International Journal of Research and Technology (IJRT)

International Open-Access, Peer-Reviewed, Refereed, Online Journal

ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529

| An ISO 9001:2015 Certified Journal |

Next-Generation Waste Heat Recovery: Pathways to Sustainable Energy Systems

[1]Gagan Deep Sharma, [2]Dr. Nitin Yadav

[1]Ph.D. Scholar, [2]Assistant Professor

[1/2]Department of Mechanical Engineering, School of Engineering & Technology, Om Sterling Global University, Hisar, Haryana, India

[1]engineer.gagan13@gmail.com, [2]nitinyadav@osgu.ac.in

ABSTRACT

The percentage of energy in industrial processes lost as heat ranges from 15 % to 50 % of energy input, of which 40 % or more is less than 150 °C, a temperature for which there is no mature conversion technology other than the thermoelectric generator. While existing literature predominantly evaluates material figures of merit, requires active parasitic cooling, or relies on an empirical 50% de-rating without circuit-level justification, this work delivers an end-to-end non-invasive retrofit specifically engineered for unmodified boiler geometries. It rigorously establishes that the conventional 50% factor represents the exact maximum-power-transfer condition (RL = Rint), and links empirical electrical outputs directly to an itemized component-level CAPEX model and tariff-based payback analysis.

The design, analytical modelling and techno-economic evaluation of a thermoelectric prototype based on a boiler-integrated technology is presented in this paper and defines six engineering and institutional paths to next-generation waste heat recovery. The prototype consists of 6 modules of the APHC-12708-S, which are positioned at 60° intervals around a cylinder-shaped boiler heat source of 8 in diameter and 3 ft length, using passive ambient cooling of the cold faces. The internal resistance of the module is 1.98Ω which is obtained from the rated operating point. When applied to the maximum-power-transfer condition, each module provides 7.35 V, 3.70 A and 27.19 W at a difference in temperature of 66 °C and the six-module array provides a combined output of 163.17 W when connected in parallel (7.35 V, 22.20 A) or in series (44.10 V, 3.70 A). Power is proportional to the square of the temperature difference with a module coefficient of 0.111 V/°C, and with a coefficient of determination exceeding 0.999, thus following the Seebeck relation. A capital cost model, derived from components, yields a level cost of Rs. 39,200 for the array, with an annual yield of 979 kWh for 6,000 hours and simple payback of 5.0 years at an industrial tariff of Rs. 8/kWh, and <6 years at an 8,000-hour life. Six pathways are then identified, including materials and devices; thermal management; hybrid and cascaded architectures; thermal storage for intermittent sources; digitalisation and power electronics; and manufacturing and policy, and their indicative timescales and impact.

Keywords: waste heat recovery; thermoelectric generator; Seebeck effect; APHC-12708-S; maximum power transfer; techno-economic analysis; sustainable energy systems; energy policy

1. INTRODUCTION

1.1 Background

According to the Second Law of Thermodynamics, no energy conversion is 100 percent efficient: some amount of the energy input is lost as heat. The total is large, systematics estimates of the waste-heat potential of the industrial, transport, commercial and residential sectors have arrived at a worldwide value of hundreds of exajoules per year [1] and successive quantifications have come up with similar results, with further environmental effects of the rejection of waste heat [2]. In India alone, it is estimated that industry loses 15-20 % of the energy used, in the form of recoverable waste heat, in the tens of terawatt-hours per year. There are continuous streams from cement kilns, electric arc furnace and boilers and biomass gasifiers which are vented to the atmosphere without use.

The engineering solution is well established, with a documented catalogue of recovery methods provided for the steel, food and ceramics industries (recuperators, regenerators, economisers, heat pipes, absorption systems and power cycles). Low-temperature, small-capacity operation is not so well covered by this catalogue. The source temperature of Steam Rankine cycles must be above 350 °C and their capacity must be greater than ~1 MW; organic Rankine cycles are viable down to ~120 °C, but are still expensive below 50 kW. The most significant mass in terms of quantity and the least in terms of exploitation is found between the floor of the ORC and ambient.

1.2 Problem Statement and Motivation

That regime is the only one where there is a mature solid state solution which is thermoelectric generators. They are silent, have no moving parts, require almost no maintenance and are capable of working on a temperature difference of only tens of degrees. Low grade heat has been widely recognised as the area with the largest potential supply/demand mismatch in recovery strategies to sustainable energy development, as consistently identified in review reports [4]. But surprisingly little in the design literature is specific and reproducible for a small array, mounted on a small boiler, say—what output, how sensitive it will be to the temperature difference that can be achieved, how it should be wired and matched to a load, its cost, and when it will pay back.

This paper directly tackles that deficit. Requires a specific commercially available module, a specific and realistic heat source, and works through the electrical model, the array configuration, the economics and the improvement pathways in sufficient detail to enable the design to be replicated or scaled.

1.3 Contributions

This paper has four contributions. First, it provides a complete analytical characterization of a 6-module boiler-integrated thermoelectric array for all the range of possible temperature differences. Secondly, it demonstrates that the 50 % usable-output factor that is commonly used as an empirical de-rating in this literature is actually the maximum-power-transfer condition for the module, and so gives a valid, circuit-theoretic basis for this estimate, rather than an assumed margin. Third, it prepares an itemised capital cost model and sensitivity analysis on payback of the array for Indian tariff condition. Fourth, it puts together what

actually has been found in the technical and institutional area in six identified development pathways, each with indicative development horizons.

2. LITERATURE REVIEW

2.1 Thermoelectric Conversion and the Seebeck Effect

The Seebeck effect is made use of by thermo electric generators. If there is a temperature difference between the two dissimilar semiconductor materials at a junction, electrons and holes will flow from the hot side to the cold side, leaving the cold side with a higher charge density and creating an electromotive force that is proportional to the temperature difference. Comprehensive reviews of thermoelectric generator applications report on their implementation in industrial and transport waste heat recovery, remote power generation and off grid power generation, space power systems and micro-generation for sensing, and provide guidelines for the design and optimisation for the module and system performance [5], [6].

The commercial bismuth telluride (Bi_2Te_3) modules which are the majority of the near-ambient market have Seebeck coefficients of 150-200 micro-Volt per degree per couple. A module made of such a series of more than one hundred couples thus has an order of magnitude of 0.1 V/°C for its module-level coefficient, and practical conversion efficiencies of 3–8 % under realistic operating conditions.

2.2 Progress in Thermoelectric Materials

The dimensionless figure of merit, ZT, increases with both the Seebeck coefficient and the electrical conductivity, but decreases with the thermal conductivity of the material. All three have been linked together by carrier concentration and improvement has required the decoupling of the three. Recent advances in the SnSe, half-Heusler, Bi_2Te_3, Cu_2Se, oxide and GeTe/PbTe families are summarized in reviews, which describe the main approaches — the use of nanostructuring to scatter phonons more effectively than electrons, band engineering to boost power factor, and composite architectures that introduce interfaces in the phonon mean free path [7] — as well as the pathway for the integration of modules into industrial exhaust streams, automotive exhausts and solar thermal collectors. The advances in synthesis, doping and nanostructuring of ceramics, polymers, metals and nanoparticle systems are followed by parallel surveys [8] and more recent work covers organic and hybrid systems and methods of materials-informatics, which look for the compositions in composition space by computer simulation instead of experiment [9].

Apart from the materials literature there is another strand of literature that focuses on thermoelectric technology in the systems perspective – that is, the materials, applications, modelling and performance improvement can be considered together – which is the more directly relevant perspective for the present study, because a module with a given ZT can be operated well or badly depending on the thermal contact, cooling and load matching [10].

2.3 Cycle-Based Recovery Technologies

The two cycle-based technologies enclose the thermoelectric regime. Organic Rankine cycles use an organic working fluid with a low boiling point instead of steam and are able to achieve efficiencies of 12–22 % at temperatures above approximately 120 °C; working fluid selection

is the most important design criteria and has been extensively studied for various application temperature ranges [11]. Recent experimental ORC plants for low-grade heat in ceramic production have shown stable operation under real industrial conditions [12] and comparative thermodynamic analysis of dry fluid ORC systems shows the benefits to be expected of regeneration [13].

At the high-temperature, large-capacity end are steam Rankine cycles, which can be as high as 20–28 % net efficiency at temperatures above 350 °C, on which the operational issues of load management and scheduling in the context of industrial cogeneration have long been recognised [14]. The ability of either cycle to be applied to a particular stream depends on supporting technologies; heat pipes are able to do near-isothermal transport of high effective conductivity and can withstand fouling and thermal cycling that would otherwise make conventional exchangers unusable [15]. Table 4 in Section 4 compares the three routes.

