TEC vs. TEG Systems: Different Jobs, Different Optimization

Same thermoelectric physics — opposite mission

A practical engineering comparison of thermoelectric coolers (TECs) and thermoelectric generators (TEGs)

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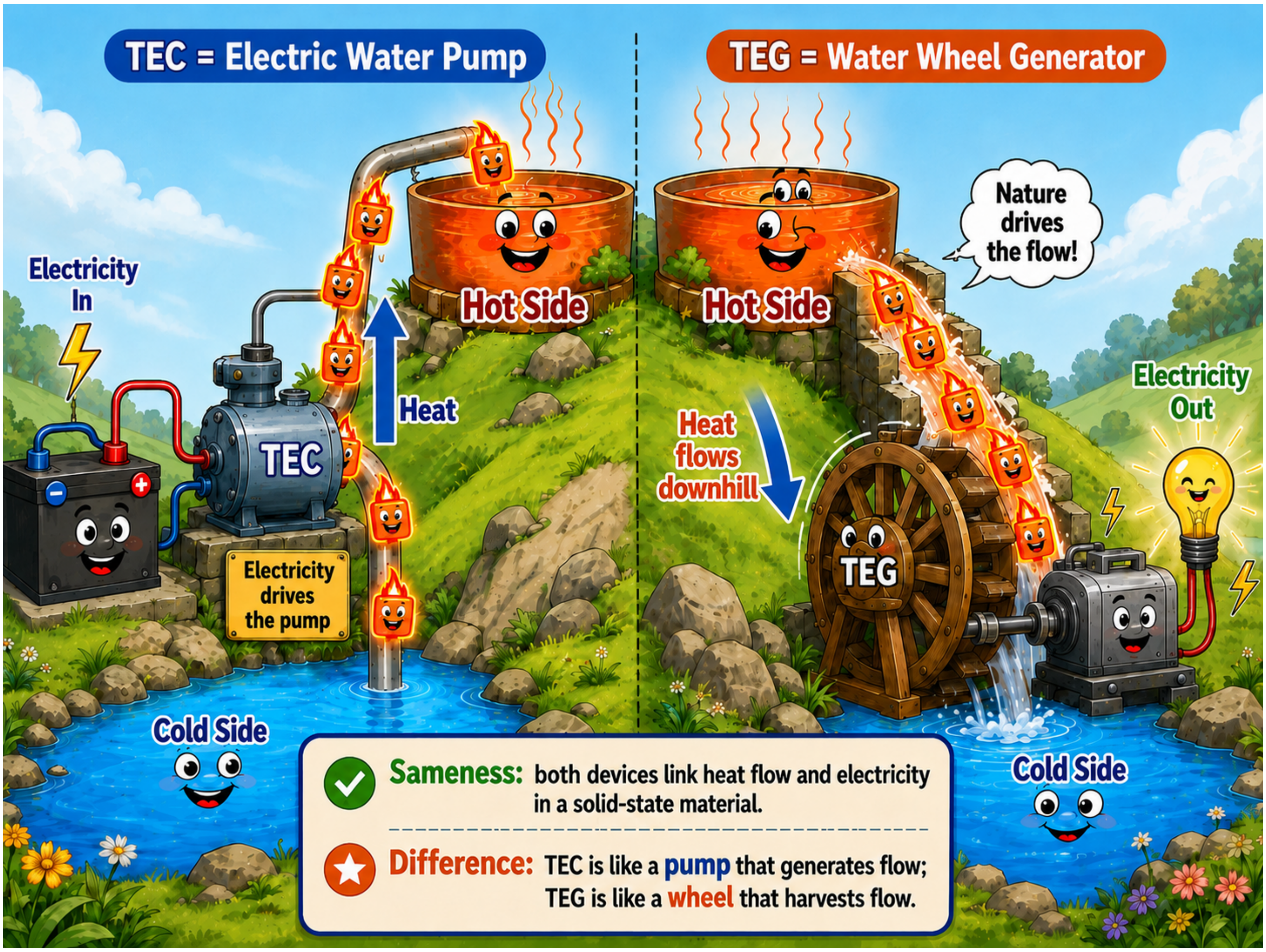
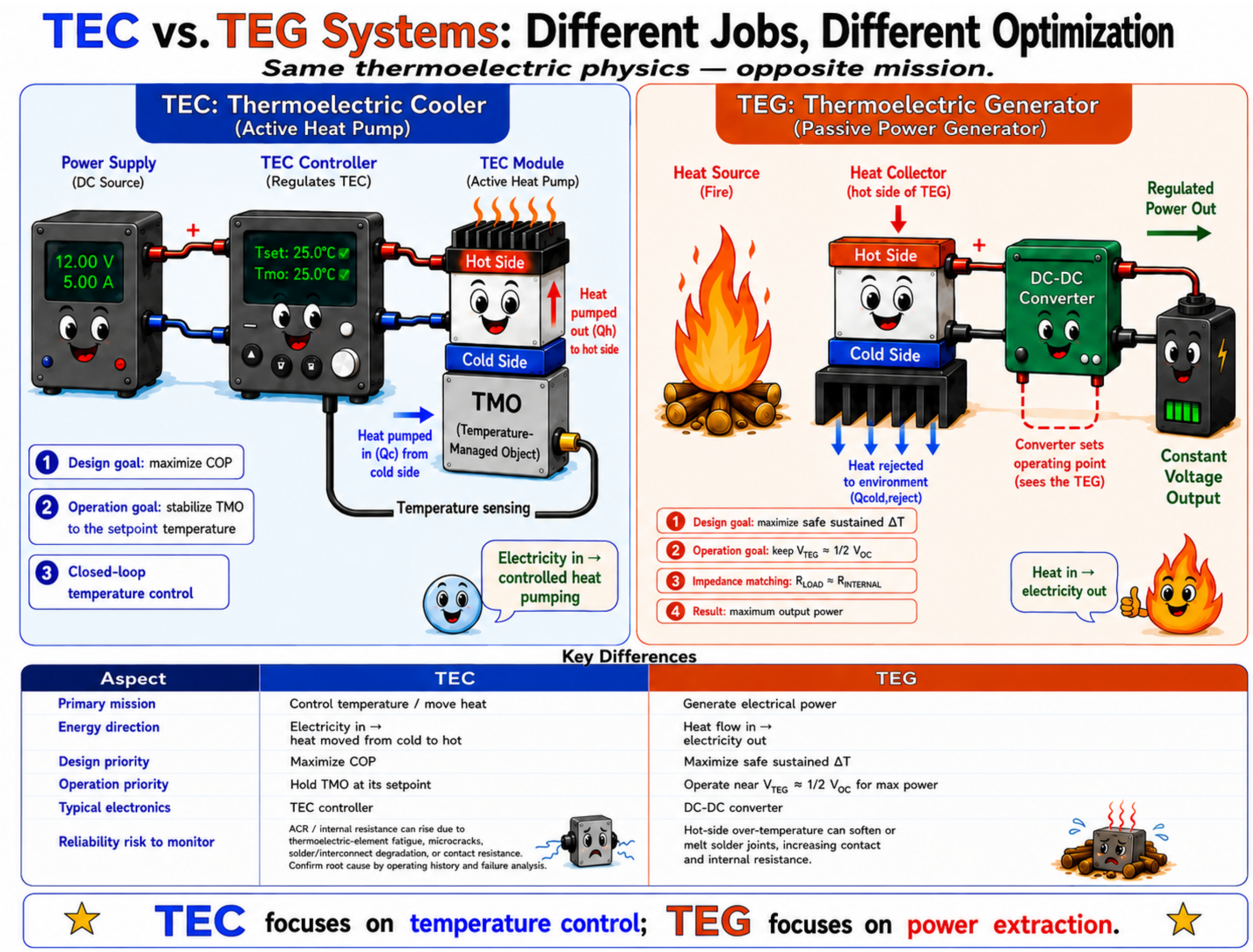


