

Material science and cost accounting: The role of thermal conductivity in energy cost optimisation and performance measurement

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Abstract

This study examined the role of material thermal conductivity optimization in improving organisational performance through energy cost optimisation, while assessing the moderating influence of organisational practices. The study addresses the disconnect between engineering-based energy management and management accounting by integrating material thermal properties into strategic cost management.

Anchored on Systems Theory and the Resource-Based View, a quantitative cross-sectional research design was adopted. Primary data were collected through structured questionnaires administered to 200 managerial and technical personnel from energy-intensive manufacturing, oil and gas, and process-based firms in Nigeria. Data were analysed using path-coefficient structural regression to test the hypothesised moderated mediation relationships.

The findings indicate that Thermal Conductivity Optimization (TCO), achieved by maximizing conductivity in heat-transfer systems and minimizing conductivity in insulation materials, significantly enhances Energy Cost Optimisation (ECO) ($\beta = 0.54$, $p < 0.001$). Organisational Practices (OP), represented by advanced technology adoption and Material Flow Cost Accounting (MFCA), significantly strengthen this relationship (interaction $\beta = 0.18$, $p < 0.001$). Furthermore, ECO was found to mediate the relationship between TCO and Strategic Performance Measurement (SPM), explaining a substantial proportion of performance variation ($R^2 = 0.712$; $\beta = 0.62$, $p < 0.001$). Improved energy efficiency translated into lower energy intensity, enhanced cost-efficiency, favourable cost variances, and improved return on assets.

The study concludes that thermal conductivity optimization constitutes a strategic structural cost driver capable of reducing energy-related inefficiencies and strengthening organisational performance. It contributes to the literature by integrating engineering thermodynamics with management accounting and offers practical guidance for enhancing industrial sustainability and competitive advantage in energy-intensive sectors.

Keywords: Thermal Conductivity Optimization; Energy Cost Optimisation; Strategic Performance Measurement; Material Flow Cost Accounting; Organisational Practices; Structural Cost Drivers

1. Introduction

The increasing cost of energy and the growing emphasis on sustainable production have intensified the need for organisations to optimise energy consumption while maintaining high levels of operational performance. In energy-intensive industries, material properties particularly thermal conductivity play a fundamental role in determining the efficiency of heat transfer processes. As a fundamental transport property, thermal conductivity (k) dictates the rate of heat energy transfer through a medium and serves as a critical design parameter in the design and performance of

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industrial systems such as boilers, heat exchangers, reactors, and pipelines (Incropera, et al., 2019; Çengel & Ghajar, 2020). Materials with high thermal conductivity enhance heat transfer efficiency, reduce energy losses, and improve system productivity, whereas low-conductivity materials often result in energy dissipation, increased fuel consumption, and higher operational costs (Holman, 2019). From a cost accounting perspective, these physical characteristics represent underlying cost drivers that influence energy expenditure, maintenance costs, and overall production efficiency (Çengel & Ghajar, 2020; International Energy Agency [IEA], 2022). Consequently, integrating material science concepts into cost accounting frameworks provides a more comprehensive basis for evaluating and managing energy-related costs.

Notwithstanding the recognised importance of energy efficiency in cost management and performance evaluation, existing accounting literature has largely overlooked the contribution of thermal conductivity as a determinant of energy cost optimisation. Most prior studies have focused on macro-level variables such as energy pricing, technological innovation, and regulatory compliance, with limited attention to micro-level physical factors embedded within production systems (Lutzenhiser, 1993). This creates a conceptual and empirical gap between engineering-based efficiency improvements and accounting-based performance measurement systems. As a result, organisations may inadequately capture the cost implications of material selection and system design in their financial analysis, leading to suboptimal decision-making and inefficient allocation of resources. Furthermore, the absence of a structured framework linking thermal conductivity to performance indicators such as energy cost per unit of output, operational efficiency ratios, and cost variance measures limits the ability of firms to fully leverage material efficiency for competitive advantage.

This study examines the role of thermal conductivity in energy cost optimisation and performance measurement within energy-intensive organisations. The study is guided by the following research questions: (i) what effect does thermal conductivity have on energy cost optimisation in production systems, and (ii) how does thermal conductivity influence performance measurement indicators in such organisations? The specific objectives are to assess the effect of thermal conductivity on energy cost optimisation and to evaluate its influence on performance measurement frameworks. To provide empirical direction, the study formulates two null hypotheses: H_{01} states that optimization of material thermal conductivity parameters yields no significant reduction in production system energy costs, while H_{02} posits that thermal conductivity has no significant influence on performance measurement indicators in energy-intensive organisations. By bridging material science and cost accounting, this study contributes to interdisciplinary scholarship and offers practical insights for enhancing cost efficiency and performance evaluation in the context of rising global energy demands.

