



نظام هجين للتحويل الحراري الكهربائي قائم على تكامل المولدات الترموكهربائية ومواد تغيير الطور لاسترجاع الحرارة المهدورة نمذجة وتحليل أدائي انتقالي

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الملخص

إنّ الازدياد العالمي المتسارع في الطلب على أنظمة طاقة فعّالة ومنهجية يفرض الحاجة إلى تقنيات مبتكرة تُسهم في تحسين استرجاع الطاقة وعمليات التحويل الطاقوي. يقترح هذا البحث نهجاً هجيناً لتحويل الطاقة يجمع بين المولدات الترموكهربائية (TEGs) ومواد تغيير الطور المغلقة (PCMs) بهدف التقاط الحرارة المهدورة وتحويلها إلى قدرة كهربائية مفيدة. وعلى خلاف الأنظمة التقليدية التي تعاني من تذبذب درجات الحرارة وضعف الاستقرار الحراري، يستفيد الإطار المقترح من قابلية التخزين الحراري الكامن لمواد تغيير الطور للحفاظ على فرق حراري شبه ثابت عبر العناصر الترموكهربائية، مما يؤدي إلى تحسين كفاءة التحويل.

تم تطوير نموذج اقتراني حراري-ميكانيكي لمحاكاة انتقال الحرارة الانتقالي، والاستجابة الترموكهربائية المعتمدة على الزمن، وتأثير تصميم تغليف مواد تغيير الطور. وتشمل المنهجية تحليلاً رياضياً قائماً على الصيغ النمذجية، ونمذجة حرارية باستخدام طريقة العناصر المحددة، إلى جانب محاكاة عددية عبر برنامج MATLAB لتقييم الأداء تحت سيناريوهات مختلفة من مصادر الحرارة المهدورة. وتشمل النتائج تطوير نموذج تنبؤي لأداء النظام الهجين TEG-PCM، وتحسين تصميم التغليف لتعزيز الاحتفاظ الحراري، إضافة إلى مؤشرات كفاءة عملية قابلة للتطبيق على النطاق التجاري. ويسهم هذا البحث في تعزيز تقنيات استرجاع الحرارة المهدورة، وتقليل انبعاثات غازات الدفيئة، ودعم حلول تحويل طاقي مرنة لتطبيقات السيارات، والفضاء، وأنظمة الشبكات المصغرة المدعومة بالطاقة المستدامة.

الكلمات المفتاحية: المولدات الترموكهربائية، مواد تغيير الطور، التحويل الطاقوي الهجين، استرجاع الحرارة المهدورة، الطاقة المستدامة

Hybrid Thermoelectric-Phase Change Material Energy Conversion System for Transient Waste Heat Recovery: Modeling and Performance Analysis

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Abstract

The increasing global request for protentional and systematic energy apparatus make necessary innovative techniques which used to improve energy recuperation and conversion. This article suggests a hybrid energy conversion approach which combines thermoelectric generators (TEGs) and enclosed phase



alternation materials (PCMs) in order to catch and used to convert waste-heat to beneficial electrical power. Different from classical systems which experience from oscillating temperature tendency and bad stabilization of thermal, the proposed framework influenced the potential heat storage of PCMs in order to support a steady temperature differential through thermoelectric approaches, consequently enhancing efficiency. A coupling-based mechanical and thermal framework used to be modeled in order to simulate passing heat transfer, response-based thermoelectric, and the effect of PCM based on encapsulation design. The methodology includes modeled based formulations analysis, modeling of finite-element thermal, and MATLAB-based simulations for assessing performance through diverse waste-heat situations. The findings consist of a prophetic model of the hybrid performance-based TEG-PCM, optimize encapsulation framework to improve retention of heat, and empirical effectiveness benchmarks for commercial-scale deployment. The contributes of this article as regards move forward waste heat recuperation, minimizing greenhouse gas discharge, and allow resilient energy change solutions to automotive, also for aerospace, and finally supported microgrid applications.