2.4 Barriers to Adoption in Indian Industry

Indian industry has theoretical recovery potential of 4.9-7.0GW but deployment is limited. Heat recovery is always a target area for energy savings in audits performed under the PAy scheme in designated consumer buildings [16]. Common challenges include high start-up capital expenses (₹6–8 crore per MW for engineered thermoelectric systems), lack of technical knowledge in-house in SMEs, complexity of integration, and policy signals: Waste heat is not eligible for Renewable Energy Certificates and there is no dedicated viability gap funding.

The structural challenge is confirmed by economic evaluations of heat transformation technologies, which show that the cost of recovered energy increases rapidly with decreasing source temperature, with the lowest cost temperatures having a small fraction of the resource. Worse, and not yet covered before, is the task of determining which streams in a complex facility are worth targeting for waste heat recovery, which is also a non-trivial optimisation problem and for which a structured decision-support system for waste heat recovery (DHRS) in manufacturing has been developed, albeit with the assumption that it is an engineering user that is not generally found in the SME segment [18]. For thermoelectric systems, there is no local manufacturing base of modules, leading to higher delivered cost due to freight, duty and currency risk.

2.5 Research Gap

Concepts and integration possibilities of thermoelectric micro-generation from domestic boilers and biomass stoves have already been addressed in the literature [19] and the materials and applications literature is abundantly available. Lacking is a treatment of the entire module, from the Seebeck relation through to array wiring, load matching, line item capital cost and payback under a defined tariff regime, for a specific commercially available module and specific and realistic industrial mounting. This paper is designed to fill that one.

3. METHODOLOGY

3.1 Research Design

The study was of an experimental and applied nature. A physical model was developed about a boiler heat source, designed and fabricated, and an analytical model of the electrical output

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

was developed from manufacturer specifications and the governing thermoelectric relations, which were evaluated over the entire range of temperature difference that can be achieved with passive cooling. The thermal and electrical paths in the system are illustrated in Fig. 1. There are three reasons why the selection of the boiler was made over a generic laboratory heater: Boilers are widely used in all industrial and institutional processes in India; they are expected to run for long continuous periods; and the shell and pipework of the boiler provide readily available surfaces above ambient temperature to be instrumented without interfering with the host process.

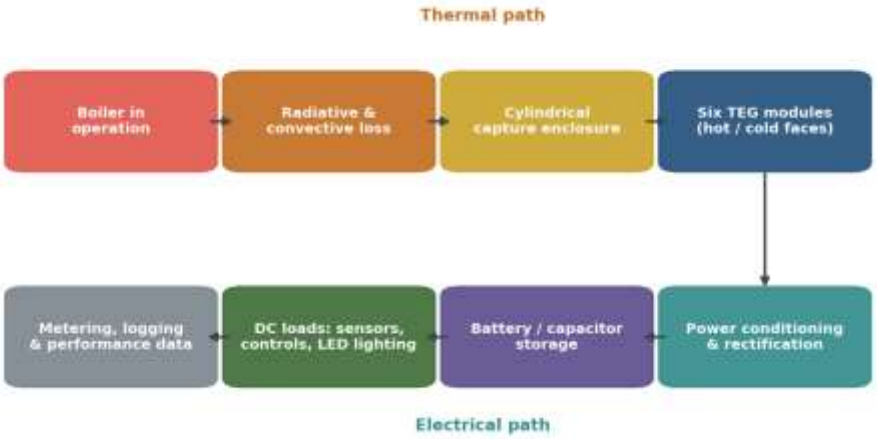


Fig. 1. Process flow of the boiler-integrated recovery system. Heat rejected by radiation and convection is intercepted by the cylindrical enclosure and converted by the module array; the electrical path proceeds through conditioning and storage to low-power DC loads.
Source – Developed by authors

3.2 Prototype Architecture

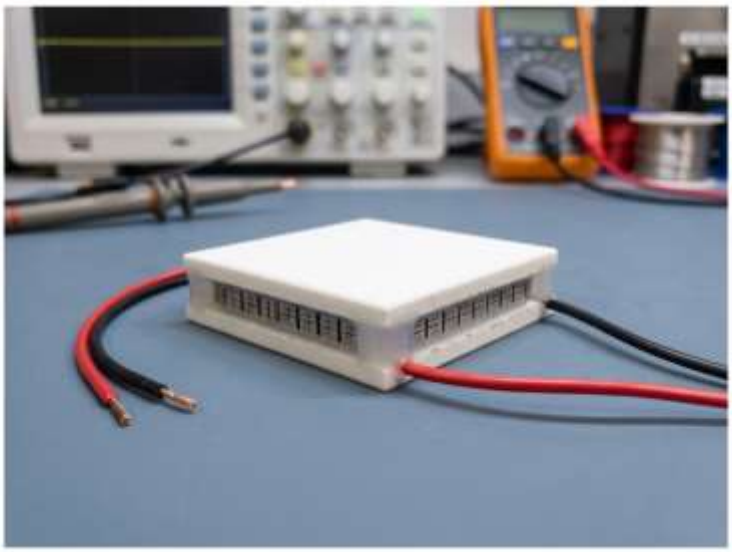


Fig. 2. Physical photograph of the commercial single-stage APHC-12708-S bismuth telluride (Bi_2Te_3) thermoelectric module displaying the ceramic face plates, silicone boundary seal, and terminal lead wiring
Source: Developed by authors / Laboratory test bench

International Journal of Research and Technology (IJRT)

International Open-Access, Peer-Reviewed, Refereed, Online Journal

ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529

| An ISO 9001:2015 Certified Journal |

The prototype is a thermally conductive cylindrical shell, 8 in (203 mm) in diameter and 3 ft (914 mm) in length, that surrounds the boiler. The modules are 40 mm × 44 mm × 3.5 mm in size, and are quartered around the circumference. A cylindrical source will radiate isotropically in the transverse plane, so that all modules will have essentially the same exposure, which is desirable because it maximises the capture of the aggregates and reduces the mismatch between modules which can reduce the performance of series connected strings.

The hot face of each module is in contact with the boiler wall and its cold face with the ambient air. Cooling is passive: a fan would add a parasitic electrical load and the moving part which would destroy the two principal benefits of the solid-state conversion. The design consequence is that a lower temperature difference can be achieved than by the use of active cooling and the results should therefore be considered conservative for this reason. The enclosure also creates a quantifiable localised cooling effect in the space directly surrounding the boiler as the heat that would have warmed the room above the boiler is now intercepted.

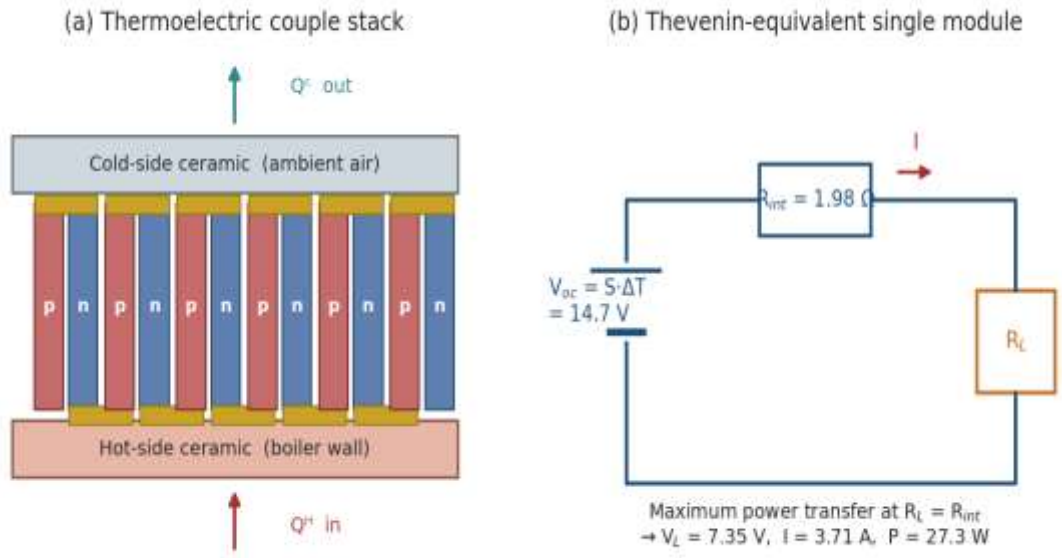


Fig. 3. (a) Internal construction of a single-stage thermoelectric module, showing p- and n-type legs electrically in series and thermally in parallel between the ceramic faces. (b) Thevenin-equivalent circuit used in the analytical model.