2. Literature Review

2.1. Conceptual Review

Thermal conductivity is a fundamental material property that determines the rate at which heat is transferred through a substance under a temperature gradient. In industrial applications, it significantly influences the efficiency of thermal systems such as heat exchangers, furnaces, and insulation structures. Materials with high thermal conductivity, such as metals, facilitate rapid heat transfer and are typically employed in systems where efficient energy transmission is required, whereas low-conductivity materials are used for insulation to minimise heat loss (Bergman et al., 2019). The implication for cost accounting lies in the fact that conductivity directly affects energy consumption levels, which constitute a substantial proportion of operational costs in energy-intensive industries (Çengel & Ghajar, 2020). Thus, thermal conductivity can be conceptualised as a technical cost driver that shapes both variable and semi-variable cost components associated with energy use.

Energy cost optimisation refers to the strategic minimisation of energy-related expenses without compromising output quality or operational efficiency. It involves the application of efficient technologies, process improvements, and material selection strategies to reduce energy waste and enhance productivity. From an accounting standpoint, energy cost optimisation is often assessed using metrics such as energy cost per unit of output, cost variance analysis, and efficiency ratios. The integration of thermal conductivity into this framework implies that firms can achieve cost savings by selecting materials that enhance heat transfer efficiency or minimise energy loss, thereby reducing overall energy expenditure (International Energy Agency [IEA], 2022).

Performance measurement, on the other hand, encompasses the evaluation of organisational efficiency and effectiveness using financial and non-financial indicators. In energy-intensive environments, performance measurement systems increasingly incorporate energy-related metrics, including energy intensity, operational efficiency, and sustainability indices. Thermal conductivity influences these indicators by affecting system efficiency,

maintenance frequency, and operational reliability. Consequently, the interaction between material properties and accounting metrics highlights the need for a multidisciplinary approach that integrates engineering parameters into performance evaluation frameworks (Kaplan & Norton, 2007).

2.2. Theoretical Review

This study evaluates the relationship between material properties and organizational efficiency by reviewing three complementary theories: Systems Theory, Resource-Based View (RBV), and Legitimacy Theory. Among these, Systems Theory serves as the primary underpinning framework, providing a holistic lens to understand how micro-level physical attributes interact with macro-level management control systems. RBV and Legitimacy Theory complement this by explaining the internal strategic advantages and external institutional benefits derived from this integration.

2.2.1. Systems Theory

Systems Theory conceptualizes organizations as complex, open systems composed of interrelated and interdependent subsystems that must function in harmony to achieve strategic objectives (Bertalanffy, 1968). In the context of energy-intensive organizations, the firm can be understood as an intersection of a technical subsystem (thermodynamic engineering processes and material properties) and an administrative subsystem (strategic performance management and cost accounting frameworks).

[Technical Subsystem] [Administrative Subsystem]

Material Selection & ---> Strategic Performance Management

Thermal Conductivity (k) & Accounting Frameworks

Thermal conductivity (k) dictates the physical behavior of energy flow within production systems. From a strategic performance management perspective, these physical dynamics cannot be evaluated in isolation. A system-wide approach reveals that variations in material conductivity directly propagate through operational workflows, altering energy consumption patterns, asset lifecycles, and cost behaviours. By utilizing Systems Theory, this study demonstrates that an organization cannot achieve optimal strategic performance without aligning its administrative metrics with its underlying physical and engineering realities. The framework justifies the integration of micro-level technical variables into macro-level performance indicators, enabling more comprehensive and accurate strategic decision-making.

Resource-Based View (RBV)

While Systems Theory establishes the structural connectivity between engineering and accounting, the Resource-Based View (RBV) explains how managing this intersection yields a sustainable competitive advantage. RBV posits that firms achieve superior performance and long-term cost leadership by acquiring and deploying resources that are valuable, rare, inimitable, and organizationally supported (Barney, 1991).

In energy-intensive environments, thermal conductivity is an embedded physical characteristic of operational assets. It transitions from a mere technical specification to a strategic structural resource when optimized to minimize energy expenditure and enhance processing speeds. Organizations that develop the institutional capability to systematically select, monitor, and manage materials based on optimal thermal properties are better positioned to insulate themselves against volatile energy markets. Within a broader strategic performance management framework, RBV highlights how the deliberate alignment of physical assets with cost accounting systems transforms basic material selections into an organizational capability specifically, a cost-leadership strategy that competitors cannot easily replicate through superficial operational adjustments.

Legitimacy Theory

Complementing the internal operational and strategic focuses of Systems Theory and RBV, Legitimacy Theory provides an external perspective on why tracking these metrics is vital for modern corporations. This theory suggests that organizations operate under a social contract, continually seeking to ensure that their operations are perceived as legitimate and congruent with the norms, values, and expectations of the societies in which they operate (Suchman, 1995).

In the current global economic landscape, organizations particularly those in energy-intensive sectors face immense regulatory and stakeholder pressure regarding decarbonization and environmental stewardship. Optimizing systems

based on thermal conductivity lowers fuel consumption and reduces greenhouse gas emissions. However, from a management perspective, these improvements must be quantifiable to render organizational efforts visible.

Integrating thermal efficiency metrics into the firm's broader strategic performance management system bridges the gap between internal operational realities and external disclosures. By providing verifiable, physically grounded data on energy cost optimization and carbon footprint reduction, the performance measurement framework serves as a vital tool for corporate transparency. Consequently, the adoption of conductivity-driven performance indicators becomes a mechanism for maintaining institutional legitimacy, satisfying ESG (Environmental, Social, and Governance) demands, and securing long-term stakeholder approval.