Figure 1. TEC = active heat pump; TEG = passive power generator. A TEC behaves like an electric water pump that uses electrical power to drive heat from the cold side to the hot side. A TEG behaves like a water wheel placed in a stream of heat flowing from a hot side to a cold side; it harvests a fraction of that flow as electrical power.

The analogy above captures a fundamental distinction between the two devices before any electronics, datasheet, or equation is introduced. A TEC must be powered to do its job; remove the electrical drive and active heat pumping stops, although passive heat conduction through the module continues (the $K \cdot \Delta T$ term in Section 5). A TEG module, at the module-physics level, does not require an electrical drive to generate — it needs only an existing temperature difference and a heat-rejection path — but a practical TEG system still needs power-management electronics, thermal interfaces, mechanical mounting, and protection limits to convert its variable DC output into useful regulated power. Both devices share the same underlying thermoelectric physics inside a solid-state material, but one consumes electricity to control temperature and the other generates electricity from a temperature gradient. The rest of this paper turns this intuition into the system-level architectures, equations, and selection rules an OEM engineer needs to specify the correct module, electronics, and thermal design.



Aspect	TEC	TEG
Primary mission	Control temperature / move heat	Generate electrical power
Energy direction	Electricity in → heat moved from cold to hot	Heat flow in → electricity out
Design priority	Maximize COP	Maximize safe sustained ΔT
Operation priority	Hold TMO at its setpoint	Operate near $V_{TEG} \approx 1/2\ V_{OC}$ for max power
Typical electronics	TEC controller	DC-DC converter
Reliability risk to monitor	ACR / internal resistance can rise due to thermoelectric-element fatigue, microcracks, solder/interconnect degradation, or contact resistance. Confirm root cause by operating history and failure analysis.	Hot-side over-temperature can soften or melt solder joints, increasing contact and internal resistance.

Figure 2. The TEC controller closes a temperature loop; the TEG converter closes an electrical operating-point loop. On the TEC side, the controller reads the temperature sensor, compares it with the setpoint, and adjusts current to drive heat from cold side to hot side, while also enforcing current, voltage, and hot-side-temperature protection limits. On the TEG side, the DC-DC converter manages the electrical operating point of the generator and delivers a regulated DC output — regulated only while the TEG input voltage, heat flow, and converter operating range are all within specification, and while hot-side/cold-side temperature and datasheet limits are observed by system thermal design — while a sustained ΔT is maintained by the heat source and heat sink. Same thermoelectric physics, opposite mission: closed-loop temperature control vs. electrical operating-point management, each within its own protection envelope.

Figure notes: (1) the "$V_{TEG} \approx ½ \cdot V_{oc}$" label shown in the TEG panel is a shorthand for $V_{TEG,load} \approx ½ \cdot V_{oc}$ — a first-order matched-load simplification; practical TEG converters implement MPPT or validated fractional-V_{oc} control rather than a fixed $½ \cdot V_{oc}$ target.

(2) "Maximize safe sustained ΔT" means the largest ΔT that stays within hot-side, cold-side, solder-system, mechanical, and converter datasheet limits — not the highest achievable hot-side temperature.

DIRECT ANSWER A TEC (thermoelectric cooler) system uses electrical power to actively control temperature. A TEG (thermoelectric generator) system harvests electrical power from an existing temperature difference. The physics are reciprocal; the engineering objectives are opposite. Optimized TECs and optimized TEGs are not automatically interchangeable. A TEC may generate voltage from a temperature difference, but reuse as a TEG requires verifying solder system, temperature rating, electrical resistance, sealing, and datasheet limits.