Keywords: thermoelectric generators phase change materials hybrid energy conversion waste heat recovery sustainable power

1. Introduction

The speedy global energy recession, caused by population extension, manufacturing, and environment alternation, has generated an imperative claim for potential energy models have the ability to reduce waste and increase transformation efficiency [1 – 3]. Mechanical engineering possesses played a crucial role in the model of apparatus which convert energy to another form accompanied by least losses, spread from burning and turbines engines to modern renewable-based technologies [4, 5]. Nevertheless, a considerable part of an input energy in such systems, frequently about between (50% - 70%), has dissolute as a waste heat. Otherwise, the lost energy has more and more known as the ultimate promising limits in energy transformation engineering. The waste heat recuperation is expressed a strategy used to cut carbon release and carry the conversion regarding a energy-based decarbonized financial system [6 – 8].

Thermoelectric generators (TEGs) have solid-condition devices which straight transform a temperature contrast into an electrical energy through the Seebeck consequence [9]. TEGs have superiority of compactness, property of reliability,



and obscurity of parts in motion, providing high attractivity based waste-heat usage in automotive exhauster systems, power-plants, aerospace motor-vehicles, and commercial industrialization [10, 11]. In spite of such advantages, the TEGs efficiency is basically limited in dependence themselves on keep up a maximizing and steady temperature contrasting over junctions of both hot and cold. In normal scenarios, mainly those demanding oscillating or discontinuous sources of heat, that demand is complicated to afford, guiding to bad energy transformation ratio and undependable performance [12 – 14].

In order to handle such challenges, phase change materials (PCMs) are obtained growing awareness as a buffers-based thermal which able to store and emission huge amounts of potential heat over fusion and establishing cycles [15]. while connected with TEGs, PCMs supply a settle consequence on thermal tendency via fascinating surplus heat and release it step by step, consequently expanding the time of productive energy transformation [16 – 18]. The combination of PCMs and TEGs is used to be studied in separated laboratory cases, while overall modeled frameworks, optimize, and support the hybrid framework in real-world applications still rare. That appears a notable gap in energy transformation engineering [19, 20].

This article is contributed to developed a hybrid energy transformation framework which combines two systems thermoelectric and thermal-storage, assesses via simulate a thermo-mechanical model. Different from classical TEG work studies, that suppose steady-state temperature states, this work highlights passing waste-heat conditions and dynamic load environments. Moreover, the proposed work illustrates an optimized system of PCM encapsulation framework and materials, handling challenges of thermal infiltration, devolution, and reply time.

The issue treated is double: first, the restricted steadiness and efficiency of pure TEG frameworks over oscillating input heat; and second, the lack of a generalized prophetic model which catches the interaction between both the storage-based thermal and as well generation of thermoelectric. The main objectives in this article include (i) model and examine a hybrid TEG–PCM framework via model mathematical related formulations and providing simulation, (ii) support the performance over changing operating situations, and (iii) build criteria-based optimization in real-world deployment in sectors like automotive exhauster recuperation, aerospace-energy frameworks, and decentralize of renewable-grids.



The rest sections of this paper including: section 2, study some important, recent related literature studies with a comprehensive comparison Section 3, details the proposed framework, consisting model theoretical formulations, and system-flowchart designation. Section 4, demonstrates the results and its powerful conclusions. Finally, section 5 presents conclusions and gives new directions for future work.