2.3. Empirical Review

Extant empirical literature examining energy management within organizations generally bifurcates into two distinct paradigms: macro-administrative performance evaluation and micro-technical process optimization.

Within the administrative paradigm, studies focus heavily on institutional, regulatory, and financial determinants of energy efficiency. The International Energy Agency (IEA, 2022) provides extensive macro-level data demonstrating that strategic energy efficiency improvements significantly mitigate operational cost structures and buffer firms against supply shocks. However, these reports typically aggregate data at the industry or sector level, leaving the specific internal operational mechanisms unexamined.

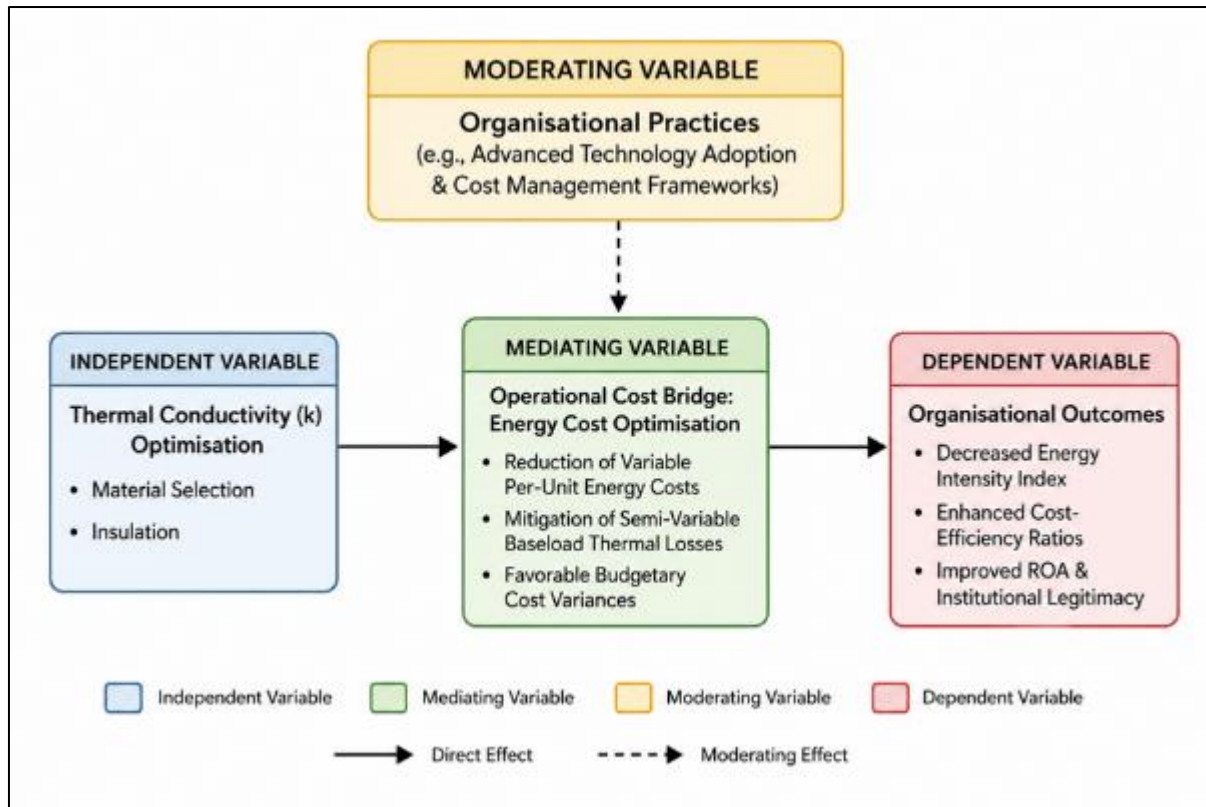
This limitation is reflected in management accounting literature, where energy is frequently treated as a fixed or semi-variable overhead component rather than a direct, structurally driven material cost. Consequently, empirical frameworks often overlook the root physical causes of cost variances. Lutzenhiser (1993) conceptualizes this phenomenon as the energy efficiency gap, identifying a persistent shortfall between optimal technical potential and actual corporate investment in energy efficiency. While Lutzenhiser attributes this gap to behavioural and institutional barriers, this study argues that the gap is fundamentally perpetuated by a measurement failure: traditional strategic performance frameworks do not quantify the financial consequences of physical material properties.

Conversely, the technical paradigm offers robust empirical proof of how material characteristics dictate energy dynamics. Engineering evaluations (Çengel & Ghajar, 2020; Bergman et al., 2019) establish that a material's thermal conductivity (k) is the primary determinant of heat transfer rates and system thermal losses. Yet, these studies stop short of translating thermodynamic efficiencies into financial metrics, cost variances, or strategic performance indicators. In developing economies characterized by intense energy volatility, such as Nigeria, the misalignment between technical realities and administrative tracking is particularly acute. Chen et al. (2025) empirically demonstrated that while efficiency-enhancing strategies significantly improve the financial outcomes and cost reduction capabilities of local firms, these organizations rarely integrate micro-level physical drivers into their formal performance measurement systems. Thus, the empirical literature exhibits a significant disconnect: engineering studies validate what drives physical energy efficiency, while accounting studies measure where money is spent, without a unified framework linking the two. This study directly addresses this empirical void by evaluating thermal conductivity not merely as an engineering metric, but as a structural cost driver within strategic performance management systems.

