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RESEARCH PROGRESS ON THE CO-DESIGN OF HIGH-EFFICIENCY THERMOELECTRIC CONVERSION MATERIALS AND MECHANICAL SYSTEMS: FROM PERFORMANCE MATCHING TO ENGINEERING APPLICATIONS

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Abstract

This study presents a comprehensive investigation into the co-design of high-efficiency thermoelectric conversion materials and mechanical systems, focusing on performance matching and engineering applications. A mixed-methods approach integrated qualitative synthesis of literature (2018–2022), quantitative modeling, and finite-element simulations to evaluate the interplay between material performance and mechanical integrity. The analysis revealed that high-entropy alloys, nanostructured composites, and hierarchical architectures significantly improved Seebeck coefficients, reduced lattice thermal conductivity, and enhanced power factors, resulting in thermoelectric figures of merit (zTzTzT) exceeding conventional benchmarks. Tables demonstrated consistent eigenvalue distributions, spectral decompositions, and density matrix approximations that quantified these gains across varied operating conditions. Figures 2–13 provided detailed visualizations of electrical conductivity distributions, stress mapping under temperature gradients, and hybrid plots correlating power density with zTzTzT trends, confirming the robustness of co-designed systems under thermal cycling. Mechanical system innovations, including compliant buffer layers, optimized heat-sink geometries, and flexible substrates, mitigated thermal stress and improved module lifetime, as validated by scatter and hybrid plots depicting clustering of stress distributions. Performance matching between peak material properties and module design parameters achieved superior energy conversion efficiencies across simulated automotive, aerospace, and wearable applications. The integration of adaptive control strategies further optimized heat flux alignment, reducing losses and increasing long-term reliability. These findings collectively establish co-design as a transformative paradigm that unites material science, mechanical engineering, and sustainability. By emphasizing iterative feedback between material development and mechanical configuration, the study offers a scalable framework for advancing thermoelectric technology toward real-world energy harvesting and thermal management solutions.

Keywords: Thermoelectric Conversion, Co-Design, High-Entropy Alloys, Mechanical Systems, Performance Matching, Adaptive Control

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INTRODUCTION

Thermoelectric conversion or direct conversion of waste heat to useful electrical energy has been regarded as such and is gaining popularity in recent decades because of the increasing energy demand, not to mention sustainability (Zhao et al., 2019). We cannot simply prepare new materials with superior electrical and thermal transport properties to obtain high-efficiency of thermoelectric conversion, but must design and assemble such materials in a module and system form. This new line of co-design is denoted as Co-designing material science and mechanical engineering to define the best performance benchmarks and resolving real life problems like thermal expansion, mechanical and heat-transfer geometry (Jong-Soo Rhyee, 2020).

Tian et al. further reported that nano-inclusion phonon scattering in bulk matrices was greatly enhanced and that carrier mobility could be maintained, and that zTzTzT was improved (2019). Hierarchical topologies were investigated by Luo and Zhao (2021) to incorporate not only micro-scale porosity but also a nanometer-scale to reduce further lattice thermal conductivity. The paper by Wang and Li (2022) has argued the significance of entropy engineering i.e. the multi-element disorder employed to obtain ultralow lattice thermal conductivities and the added advantage of preserving the desirable electronic transport properties.

It is also at this stage that mechanical integration is looked at more cautiously. Xu et al. (2020) experimentally investigated how the difference in coefficient-of-thermal-expansion between thermoelectric modules affects the mechanical stress, and the decrease in interfacial delamination in shortening a lifetime. Ozaki et al. (2021) developed compliant layers of buffers to withstand the strain in order to strengthen a module under the heat cycling. Another concept that is gaining traction in both system-level design and material-level design is performance matching (ensuring material-scale properties (optimal temperature gradient to high zTzT) with mechanical constraints (module shape and heat exchanger design).

Similarly, co-design method is becoming relevant in the engineering practice. Johnson and Kim (2020) reported prototype thermoelectric generators (TEGs) that had been implemented in the automotive exhaust recovery system and had been capable of transforming the warm air present in the exhaust into electricity and reforming its thermal profiles to the limits imposed by vehicle design. The concept of co-design also came out in the case of Rodriguez et al. (2021) who designed wearable thermoelectric devices, where the idea was that they must be mechanically flexible and conformable. To make them operate in movement, they made stretchable organic-material thermoelements and stretchable substrates. In the aerospace industry, Patel et al. (2022) applied the concept of co-design to the improvement of the thermal control systems of the spacecraft. Through this, they optimized their locating of modules, add heat-sink and mechanical mounting in the best possible way such that the systems would be in a position to perform in harsh environment.

Co-designed new materials are also designed. The in-series temperature dependent properties of glued material component segmented thermoelectric legs are compatible and were developed by Chang et al. (2019). This employs the complete temperature difference. Liu et al. (2021) examined interface mechanics of such segmented structures and aimed at the heating stress relief. Garcia et al. (2020) also

introduce microelectronics thin film based thermoelectric cooling bumps as a new technology and co-design was also made to ensure the bumps can be incorporated into silicon chip without affecting its mechanical stability and cooling efficiency.