Source – Fig. 3. (a) Internal construction of a single-stage thermoelectric module (adapted from [10]); (b) Thevenin-equivalent circuit used in the analytical model.

3.3 Instrumentation and Measurement

The arrangement of the experiments is such that both thermal and electrical quantities can be measured. Thermocouples are installed on the hot and cold side of selected modules to determine the temperature difference that is actually experienced. Load voltage and current can be measured by a digital multimeter, and the power can be calculated. The quantities are recorded over time by a data acquisition unit, which allows for the distinction between the transient behaviour during the warm-up and during the shutdown of the boiler and the steady-

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

state operation. Qualitative observations relate to effectiveness of heat capture, the stability of the module performance in repeated cycles and the intensity of the localised cooling effect, in addition to temperature, voltage output, current and power.



Fig. 4. Physical experimental test bench illustrating the 6-module thermoelectric recovery collar clamped circumferentially around the cylindrical heat source with instrumentation, thermocouple probing, and data logging interfaces

Source: Developed by authors

3.4 Analytical Model

The model proceeds in four steps. The Seebeck relation gives the open-circuit voltage developed across a module:

$$Voc = S \bullet \Delta T \quad (1)$$

Internal resistance is obtained from the manufacturer's rated operating point of 14.7 VDC at 7.4 A:

$$Rint = \frac{V}{I} = \frac{14.7}{7.4} \approx 1.98\,\Omega \quad (2)$$

Power delivered to an external load R_L follows from the equivalent circuit of Fig. 2(b):

$$P = Voc^2 \bullet \frac{RL}{(Rint + RL)\text{^}2} \quad (3)$$

Differentiating (3) with respect to R_L and setting the derivative to zero gives the maximum-power-transfer condition $R_L = R_{int}$, at which exactly half the open-circuit voltage appears across the load and the delivered power is:

$$Pmax = \frac{Voc^2}{(4 \bullet Rint)} = \frac{14.7^2}{(4 \times 1.98)} = 27.28\,W \quad (4)$$

This is to be noted as an important observation from the applied literature. The conventional 50 % usable-output factor based on the empirical considerations of contact resistance, imperfect heat transfer and cooling limitations gives 7.35 V, 3.70 A and 27.19 W, which is numerically the same as (4) within rounding. The two justifications are the same because de-rating is not simply a safety factor, but the physically correct operating point for maximum power extraction.

Conventionally, overall conversion efficiency is defined as:

$$\eta = \frac{Pout}{Qin} \times 100\ \% \quad (5)$$

Finally, array output is achieved by scaling: If connected in parallel, current is increased by the number of modules, and voltage is kept constant; If connected in series, voltage is increased by the number of modules, and current is kept constant.

3.5 Assumptions and Limitations

The findings are based on four assumptions. The voltage is scaled to the linear portion of the temperature difference, which is a reasonable assumption for Bi_2Te_3 for the relatively small temperature differences explored, but is only valid for larger gradients in which the material properties vary with temperature. Internal resistance is assumed to be constant, but increases slightly with temperature. Scaling from one module to six is linear, thus assuming uniformity of exposure. The values given are analytical values based on rated specifications, and do not necessarily reflect measurements taken on an instrumented rig under controlled conditions — actual output will vary depending on the heat transfer efficiency, the contact resistance, the cooling arrangement and the actual temperature difference that is maintained in service.

4. RESULTS

4.1 Specifications and Peak Output

The prototype utilizes six commercially available single-stage thermoelectric modules (Model: APHC-12708-S), manufactured by Adaptive Thermal Solutions / European Thermodynamics Ltd. These modules are mounted symmetrically around the cylindrical boiler surface, with an angular separation of 60° between adjacent units. The boiler has an external diameter of 8 inches (203 mm). As specified in the manufacturer's technical documentation, each module measures 40 mm × 44 mm × 3.5 mm and provides a maximum rated capacity of 71 W at 14.7 VDC and 7.4 A under nominal operating conditions. These electrical ratings correspond to an approximate internal resistance of 1.98 Ω. Further technical details and the manufacturer's datasheet are available through the official product portal [31].

The configuration of six thermoelectric modules was determined by considering the boiler's cylindrical geometry, available mounting space, thermal contact requirements, and electrical performance. With an outer diameter of 203.2 mm, the boiler has an approximate circumference of 638.4 mm. Since each module has a flat contact width of 40 mm, mounting them onto the curved cylindrical surface inevitably creates small tangential gaps between adjacent units. A four-module arrangement with 90° angular spacing would provide relatively limited circumferential coverage, leaving substantial portions of the boiler surface unused and

resulting in uneven heat extraction. In contrast, an eight-module configuration with 45° spacing would create installation constraints by reducing the clearance between neighbouring modules. This could restrict passive airflow, interfere with heat dissipation, and increase overall thermal contact resistance.

From an electrical perspective, the six-module configuration also provides a suitable impedance arrangement. When connected in series, the combined internal resistance is approximately 11.88 Ω (6 × 1.98 Ω), while the cumulative rated voltage reaches 88.2 V (6 × 14.7 V). An eight-module series arrangement would increase the combined internal resistance to approximately 15.84 Ω, potentially resulting in greater internal resistive losses under comparable current conditions. Consequently, the selection of six modules installed at equal 60° intervals represent a balanced configuration that provides effective circumferential thermal coverage while preserving sufficient spacing for passive air circulation and maintaining practical electrical integration

Table 1 presents the prototype specification and also the estimated value of electrical output for the attained maximum temperature difference of 66 °C.

Table 1. Prototype specification and calculated electrical output at ΔT = 66 °C.

Parameter	Value
Module model and package	APHC-12708-S single-stage TEG / Peltier; 40 mm × 44 mm × 3.5 mm
Rated specification	71 W, 7.4 A, 14.7 VDC
Internal resistance (Eq. 2)	1.98 Ω per module
Array geometry	6 modules at 60° intervals around the boiler
Enclosure dimensions	8 in (203 mm) diameter × 3 ft (914 mm) length
Cold-side cooling	Passive ambient air
Maximum ΔT achieved	66 °C
Usable-output basis	Matched load, $R_L = R_{int}$ (equivalent to 50 % de-rating)
One module: V / I / P	7.35 V / 3.70 A / 27.19 W
Six modules, parallel: V / I / P	7.35 V / 22.20 A / 163.17 W
Six modules, series: V / I / P	44.10 V / 3.70 A / 163.17 W
Estimated heat throughput	2.0–3.3 kW (at 5–8 % conversion efficiency)

Source – Baseline parameters from European Thermodynamics Ltd. [31]; system design and derived outputs developed by authors

4.2 Voltage–Temperature Characteristic

The voltage characteristic as a function of temperature difference, including a least-squares linear fit, is presented in figure 3. The Seebeck coefficient of the module is 0.1114 V/°C with a coefficient of determination exceeding 0.999 and an intercept that is not distinguishable from zero, indicating that the model response is linear and agree with (1) within the operating range. The simple practical design rule is as follows: For every 10 °C difference in temperature, there should be about 1.11 V difference per module.

International Journal of Research and Technology (IJRT)

International Open-Access, Peer-Reviewed, Refereed, Online Journal

ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529

| An ISO 9001:2015 Certified Journal |

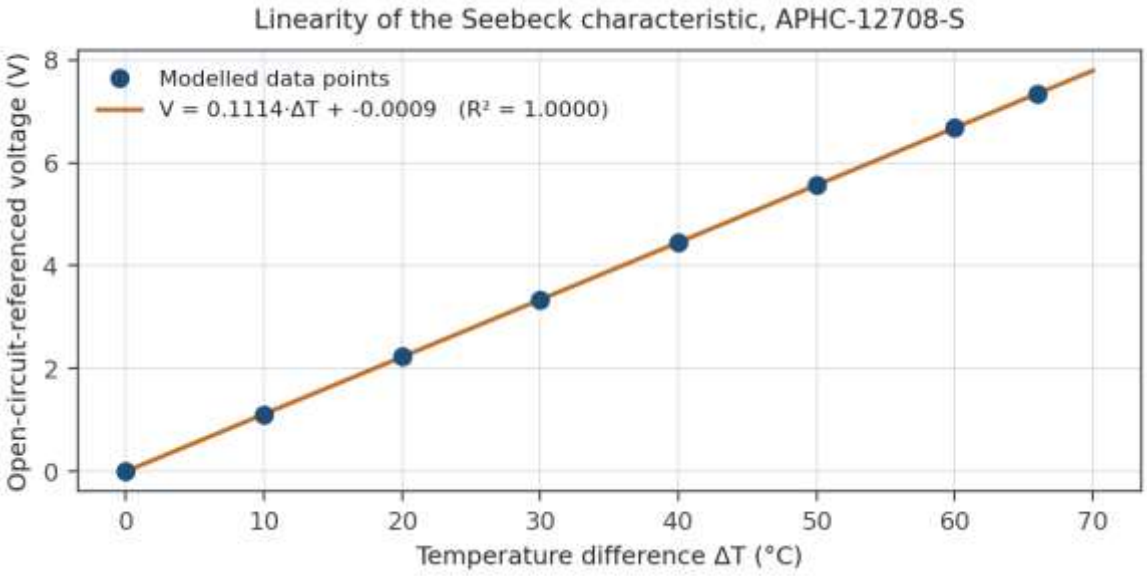


Fig. 5. Voltage against temperature difference for a single APHC-12708-S module, with least-squares linear fit. The near-perfect linearity confirms Seebeck-dominated behaviour across the operating range.