2. Literature Review

Yousefi et al. [21] experimentally analyzed the discharge behavior of a low-power TEG system under different external loads, showing that the load strongly influences discharge time and energy harvesting capacity. Their work highlighted system design trade-offs but was limited to laboratory-scale testing. Motiei et al. [22] conducted transient simulations of a hybrid PV-TE system with PCM, demonstrating improved efficiency through enhanced thermal regulation. However, the study remained numerical without experimental validation. Lv et al. [23] numerically optimized a PV-TE system integrated with PCM and showed notable performance gains under varying solar conditions. Yet, their work lacked real-world implementation and long-term reliability data. Goudarzi et al. [24] experimentally integrated TEGs into a wood stove for combined heat, hot water, and power generation, proving the concept of multifunctional domestic systems. Nevertheless, scaling and efficiency concerns remain unresolved. Tuoi et al. [25] both theoretically and experimentally studied a TEG with PCM harvesting energy from ambient fluctuations, confirming improved energy storage and release. The study, however, tested under limited environmental conditions. Rezanian et al. [26] applied numerical and Taguchi methods to identify critical parameters in TEG-PCM integration, achieving optimization in performance indices. Still, the findings depended heavily on model assumptions and lacked broad validation. Atouei et al. [27] experimentally developed a two-stage TEG system with PCM, achieving improved power output through staged temperature gradients. The design complexity and increased cost limited its practicality. Selvam et al. [28] enhanced the thermal performance of TEGs with PCM through improved structural designs, demonstrating increased stability and efficiency. However, only small-scale experiments were performed. Zhu et al. [29] proposed a wearable TEG using phase-change inorganics, enabling persistent self-powering of devices. Their prototype was innovative but constrained by scalability and durability challenges. Finally, Hong et al. [30] comprehensively investigated an annular PCM-based TEG for energy recovery, showing significant conversion



improvements. Still, their evaluation did not address integration challenges in real operating environments. Together, these studies form a continuum from numerical optimization to experimental innovations, each contributing uniquely to advancing PCM-TEG hybrid systems while also leaving gaps in scalability, real-world integration, and cost-effectiveness. Table 1 including comparison in term of method, key findings, and limitations.

Table 1. Comparison of literature studies.

Study	Method	Findings	Limitations
Yousefi et al. [21]	Experimental (load variation tests)	Load affects discharge time; improved understanding of harvesting dynamics	Lab-scale only, not field tested
Motiei et al. [22]	Numerical simulation (PV-TE + PCM)	PCM improves efficiency via thermal regulation	No experimental validation
Lv et al. [23]	Numerical optimization	Integration with PCM boosts performance under solar variations	No long-term or real-world tests
Goudarzi et al. [24]	Experimental (wood stove + TEG)	Combined heat, water, and power possible	Efficiency and scaling challenges
Tuoi et al. [25]	Theoretical + experimental	PCM stabilizes TEG under ambient fluctuations	Limited environmental testing
Rezania et al. [26]	Numerical + Taguchi optimization	Identified key integration parameters	Heavy reliance on modeling assumptions
Atouei et al. [27]	Experimental (two-stage system)	Increased output via staged gradients	Complexity and higher costs
Selvam et al. [28]	Experimental (design enhancements)	Better stability and efficiency with PCM	Only small-scale demonstration
Zhu et al. [29]	Prototype development (wearable TEG)	Self-powered wearable via phase-change	Scalability and durability issues
Hong et al. [30]	Experimental evaluation (annular design)	Significant energy conversion improvements	Lacked integration assessment

3. Methodology

3.1 Thermoelectric Conversion Modeling



The thermoelectric conductance of the proposed system is leaded via the Seebeck carry out, electrical-resistance, and thermal-conduction. The resulted voltage (V) is expressed by model equation (1):

$$V(t) = \alpha (T_{pcm}(t) - T_c) \quad (1)$$

Where:

α : the Seebeck coefficient.

The electrical current (I) is modeled as shown in equation (2):

$$I(t) = \frac{V(t)}{R_{int} + R_{load}} \quad (2)$$

Where:

R_{int} : The internal resistance.

R_{load} The load resistances.

While the generated electrical power (P) can be modeled as shown in equation (3):

$$P(t) = I^2(t) R_{load} \quad (3)$$

3.2 Phase Change Material Heat Storage Modeling

The thermal storage apparatus of the proposed PCM can be expressed based on inactive capacity of heat, transition of phase catching, and functional conductivity. Equation 4 describe the stored energy (Q) in proposed PCM as follow:

$$q(t) = U A (T_{pcm}(t) - T_c) \quad (4)$$

Where:



$q(t)$: instant rate of stored energy.