Quick Decision Guide

If you need to…	Choose…
Hold an object at a controlled temperature, or cool it below ambient	**TEC** — TEC module + TEC controller + temperature sensor

Stabilize a laser diode, detector, or precision instrument	**TEC** — closed-loop temperature control
Harvest electrical power from an existing sustained heat flow	**TEG** — TEG module + DC-DC power-management converter
Generate regulated DC from waste heat, exhaust, or solar/process heat	**TEG** — electrical operating-point management (often MPPT)
Reuse a TEC as a TEG (or vice versa) without redesign	**Verify first** — optimized TECs and optimized TEGs are not automatically interchangeable (see Section 8)

Next step — ATI path: for TEC systems, TEC module + TEC controller + thermistor/heat sink. For TEG-style power harvesting, confirm module availability and the DC-DC converter path (converter design and validation remain the integrator's responsibility) against your hot-side, cold-side, and output requirements before committing to a design.

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1. Executive Summary

Thermoelectric coolers (TECs) and thermoelectric generators (TEGs) are often confused because they can look physically similar: ceramic plates, internal N-type and P-type thermoelectric elements, and two electrical leads. The critical difference is not the appearance. The critical difference is the direction of energy flow and the system's control objective.

A TEC is an active heat pump. It uses controlled DC current to move heat from the cold side to the hot side. In a real temperature-control system, the TEC is driven by a TEC controller that reads a temperature sensor attached to the TMO (temperature-managed object — the component or surface whose temperature is being held to a setpoint) and adjusts current to hold the setpoint. The control system, the sensor, and the heat sink are part of the TEC system; the module alone does not guarantee performance.

A TEG is a passive power generator at the module-physics level; a practical system still requires power-management electronics and thermal/safety design. It uses heat flow through a temperature gradient to produce DC voltage and current. In a real power-harvesting system, the TEG is connected to a DC-DC power-management converter that extracts power while keeping the electrical operating point near the maximum-power condition. The converter, hot-side thermal interface, and cold-side heat-rejection path are part of the TEG system; the module alone does not guarantee usable output.

The engineering mistake is to treat TECs and TEGs as the same product used in two directions. They share thermoelectric physics, but they are optimized, controlled, mounted, and protected differently. Selecting the wrong module family, electronics, or thermal architecture is often the root cause of avoidable thermoelectric system problems.

Key takeaways

- TECs consume electricity to move heat and control the temperature of a target object; TEGs harvest electrical power from an existing temperature difference.
- TEC systems need a dedicated TEC controller with temperature-sensor feedback; TEG systems need a DC-DC power-management converter, often with MPPT.
- Optimized TECs and optimized TEGs are not automatically interchangeable — materials, solder limits, resistance, and packaging typically differ across families and suppliers, so overlap should be verified rather than assumed.

- Hot-side heat sinking matters for both, but for different reasons: for a TEC it must reject $Q_h = Q_c + P_{in}$ (where $P_{in} = V_{TEC} \cdot I_{TEC}$ is the electrical input power); for a TEG it maintains the sustained ΔT that drives power output.

2. Peltier Effect vs. Seebeck Effect: TEC vs. TEG System Physics

Both TECs and TEGs rely on the coupling between heat flow and electrical charge in thermoelectric materials. The two most important effects are:

- Peltier effect: electrical current causes heat pumping at material junctions. This is the main effect used in TEC operation.
- Seebeck effect: a temperature difference produces voltage. This is the main effect used in TEG operation.

The same solid-state physics can therefore be used in two opposite ways. A TEC asks: “How much controlled current should I apply to hold the object at the target temperature?” A TEG asks: “Given this heat flow and temperature difference, how should I load the module to extract the most electrical power?” The two questions lead to opposite choices for module construction, electronics, mounting, and protection. Reciprocal physics does not mean reciprocal product qualification: construction, solder system, temperature rating, sealing, and electrical resistance must be verified by part number before reuse.

3. TEC vs. TEG Differences at a Glance

Aspect	TEC System	TEG System
Primary mission	Control temperature; move heat on command.	Generate electrical power from a sustained temperature difference.
Energy direction	Electrical input -> thermal heat pumping.	Thermal heat flow -> electrical output.
Primary physical effect in use	Peltier effect: current drives heat pumping.	Seebeck effect: ΔT produces voltage.
Typical inputs	Controlled DC current from power supply + TEC controller.	Heat at hot side and heat removal at cold side.
Typical outputs	Cold-side cooling or heating; stabilized TMO temperature.	Variable DC voltage and current before conversion; regulated output after converter.
System electronics	TEC controller with temperature feedback, often bipolar current drive for heat/cool control.	DC-DC power-management converter; sometimes MPPT or fraction-of-open-circuit-voltage control.
Design priority	Maximize COP for the required cooling load and temperature lift while maintaining stability.	Maximize safe sustained ΔT across the module within hot-side and solder limits specified by the module datasheet, ensure adequate usable heat flow, and match/load the generator for maximum output power at a validated operating point.
Operation priority	Hold the TMO at setpoint with stable closed-loop control.	Keep the TEG operating near its maximum-power point. For a simple matched-load Thévenin model, $V_{TEG,load} \approx ½ \cdot V_{oc}$; practical converters may use MPPT or fractional-V_{oc} control instead of a fixed $½ \cdot V_{oc}$ target.