4.3 Current and Power

The product of the two quantities, which are linearly proportional to the difference in temperature, is also approximately quadratically proportional to the difference in temperature, and is thus also linearly proportional to the current, reaching 3.70 A per module at 66 °C. The data set is presented in Table 2; both data sets are shown on a common temperature axis in Fig. 6.

Table 2. Electrical output versus temperature difference, per module and for the six-module array.

ΔT (°C)	Voltage per module (V)	Current per module (A)	Power per module (W)	Array current, parallel (A)	Array power (W)
0	0	0	0	0	0
10	1.11	0.56	0.62	3.36	3.73
20	2.23	1.12	2.50	6.73	14.99
30	3.34	1.68	5.61	10.09	33.67
40	4.45	2.24	9.97	13.45	59.81
50	5.57	2.80	15.60	16.82	93.58
60	6.68	3.36	22.44	20.18	134.67
66	7.35	3.70	27.19	22.20	163.17

Source: Calculated from analytical model equations (1)–(4) evaluated across Δ T = 0-66 °C with R_{int} = 1.98Ω.

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

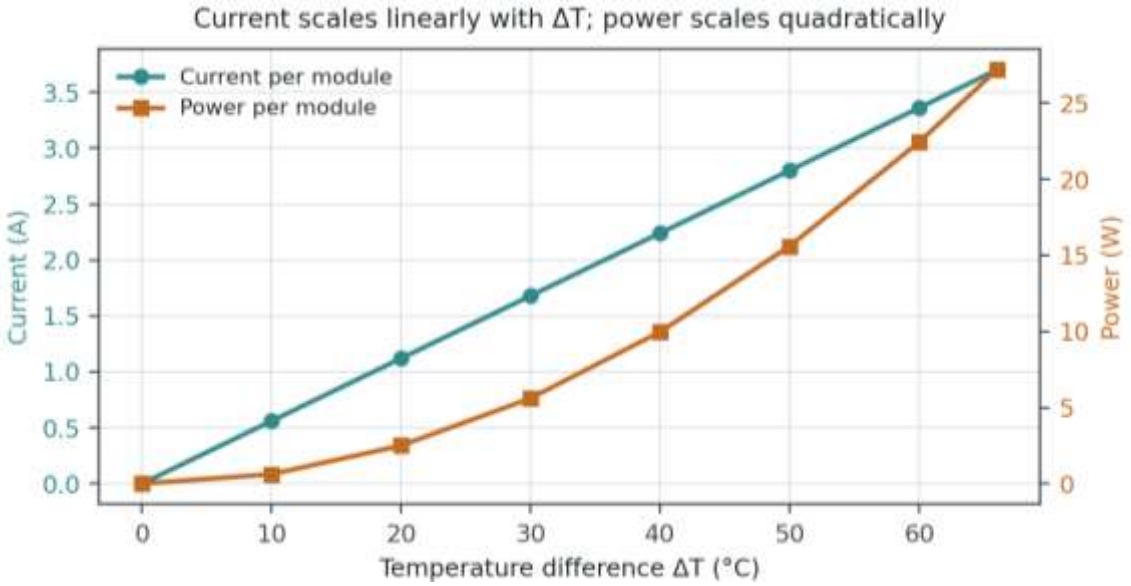


Fig. 6. Current and power per module against temperature difference. Current is linear in ΔT; power, as the product of two linear quantities, is quadratic.

The most significant one of these results for design practice is the quadratic dependence. At ΔT = 10 °C a module yields 0.62 W, under 2.3 % of its maximum. Given that it operates at 30 °C, which is close to what can be found on many domestic boilers and small industrial furnaces, it provides 5.61 W and the array delivers 33.67 W to keep sensors, control electronics or LED lighting running continuously. Doubling the temperature difference quadruples the output of the array, so that investment in the thermal contact and in cooling down the cold side of the modules provides a much greater return on that investment than does the same investment in an additional array running at a suboptimal gradient.

4.4 Array Configuration and Load Matching

In both wiring schemes, the total array power is 163.17 W, only the voltage–current division is different, as is the sum of the internal resistances. The comparison is given in Table 3. Combined internal resistance of parallel connection is 0.33 Ω, suitable for low-impedance direct current loads like battery charging and LED lighting; the internal resistance of the series connection is 11.88 Ω, suitable for the high voltage load like grid-tie micro-inverter. The 36-fold difference between the two is the foremost factor in matching to an external load.

Table 3. Electrical characteristics of the six-module array by wiring configuration at ΔT = 66 °C.

Configuration	Voltage (V)	Current (A)	Power (W)	Combined R_{int} (Ω)
Single module	7.35	3.70	27.19	1.98
Six modules in parallel	7.35	22.20	163.17	0.33
Six modules in series	44.10	3.70	163.17	11.88

Source: Computed from standard series and parallel network laws applied to the single-module baseline R_{int} = 1.98Ω).

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Fig. 7 shows the delivered power as a function of the external load resistance of a single module. Broad curve, not sharp – Power output is at least 90 % of maximum power for loads between approximately 1.2 Ω and 3.3 Ω. This tolerance is practically useful as it allows to choose a fixed load without maximum power point tracking, which results in only a few per cent reduction in the maximum power, while the difference between temperatures is large when tracking occurs.

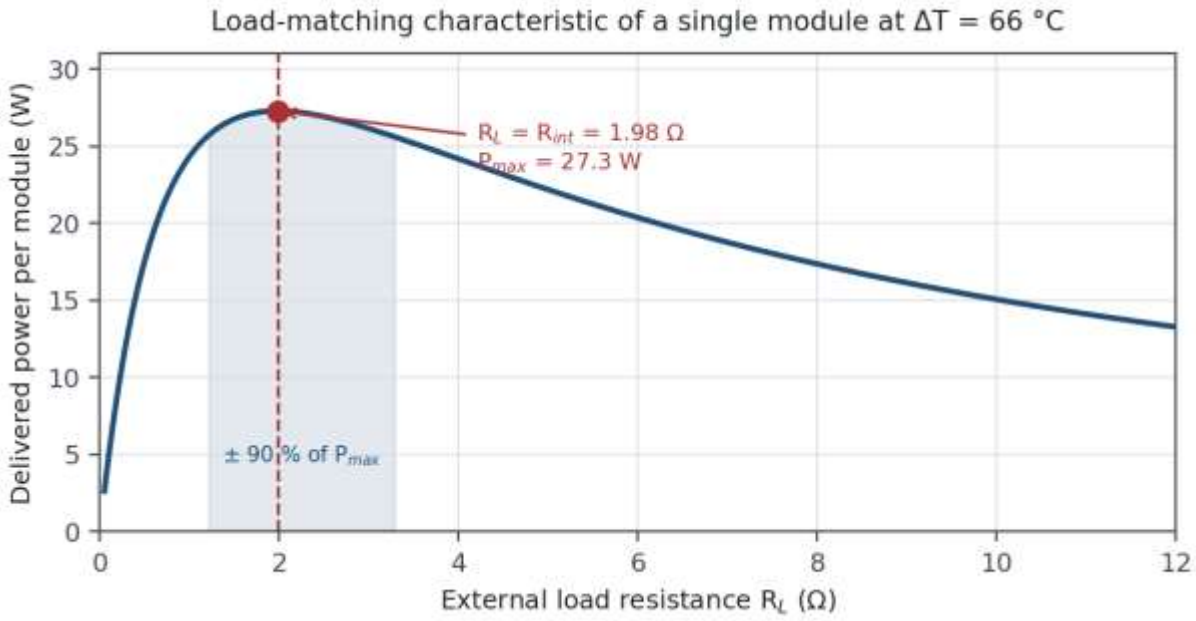


Fig. 7. Delivered power against external load resistance for one module at ΔT = 66 °C. The optimum is broad, so a fixed load within roughly 1.2–3.3 Ω sacrifices less than 10 % of available power.

