consequently be determined from the net electrical benefit rather than from heat-transfer enhancement alone. The operating environment also matters: automotive exhaust and other variable heat sources impose transient conditions that cannot always be represented adequately by steady-state calculations. A design optimized for a fixed temperature and flow rate may not retain the same advantage under realistic variations in source conditions. The comparative assessment reveals a persistent limitation in the available evidence: reported performance improvements are often obtained under different operating conditions, reference configurations, and evaluation boundaries. Changes in peak electrical power, PCM phase-change behavior, heat-transfer performance, and net energy generation represent distinct outcomes and should not be interpreted as equivalent measures of system effectiveness. Consequently, the significance of any reported improvement must be assessed in relation to the original study conditions and the performance objectives of the intended application.

Numerical modeling remains a valuable means of investigating coupled thermal, electrical, and fluid-flow behavior and of exploring configurations that would be difficult to test exhaustively. Analytical models, finite-element methods, computational fluid dynamics, and Multiphysics simulations can provide complementary information, but their predictions depend on the assumptions, material properties, contact conditions, and boundary conditions used. In particular, simplifying the temperature difference across the entire source-to-sink pathway as though it were applied directly across the active thermoelectric legs can lead to misleading estimates when thermal resistances elsewhere in the system are significant. Transient phase-change behavior and variable heat-source conditions also require suitable time-dependent treatment. Experimental validation should therefore be used to assess model reliability, and discrepancies between measured and predicted results should inform revisions to the model rather than being treated as incidental differences.

These findings indicate that progress toward practical deployment depends on demonstrating consistent system-level benefits rather than isolated improvements in component performance. Future investigations should therefore establish whether the reported advantages remain reproducible under representative operating conditions and whether they justify the additional technical and economic complexity of integrated configurations. The research priorities outlined in Section 10 provide a framework for addressing these remaining challenges.

Overall, the reviewed evidence supports a system-oriented approach to thermoelectric integration. Neither a high-performing thermoelectric material, an enhanced heat exchanger, nor the addition of PCM is sufficient by itself to guarantee a meaningful improvement in energy recovery. The strongest designs will be those in which the thermoelectric module, thermal storage, heat-transfer pathway, cooling arrangement, and electrical system are optimized together and evaluated against an appropriate reference. Demonstrating repeatable net-energy gains under realistic operating conditions, supported by transparent reporting and independent experimental validation, remains the essential step toward establishing the practical value of integrated PV–TEG–PCM and waste-heat recovery systems.

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