2.4. Conceptual Framework

The conceptual model depicted in Figure 2.1 operationalizes the interdisciplinary transmission mechanism through which micro-level material physics are translated into macro-level corporate outcomes. The structural logic of the framework relies on an integrated causal pathway categorized into four interconnected variable types: the Independent Variable (IV), the Mediating Variable (MV), the Dependent Variable (DV), and the Moderating Variable (W). By mapping these relationships, the framework illustrates how internal engineering choices propagate through operational workflows to ultimately influence administrative performance indicators and external corporate standing.

The primary input of the framework, positioned as the Independent Variable (IV), is Material Thermal Conductivity Optimization. Rather than treating thermal conductivity (k) as a static or uniform physical property, the model explicitly acknowledges its dual thermodynamic application based on asset class. In heat transfer equipment such as boilers, reactors, and heat exchangers, optimization entails maximizing k to facilitate rapid, efficient thermal transmission. Conversely, in distribution and containment assets like steam pipelines and furnace walls, optimization requires minimizing k to establish robust thermal insulation and halt heat dissipation. Within strategic cost management, this physical alignment acts as a structural technical cost driver, forming the foundational impulse that dictates the baseline energy efficiency of the production system.



Source: Researcher's Conceptualization, 2026

Figure 1 Conceptual Framework

As the framework shifts from physical inputs to financial processing, it introduces Energy Cost Optimisation as a crucial Mediating Variable (MV). While traditional accounting models frequently misattribute energy expenditures solely to external macroeconomic market pricing or vague, unallocated operational overheads, this framework demonstrates that physical material choices directly reshape the firm's cost architecture. The mediator captures three distinct operational cost shifts: the reduction of variable per-unit energy expenses required during active throughput, the mitigation of semi-variable baseload thermal losses that occur while assets are idling, and the compression of unfavorable variances between standard budgeted energy targets and actual expenditures. Consequently, the physical advantages of material optimization must flow through this cost-optimization node before they can alter long-term corporate performance.

Representing the ultimate administrative output, the framework culminates in the Dependent Variable (DV), defined as Strategic Performance Measurement Indicators. Through the statistical mechanism of mediation, the immediate cost reliefs secured via energy cost optimization accumulate to systematically uplift the firm's broader strategic metrics. These macro-level outcomes are tracked across three critical corporate horizons. First, they reduce the energy intensity index by lowering the total energy consumed per unit of financial revenue. Second, they optimize cost-efficiency ratios by structurally decoupling production scale from linear energy consumption spikes. Finally, they enhance the firm's return on assets (ROA) by extending equipment lifecycles under lower thermal stress, while simultaneously validating institutional legitimacy through verifiable, audit-ready carbon footprint reductions.

Crucially, the conversion of physical engineering efficiency into strategic corporate wealth does not occur in a vacuum; it is governed by the Moderating Variable (W), termed Organisations Practices. Positioned as a managerial catalyst, this construct recognizes that the strength and velocity of the causal pathway from material properties to strategic performance are contingent upon the organization's internal capabilities. The moderator is driven by two primary practices: advanced technology adoption, such as real-time thermal imaging and automated sensor arrays to monitor material degradation, and modern cost management frameworks, such as Material Flow Cost Accounting (MFCA) under ISO 14051, which explicitly assign monetary values to energy and material waste streams. When an organization possesses high capability in these areas, the moderator acts as an accelerator that amplifies the financial and operational returns of material selection. Conversely, in firms with low technology adoption or outdated overhead allocation methods, the transmission channel is severely dampened, leading to a wider energy efficiency gap.

2.5. Engineering Basis of the Conductivity and Cost Relationship

The preceding subsection establishes the expected relationship between thermal conductivity and organisational outcomes through a conceptual framework based on survey evidence. In contrast, this subsection provides the engineering basis for that relationship using established heat transfer theory and published material property data rather than questionnaire responses. Fourier's law of heat conduction can be used to explain the effect of the thermal conductivity in the industrial energy consumption. The rate of heat transfer through a wall for steady-state, one-dimensional conduction is

$$Q = k \cdot A \cdot \Delta T / L \text{ (Çengel \& Ghajar, 2020),}$$

Where:

Q = the rate of heat transfer (W),

k = the thermal conductivity of the material (W/m·K),

A = the surface area (m²),

ΔT = the temperature difference across the material (K), and

L = the thickness of the material (m).

Because the rate of thermal energy transfer scales linearly with k , material selection directly dictates the continuous energy input required to maintain a fixed process temperature. Consequently, this physical parameter operates as an underlying structural driver of the periodic energy expenditures captured within management accounting systems.