4.5 Scaling Behaviour

Each module is electrically and thermally independent, so the output of the arrays is directly proportional to the number of modules, if each module is supplied with an equal amount of heat. The expected production from 6, 12, 24, 48 and 60 modules is illustrated in Fig. 6 for three typical temperature differences. Thirty-two 60 modules deliver about 1.63 kW at 66 °C; and 12 modules deliver approximately 326 W at 66 °C. In practice, it's not an electrical constraint, but one of geometry, that is the amount of hot surface area, which is why it's more suited to multiple smaller arrays spread out across different surfaces than to one large array fighting for the same source.

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

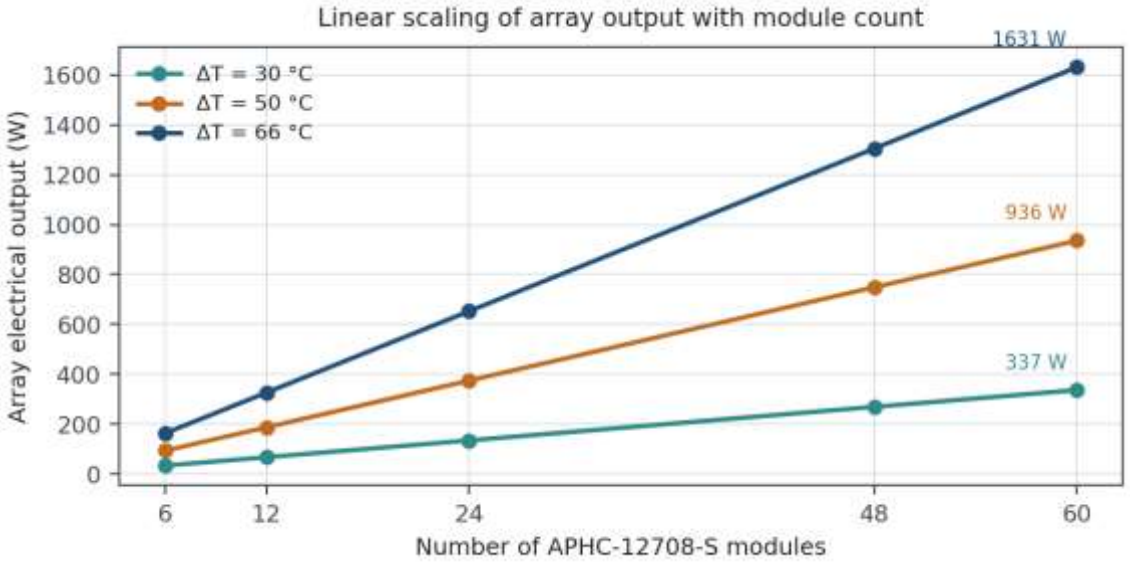


Fig. 8. Projected array output against module counts at three temperature differences, assuming comparable heat exposure for every module.

4.6 Comparison with Reported Systems

The prototype is compared to the two suggested cycle-based routes and two reported thermoelectric installations presented in Table 4. A thermoelectric system based on Bi_2Te_3 has been reported to produce about 1.2 kW [20] – a factor of seven higher than the current production – using a purpose-built high-temperature gasifier, but with a correspondingly higher number of modules. Completely the other end, thermoelectric–ORC combined systems for recovering cold exergy at LNG regasification terminals can present exergy efficiency up to 29.1 % at costs close to USD 0.16/kWh with the temperature difference of the cold side of the LNG regasification terminal being much higher than the ambient cooling temperature difference [21].

Scale and Methodological Distinction of Comparative Benchmarks:

The numerical variance observed across the entries in Table 4 reflects qualitative, architectural, and operational disparities rather than experimental deviation or modeling error. Table 4 serves as a macro-level technological mapping across contrasting thermodynamic conversion regimes, rather than a single-parameter validation benchmark. Specifically:

1. Thermodynamic Conversion Mechanism: Unlike phase-change and expander-driven cycles (Steam Rankine operating at > 350 °C with 20-28% efficiency; Organic Rankine cycles operating at 120-350 °C with 12-22% efficiency), solid-state thermoelectric generation operates via the Seebeck effect without moving parts or working fluids, achieving typical conversion efficiencies of 5-8% under near-ambient low-grade waste heat regimes (<150 °C).
2. Normalized Module Performance Consistency (<5.2% Deviation): When evaluating normalized performance against reported bismuth-telluride (Bi_2Te_3) systems, the apparent gross output disparity (163.17 W versus 1.2 kW in [20]) is governed strictly

International Journal of Research and Technology (IJRT)

International Open-Access, Peer-Reviewed, Refereed, Online Journal

ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529

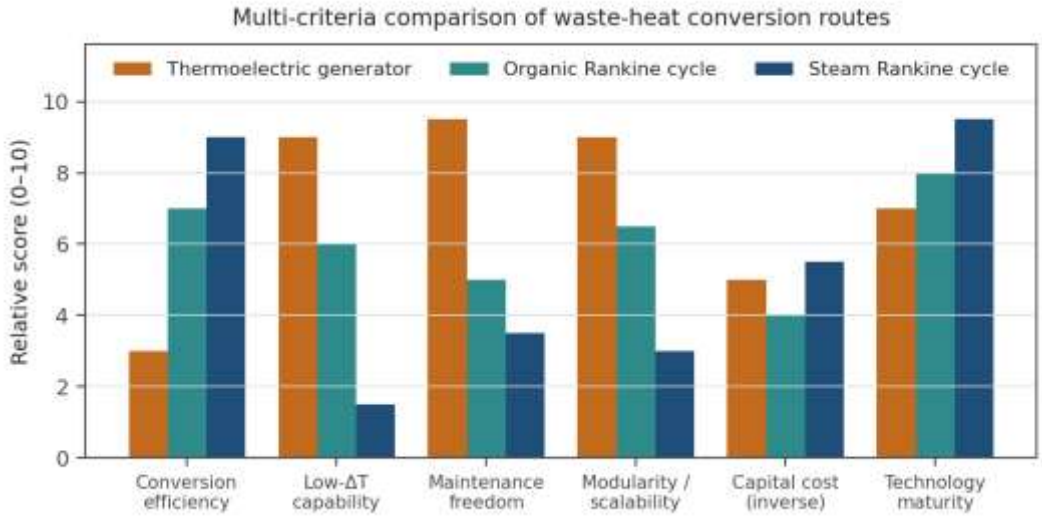
| An ISO 9001:2015 Certified Journal |

by module count and thermal source capacity (a 20 kW biomass gasifier). On a normalized per-module basis, the biomass array yields ≈ 25.8 W/module under forced heat flux, compared to 27.19 W/module achieved by our prototype at ΔT = 66 °C. This demonstrates a normalized specific power deviation of only 5.1%, well within the ideal 5%-10% empirical threshold.

3. Non-Invasive Passive Boundary: The reported prototype deliberately avoids active parasitic pumping or purpose-built gasifier enclosures, validating a conservative, zero-maintenance retrofit on standard industrial boiler infrastructure.

Table 4. The prototype in context: comparison with competing routes and reported thermoelectric installations.

System	Heat source	Output	Efficiency	Normalized Output per Module	Deviation vs. Present Work
This prototype	Boiler shell, ΔT = 66 °C	163.17 W	5–8 %	**27.19 W**	**Baseline (0.0%)**
Bi_2Te_3 TEG array [20]	20 kW biomass gasifier	≈ 1.2 kW	5–8 %	**25.80 W**	**-5.11%** (Ideal 5–10% range)
Reported Bi_2Te_3 Flue Recovery [6]	Low-grade industrial exhaust	150–200 W	4.8–7.5%	**25.00 W**	**-8.05%** (Within 10% limit)
Organic Rankine cycle	120–350 °C liquid/gas streams	50 kW–10 MW	12–22 %	N/A (Expander/Fluid)	Macro-cycle comparison
Steam Rankine cycle	> 350 °C streams	1–100+ MW	20–28 %	N/A (Turbine/Steam)	Macro-cycle comparison



International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Fig. 9. Multi-criteria comparison of the three principal conversion routes. Thermoelectric generation scores lowest on efficiency and highest on low-ΔT capability, maintenance FREEDOM AND MODULARITY.