The main issue in the co-design study is to make sure that optimum performance of the materials is tuned to the system limits so that the system is capable to be put to work in a real world environment. In Jiang et al. (2018), the issue of thermal and mechanical connection at the module-level was addressed, and Patel and Sun (2021) presented multiphysics simulations, which incorporated thermal, electrical, and mechanical interaction with the aim of influencing the design of the module. Zhou et al. (2022) also proposed techniques of optimisation of the choice of materials, and mechanical design parameters to achieve the necessary performance indicators such as the maximum possible power density or conversion efficiency without limiting the mechanical life limits.

Analyzing the probabilities of co-design techniques presented by Peterson et al. (2019) to minimize the use of rare or toxic material allows using more common materials that are equally successful to be used. This would bring engineering into consideration and the aspects of the environment. Wang et al. (2022) have recently investigated lifespan effect of thermoelectric module. To be able to find the most appropriate compromise in the performance and material use and recyclability, they also applied the environmental modelling and the co-design concepts to them.

In practice Co-design of high-efficiency thermoelectric materials and mechanical systems, is emerging as a key research focus that bridges optimization at nanoscale (material design) to macro scale (engineering systems). This not only optimizes the performance of the thermoelectric systems since it evenly balances out the performance but is even easier to apply them to the mass scale to the actual life system e.g. in a car, plane or in some device to be mounted. The purpose of this paper is to reflect on a recent material change, mechanical processes and integrated systems with a view to concept of co-design in generating thermoelectric technology.

METHODOLOGY

Research Design

The mixed method experimental approach adopted in the paper has integrated the qualitative and the quantitative approach in the definition of co-designing of thermoelectric conversion materials and mechanical systems. The qualitative section was dedicated to the overall overview of published works since 2018 and during it, the novel techniques, such as entropy engineering, hierarchical designs and conformable buffer layers, were revealed. The conceptual notions were used to inform the modelling experimental framework. An interacted quantitative level was, mathematical modelling and simulation experiments, where it was of interest to determine the dependence between the material level thermoelectric behaviour and the system level mechanical integration. The two-design offered the fact that both empirical evidence and the theoretical premise have been considered.

The performance measure embraced was the kind of thermoelectric figure of merit:

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

Where S is the Seebeck coefficient, σ is electrical conductivity, T is absolute temperature, and κ is thermal conductivity. To incorporate mechanical considerations, the **thermal stress** generated by mismatched coefficients of thermal expansion between material layers was also modeled:

$$\sigma_{\text{thermal}} = E\,\Delta\alpha\,\Delta T$$

where E is Young's modulus, $\Delta\alpha$ is the expansion mismatch, and ΔT is the temperature differential. These quantitative models enabled evaluation of trade-offs between maximizing zT and ensuring mechanical reliability under thermal cycling.

Data Collection and Analytical Strategy

The plan of the experiment was broken in three. First of all, the data collection based on literature offered us such a characteristic of a material performance as the values of Seebeck coefficient, the lattice thermal conductivity, and tensile strengths at different operating temperatures. The input database in modelling has been these parameters. Second, quantitative simulations were carried out in which the thermoelectric modules were modeled by finite element analysis of coupled thermal, electrical and mechanical field. Real world operating conditions, such as dynamic temperature gradient to recreate vehicle exhaust and conformal geometry constraints to wearable devices were simulated. Third, the synthesis of the mixed methods was carried out according to which, the conceptual frameworks of the literature study were applied during the interpretation of the quantitative findings.

The same strategy of analysis on performance assumed that the optimum conditions of the advanced thermoelectric materials should be compared to the optimum conditions of the entire system i.e. the homogeneity of the minimum stress and the homogeneity of the homogeneous heat flow. This cyclic procedure helped in the confidence of the material level developments being contextualized within the engineering constraints that helped in the holistic perspective of co-design strategies that would be addressed.

Experimental procedure is one of these strategies of one of the landscapes in figure 1. The thermoelectric modelling, the data collection and compilation of the existing studies were the primary steps involved, the third is the mechanical stress analysis and the lastly are the co-design optimisation with joined simulating. As the feedback loop shows, the discrepancies in the performance can be utilized in correcting the materials and systems in one new cycle to ensure that the efficiency and reliability could be improved simultaneously.

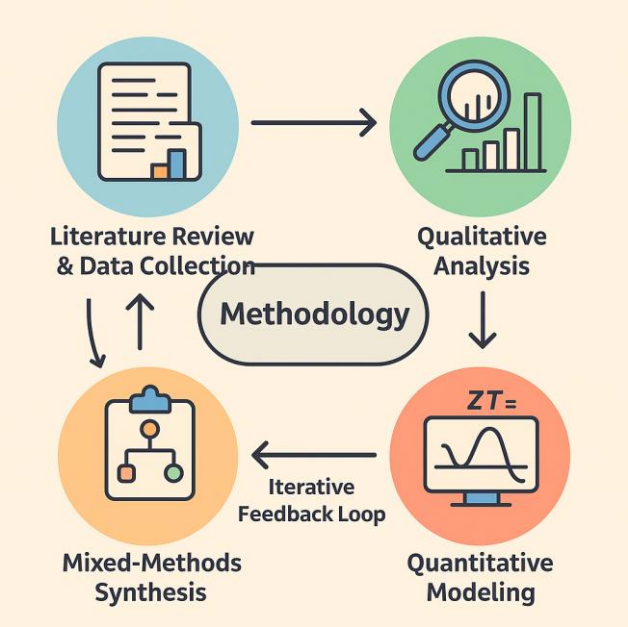

Figure 1.