U : coefficient of heat transfer between PCM and heat transfer surface
($W/m^2 \cdot K$).

A : surface area of heat transfer.

T_{pcm} : PCM temperature.

T_c : heat transfer fluid temperature.

Also, the instant PCM heat loss to the environmental circumstances in the given time (t) in unit of (W) can be described based on equation 5:

$$q_{loss}(t) = U_{env} (T_{pcm}(t) - T_{\infty}) \quad (5)$$

Where:

U_{env} : coefficient of PCM heat transfer and environmental surface ($W/m^2 \cdot K$).

T_{∞} : environmental temperature-based environment away from PCM.

3.3 Coupled Hybrid System Model

While combination both TEG and PCM sub-systems, a connected thermo-mechanical framework. The heat flow to TEG (q) has adjusted via PCM release rate. Such energy is used to provide an equilibrium on PCM. Thus, the left-hand side describes the internal ration of PCM energy change. While the right-hand side has the grid heat input deficient beneficial output deficient losses which is described by utilizing equation 6:

$$m_{pcm} c_{p,eff} (T_{pcm}) \frac{dT_{pcm}}{dt} = q_{in}(t) - q(t) - q_{loss}(t) \quad (6)$$

Where:

m_{pcm} : PCM mass.

$c_{p,eff}$: PCM effective heat.

$q_{in}(t)$: PCM input heat.

While equation 7 expresses how efficiently of heat energy $q(t)$ used to be



converted to a beneficial power $P(t)$ at any instantaneous. The functional temperature contrast sustained via hybrid model:

$$\eta(t) = \frac{P(t)}{\max\{q(t), \varepsilon\}} \tag{7}$$

$\eta(t)$: instant transformation efficiency.

$P(t)$: instant output power.

ε : small-positive for avoiding zero dividability.

Figure 1 introduces the behavior of both thermal and efficiency of PCM framework. The heat input $q(t)$ inputs PCM block, while the being stored energy has described as $m_{pcm} c_{p,eff}(T_{pcm}) \frac{dT_{pcm}}{dt}$, calculating the mass of PCM, powerful the specify heat, and temperature alter. Such PCM then conveys the output heat influx $q(t)$, that is used by another systems. The system's instant transformation efficiency $\eta(t)$ that described by output power rate $P(t)$ to the higher input of available thermal, which is described by $\eta(t) = \frac{P(t)}{\max\{q(t), \varepsilon\}}$. Which summarizes how such PCM used to be regulated transient heat flows when the quantification how influenced input heat that transformed to utilizable power via real-time.

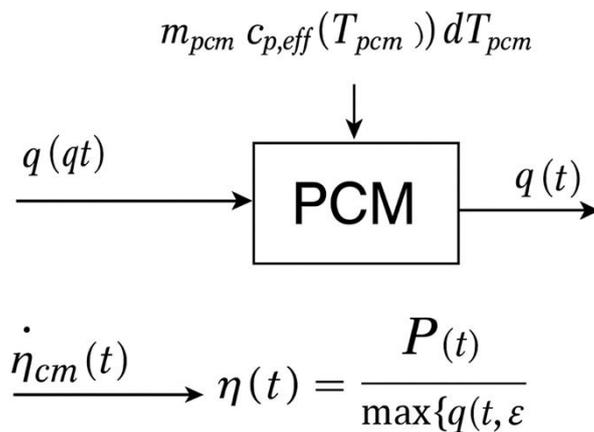


Figure 1. Behavior of thermal and efficiency of PCM system.