Aspect	TEC System	TEG System
Thermal design focus	Remove $Q_h = Q_c + P_{in}$ from the hot side; the heat sink must reject both pumped heat and electrical input power.	Deliver heat into the hot side (Q_{hot}) and remove the rejected heat from the cold side ($Q_{cold,reject}$) without overheating the module or solder joints. As a simplified first-order steady-state balance, $Q_{cold,reject} \approx Q_{hot} - P_{elec}$, where P_{elec} is electrical power extracted at the TEG terminals, neglecting parasitic losses through interfaces, leads, and the converter. Note: in TEG context, the cold-side heat term is rejected waste heat, not the "Q_c" cooling capacity used in TEC sizing.
Useful figure of merit in system design	COP (coefficient of performance), cooling capacity Q_c, ΔT, temperature stability, ripple, sensor placement.	Open-circuit voltage V_{oc}, internal resistance, matched-load power, output voltage range, hot-side temperature limit.
Reliability risk to monitor	Under cyclic or stressed operation, alternating-current resistance (ACR), used here as a practical internal-resistance trend indicator, can rise due to thermoelectric-element fatigue, microcrack development, solder/interconnect degradation, or contact-resistance growth. ACR/internal-resistance increase is a diagnostic clue, not a standalone root-cause diagnosis; root cause should be confirmed by operating history and failure analysis. The dominant risk in any given application still depends on cycling, clamping, humidity, sealing, and hot-side temperature.	Hot-side over-temperature can soften or melt solder joints, depending on solder system and datasheet limits; contact resistance and internal resistance can rise. Severe overheating can cause irreversible open-circuit or high-resistance failure.

4. System-Level Difference: Controller vs. Converter

4.1 TEC system electronics: a controller, not just a power supply

A TEC should normally be driven by a TEC controller rather than directly by a raw power supply. The controller reads a temperature sensor on the TMO or cold plate, compares it with the setpoint, and adjusts TEC current through a regulated H-bridge or linear stage. For bidirectional temperature control, the controller may reverse current so the same module can cool or heat. The desired drive is low-ripple regulated DC: the average DC component is what drives net Peltier heat pumping, while the ripple component adds RMS current and I^2R (Joule) heating without an equivalent control benefit and can worsen stability and fatigue. Switching power stages are common, but they are normally followed by current regulation and filtering to keep the ripple seen by the module low.

The controller's job is not only to supply current. It must deliver current that meets the module's ripple requirement, prevent runaway hot-side temperature, avoid excessive current, and maintain loop stability. Ripple depends on drive topology and load: some controllers regulate current directly, switching stages need adequate filtering, so precision designs use low-ripple linear or well-filtered switching drive per the controller datasheet. Thermal runaway in this context means that if the hot-side heat sink cannot reject the total heat ($Q_h = Q_c + P_{in}$), T_h rises and ΔT across the module widens. The controller then commands more current to hold the setpoint, Q_h grows further, and the loop diverges toward the hot-side over-temperature limit. A well-designed controller prevents this by enforcing current, voltage, and hot-side-temperature limits, and by monitoring the sensor. In precision laser, detector, and instrumentation systems, sensor placement and PID tuning can matter as much as TEC size: a sensor mounted too far from the TMO, or coupled through a high thermal resistance, will limit closed-loop stability no matter how powerful the controller is. Note that a raw PWM signal driven directly into a TEC is not the same as a regulated TEC controller: acceptable switching controllers include current regulation and filtering so the module sees controlled low-ripple current, and precision applications commonly use low-ripple linear or filtered-switching TEC controllers rather than raw PWM.

4.2 TEG system electronics: a DC-DC converter, not usually an inverter

A TEG produces DC voltage and DC current. Therefore, the first downstream electronics block is normally a DC-DC converter or power-management converter, not an inverter. An inverter is only needed later if the final load requires AC power.

The converter must accept a variable, source-impedance-limited TEG input and produce a regulated output voltage. A TEG power-management converter should manage the input operating point rather than simply clamp the TEG voltage, so the generator can deliver useful power without collapsing its voltage or overheating the thermal stack. In other words, the converter manages the TEG's electrical operating point and helps prevent electrical loading errors; thermal protection still requires hot-side/cold-side temperature limits, heat-sink design, and adherence to module datasheet limits. In low-ΔT harvesting applications, the converter may also need a cold-start mechanism, because the TEG open-circuit voltage at small temperature differences can be lower than the converter's minimum startup voltage. Specific converter IC selection must be verified independently against the actual TEG and system conditions; any third-party IC examples cited in this paper are design-concept references, not ATI compatibility endorsements or ATI-supplied products.

5. Design Optimization: COP vs. ΔT and Power Extraction

Design-rule summary. For TECs, the design objective is to maximize useful controlled cooling per watt of electrical input at the required temperature lift. For TEGs, the design objective is to maximize usable electrical power extracted from a safe sustained temperature difference and heat-flow path within module limits. The equations that follow are first-order sizing tools; final selection requires datasheet performance curves and prototype verification.

5.1 TEC design goal: maximize useful cooling per watt

First-order sizing model. Sign convention: positive current I is the polarity that pumps heat from the cold side to the hot side; $\Delta T = T_h - T_c$; Q_c is positive when heat is removed from the cold side; Q_h is positive when heat is rejected at the hot side. For a TEC, the basic cold-side cooling equation is:

$$Q_c = \alpha \cdot T_c \cdot I - \tfrac{1}{2} \cdot R \cdot I^2 - K \cdot \Delta T$$

where:

- Q_c = net cooling capacity at the cold side, W
- α (alpha) = effective module-level Seebeck coefficient, V/K (module-level total, not a per-junction constant; the same quantity denoted S below)
- T_c = absolute cold-side temperature, K
- I = TEC drive current, A (DC, low-ripple)
- R = module electrical resistance, Ω
- K = module thermal conductance, W/K
- $\Delta T = T_h - T_c$ = temperature lift across the module, K

The equation assumes a simple one-dimensional module model with constant material properties and a clean low-ripple DC drive current; in practice α, R, and K are temperature-dependent, so it is a first-order sizing aid, not a substitute for datasheet curves. It is useful for first-pass sizing and for understanding trade-offs. Final selection should use the module datasheet performance curves (Q_c vs. I at specified ΔT), not this analytical expression alone.