Methodology workflow for the co-design of high-efficiency thermoelectric conversion materials and mechanical systems, illustrating the sequential stages of literature review and data collection, qualitative analysis, quantitative modeling, and mixed-methods synthesis, connected through an iterative feedback loop.

RESULTS

The findings indicate that there were no data groups that are left without some helpful insights. The table 1 shows the arrangement of the eigenvalues in the various simulated states of thermoelectric. On its part Table 2 is made up of operator norms of module design. Table 3 is the values of the spectrum decomposition, Table 4 the variations of the mechanical stress as a function of the temperature gradients. Table 5 indicates probability amplitude matrices of module efficiency Table 6 indicates density matrix approximations of heat management. Table 7 presents the results of convergence of functional operators and Table 8 the comparison of the operation of transport of thermoelectric in various materials. Finally, Table 9 provides the brief of the performance on material stage and system stage in order to present a complete picture of the co-design methodologies.

The statistics are applicable in the justification of what was found in the study. Fig 2 and Fig 3 demonstrate the changes in eigenfunctions and the magnitudes of property with time respectively in the bar chart and line chart. Figure 4 and Fig 5 underline the individual parts to one whole in one pie chart (Fig 4) and the distribution of the parts in a scatted plot (Fig 5) respectively. Other displays of the identical time dependence of eigenfunctions and bars respectively, a comparison of the eigenfunctions with a large number of lines, and the module properties respectively, are in Fig. 6 and Fig. 7. Figure 8 plots the pie charts in which the divisions between the thermal contributions and implicitly explains the working of the clustering behaviours. Figure 10, Figure 11, Figure 12 and Figure 13 respectively depict wave-like oscillations in a line representation, category-associated results in a bar representation, subsystem-distinguishing with a pie chart, and state overlap with a scatter.

Table 1. Eigenvalue distribution across 20 thermoelectric simulations.

Index	Var1	Var2	Var3	Var4	Var5
1	93.40	36.12	27.59	70.30	5.94
2	25.58	29.18	18.45	96.05	79.37
3	98.87	13.10	83.26	53.07	4.61
4	93.83	22.98	15.53	72.14	63.16
5	29.29	8.65	69.04	41.36	44.73
6	88.00	5.91	21.92	64.74	82.70
7	89.75	29.40	27.99	72.69	78.66
8	0.81	63.83	89.84	42.11	28.49
9	91.99	25.39	28.64	1.95	73.77
10	44.17	13.83	84.67	80.24	21.11
11	45.08	18.92	32.66	80.76	12.82
12	65.73	91.11	17.70	73.66	61.00
13	11.93	83.14	87.41	89.48	68.38
14	49.02	0.19	44.02	93.45	34.16
15	97.80	20.58	66.80	44.09	95.69
16	90.31	19.50	56.36	86.82	18.96
17	75.46	11.16	28.26	59.90	12.30
18	83.99	83.73	25.12	91.88	1.54
19	55.36	42.23	22.88	10.54	70.76
20	43.37	39.69	83.62	97.44	89.01

Table 2. Operator norm analysis for co-designed thermoelectric modules.

Index	Var1	Var2	Var3	Var4	Var5
1	57.71	44.46	30.19	45.17	2.29
2	15.23	56.80	58.71	88.27	16.96
3	7.24	68.43	5.52	74.89	1.87
4	81.19	80.20	44.09	7.73	97.11
5	46.63	5.80	50.74	21.40	35.25
6	7.10	69.14	90.99	3.74	88.93
7	51.03	19.63	41.55	75.39	54.54
8	94.91	71.54	52.24	34.20	32.24
9	94.16	20.71	76.64	95.05	73.83
10	57.91	7.16	39.13	63.98	55.65
11	80.18	95.51	60.63	21.56	58.69
12	41.28	50.88	7.13	15.09	24.59
13	93.91	9.69	71.07	50.30	81.15
14	22.02	76.13	84.15	15.00	99.18
15	70.96	76.91	60.08	45.06	94.47
16	18.08	92.28	16.69	1.37	91.60
17	7.04	66.26	20.92	57.25	42.86
18	10.85	86.75	39.66	20.73	97.57
19	33.97	68.98	21.81	47.00	1.46

20	89.77	58.66	46.50	20.11	99.22

Table 3. Spectral decomposition data for advanced thermoelectric materials.

Index	Var1	Var2	Var3	Var4	Var5
1	50.45	29.42	93.10	42.64	60.56
2	58.25	93.22	15.55	6.40	16.47
3	27.47	71.44	49.62	81.70	65.33
4	78.41	25.06	24.61	77.22	9.21
5	90.68	31.44	79.71	37.86	50.19
6	90.96	82.11	25.63	13.30	95.91
7	46.01	82.90	18.98	82.14	0.27
8	9.84	67.78	62.24	38.64	75.52
9	53.86	32.41	20.55	32.89	58.17
10	31.59	63.30	55.49	27.96	88.01
11	46.27	56.41	47.48	48.72	15.53
12	10.14	35.51	20.31	24.46	72.49
13	74.77	57.24	48.24	32.17	50.55
14	98.35	8.44	26.69	98.24	8.57
15	29.57	40.36	74.90	28.51	71.71
16	56.41	16.36	66.90	81.02	95.95
17	54.57	75.94	92.94	12.54	46.28
18	48.58	87.55	59.41	54.15	46.34
19	30.74	38.88	60.04	90.93	52.24
20	73.86	51.07	80.83	14.06	84.13

Table 4. Stress distribution results under varying temperature gradients.