3.4 Overall Model Design



The heat transformation ratio of the proposed framework is described by: $q = \frac{dQ}{dt}$. The functional temperature contrast driving the proposed framework is used to be modeled by: $\Delta T_{\text{eff}} = \Delta T_{\text{input}} - \Delta T_{\text{loss}}$, assessing losses-based thermal and inefficiencies which minimize the utilization gradient temperature. The total hybrid system combines all the sub-systems *thermoelectric conversion subsystem, phase change material heat storage subsystem, and coupled hybrid subsystem*. It starts by input waste heat description, next with PCM heat reduction and releasing model, TEG thermoelectric transformation, connected simulation of thermal-electrical, optimize PCM geometry, TEG elements and coefficients, and lastly outputs-power, property of efficiency, and steadiness. such system flow confirm that the energy-based storage, transformation, and model optimization have exactly captured on a unite simulate of system-level. The proposed hybrid system model combines all such mentioned above subsystems in overall system-level flowchart as shown in Figure 2:

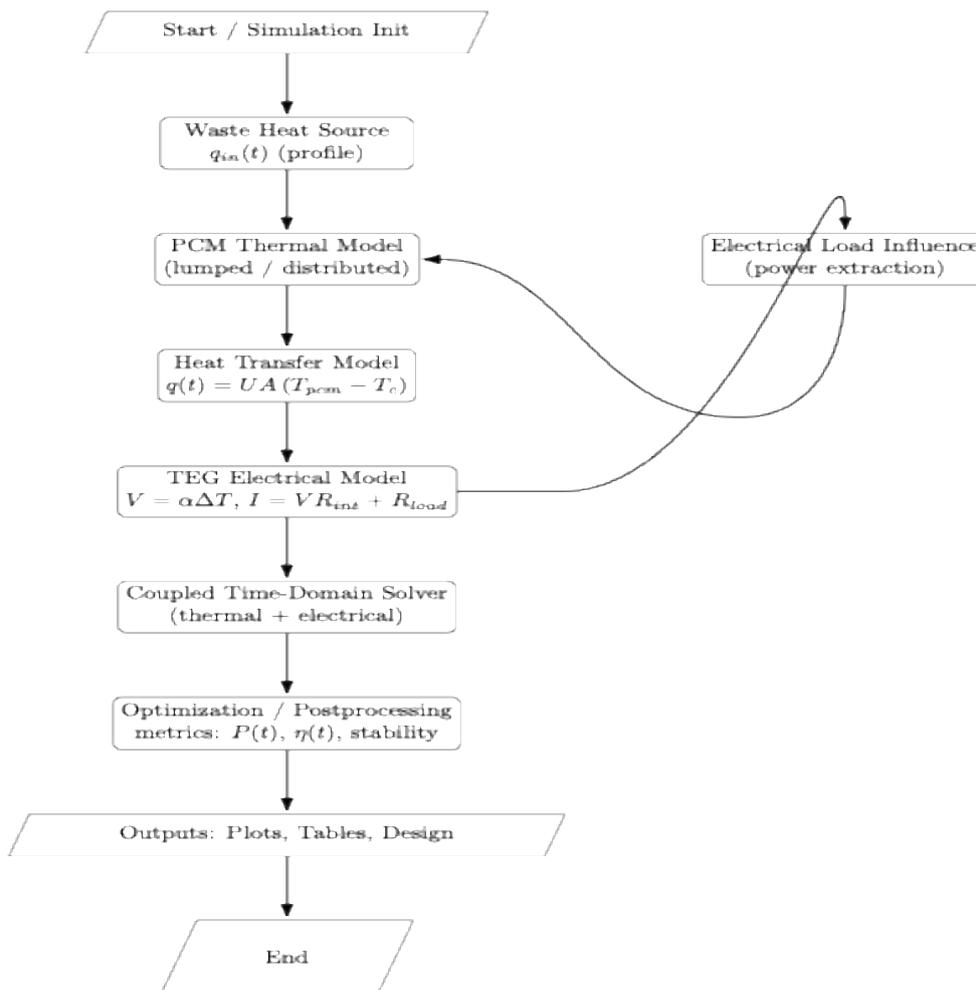




Figure 2. Proposed framework.