This equation explains why a TEC should not simply be driven at maximum current. Peltier pumping increases roughly with current, but Joule heating increases with current squared. Running too hard can reduce COP, increase hot-side heat rejection, and accelerate fatigue.

For balanced precision systems, the practical design target is to size the module large enough that it can operate well below I_{max} for the required Q_c and ΔT. That usually means designing for high COP, manageable hot-side heat, and stable control rather than maximum theoretical ΔT. Because COP improves as ΔT falls, Analog Technologies recommends keeping ΔT below approximately 30°C wherever the system design allows, as a first-pass efficiency guideline for balanced precision systems using typical Bi2Te3 modules, based on ATI application-engineering experience with Bi2Te3 COP behavior. TEC systems intentionally designed to maximize ΔT will operate at lower COP by design; this 30°C guideline is not a datasheet limit or a hard design ceiling. The specific operating current should be selected from the module datasheet performance curves (Q_c vs. I at the specified ΔT and T_h). Confirm the final operating point with prototype measurements rather than a generic fraction of I_{max}.

Hot-side heat-sink sizing constraint. Once Q_c and P_{in} (the TEC electrical input at the chosen operating current) are known, the hot-side heat sink and thermal interface must be sized so the hot-side temperature T_h stays within the module datasheet limit. A useful first-order design constraint is:

$$R_{\theta SA} \le (T_{h,max} - T_{amb}) / Q_h - R_{TIM}$$

where:

- $R_{\theta SA}$ = sink-to-ambient thermal resistance of the hot-side heat sink, K/W
- $T_{h,max}$ = maximum allowable hot-side temperature from the module datasheet, K
- T_{amb} = ambient (or coolant) temperature at the heat-sink boundary, K
- Q_h = total hot-side heat load = $Q_c + P_{in}$, W
- P_{in} = TEC electrical input power at the operating current ($P_{in} = V \cdot I$), W
- R_{TIM} = total thermal resistance of the hot-side path from the module hot ceramic to the sink-to-ambient reference, K/W (sum all layers — TIM/grease, isolation pads, adhesives, spreaders, plates — not just one)

In plain terms, this tells the designer the maximum thermal resistance the hot-side heat sink can have (after subtracting the interface material's thermal resistance) to keep the module hot-side temperature within its datasheet limit for the required cooling load. Use the full $Q_h = Q_c + P_{in}$ and include all relevant interface resistances in R_{TIM}. The numerator is a temperature difference, so °C and K values are numerically equal. If, under this first-order steady-state model, the calculated allowable $R_{\theta SA}$ is zero or negative, no passive heat sink can meet the requirement — reduce the load or ambient, use forced-air or liquid cooling, or change the module or operating point. This constraint assumes uniform ambient conditions and neglects convection/radiation nonlinearities and heat-sink orientation effects. If the constraint is violated, T_h rises, ΔT across the module widens, COP falls, and closed-loop control eventually fails. Undersized hot-side heat sinking is a frequent avoidable TEC system mistake (see FAQ).

5.2 TEG design goal: maximize power extracted from a temperature difference

For a TEG, the first-order open-circuit voltage is:

$$V_{oc} = S \cdot \Delta T$$

where:

- V_{oc} = TEG open-circuit voltage, V
- S = effective module-level Seebeck coefficient, V/K (the same module-level quantity denoted α in the TEC equation)
- $\Delta T = T_h - T_c$ = temperature difference across the module, K

This is a first-order, no-load expression. In a loaded TEG, the actual voltage drops below V_{oc} because of internal resistance and because thermal feedback from the loaded operating point slightly reduces the working ΔT.

A practical TEG behaves like a voltage source in series with internal resistance. Maximum power transfer occurs when the load resistance equals the TEG internal resistance. Under that condition, the loaded TEG voltage is approximately half of its open-circuit voltage:

$$R_{load} \approx R_{internal} \quad \text{and} \quad V_{TEG,load} \approx \tfrac{1}{2} \cdot V_{oc}$$

where:

- R_{load} = effective electrical load resistance seen at the TEG terminals, Ω
- $R_{internal}$ = TEG internal electrical resistance, Ω (temperature-dependent)
- $V_{TEG,load}$ = loaded TEG terminal voltage at the maximum-power operating point, V

Under the same first-order matched-load model, the maximum extractable power is approximately $P_{max} \approx V_{oc}^2 / (4 \cdot R_{internal})$. Like the relations above, this is a first-order estimate: V_{oc} and $R_{internal}$ are temperature-dependent, so confirm actual output against datasheet curves and prototype measurements.

Do not design for exactly ½·V_{oc}. The ½·V_{oc} relation is a first-order sizing starting point, not an operating rule. Use MPPT (or a fractional-V_{oc} control that adapts to temperature) in real systems.

These relations assume a first-order Thévenin model with fixed internal resistance. They are a useful starting point for converter sizing, not an operating rule for all conditions. In practice, TEG internal resistance and Seebeck coefficient are temperature-dependent, so the actual maximum-power operating point shifts with hot-side and cold-side temperature; a static ½·V_{oc} control target can therefore drop away from the true MPP under changing thermal load. Practical TEG converters implement maximum-power-point tracking (MPPT) or a fraction-of-open-circuit-voltage method rather than relying on a fixed ½·V_{oc} target. Safe hot-side temperature and safe sustained ΔT must be taken from the specific module datasheet; solder-system limits differ among module families.

The goal of MPPT or fractional-V_{oc} control is not to force a fixed current; the goal is to keep the TEG near its maximum-power operating point while the heat source, cold-side temperature, and load vary.