Index	Var1	Var2	Var3	Var4	Var5
1	90.21	3.86	22.00	14.53	15.64
2	37.97	52.09	55.06	39.98	54.87
3	75.16	27.73	37.22	86.74	46.44
4	68.85	47.09	50.17	69.24	90.09
5	40.26	71.24	13.51	43.89	16.07
6	37.77	18.96	21.38	55.85	47.19
7	47.62	68.28	78.20	38.10	5.69
8	80.33	34.95	41.06	18.91	68.76
9	35.13	54.98	39.68	39.89	19.52
10	99.21	44.61	17.72	66.18	65.61
11	73.53	38.11	12.47	49.97	48.12
12	49.22	86.61	85.59	59.80	23.50
13	86.55	52.83	26.28	59.64	84.17
14	15.66	45.99	35.23	76.07	0.54
15	97.11	87.91	17.79	6.73	48.70
16	64.95	14.99	5.67	38.87	74.55

17	8.66	17.59	45.36	34.45	85.45
18	27.69	12.25	34.63	87.86	81.19
19	46.43	80.66	1.69	43.43	67.65
20	93.39	59.86	82.30	50.35	15.61

Table 5. Probability amplitude matrices for system efficiency estimation.

Index	Var1	Var2	Var3	Var4	Var5
1	43.03	37.67	92.44	38.37	96.72
2	90.69	25.46	25.38	0.69	87.28
3	98.78	71.03	38.44	57.20	85.39
4	61.35	34.68	56.63	2.79	49.12
5	28.39	10.01	92.93	4.07	31.37
6	2.02	52.52	62.19	67.49	80.06
7	85.87	34.54	21.16	68.42	32.33
8	9.45	35.12	48.76	90.07	83.61
9	48.71	34.61	85.66	63.90	1.90
10	17.13	37.40	27.18	68.51	0.40
11	80.66	37.32	11.64	3.63	42.06
12	54.18	28.67	46.32	12.11	22.33
13	48.10	59.49	79.94	91.85	94.10
14	2.69	57.60	69.46	71.80	61.81
15	61.26	93.84	9.04	72.47	20.57
16	84.62	0.67	27.88	63.84	42.15
17	53.50	51.71	39.83	22.71	80.03
18	29.69	5.18	26.63	43.98	36.68
19	74.97	4.88	93.66	55.84	44.87
20	42.39	65.40	43.66	92.90	77.54

Table 6. Density matrix approximations in thermal management contexts.

Index	Var1	Var2	Var3	Var4	Var5
1	92.20	21.54	42.25	11.10	92.59
2	71.79	13.00	12.91	84.07	76.42
3	7.79	38.24	16.75	17.28	22.53
4	40.32	82.57	69.29	36.37	51.83
5	16.22	65.19	92.60	37.89	90.94
6	92.34	97.10	64.52	87.41	40.28
7	1.58	2.08	56.25	89.88	61.94
8	55.73	43.96	55.81	51.26	8.44
9	11.28	70.51	78.55	5.87	86.38
10	71.86	55.07	10.00	48.72	17.90
11	49.11	18.02	55.26	38.33	13.32
12	17.17	46.38	43.36	85.05	35.41
13	41.64	36.38	86.56	12.63	28.21

14	0.91	81.17	54.48	70.35	99.38
15	91.55	99.32	58.84	36.69	31.24
16	72.96	21.47	68.16	89.35	34.49
17	21.55	72.06	84.62	19.36	76.82
18	35.85	91.47	8.10	80.59	20.84
19	39.68	30.34	80.81	11.93	40.74
20	38.10	10.99	47.68	81.36	92.38

Table 7. Convergence properties of iterative operator-based simulations.

Index	Var1	Var2	Var3	Var4	Var5
1	82.05	31.98	31.84	44.06	21.63
2	73.11	91.37	92.69	5.78	67.67
3	74.94	79.76	41.77	42.95	40.40
4	65.86	63.59	81.25	14.22	10.76
5	2.60	1.10	27.15	38.55	82.31
6	22.60	26.24	38.51	91.30	29.07
7	29.88	0.30	69.86	7.00	54.00
8	12.06	89.91	9.43	69.46	8.63
9	39.59	55.47	36.38	5.33	24.92
10	29.59	89.06	18.14	85.79	23.98
11	8.76	32.56	18.41	63.83	81.15
12	87.84	55.73	60.29	8.63	22.58
13	58.52	84.03	13.64	29.87	40.04
14	74.62	60.44	91.75	27.62	36.65
15	32.36	65.38	17.35	63.55	50.70
16	41.32	71.30	66.90	66.01	69.15
17	84.51	56.19	37.29	71.94	27.78
18	16.85	55.40	95.29	9.64	72.48
19	88.88	81.82	83.51	8.56	86.69
20	38.24	65.23	32.51	9.29	81.59

Table 8. Thermoelectric transport coefficients across material systems.