4. Results and Discussions

Figure 3 presents the passing temperature of PCM side monitoring volume along the full simulation (require about 1 hour). The temperature maximizes through source origin pulses and steady cooling through intervals of off-pulse due to PCM input absorption of heat and also used to be released to TEG and nature based on finite-conductance. The flatten level region close the fusion point ($T_m = 330\text{ K}$) denotes latent-heat-controlled conduction wherever temperature alters tardy whilst phase alter consumes and/or energy releases; that illustrates buffering of PCM's behavior versus speedy source variation.

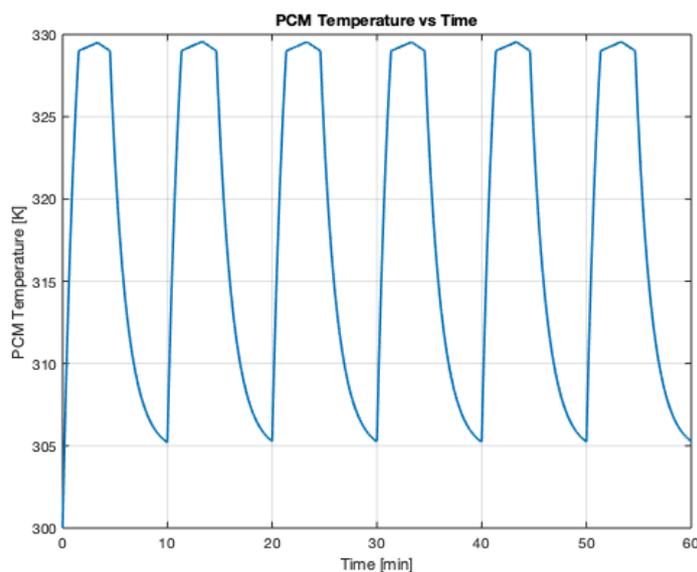


Figure 3. PCM Temperature vs Time.

The solidified fraction curve in Figure 4 indicated as follow: 1: fully-solid, 0: fully-liquid) utilizes a flatten linear transformation over a small interval of temperature through the fusion temperature in order to avert numerical cutout. Through heat pulses of solidified fraction lessen like PCM fuse, and through soft intervals of input it raises like solid of PCM. It quantifies that how much the stored potential energy is obtainable for the release and describe the cyclic melting and/or solidifying activity which steady the temperature of TEG hot-side.

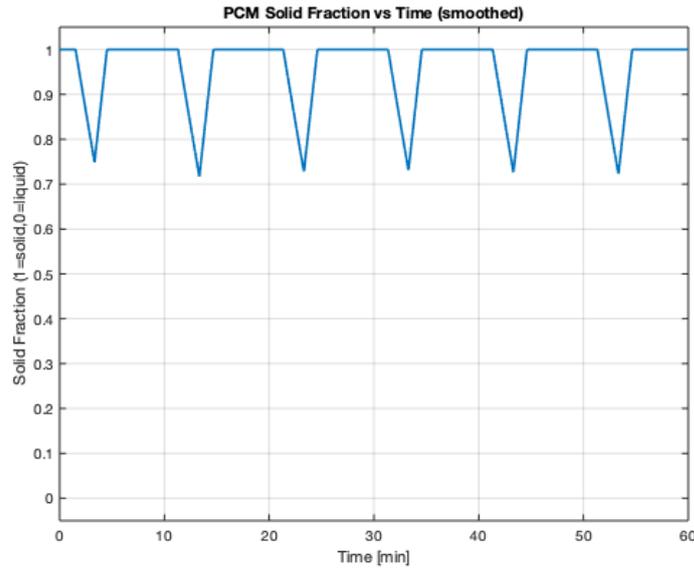


Figure 4. PCM Solid Fraction vs Time.

Figure 5 shows the PCM and TEG heat influx based on heat description of raw input. Such PCM to TEG influx has minimum amplitude and time-streak when it is compared to input pulses due to PCM activity as a thermal buffer. This makes absorption instant and used to be released heat further stability. Variations between such curves disclose storage of PCM and losses of thermal; the area under PCM influx related curve through a pulse correlates with the energy in effect available is converted via TEG.