6. Operation Optimization: Temperature Setpoint vs. Matched-Load Operating Point

Operating Question	TEC System Answer	TEG System Answer
What does the control loop try to hold?	TMO temperature at the setpoint.	Electrical operating point near maximum power.
What feedback is most important?	Temperature sensor feedback from the TMO/cold plate.	TEG input voltage/current and sometimes hot-side/cold-side temperatures.
What happens if the load changes?	Controller changes current to maintain the same TMO temperature.	Converter changes duty cycle or input impedance to maintain efficient power extraction.
What is the main protection limit?	TEC current, hot-side temperature, controller voltage/current capability, condensation risk.	Hot-side temperature, solder system, cold-side heat rejection, converter input range.
What is the common design mistake?	Driving a TEC at I_{max} and undersizing the hot-side heat sink.	Maximizing hot-side temperature without protecting solder joints or matching the electrical load.

7. Failure Modes and Reliability Clues

Failure mode language must be used carefully. Dominant failure mechanisms in thermoelectric modules are highly application-dependent: steady-state cooling, rapid thermal cycling, high humidity, high clamping force, high hot-side temperature, and lead-wire strain can each change which failure path dominates. The following table gives practical, commonly observed reliability clues rather than a universal failure ranking for every application.

ATI end-of-useful-life definition. Analog Technologies defines the end of useful life for a TEC module as a 10% rise in AC resistance (ACR) from its initial value, measured with ATI's approved ACR method — an LCR meter at a fixed test frequency, a stable ambient temperature, and a consistent fixture and contact method, referenced to the initial value recorded at incoming inspection or qualification. This 10% ACR figure is a design-engineering reference point for cycling-life assessment and reliability trending under ATI's internal reliability criteria; it is not a warranty specification, and actual application life depends on the specific operating conditions, thermal profile, and system requirements. ATI family-specific cycling references: under repeated full-scale current reversal, Regular Temperature TEC modules typically reach this threshold in roughly 500–1,000 reversals, while ATI's long-life ATE1-TC and ATE1-TCHE families are engineered for approximately 20,000 reversals — about a 20× extension in cycling endurance. In practice, ACR is typically measured at incoming inspection and during qualification testing, and trended periodically or at scheduled maintenance intervals in high-cycling duty. ACR is best measured with an LCR meter; a standard DC multimeter measures only DC resistance and is less sensitive than ACR trending to the early fatigue and interconnect-degradation modes that produce internal micro-cracking. Comparisons between measurements taken under different methods, frequencies, or fixtures are not directly interchangeable. Root cause still requires operating history and, when necessary, teardown or failure analysis. ATI applies a three-gate TEC selection method (capacity, temperature class, cycling lifetime) that maps operating conditions to ATI product families; contact ATI applications engineering for the detailed selection method and worked examples. Source basis for the ATI-specific numeric claims in this paper (Regular Temperature ~125 °C surface limit, high-temperature −H family ~238 °C internal solder and 200 °C operating rating, Regular Temperature ~500–1,000 reversals to 10% ACR, ATE1-TC / ATE1-TCHE ~20,000 reversals to 10% ACR, and the 10% ACR end-of-useful-life criterion): the current ATI product datasheets and reliability notes. These values reflect ATI internal test and qualification references, not warranty limits; confirm current values against the applicable ATI datasheet before design-in.

Reliability Topic	TEC System	TEG System
Internal resistance / ACR trend	Rising ACR can reflect thermoelectric-element fatigue, microcrack development, solder/interconnect degradation, or contact-	Rising internal resistance can indicate solder-joint resistance increase, contact degradation, or damage from over-

	resistance growth, especially after thermal cycling. Confirm root cause by operating history and failure analysis.	temperature.
Thermal cycling	Current reversals and large temperature swings stress pellets, solder joints, and interconnects.	Usually less reversal stress, but thermal gradients and repeated heat-up/cool-down cycles still fatigue joints.
Hot-side temperature	High T_h reduces margin, increases heat-sink burden, and accelerates aging.	High hot-side temperature is often the critical risk; exceeding solder or package limits can cause permanent resistance increase or open failure.
Moisture / condensation	Cold-side operation below dew point can corrode internal joints unless sealed or protected.	Less likely to condense on the hot side, but environmental sealing may still matter in outdoor or exhaust-energy harvesting.
Electrical overstress	Ripple or excessive current adds I^2R heat and fatigue.	Overloading, shorting, or startup faults can force excessive current, drop terminal voltage, disturb the thermal operating point, and add Joule heating; severity depends on source temperature, ΔT, internal resistance, and converter behavior.

8. When to Choose TEC, TEG, or Both

Choose a TEC when...

- The target is a controlled temperature, not harvested power.
- The TMO must be cooled below ambient (below-ambient operation requires condensation and dew-point control through appropriate sealing or environmental protection), heated above ambient, or stabilized tightly around a setpoint.
- The system can supply electrical power and reject $Q_h = Q_c + P_{in}$ from the hot side.
- Applications include laser diode wavelength control, detector cooling, optical benches, precision instruments, and medical or analytical equipment where independently qualified by the end-system integrator.

Match the ATI TEC family to the environment and duty. If the hot-side or ambient temperature can approach or exceed ~125°C (the surface limit of Regular Temperature modules), specify ATI's high-temperature −H family, which uses ~238°C internal solder and is rated for operation to 200°C. If the application involves frequent full-scale current reversal — such as PCR/qPCR thermal cycling or repeated heat/cool duty — specify ATI's long-life ATE1-TC or ATE1-TCHE family, engineered for approximately 20,000 reversals to the 10% ACR end-of-useful-life threshold, versus roughly 500–1,000 for Regular Temperature modules. Confirm exact ratings against the current ATI datasheet.

Note: Application examples do not imply regulatory certification or suitability for a specific safety-critical system. ATI modules and controllers are not inherently qualified to FDA, ISO 13485, DO-160, IATF 16949, AEC-Q, or other regulated-market standards unless explicitly documented per part number. Final qualification for medical, automotive, aerospace, or other regulated end uses is the responsibility of the system designer, and requires all applicable qualification testing to be performed by the end-system integrator. Even where a component holds specific part-number certification, full compliance at the operational system level remains the responsibility of the end-system integrator.