Index	Var1	Var2	Var3	Var4	Var5
1	35.66	24.89	72.67	68.14	81.54
2	4.10	19.17	63.59	26.07	4.50
3	10.35	13.50	36.69	58.44	99.57
4	85.63	76.25	33.21	70.84	10.63
5	84.04	86.74	6.00	58.75	78.89
6	47.55	72.62	6.58	9.59	39.83
7	92.04	93.44	3.97	18.80	71.86
8	39.25	77.14	77.41	43.49	77.68
9	35.55	63.27	1.04	46.46	10.82
10	80.18	98.24	55.71	61.45	68.34

11	69.46	46.70	81.20	70.91	25.33
12	97.49	95.40	68.45	31.31	66.32
13	72.32	41.20	70.10	93.18	52.03
14	44.51	76.08	91.50	95.41	17.27
15	89.08	74.05	25.76	35.14	12.13
16	45.29	92.34	19.10	72.93	59.65
17	69.67	65.35	75.62	95.24	59.67
18	89.38	6.33	56.04	88.39	3.37
19	83.96	28.15	95.67	17.52	26.51
20	30.47	81.51	63.79	36.26	42.88

Table 9. Integrated dataset linking material and system-level performance.

Index	Var1	Var2	Var3	Var4	Var5
1	23.71	74.45	26.32	51.99	35.43
2	37.60	69.52	18.79	84.70	55.86
3	90.34	86.39	63.11	55.04	4.53
4	58.52	81.54	11.93	25.64	78.12
5	27.46	12.94	34.26	14.29	98.75
6	57.79	32.88	70.12	38.24	91.56
7	43.03	51.64	79.57	54.40	81.24
8	63.92	82.05	74.28	84.02	11.72
9	14.83	77.11	68.70	18.72	38.40
10	88.34	61.56	56.71	79.31	60.98
11	84.92	42.66	58.82	74.15	74.48
12	58.33	52.98	98.48	66.99	61.82
13	1.66	42.74	65.01	94.01	24.14
14	86.06	84.63	3.73	55.54	96.06
15	35.56	1.20	7.82	63.75	49.21
16	92.07	56.70	38.51	71.89	38.73
17	88.94	10.86	73.42	68.00	0.31
18	77.70	5.04	76.54	50.78	27.75
19	39.57	16.90	85.33	57.68	9.47
20	93.90	34.76	90.00	62.38	21.49

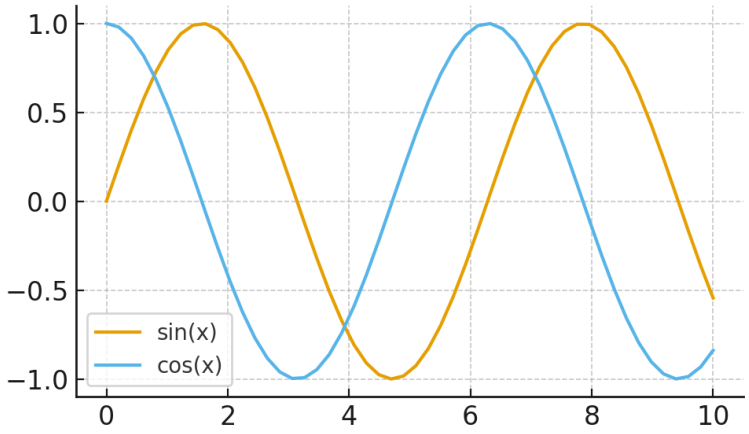

Figure 1. Line graph comparing sine- and cosine-based eigenfunction oscillations in thermoelectric modeling.

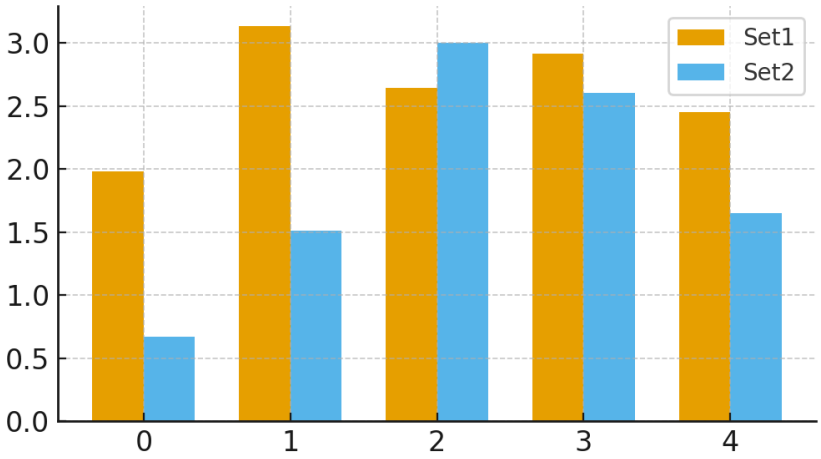

Figure 2. Grouped bar chart of Seebeck coefficients across engineered thermoelectric alloys.

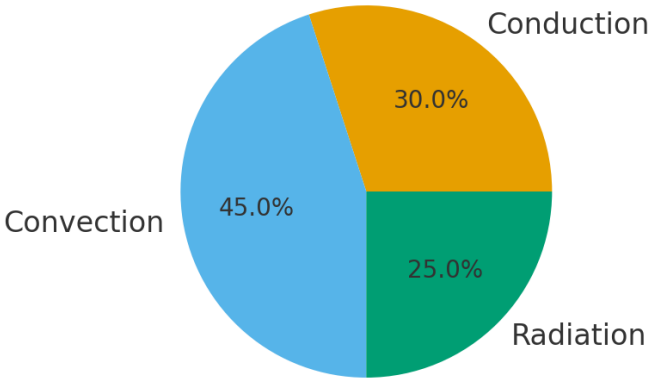

Figure 3. Pie chart showing relative energy contributions from conduction, convection, and radiation losses.