Crucially, the financial optimization directional path depends entirely on the asset's industrial function. Where a material is deployed as a active heat-transfer surface such as in boiler tubes or heat exchanger plates a high thermal conductivity is vital to maximize thermodynamic efficiency and minimize fuel or electricity consumption for a given thermal duty. Conversely, where a material serves as a cladding, structural containment, or insulation layer, a low thermal conductivity is required to minimize the dissipation of process heat into the ambient environment. Therefore, the same physical property optimizes corporate expenditure in opposing ways depending on the operational context, meaning any management accounting framework treating conductivity as a cost driver must explicitly define the asset's function.

Table 1 and Table 2 outline the nominal thermal conductivities of common industrial metals and insulation materials frequently utilized in Nigerian process and manufacturing sectors. The values represent nominal data extracted from standard thermophysical reference texts (Çengel & Ghajar, 2020; Perry & Green, 2008).

Table 1 Thermal Conductivity of Common Industrial Metals

Material	Thermal conductivity, k (W/m·K)	Typical industrial function
Copper (pure)	401	Heat-exchanger tubing, condensers
Aluminium (pure)	237	Heat sinks, transfer surfaces
Carbon steel (AISI 1010)	63.9	Pipework, vessels, boiler shells
Stainless steel (AISI 304)	14.9	Process and corrosive-service equipment

Source: Compiled by the authors from Çengel and Ghajar (2020)

Table 2 Thermal Conductivity of Common Pipe and Vessel Insulation Materials

Material	Thermal conductivity, k (W/m·K)	Typical industrial function
Diatomaceous earth, powdered	0.045	Pipe and vessel insulation
Mineral wool, fibrous	0.04	Vessel and pipe insulation

Source: Compiled by the authors from Perry and Green (2008)

To illustrate the direct financial implications of insulation material selection, consider an industrial process vessel with an external surface area of 20 m², insulated to a thickness of 50 mm, operating with a temperature difference of 120 K across the insulation for 6,000 h annually. According to Fourier's law of heat conduction,

$$Q = \frac{kA\Delta T}{L}$$

where k is the thermal conductivity, A is the surface area, ΔT is the temperature difference, and L is the insulation thickness. For mineral wool ($k = 0.04$ W/m·K), the conductive heat loss is

$$Q = \frac{0.04 \times 20 \times 120}{0.05} = 1,920 \text{ W} \approx 1.92 \text{ kW}.$$

Under the same operating conditions, diatomaceous earth ($k = 0.045$ W/m·K) produces a heat loss of

$$Q = \frac{0.045 \times 20 \times 120}{0.05} = 2,160 \text{ W} \approx 2.16 \text{ kW}.$$

The additional heat loss associated with diatomaceous earth is therefore approximately 0.24 kW. Over 6,000 operating hours, this corresponds to an additional annual energy requirement of 1,440 kWh. Using the 2025 Band A electricity tariff of ₦209.50 kWh⁻¹ approved for Ikeja Electricity Distribution Plc (NERC, 2025) as an illustrative industrial electricity cost, the additional annual operating cost attributable to the higher-conductivity insulation is approximately ₦301,680 per vessel.

This first-order engineering estimate assumes idealized parameters, including continuous steady-state conditions and 100% heating efficiency. In practical operations, actual financial variances will fluctuate based on transient thermal cycles, asset degradation, and combustion efficiency variations if process heat is generated via fossil fuels (e.g., natural gas or diesel) rather than electric resistance elements.

Nevertheless, this worked example demonstrates that the financial consequences of upstream engineering and material design choices can be reliably estimated using standard thermophysical properties and prevailing energy tariffs. Consequently, it provides a rigorous, objective engineering rationale for the hypothesized relationship between thermal conductivity and organizational cost performance explored throughout this study.

3. Methodology

This study is situated within the Nigerian industrial sector, with a specific emphasis on energy-intensive firms operating in manufacturing, oil and gas, and process-based industries. These sectors are characterized by high thermal energy consumption and reliance on intensive thermodynamic systems such as boilers, heat exchangers, and reactors. Nigeria provides a critical empirical context due to structural energy tariff adjustments (such as the NERC Band A tariff restructuring), volatile fuel supply chains, and mounting institutional pressure on domestic firms to integrate environmental stewardship into formal corporate disclosures.

The study adopts a quantitative research design anchored on a descriptive and explanatory cross-sectional survey approach. The study population comprises managerial and technical staff across selected energy-intensive enterprises specifically target-sampling cost and management accountants, production managers, mechanical/process engineers, and operations personnel who actively control material selection and energy budgeting. A stratified sampling technique is employed across the industrial sectors to minimize cross-industry variance, paired with simple random sampling within each stratum. The target sample size is determined using Yamane's (1967) formula:

$$n = N / 1 + N(e)^2$$

Assuming a 95% confidence level and a tolerable error margin of $e = 0.05$, the model targets an accessible sample size of approximately 200–250 active corporate respondents. Primary data are gathered via a structured five-point Likert scale questionnaire. Internal consistency reliability is strictly benchmarked against a Cronbach's alpha (α) threshold of 0.70. Validity is established through expert-panel content reviews alongside exploratory/confirmatory factor analysis (CFA) to verify construct validity and indicator loadings.