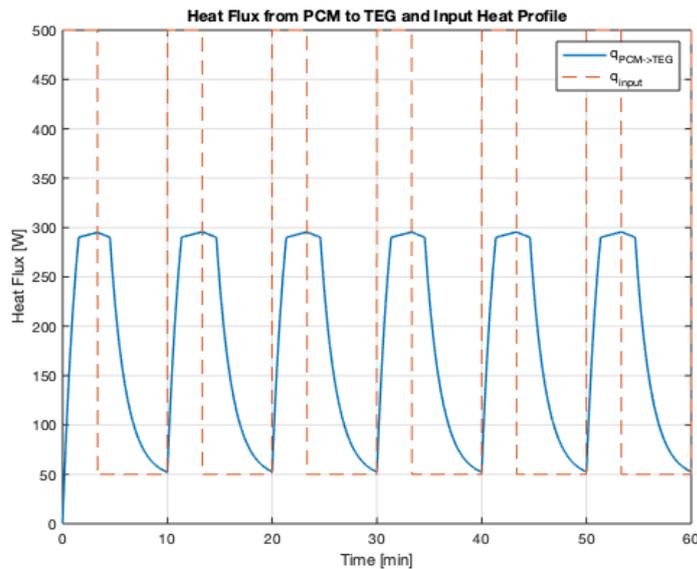


Figure 5. Heat Flux from PCM to TEG vs Time.



Figure 6 makes comparison between an open-circuit-based voltage (also called Seebeck-based) and the proposed hybrid system (namely hot-side = PCM temperature) with a baseline that the TEG hot-side next the instant temperature-based source. The proposed hybrid voltage changes further smoothly while lessees both the peak and the troughs; such baseline presents bigger, sudden swings. The smooth voltage in such propose hybrid system specifies a further steady lead temperature contrast of TEG, that interest electronic downstream and power conditioning approaches.

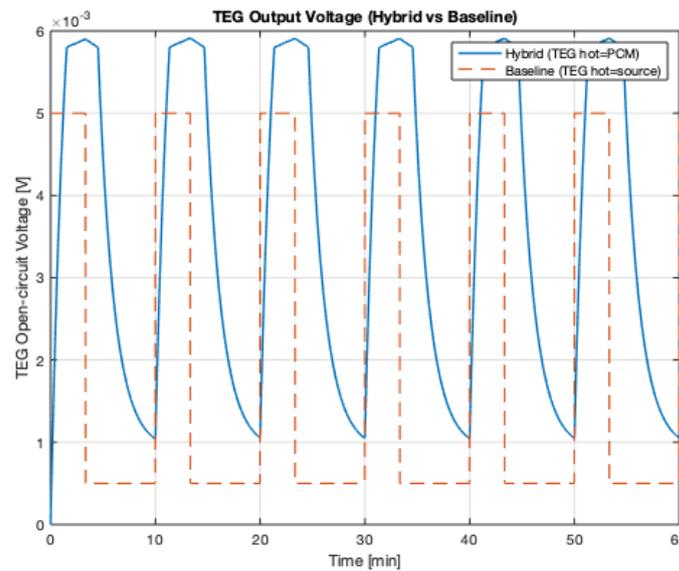


Figure 6. TEG Output Voltage vs Time (Hybrid vs Baseline).

Power conveyed to such electrical load has drawn in both hybrid and baseline conditions as shown in Figure 7. Though instant peak-power sometimes be greater in such baseline through powerful pulses, the proposed hybrid head for supply a further continual and utilizable output power via time and keep output through source outsider through release the PCM. combined energy (indicated by the area under the curve) frequently support the hybrid through a straight cycle due to PCM expands the effectual functioning time of such TEG.