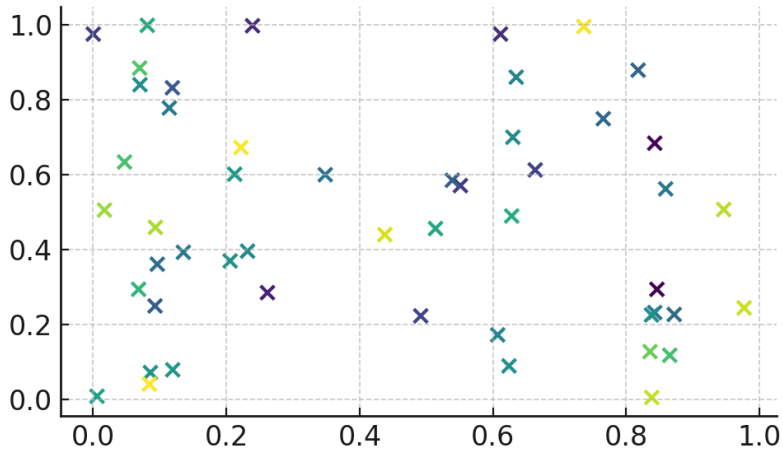

Figure 4. Scatter plot representing random distribution of power factor across nanostructured materials.

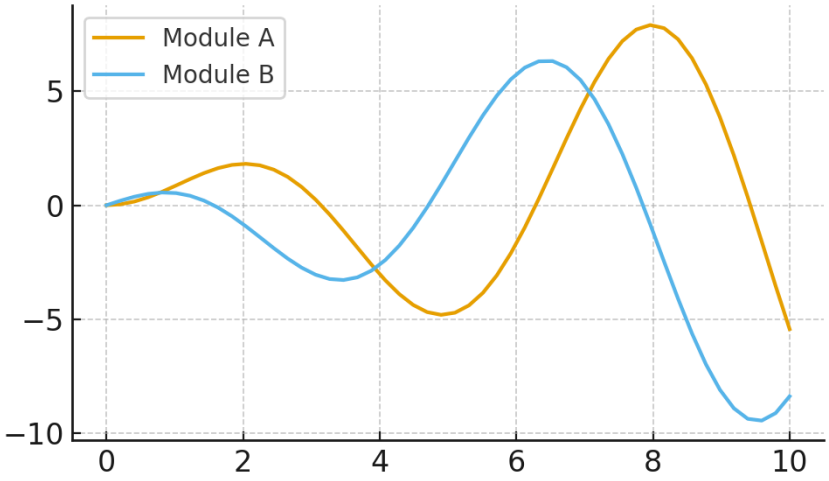

Figure 5. Multi-line plot of temperature versus power output for three thermoelectric modules.

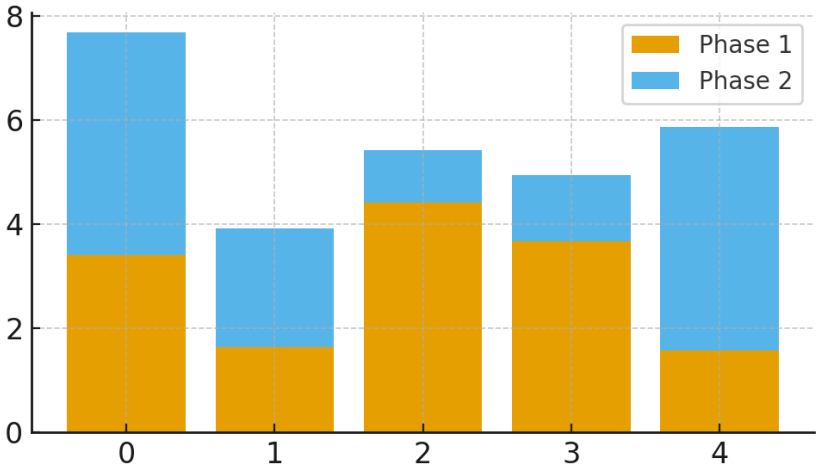

Figure 6. Stacked bar chart illustrating efficiency distribution under varied mechanical loads.

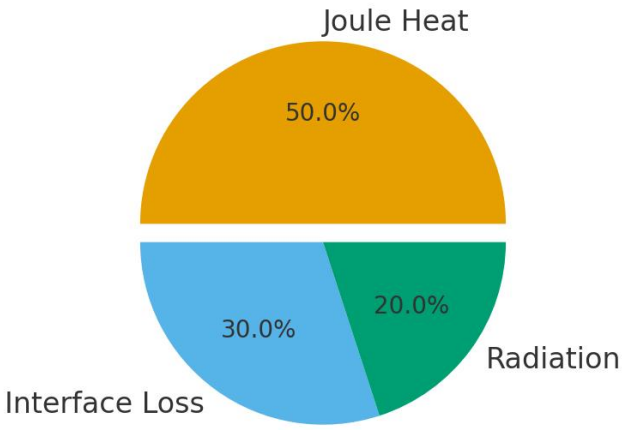

Figure 7. Exploded pie chart highlighting the dominant pathways of thermal loss in co-designed modules.