Choose a TEG when...

- A sustained temperature difference already exists and would otherwise be wasted.
- The useful output is electrical power, not a controlled object temperature.
- The system can maintain a safe hot-side temperature and a cold-side heat-rejection path.
- Applications include waste-heat recovery, remote sensors, exhaust-powered electronics, and energy harvesting from industrial heat sources, where independently qualified by the end-system integrator.

Use both ideas carefully when...

A thermoelectric module can sometimes be operated in the opposite mode for demonstration or limited use, but optimized TECs and optimized TEGs are not automatically interchangeable. Before reusing a TEC as a TEG or a TEG as a TEC, verify material optimization, solder temperature rating, electrical resistance, mechanical limits, sealing, and expected temperature range.

TEG safety-scope note. High-temperature sources, exhaust/process heat, high-pressure or vibration environments, outdoor installations, and regulated power systems require mechanical, thermal, electrical, insulation, environmental, and safety review by the system designer. This paper is a first-pass technical comparison, not a safety certification, installation procedure, or code-compliance document. Burn risk, fire risk, thermal runaway, condensation, electrical isolation, and structural mounting are the responsibility of the system designer or OEM integrator.

9. Practical Checklist

Checklist Item	For TEC	For TEG
Define the mission	Temperature control of the TMO.	Power extraction from a heat source.
Identify thermal boundary conditions	Q_c, target TMO temperature, ambient, hot-side heat sink.	Hot-side source temperature, cold-side sink temperature, available heat flow.
Choose electronics	TEC controller matched to current, voltage, sensor, stability, and ripple requirements.	DC-DC converter / power-management converter matched to V_{oc} range, power level, and MPPT method. Check minimum cold-start voltage, minimum startup power, post-startup input-voltage range, and load-transient behavior against the actual TEG module and ΔT profile.
Optimize operating point	Design for COP and stability; avoid unnecessary I_{max} operation.	Design for maximum safe sustained ΔT within module limits, and target an operating point near $V_{TEG,load} \approx ½ \cdot V_{oc}$ only when using the simple matched-load Thévenin model; otherwise use MPPT or fractional-V_{oc} control.
Protect reliability	Limit current, cycling stress, hot-side temperature, condensation, and mechanical shear.	Limit hot-side over-temperature, solder stress, cold-side heat-sink saturation, and converter loading errors.
Validate on prototype	Measure TMO stability, hot-side temperature, input power, and ACR trend.	Measure V_{oc}, loaded voltage, output power, hot-side/cold-side temperatures, and internal-resistance trend.

10. Conclusion

TECs and TEGs are thermoelectric cousins, not identical system blocks. The TEC system is designed around closed-loop temperature control. The TEG system is designed around sustained ΔT and power extraction. Confusing these two missions leads to wrong electronics, wrong thermal design, and wrong reliability assumptions.

For TEC applications, start with the TMO temperature target, cooling load, hot-side heat sink, and controller. For TEG applications, start with the heat source, cold-side heat sink, open-circuit voltage, internal resistance, and DC-DC converter. The same thermoelectric physics leads to opposite engineering priorities.

When the boundary conditions are well defined — thermal loads, target temperature or target power, ambient envelope, and reliability expectations — the correct module family, controller or converter, and heat-sink architecture usually become straightforward to identify. Sending those inputs to a thermoelectric applications engineer early is a useful way to reduce the risk of a redesign cycle. In every case, final performance and reliability depend on module datasheet limits, thermal-interface quality, clamping, condensation and sealing, electrical isolation, and prototype validation; the module alone does not guarantee the result.

11. Frequently Asked Questions

What is the difference between a TEC and a TEG?

A TEC (thermoelectric cooler) uses electrical input to move heat and control the temperature of an object. A TEG (thermoelectric generator) uses an existing temperature difference to produce electrical output. Both rely on thermoelectric physics, but a TEC consumes electricity (Peltier effect) while a TEG generates electricity (Seebeck effect). Their system electronics, optimization targets, and protection limits are different and the modules are not automatically interchangeable.

Can a TEC be used as a TEG, or a TEG as a TEC?

In a demonstration or limited-use sense, yes — both effects coexist in any thermoelectric module. In an optimized system, no. TEC modules are optimized for high cooling capacity per watt of input current at modest ΔT; TEG modules are optimized for power generation at sustained higher hot-side temperatures and often use different solders and packaging. Before substituting one for the other, verify material grade, maximum hot-side temperature, solder rating, electrical resistance, mechanical and sealing limits, and prototype the result.

Do I really need a TEC controller, or can I drive a TEC from a bench power supply?

A bench supply with no temperature feedback can prove that a module pumps heat, but it cannot hold a setpoint, react to disturbances, or protect the module from runaway hot-side temperature. Production TEC systems use a dedicated TEC controller with a temperature sensor on the TMO, low-ripple DC drive, current and voltage limiting, and (where required) bidirectional drive for heat/cool operation.

Why is a DC-DC converter, not an inverter, the right first block after a TEG?

A TEG produces a DC voltage and DC current that vary with ΔT and load. A DC-DC power-management converter regulates that variable DC into a usable DC bus and manages the input operating point so the TEG is not loaded outside its useful range. An inverter (DC-to-AC) is only needed if the end load itself requires AC.

Is the rule $V_{TEG,load} \approx ½\cdot V_{oc}$ always correct for TEG operation?

No — it is a first-order matched-load approximation from a simple Thévenin model. The true maximum-power point shifts with temperature and load, so practical converters use MPPT or fractional-V_{oc} control rather than a fixed $½\cdot V_{oc}$ target.

What does it mean when a thermoelectric module’s ACR rises over time?