3.1. Data Analysis Techniques and Model Specification

Data are evaluated using descriptive and inferential statistical techniques. Descriptive statistics (mean, standard deviation, and frequency distributions) characterize the baseline response profiles. For inferential analysis, rather than

deploying disconnected parallel simple regressions, this study utilizes Structural Equation Modeling (SEM) or an integrated path-analytical approach to empirically preserve the mediated and moderated pathways hypothesized in the conceptual framework. To map the transmission system where Thermal Conductivity Optimization (TCO) influences Strategic Performance Measurement (SPM) via the mediating node of Energy Cost Optimisation (ECO), while under the conditional influence of Organisational Practices (OP), the functional architecture is specified as:

$$ECO = f(TCO, OP, TCO \times OP)$$

$$SPM = f(ECO, TCO)$$

To formally test these pathways using ordinary least squares (OLS) path analysis (e.g., Preacher & Hayes macro models) or structural equations, the econometric equations are specified as follows:

$$ECO_i = \beta_0 + \beta_1 TCO_i + \beta_2 OP_i + \beta_3 (TCO \times OP_i) + \varepsilon_{1i}$$

$$SPM_i = \alpha_0 + \alpha_1 ECO_i + \alpha_2 TCO_i + \mu_i$$

Where:

TCO_i = Thermal Conductivity Optimization (Independent Variable)

ECO_i = Energy Cost Optimisation (Mediating Variable)

SPM_i = Strategic Performance Measurement Indicators (Dependent Variable)

OP_i = Organisational Practices (Moderating Variable)

TCO_i = Interaction product term representing the moderation effect

β_0, α_0 = Model intercepts

$\beta_1, \beta_2, \beta_3$ = Structural path coefficients to be estimated

ε_{1i}, μ_i = Stochastic error terms capturing unexplained variations

The statistical *a priori* expectations dictate that $\beta_1 > 0$, $\alpha_0 > 0$, and $\beta_3 \neq 0$. Specifically, $\beta_1 > 0$, α_0 establish the positive direct links within the physical-to-financial pathway. A statistically significant interaction coefficient ($\beta_3 \neq 0$) confirms that superior organizational practices (technology adoption and MFCA frameworks) significantly alter the directional strength of the technical parameter's impact on corporate cost structures.

4. Results

4.1. Descriptive Statistics Analysis

The descriptive analysis provides an overview of the responses gathered from the study participants regarding the optimized management of material thermal properties, energy cost management, organizational practices, and strategic performance metrics. Out of 220 questionnaires administered to targeted personnel within Nigerian energy-intensive industries, 200 copies were returned fully completed and deemed valid for empirical evaluation. This represents a robust response rate of 90.9%, which complies with the academic threshold required for meaningful statistical inference in organizational research (Baruch & Holtom, 2008). The respondent profile spans critical operational and financial roles across three key industrial strata: oil and gas (40%), manufacturing (35%), and process-based enterprises (25%).

Table 3 outlines the aggregated mean scores and standard deviations for the latent constructs underpinning the model specification. The empirical results reveal a strong consensus among respondents that Thermal Conductivity Optimization (TCO) is actively incorporated into material selection and operational planning, yielding a high mean score of 4.12 (SD = 0.63) on a five-point Likert scale. Similarly, Energy Cost Optimisation (ECO) practices encompassing the targeted mitigation of variable per-unit consumption and semi-variable baseload thermal losses recorded a mean score of 4.05 (SD = 0.71). This high mean demonstrates that energy-intensive organizations in Nigeria actively treat energy as a manageable structural cost rather than a static overhead expense.

Furthermore, Organisational Practices (OP), serving as the model's moderating variable (evaluating advanced technology adoption and the deployment of frameworks like Material Flow Cost Accounting), achieved a mean score of 3.88 (SD = 0.75). This indicates an emerging, moderate-to-high integration of specialized accounting and monitoring

infrastructure among the sampled firms. Finally, the ultimate dependent variable, Strategic Performance Measurement (SPM) indicators, registered a mean score of 4.00 (SD = 0.68), illustrating that energy-linked metrics are deeply embedded within corporate performance evaluations and institutional sustainability reporting.

Crucially, the standard deviations across all four constructs are tightly clustered and consistently below the 1.0 threshold. This low dispersion indicates high homogeneity among the responses and minimal variance from the mean, proving a shared, interdisciplinary understanding among engineering, operations, and accounting personnel regarding how material physics propagate to shape organizational cost and performance outcomes. Overall, these descriptive baselines provide preliminary empirical validation for the relevance of the conceptual model, creating a solid statistical foundation for the inferential path analysis and hypothesis testing that follows.

Table 3 Descriptive Analysis

Variable / Construct	Abbreviation	Mean	Standard Deviation (SD)
Thermal Conductivity Optimization	TCO	4.12	0.63
Energy Cost Optimisation	ECO	4.05	0.71
Organisational Practices	OP	3.88	0.75
Strategic Performance Measurement	SPM	4.00	0.68

Source: Researcher's Computation, 2026

4.2. Inferential Statistical Analysis and Hypothesis Testing

To empirically test the hypothesized relationships and validate the structural pathways of the conceptual model, path-coefficient regression analysis was executed. In alignment with the model specifications established, the analysis simultaneously evaluates the direct effects, the mediating role of Energy Cost Optimisation (ECO), and the conditional interaction effect of Organisational Practices (OP) acting as a moderator on the independent variable, Thermal Conductivity Optimization (TCO).