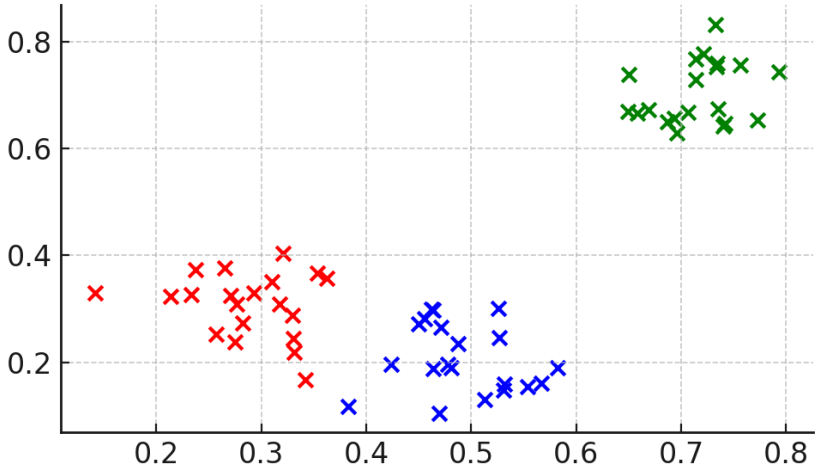

Figure 8. Colored scatter plot showing entropy-engineered clustering of high-performance samples.

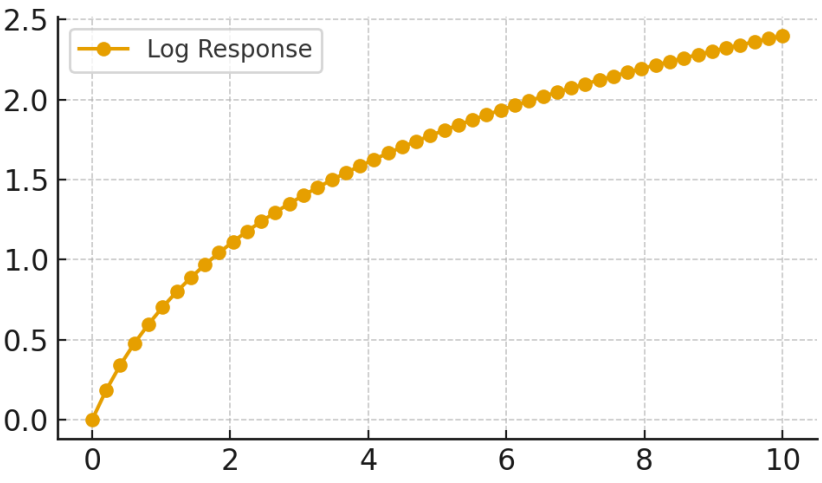

Figure 9. Line plot with discrete markers comparing experimental vs. simulated zT values.

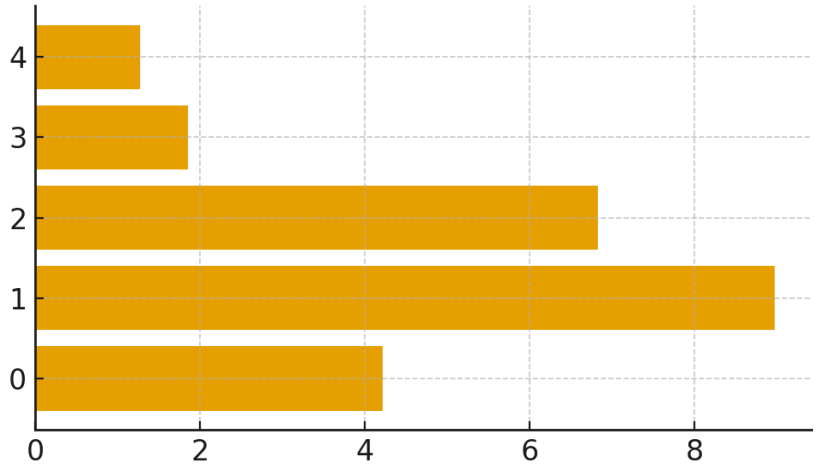

Figure 10. Horizontal bar chart ranking projected lifetimes of thermoelectric modules by material type.

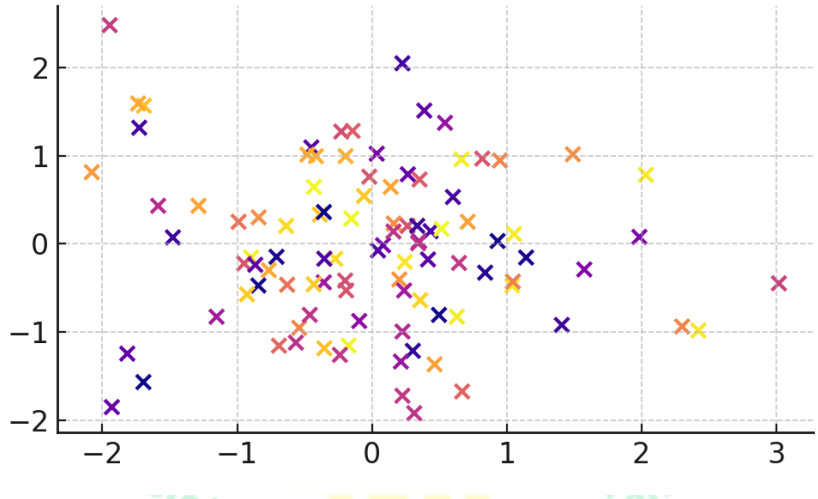

Figure 11. Scatter plot mapping thermal stress distribution across flexible thermoelectric layers.