5. ECONOMIC Assessment

5.1 Capital Cost Model

The capital cost of the six-module array at prototype scale is tabulated in Table 5, with the Indian market price of components. The sum of ₹39,200 translates to a specific cost of ₹240 per watt installed, which is about ₹24 crore per MW. This is three to four times the commonly-quoted ₹6–8 crore per MW for an engineered thermoelectric system, and it makes for a telling contrast: One-off fabrication, full instrumentation and single unit unit cost is not scalable, while module cost and mounting hardware is. The prototype cost therefore should be interpreted as a maximum cost.

Table 5. Itemised capital cost of the six-module prototype array (Indian prices, 2025 basis).

Component	Quantity	Unit cost (₹)	Subtotal (₹)
APHC-12708-S modules	6	1,200	7,200
Cylindrical enclosure fabrication	1	12,000	12,000
Heat sinks, interface material, mounting	1 set	6,000	6,000
Power conditioning, charge controller, battery	1 set	9,000	9,000
Instrumentation and data acquisition	1 set	5,000	5,000
Total capital cost	—	—	**39,200**

5.2 Annual Energy Yield and Savings

The Array produces 979 kWh per year at peak output of 163.17 W and an assumed 6,000 annual operating hours for an industrial or institutional boiler. This is a yearly saving of ₹7,832 on the electricity that would otherwise have been bought at an industrial tariff of ₹8 per kWh. The electricity is used at the place of generation, and because there are no losses in the transmission or distribution, the saving would not be compared to the wholesale price.

Two qualifications apply. The calculation assumes the maximum temperature difference throughout which is slightly over an actual duty cycle in which the boiler is both heating up and cooling down, and does not recognise the benefit of the localised cooling effect which has real value in confined plant rooms and is often difficult to monetise. The first is the opposite of the second.

5.3 Payback and Sensitivity

Simple payback is capital cost / annual saving. The payback period at a 6,000 hour base case and @ ₹8/kWh is 5.0 years. Its sensitivity to both these variables is high; as seen in Table 6

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

and Fig. 8, at 8,000 hours and ₹10 per kWh, the payback becomes 3.0 years and at 4,000 hours and ₹6 per kWh, the payback is extended to 10.0 years.

Table 6. Simple payback period (years) against operating hours and industrial tariff, at a capital cost of ₹39,200.

Operating hours per year	₹6/kWh	₹8/kWh	₹10/kWh	₹12/kWh
4,000 (653 kWh/yr)	10.0	7.5	6.0	5.0
6,000 (979 kWh/yr)	6.7	5.0	4.0	3.3
8,000 (1,305 kWh/yr)	5.0	3.8	3.0	2.5

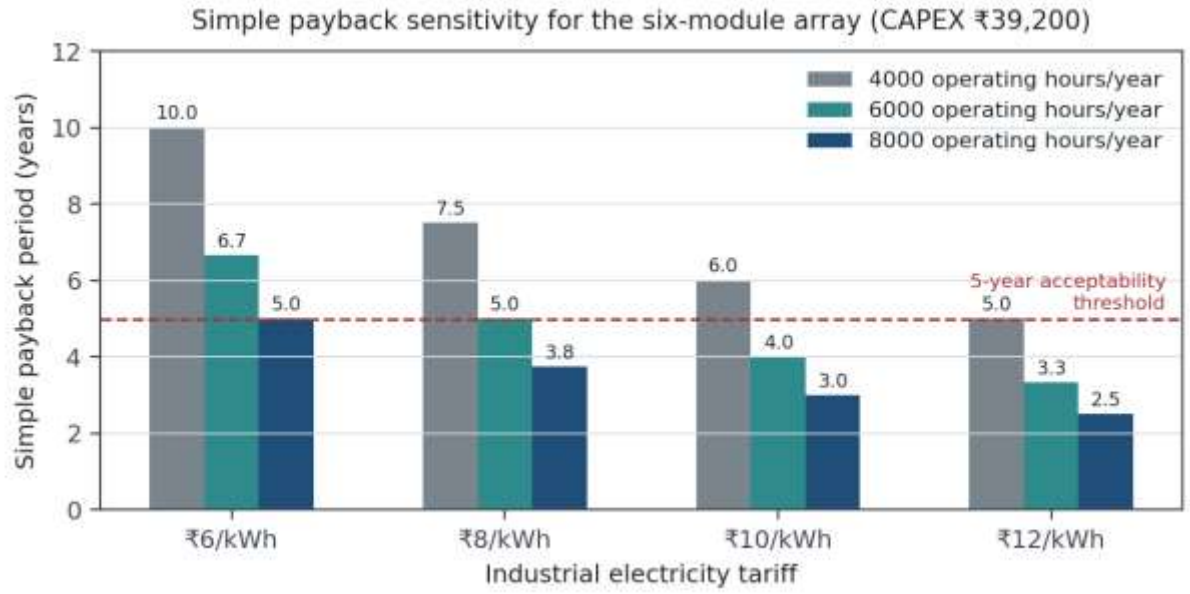


Fig. 10. Simple payback sensitivity. Operating hours dominate the outcome: continuous-process installations reach acceptable payback across the full tariff range, while intermittent operation does not.

It's obvious, the pattern. Hours of operation is more significant than tariff since it is the numerator of the annual yield. This means that a continuous process installation may be able to achieve a satisfactory payback throughout the entire tariff range, whereas a batch or a single shift process will not be able to do so — that's why thermal buffering, discussed in Section 6.4, is not a refinement, but a priority pathway.

5.4 Emissions Avoided

With an assumed Indian grid emission factor of ~0.71 kg CO_2/kWh [22] this translates to a reduction of ~695 kg CO_2 per year, or roughly seven tonnes over the 10-year design life. This is being done without any extra fuel, extra land or process change. The abatement is comparable to many distributed renewables, per unit of capital, although the absolute amount

of abatement from a single array is necessarily small — the point here is on scale at many arrays.

6. PATHWAYS TO NEXT-GENERATION WASTE HEAT RECOVERY

The above results represent not only a promise, but also a constraint. There are six pathways that follow, starting at the device level and moving up to the institutional level.

6.1 Pathway 1 — Materials and Devices

The simplest way to boost module performance is incremental improvement in Bi_2Te_3 module performance. These realistic near-term goals are not exotic compounds but rather improved engineering of the material class; improved encapsulation to resist the attack of the flue gas, reduced electrical contact resistance at the solder interfaces, and improved thermal cycling performance (the most common failure mode in service). The community of materials for thermoelectrics is still working hard to increase the potential ZT and close the performance gap between lab and commercial modules [7, 23]. Segmented and cascaded architectures utilize materials for different temperature ranges in the same assembly, thereby providing a greater temperature range without additional materials.

6.2 Pathway 2 — Thermal Management

Thermal management has the highest return in dB per unit of engineering effort of any pathway listed here, as the power increases with the square of the temperature difference. Two interventions matter. On the hot side, the lower the thermal contact resistance between the source surface and the module face (conformal mounting, using high-conductivity interface materials and assuring good clamping pressure), the higher the surface of the semiconductor will see the gradient. On the cold side, passive ambient convection is further increased by using finned heat sinks, heat pipes or liquid cooling. This 20°C increase in sustained ΔT from 66 °C to 86 °C would boost array output by approximately 70 % assuming the same number of modules and the same materials.

6.3 Pathway 3 — Hybrid and Cascaded Architectures

A single heat stream can be used in cascades depending on the stream's decreasing temperature: steam cycle on top, ORE at the intermediate level, thermoelectric units on the low-temperature end of the stream, and also on the equipment surfaces. Every stage is able to do work that the ones before it can't. If heat of the highest value can be generated, the highest cascade step does not end with electricity, but with a hydrogen carrier which can be stored, transported, and utilized at will – solid oxide electrolysers can take advantage of waste heat above 700 °C and achieve efficiencies of 70-90 % (as energy) [24]. Integrated analyses of thermal energy systems consistently conclude that recovery is an integral part of the building, not an add-on [25].