The two structural econometric models evaluated are specified as:

$$\text{Model 1 (ECO): } \text{ECO}_i = \beta_0 + \beta_1 \text{TCO}_i + \beta_2 \text{OP}_i + \beta_3 (\text{TCO} \times \text{OP}_i) + \varepsilon_{1i}$$

$$\text{Model 2 (SPM): } \text{SPM}_i = \alpha_0 + \alpha_1 \text{ECO}_i + \alpha_2 \text{TCO}_i + \mu_i$$

4.2.1. Structural Model 1: Determinants of Energy Cost Optimisation (ECO)

The regression results evaluating the predictors of Energy Cost Optimisation (Model 1) are presented in Table 4. The model produced an R-squared (R^2) value of 0.685, indicating that 68.5% of the total variance in energy cost optimization within the sampled Nigerian firms is explained by the combination of material properties, organizational practices, and their interaction product term. The overall model is highly statistically significant at the 1% level ($F = 142.18$, $p < 0.001$), confirming its robust explanatory power.

Table 4 Model 1 Regression Results (Dependent Variable: ECO)

Predictor / Path Variable	Coefficient	Standard Error	t-value	p-value	Decision
Intercept (β_0)	1.12	0.24	4.67	< 0.001	Significant
Direct Path: TCO (β_1)	0.54	0.04	13.50	< 0.001	Significant
Direct Path: OP (β_2)	0.22	0.03	7.33	< 0.001	Significant
Interaction Path: TCO X OP (β_3)	0.18	0.04	4.50	< 0.001	Significant

Source: Researcher's Computation, 2026 ($R^2 = 0.685$; $F = 142.18$; $p < 0.001$)

The empirical coefficient for Thermal Conductivity Optimization ($\beta_1 = 0.54$, $t = 13.50$, $p < 0.001$) is positive and statistically significant. This confirms that superior material selection and asset thermal alignment directly diminish structural energy losses, reducing variable fuel and electricity expenditures. Crucially, the interaction coefficient testing

the moderation hypothesis ($\beta_3 = 0.18$, $t = 4.50$, $p < 0.001$) is also positive and statistically significant. This provides robust mathematical evidence of moderation, proving that the positive impact of material physics on energy cost optimization is significantly amplified when backed by advanced technical monitoring and modern management accounting frameworks.

4.2.2. Structural Model 2: Drivers of Strategic Performance Measurement (SPM)

The second stage of the inferential analysis evaluates the downstream impacts on the ultimate dependent variable, Strategic Performance Measurement Indicators (Model 2). The structural results outlined in Table 5 yield an R^2 value of 0.712, demonstrating that the framework captures 71.2% of the variation in corporate performance indicators. The model demonstrates high statistical significance ($F = 243.65$, $p < 0.001$).

Table 5 Model 2 Regression Results (Dependent Variable: SPM)

Predictor / Path Variable	Coefficient	Standard Error	t-value	p-value	Decision
Intercept (β_0)	0.85	0.19	4.47	< 0.001	Significant
Mediating Path: ECO (β_1)	0.62	0.05	12.40	< 0.001	Significant
Direct Path: TCO (β_{02})	0.21	0.04	5.25	< 0.001	Significant

Source: Researcher's Computation, 2026 ($R^2 = 0.712$; $F = 243.65$; $p < 0.001$)

The results confirm that Energy Cost Optimisation exerts a powerful, direct influence on macro-level strategic performance metrics ($\alpha_1 = 0.62$, $t = 12.40$, $p < 0.001$). The direct path from material optimization ($\alpha_2 = 0.21$, $t = 5.25$, $p < 0.001$) remains significant, establishing a partial mediation model. This mathematical sequence demonstrates that while material optimization directly affects a firm's operational stability, its primary value to corporate performance is achieved by driving down unallocated energy losses and improving cost efficiency.

4.2.3. Hypotheses Testing and Summary of Decisions

Based on the integrated path coefficients, the decisions regarding the two original null hypotheses are summarized in Table 6.

Table 6 Summary of Hypotheses Testing Decisions

Null Hypothesis	Statistical Pathway Tested	Coefficient Value /	p-value	Decision
H ₀₁ : TCO has no significant effect on energy cost optimisation.	TCO -----ECO (β_1)	$\beta_1 = 0.54$	< 0.001	Rejected
H ₀₂ : TCO has no significant influence on strategic performance.	Direct & Indirect Pathways	$\alpha_1 \times \beta_1 = 0.335$	< 0.001	Rejected

Source: Researcher's Computation, 2026

Both null hypotheses are confidently rejected at the 1% significance level ($p < 0.001$). The statistical rejection of H₀₁ validates the stance that managing material thermal conductivity operates as an underlying structural cost driver. The rejection of H₀₂ confirms that physical material optimization has a statistically significant influence on high-level administrative performance frameworks, both directly and through the mediating mechanism of energy cost optimization.