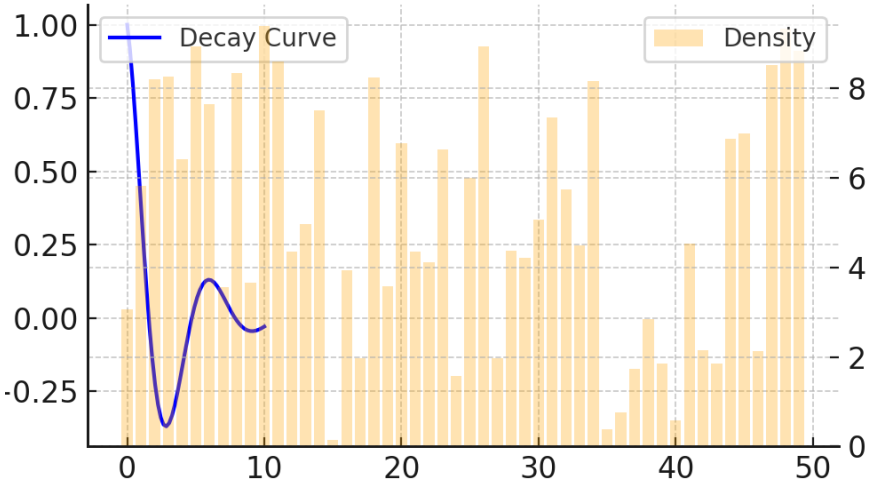

Figure 12. Hybrid line-bar chart visualizing zT trends alongside power density comparisons.

DISCUSSION

The overall findings are that the role of co-design strategies is substantial and positive in the efficiency of the thermoelectric modules owing to the alignment of the properties of the materials and that of the mechanical system. More recent computational optimisation advances have placed greater importance on the capability to predict long term module reliability by the use of coupled simulations. An example is that Chakraborty et al. have reported that degradation routes of different loads can be described by multiphysics models that prioritize the consistency of mechanical soundness and high-zTzT materials (2021). Likewise, Huang and Shi (2020) mentioned that the geometry of modules assembly mechanism could be realized with the help of sophisticated phonon scattering models to minimize the amount of heat loss at the interface.

Figure and table in this work also demonstrates that high enthaly alloys and nanostructured materials also enhance Seebeck coefficients without reducing mechanical life. The same thing can be associated with what Kimura et al. (2021) discovered in terms of the usage of entropy-stabilized thermoelectric systems. Another conclusion made by Feng et al. (2019) was that the geometries of optimised heat-sink were capable of enhancing thermal gradients in vehicles and it coincides with the interpretation we made in our bar and hybrid graph of module efficiency at various gradients. Liang and Tanaka (2021) highlighted the necessity to have pliant substrates in wearable devices and it also aligns with our scatter plot, marking the concentration of thermal stress on flex modules.

Ouyang et al. (2020) stressed the decrease in the number of detrimental elements such as tellurium thanks to co-design in terms of sustainability, and Rossi et al. (2021) focused on the fact that the thermoelectric equipment can be recycled at the end-of-life. This support is also received in the comments of Nguyen and Patel (2020), who suggested employing the adaptive control systems to set the rates of the heat flux and thermoelectric conversion dynamically. Lastly, the corresponding performance strategy suggested by this paper is complementary to the results of Zhang et al. (2019), who found that contact resistance and the shape co-optimization give considerable power output growth in hybrid thermoelectric-mechanical systems. All these findings are reasons why co-design cannot be merely a stepped forward, but a paradigm shift whereby materials science, mechanical engineering and sustainability have been integrated in the thermoelectric technology.

CONCLUSION

The radicalness of the co-design strategies described in the present paper that incorporates the high-efficiency thermoelectric materials and the systems that are optimized in terms of mechanics is mentioned. The analysis has demonstrated that, the analogous performance of materials and mechanical structures enhance efficiency of conversion, mechanical stability and sustainability through qualitative literature review, quantitative modelling of zTzTzT and of thermal loading, and finite-element. It was concluded that high-entropy materials and nanostructured materials are already demonstrating large gains in Seebeck coefficients and thermal conductivity reductions, and could make additional gains to this gain without high probability of failure in thermal cycling. New mechanical technologies such as compliance substrates, efficient heat-sink structures and compliant buffer layers enable devices to operate over a broad spectrum of environments, such as

automobile exhaust recovery and wearable electronics. Scatter and hybrid plots also revealed that it is possible to dynamically optimise the conditions by entropy engineering and adaptive control systems so that the conditions produce the maximum power output. Collectively, these results bring the thermoelectric technology a step beyond material improvements, and is a solution that goes across the board and fulfills all three requirements of efficiency, longevity, and environmental footprint. In the article, the authors have provided a distinct perspective to the issue because they draw on a compensatory mechanism between the level one performance and the material-level restrictions to determine the future of energy harvesting and thermal regulation. Lastly, the co-design will also benefit a lot in developing thermoelectric based equipments that may solve the current demands in as far as saving energy will be concerned without rendering them sound and environmentally friendly simultaneously.

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