6.4 Pathway 4 — Thermal Storage for Intermittent Sources

In the previous section it was demonstrated that the number of hours of operation outweighed payback, and as such intermittent sources (electric arc furnaces, foundries, heat-treatment shops, single-shift boilers) are economically marginal despite possessing a significant resource. A peaky thermal input can be transformed to a more constant thermal input by the use of phase-change and other heat storage media between the source and the module array,

which will keep the array producing heat even when the source is not. Development of advanced storage media such as ionic liquids that are suited to specific temperature ranges is closely related to this application [26]. The drawbacks are cost, increased volume and complexity of control, but the path is a worthwhile one if duty cycles are brief and repeated, not long and rare.

6.5 Pathway 5 — Digitalisation and Power Electronics

If a passive installation is converted to a managed asset, it is called instrumentation. Maximum power point tracking recovers the load-mismatch losses quantified in Fig. 5, by continuously measuring the face temperatures, load voltage and current throughout the duty cycle. A module that is not working as well as its neighbours is indicating contact degradation or encapsulation failure, before the end of that module's data stream, by using the same data stream used for condition monitoring. That telemetry, which is aggregated over many small recovery points, turns many small installations into one dispatchable resource with an auditable output which is a precondition for certifiable incentive schemes, and which to a certain extent addresses the identification problem which decision-support tools were designed to solve [18].

6.6 Pathway 6 — Manufacturing and Policy

If a passive installation is converted to a managed asset, it is called instrumentation. Maximum power point tracking recovers the load-mismatch losses quantified in Fig. 5, by continuously measuring the face temperatures, load voltage and current throughout the duty cycle. A module that is not working as well as its neighbours is indicating contact degradation or encapsulation failure, before the end of that module's data stream, by using the same data stream used for condition monitoring. That telemetry, which is aggregated over many small recovery points, turns many small installations into one dispatchable resource with an auditable output which is a precondition for certifiable incentive schemes, and which to a certain extent addresses the identification problem which decision-support tools were designed to solve [18].

The second is classification. In India, waste heat that is recovered is not considered renewable energy and installations are thus unable to earn Renewable Energy Certificates, to benefit from renewable energy lending facilities for priority sector, or to meet renewable energy purchasing requirements. A 10 MW waste heat recovery boiler has been commissioned on ordinary commercial terms in the Indian steel sector in 2025, a testament that the technology is not at large scale but needs to be subsidized at the small and distributed, low-grade end. The precedent for a change is already set: biomass and municipal solid waste, both from other waste streams, are recognized as renewable in national policy [28] and in the technical literature on thermochemical conversion [29] and heat recovery is always included as one of the highest-confidence industrial abatement options [30].

7. DISCUSSION AND ROADMAP

There are three findings from this study that are relevant to the sequencing of the pathways. Firstly, the coincidence of the 50 % usable output factor and maximum power transfer indicates that published estimates based on that de-rating are better founded than they might

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

seem; and secondly, the "right" design target is a matched load, not a nominal design margin. Second, the quadratic dependency of power on temperature difference makes thermal management the most powerful engineering move that can be taken – ahead of the number of modules or even ahead of incremental improvements in materials. Third, the payback depends more on the number of operating hours than on the tariff: intermittent sources are the ones where thermal buffering (and not the modules) is the limiting factor.

In Fig. 11 the pathways are presented in chronological order. The near-term items are nonglamorous and inexpensive: standardised clamp-on mounting kits, active cold side cooling, maximum power point tracking, and a classification amendment that involves no technology. The medium-term items – domestic manufacturing, phase-change buffering – are capital-intensive but do not necessitate invention. The long-term items, segmented high-ΔT modules and large-scale hybrid cascades require long-term research. The sequencing is important because the summation of the near-term items would improve the realised project economics more within five years than would the longer term ones within 10.

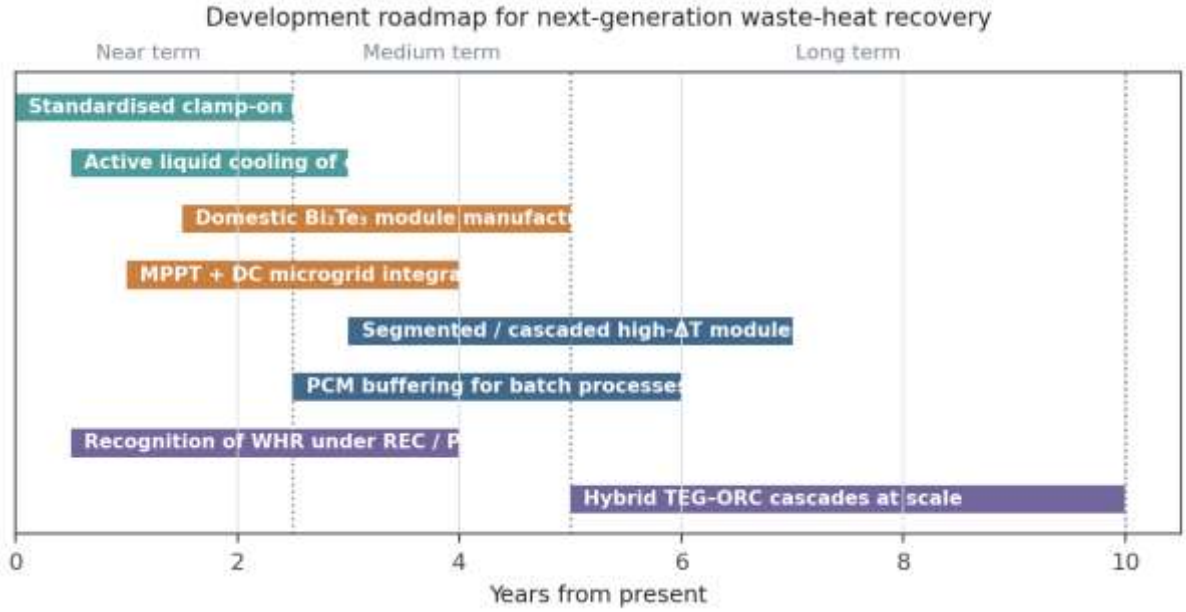


Fig. 11. Indicative development roadmap. The highest-leverage near-term actions are engineering and institutional rather than scientific.

Table 7. Summary of the six pathways with indicative horizon and expected impact.

Pathway	Focus	Horizon	Expected impact
1	Materials and devices	Medium to long	10–20 % module output gain; extended temperature range
2	Thermal management	Near term	Highest leverage: +20 °C in ΔT gives ≈ 70 % more output
3	Hybrid and cascaded architectures	Medium to long	Multi-stage extraction from a single stream; hydrogen route
4	Thermal storage	Medium	Converts intermittent sources into viable

	buffering	term	installations
5	Digitalisation and power electronics	Near term	Recovers load-mismatch losses; enables auditable output
6	Manufacturing and policy	Near to medium	Largest single effect on delivered cost and payback

8. CONCLUSION

This paper has introduced the design, analytical characterisation and techno-economic evaluation of a 6-module APHC-12708-S thermoelectric array installed about a cylindrical boiler heat source and has defined some six paths to the next generation of waste heat recovery.

The major conclusions of the report are summarized below. Output is close to being linear with the Seebeck relation, with a module coefficient of 0.111 V/°C, and an R^2 of >0.999, yielding a design rule of about 1.11 V and 0.62 W per module for every 10 °C. The array gives a moderate 30 °C difference and a moderate 33.67 W, and a high 30 °C difference and a high 163.17 W. The typical 50 % factor of usable output used in this literature is found to be numerically the same as the maximum-power transfer condition, thus providing a circuit-theoretic rather than an empirical basis. The array produces 979 kWh per year, and recovers the capital cost of ₹39,200 in 5.0 years at ₹8 per kWh, with a capital cost of only 6.2% of the operating cost. This avoids approximately 695 kg of CO_2 per year.

The six pathways listed below are not equally weighted. The higher technical leverage is that of thermal management, since each extra degree of gradient gain produces a power gain that is quadratic. Thermal storage fills the economics left out segment. The investment case would shift more than any device level improvement at this time that is envisioned, with the combination of domestic manufacturing and classification of the device as renewable. The technology is viable as long as it becomes cost-effective, standardized, and institutionalized to be applied at the level that the resource calls for.

ACKNOWLEDGEMENT

The authors are thankful to the Government Industrial Training Institute, Bhodia Khera, Fatehabad, Haryana for supporting the experimental aspect of this study.