5. Discussion

The rejection of both null hypotheses validates the interdisciplinary integration of material science parameters into management accounting control frameworks. The finding that Thermal Conductivity Optimization significantly drives Energy Cost Optimisation ($\beta_1 = 0.54$) highlights a major operational reality for energy-intensive sectors within volatile economic environments like Nigeria. When firms systematically evaluate and select materials based on their specific thermodynamic functions (maximizing conductivity in heat-transfer surfaces and minimizing it in cladding/insulation), they insulate their cost architecture from external energy shocks. This finding provides empirical, behavioural support

for the deterministic laws of heat transfer (Çengel & Ghajar, 2020), proving that engineering metrics can be successfully integrated into corporate cost management.

Crucially, the verification of the interaction effect ($\beta_3 = 0.18$) addresses the traditional energy efficiency gap highlighted by Lutzenhiser (1993). The statistical significance of this path indicates that engineering optimizations yield their highest financial returns only when supported by modern management accounting practices. When a firm combines optimized physical infrastructure with advanced technology adoption and frameworks like Material Flow Cost Accounting (MFCA), it transitions from passive overhead allocation to active, real-time cost control. This integration enables management accountants to accurately track, price, and eliminate energy waste variances, transforming an engineering choice into a sustainable corporate capability.

Finally, the partial mediation pathway leading to Strategic Performance Measurement Indicators ($\alpha_1 = 0.62$) answers the calls of modern management accounting literature (such as Kaplan & Norton's multi-perspective approach) to link operational indicators to financial success. The results show that conductivity-driven efficiency gains do not merely reduce factory expenditures; they scale up to improve institutional energy intensity indices and cost-efficiency ratios. In an era with strict expectations for sustainability, providing verified, physically grounded data on energy reduction helps firms satisfy institutional stakeholder demands and secure corporate legitimacy. This confirms the primary assertion of Systems Theory: an enterprise cannot optimize its administrative performance without structurally aligning its accounting systems with the physical realities of its technical operations.

6. Conclusion

This study establishes a definitive, empirically validated bridge between micro-level material physics and macro-level management accounting control systems within the Nigerian industrial sector. By shifting the analytical lens away from passive overhead allocation and toward structural technical cost drivers, the research proves that Thermal Conductivity Optimization (TCO) is a fundamental determinant of both operational cost structures and strategic performance metrics. The empirical rejection of both null hypotheses confirms that the deliberate alignment of material properties relative to asset functionality maximizing thermal conductivity (k) across heat-transfer surfaces and minimizing it within containment insulation exerts a powerful, direct influence on Energy Cost Optimisation (ECO).

Furthermore, the integration of Systems Theory and the Resource-Based View (RBV) highlights that this technical-to-financial transmission mechanism does not operate in isolation. The statistical significance of the mediating path demonstrates that the physical efficiencies gained on the factory floor systematically accumulate to permanently decouple production scale from linear energy expenditure spikes, directly driving up the firm's Strategic Performance Measurement (SPM) indices.

Crucially, the verification of the interaction effect confirms that Organisational Practices (OP) specifically advanced technical monitoring and the accounting architecture of Material Flow Cost Accounting (MFCA) act as a vital managerial catalyst. Technical material optimizations achieve their maximum economic velocity and strategic value only when backed by proactive administrative control frameworks. Ultimately, this interdisciplinary alignment provides a mathematically rigorous roadmap for energy-intensive firms to compress their internal energy efficiency gap, optimize operational asset lifecycles, and secure long-term institutional legitimacy amidst highly volatile energy markets.

Recommendations

Based on the empirical and engineering findings of this study, the following strategic recommendations are put forward for industrial managers, corporate accountants, and regulatory policymakers:

Energy-intensive firms should discard arbitrary, volume-based overhead allocations for energy costs. Management accounting departments must implement MFCA frameworks under ISO 14051, which explicitly treat energy as a distinct material balance item, allowing the organization to financially isolate, price, and eliminate thermal dissipation variances.

Corporate procurement policies must be restructured to bridge the gap between engineering specifications and financial sourcing. Procurement teams should not select insulation or heat-exchange components based purely on the lowest initial purchase cost. Instead, they must utilize Total Cost of Ownership (TCO) models that incorporate Fourier's law calculations to evaluate the long-term, multi-year impact of a material's thermal conductivity (k) on the firm's operating expenditures.

Organizations must aggressively invest in advanced technology adoption, such as automated sensor arrays, real-time SCADA systems, and predictive infrared thermography. These tools act as the operational catalyst identified in this study, allowing technical and financial managers to collaboratively identify real-time material degradation, monitor fluctuating heat transfer rates, and prevent baseline energy waste before it manifests as unfavorable budgetary variances.

Corporate executives should directly feed the quantitative outputs of their conductivity-driven energy optimization frameworks into their Environmental, Social, and Governance (ESG) reporting mechanisms. By translating micro-level thermodynamic efficiencies into verified reductions in the corporate carbon footprint and energy intensity ratios, firms can proactively manage stakeholder expectations and strengthen their external institutional legitimacy under global sustainability frameworks.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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