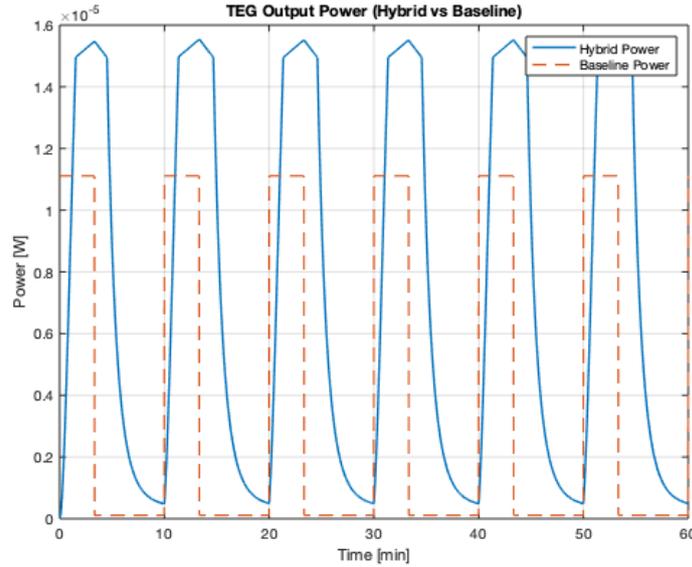
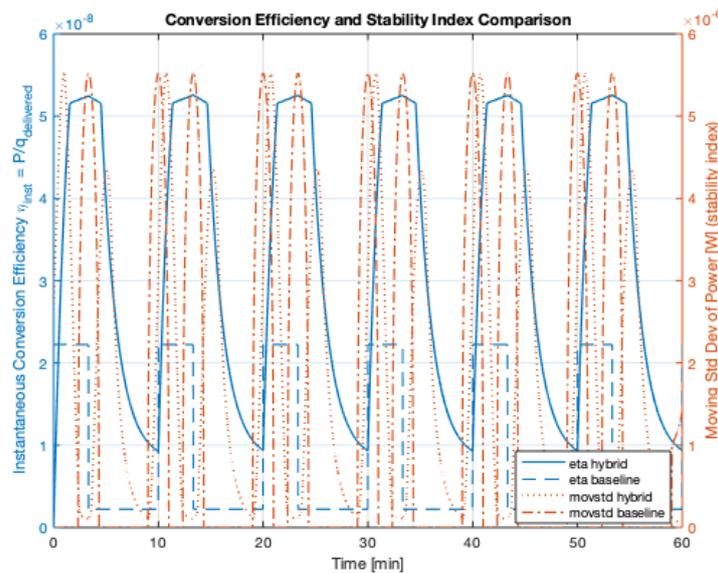


Figure 7. TEG Output Power vs Time (Hybrid vs Baseline).

Figure 8 demonstrates the instant transformation efficiency for the hybrid and baseline as well, together with the steady index calculated as the motion level power variation. The hybrid state mainly shows enhanced steadiness and enhanced instant efficiency through a lot of intervals due to PCM supplies a stable heat influx to TEG. lessen power variation clarify electronic power and maximizes powerful energy catch in almost real-world applications.



**Figure 8.** Conversion Efficiency and Stability Index.

5. Conclusions and Future Works

This work introduced a hybrid energy transformation framework combining thermoelectric generators and phase alteration materials in order to improve waste heat usage. The methodology and finding results simulations illustrated that the buffering of PCM constructively used to stabilize the hot-side temperature tendency, lessen power variation, and expanded the time of beneficial output of thermoelectric. The comparison with the baseline framework, the proposed hybrid system conveyed description of smoother voltage, further reliable power generation, in addition enhanced transformation efficiency over fluctuating heat input states. Such findings address the powerful of coupled thermo-mechanical in handling the innate restrictions of standalone TEG frameworks, especially in interrupted and transitory circumstances.

Future work has to be focused on investigational effectiveness of PCM–TEG-based prototypes encapsulations in order to confirm predictions-based system in real operation situations. As well, Testing on modern nano-improved PCMs, geometry adaptation with a powerful optimization, and intelligent-systems of thermal management approaches will be more enhanced model efficiency and thoroughness.

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