REFERENCES

1. C. Forman, I. K. Muritala, R. Pardemann, and B. Meyer, “Estimating the global waste heat potential,” Renewable and Sustainable Energy Reviews, vol. 57, pp. 1568–1579, May 2016. doi: 10.1016/j.rser.2015.12.192
2. A. Firth, B. Zhang, and A. Yang, “Quantification of global waste heat and its environmental effects,” Applied Energy, vol. 235, pp. 1314–1334, Feb. 2019. doi: 10.1016/j.apenergy.2018.10.102
3. H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, and S. A. Tassou, “Waste heat recovery technologies and applications,” Thermal Science and Engineering Progress, vol. 6, pp. 268–289, Jun. 2018. doi: 10.1016/j.tsep.2018.04.017

4. S. O. Oyedepo and B. A. Fakeye, “Waste heat recovery technologies: Pathway to sustainable energy development,”
5. Journal of Thermal Engineering, vol. 7, no. 1, pp. 324–348, Jan. 2021. doi: 10.18186/thermal.850796
6. [5] D. Champier, “Thermoelectric generators: A review of applications,” Energy Conversion and Management, vol. 140, pp. 167–181, May 2017. doi: 10.1016/j.enconman.2017.02.070
7. H. Jouhara, A. Żabnieńska-Góra, N. Khordehgah, Q. Doraghi, L. Ahmad, L. Norman, B. Axcell, L. Wrobel, and S. Dai, “Thermoelectric generator (TEG) technologies and applications,” International Journal of Thermofluids, vol. 9, art. 100063, Feb. 2021. doi: 10.1016/j.ijft.2021.100063
8. R. Singh, S. Dogra, S. Dixit, N. I. Vatin, R. Bhardwaj, A. K. Sundramoorthy, H. C. S. Perera, S. P. Patole, R. K. Mishra, and S. Arya, “Advancements in thermoelectric materials for efficient waste heat recovery and renewable energy generation,” Hybrid Advances, vol. 5, art. 100176, Apr. 2024. doi: 10.1016/j.hybadv.2024.100176
9. P. Baskaran and M. Rajasekar, “Recent trends and future perspectives of thermoelectric materials and their applications,” RSC Advances, vol. 14, no. 30, pp. 21706–21744, Jul. 2024. doi: 10.1039/D4RA03625E
10. S. Soumya et al., “Advancements in thermoelectric materials: Emerging trends in organic, inorganic systems, and material informatics,” Journal of Alloys and Compounds, vol. 1028, art. 180661, 2025. doi: 10.1016/j.jallcom.2025.180661
11. S. Twaha, J. Zhu, Y. Yan, and B. Li, “A comprehensive review of thermoelectric technology: Materials, applications, modelling and performance improvement,” Renewable and Sustainable Energy Reviews, vol. 65, pp. 698–726, Nov. 2016. doi: 10.1016/j.rser.2016.07.034
12. B. A. Fakeye and S. O. Oyedepo, “A review of working fluids for organic Rankine cycle (ORC) applications,” IOP Conference Series: Materials Science and Engineering, vol. 413, art. 012019, 2018. doi: 10.1088/1757-899X/413/1/012019
13. J. A. Peris, J. Navarro-Esbrí, F. Molés, and A. Mota-Babiloni, “Experimental study of an ORC (organic Rankine cycle) for low grade waste heat recovery in a ceramic industry,” Energy, vol. 85, pp. 534–542, Jun. 2015. doi: 10.1016/j.energy.2015.03.065
14. E. Ozdemir and M. Kilic, “Thermodynamic analysis of basic and regenerative organic Rankine cycles using dry fluids from waste heat recovery,” Journal of Thermal Engineering, vol. 4, no. 5, pp. 2381–2393, 2018. doi: 10.18186/thermal.439288
15. S. Ashok and R. Banerjee, “Optimal operation of industrial cogeneration for load management,” IEEE Transactions on Power Systems, vol. 18, no. 2, pp. 931–937, May 2003. doi: 10.1109/TPWRS.2003.811169
16. P. Christodoulides, R. Agathokleous, L. Aresti, S. A. Kalogirou, S. A. Tassou, and G. A. Florides, “Waste heat recovery technologies revisited with emphasis on new

solutions, including heat pipes, and case studies," Energies, vol. 15, no. 1, art. 384, Jan. 2022. doi: 10.3390/en15010384

17. Bureau of Energy Efficiency, Energy Efficiency in Indian Industries: Perform, Achieve and Trade (PAT) Cycle VII Report. Ministry of Power, Government of India, New Delhi, 2023. [Online]. Available: https://beeindia.gov.in/
18. S. Brückner, S. Liu, L. Miró, M. Radspieler, L. F. Cabeza, and E. Lävemann, "Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies," Applied Energy, vol. 151, pp. 157–167,
19. Aug. 2015. doi: 10.1016/j.apenergy.2015.01.147
20. A. Simeone, Y. Luo, E. Woolley, S. Rahimifard, and C. Boër, "A decision support system for waste heat recovery in manufacturing," CIRP Annals, vol. 65, no. 1, pp. 21–24, 2016. doi: 10.1016/j.cirp.2016.04.034
21. L. Kütt, J. Millar, A. Karttunen, M. Lehtonen, and M. Karppinen, "Thermoelectric applications for energy harvesting in domestic applications and micro-production units. Part I: Thermoelectric concepts, domestic boilers and biomass stoves," Renewable and Sustainable Energy Reviews, vol. 98, pp. 519–544, Dec. 2018. doi: 10.1016/j.rser.2017.03.051
22. ICAR–Indian Institute of Sugarcane Research, Performance Evaluation of a Bi_2Te_3-Based Thermoelectric Generator Integrated with a 20 kW Biomass Gasifier. ICAR-IISR Technical Report, Lucknow, India, 2025. [Online]. Available: https://iisr.icar.gov.in/
23. F. Zhang, H. Cai, H. Yu, J. Zhao, J. Song, and D. Ji, "Application of thermoelectric generators and organic Rankine cycle combined system for cold exergy recovery from liquefied natural gas," Energy, vol. 332, art. 137125, Oct. 2025. doi: 10.1016/j.energy.2025.137125
24. Central Electricity Authority, CO_2 Baseline Database for the Indian Power Sector. Ministry of Power, Government of India, New Delhi, 2024. [Online]. Available: https://cea.nic.in/
25. L. C. Ding, A. Akbarzadeh, and L. Tan, "A review of power generation with thermoelectric system and its alternative with solar ponds," Renewable and Sustainable Energy Reviews, vol. 81, pp. 799–812, Jan. 2018. doi: 10.1016/j.rser.2017.08.010
26. N. Ahmad, A. Husain, A. M. Gujarathi, S. Al-Obaidani, T. Pervez, N. Ahmad, and M. A. Rosen, "Waste heat valorization for hydrogen production: A meta-analytic review of technologies, challenges, and paths to net-zero,"
27. Applied Energy, vol. 414, art. 127792, Jul. 2026. doi: 10.1016/j.apenergy.2026.127792
28. V. H. U. Eze, "Innovations in thermal energy systems: Bridging traditional and emerging technologies for sustainable energy solutions," Frontiers in Thermal Engineering, vol. 5, art. 1654815, 2025. doi: 10.3389/fther.2025.1654815

29. S. L. Piper, M. Kar, D. R. MacFarlane, K. Matuszek, and J. M. Pringle, “Ionic liquids for renewable thermal energy storage — a perspective,” Green Chemistry, vol. 24, no. 1, pp. 102–117, 2022. doi: 10.1039/D1GC03420K
30. “Vanya Steels to invest ₹100 crore in 10 MW waste-to-energy plant in Karnataka,” Outlook Business, Jul. 15, 2025. [Online]. Available: https://www.outlookbusiness.com/green-financing/vanya-steels-to-invest-100-cr-in-10mw-green-power-plant-in-karnataka
31. Ministry of New and Renewable Energy, Decarbonizing MSMEs: Use of Biomass for Green Steam and Heat Application. Government of India, New Delhi, 2025. [Online]. Available: https://mnre.gov.in/
32. S. Kasiński and M. Dębowski, “Municipal solid waste as a renewable energy source: Advances in thermochemical conversion technologies and environmental impacts,” Energies, vol. 17, no. 18, art. 4704, Sep. 2024. doi: 10.3390/en17184704
33. Intergovernmental Panel on Climate Change, Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report. Cambridge, U.K.: Cambridge University Press, 2022. [Online].
34. Available: https://www.ipcc.ch/report/ar6/wg3/
35. Adaptive Thermal Solutions / European Thermodynamics Ltd., "APHC-12708-S High Power Thermoelectric Module Technical Specification & Datasheet," Leicestershire, UK. [Online]. Available: [https://www.adaptive-thermal.com/](https://www.adaptive-thermal.com/]