Rising alternating-current resistance (ACR) is a practical indicator that internal-resistance is trending upward. It can reflect thermoelectric-element fatigue, solder-joint or interconnect degradation, microcrack development, or contact-resistance growth. ACR alone does not identify the root cause; the operating history (cycling, hot-side temperature, clamping, humidity) and a teardown or failure analysis are normally needed to confirm what is happening. For ATI's 10% ACR design-engineering reference and family-specific cycling notes, see Section 7; those values are internal reliability references, not warranty specifications.

Why does the hot-side heat sink have to dissipate more than the cooling load?

Because the TEC pumps both the cold-side cooling load (Q_c) and dissipates its own electrical input power (P_{in}) at the hot side: $Q_h = Q_c + P_{in}$. If the hot-side heat sink is sized only for Q_c, the hot-side temperature rises, ΔT across the module increases, COP collapses, and the TEC can no longer hold the setpoint. Undersized hot-side heat sinking is a frequent avoidable TEC system mistake.

12. What to Send for Application Review

To get a useful first-pass recommendation from a thermoelectric applications engineer, the following inputs are typically sufficient. Sending the most accurate values available — even rough estimates with stated uncertainty — produces a faster, more relevant response than describing the application in general terms.

For TEC (temperature-control) applications

- TMO target temperature and acceptable tolerance / stability target

- Cooling load Q_c (steady-state and worst-case transient)
- Ambient temperature range and available hot-side heat-sink area / airflow
- Available controller power supply: voltage rail, current limit
- Sensor type and intended sensor location relative to the TMO
- Mechanical envelope: module footprint, height, clamping method
- Environmental constraints: humidity, condensation risk, sealing
- Operating profile: continuous, cycled, on-demand; expected duty cycle

For TEG (power-extraction) applications

- Hot-side temperature range (steady-state and peak)
- Cold-side temperature range and available heat-rejection path
- Heat-source type (exhaust, process, solar, body, other) and available heat flow
- Target output: voltage, current, power, and whether output must be regulated
- Required startup voltage / minimum-ΔT cold-start behavior
- Allowed maximum hot-side temperature, including transient spikes
- Mechanical and environmental constraints: footprint, vibration, sealing
- Reliability and lifetime expectations: continuous, intermittent, mission profile

ATI Resources

Analog Technologies provides TEC modules, TEC controllers, thermistors, and thermal-system components (heat sinks and assemblies) for OEM and engineering applications, and offers TEG modules for select applications where applicable. Confirm current TEG availability and product-family status with ATI before design-in. DC-DC converters for TEG power management are typically selected from third-party power-management IC suppliers and matched to the specific TEG operating range; specific converter IC selection must be verified independently by the system designer. ATI applications engineering can help with first-pass component-family guidance for TEC modules and starting-point TEC controller and thermistor recommendations, and can discuss TEG module fit for qualified projects where applicable; the TEG converter block itself is not an ATI product, and final system validation, converter design, and compliance remain the responsibility of the end-system integrator. Product pages are listed in the "Related ATI product pages" table below. For engineering domain use, visit:

Ready to specify your TEC or TEG system? For help selecting between TEC and TEG solutions, sizing a TEC controller, or defining TEG converter input requirements, ATI applications engineering can review qualified project inputs and suggest a starting product family or design direction. Final TEG converter selection, design, and validation remain the responsibility of the end-system integrator. Send the inputs listed in **Section 12 (“What to Send for Application Review”)** and contact ATI via the Contact Us page at www.analogtechnologies.com/contact.html, by email at sales@analogtechnologies.com, or by phone at +1-408-748-9100 (San Jose, CA). Use www.analogtechnologies.com for specifications and engineering information; www.analogti.com is the companion catalog/shop domain where available.

- www.analogtechnologies.com
- www.analogti.com

Note: This white paper is an engineering comparison. Final component selection should be based on the specific datasheet, operating temperature limits, controller/converter limits, assembly method, and prototype measurements.

Related ATI product pages

Product category	Page on www.analogtechnologies.com
TEC modules (Peltier modules) — Regular Temperature, high-temperature (−H), and long-life (ATE1-TC / ATE1-TCHE) families	https://www.analogtechnologies.com/tec-module.html
TEC controllers — low-ripple closed-loop temperature control	https://www.analogtechnologies.com/tec-controller.html
Thermistors / temperature sensors — feedback devices for TEC loops	https://www.analogtechnologies.com/thermistor.html

Thermal system components / heat sinks — hot-side and cold-side thermal management	https://www.analogtechnologies.com/thermal_system_components.html
TEG modules — thermoelectric generators for waste-heat harvesting (confirm current availability with ATI before design-in)	https://www.analogtechnologies.com/teg.html
Contact / applications engineering	**https://www.analogtechnologies.com/contact.html** (tel: +1-408-748-9100, San Jose, CA)

References

- H. J. Goldsmid, *Introduction to Thermoelectricity*, Springer Series in Materials Science. Standard textbook treatment of the Peltier and Seebeck effects, figure of merit Z and ZT, and module-level Q_c / COP relations.
- D. M. Rowe (Editor), *CRC Handbook of Thermoelectrics*, CRC Press, and *Thermoelectrics Handbook: Macro to Nano*, CRC Press. Reference handbooks covering thermoelectric materials, modules, generators, and applications.
- W. H. Hayt, J. E. Kemmerly, and S. M. Durbin, *Engineering Circuit Analysis*, McGraw-Hill, for the Thévenin equivalent and maximum-power-transfer theorem used in the TEG matched-load discussion.
- Application notes and datasheets from power-management IC suppliers on maximum-power-point tracking (MPPT) and fractional-open-circuit-voltage control for thermoelectric energy-harvesting converters. Cited as published design concepts, not ATI endorsements or supplied products; validate the specific converter IC against actual TEG and system conditions.