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Toward a Conceptual Framework for Energy Management in Industry

Ryan Mitchell [1*]

1. Northbridge University, Ireland
* Correspondence: ryanmitchell@northbridge.edu

Abstract: Industrial energy consumption accounts for roughly one-third of global final energy use, and energy costs have become a structural determinant of manufacturing competitiveness. Despite the widespread availability of energy-efficient technologies and decades of policy attention, a persistent gap separates technically feasible from actually implemented improvements. This paper develops an integrative conceptual framework for energy management in industry by synthesizing the literature on energy management systems, the ISO 50001 standard, organisational and behavioural drivers and barriers, maturity assessment, and the emerging role of Industry 4.0 digital technologies. Building on a systematic review of prior findings, the framework positions energy management as a multi-layered support function that integrates strategic intent, organisational structures, practices, metrics and data infrastructure across the Plan-Do-Check-Act cycle. It distinguishes three domains—an enabling context of policy, market and cultural forces; an internal management architecture comprising strategy, organisation, people and culture; and a practice portfolio of operational, technical and indirect activities—linked by continuous flows of energy information and performance metrics. The paper contributes a unifying conceptual map that clarifies the interrelationships among previously fragmented streams of research and offers a basis for practitioners seeking to design, implement and continuously improve industrial energy management programmes and for researchers seeking a common analytical lens.

Keywords: energy management; industrial energy efficiency; conceptual framework; energy management practices

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1. Introduction

Energy is simultaneously an economic input, an environmental burden and a strategic resource. The industrial sector accounts for approximately one-third of global final energy consumption, and energy-intensive sub-sectors such as chemicals, iron and steel, pulp and paper, non-ferrous metals, and non-metallic minerals together consume more than half of industrial energy in many economies (Schulze et al., 2015). Manufacturing facilities in the United States, for example, use about 35% of national energy annually, making industrial energy performance a direct determinant of both emissions trajectories and production costs (Guo et al., 2022). In parallel, the volatility of energy prices and the progressive tightening of decarbonisation policy have transformed energy from a peripheral support concern to a board-level strategic variable.

In response, firms across the globe have invested in energy management systems, energy audits, monitoring and targeting schemes, and best-practice programmes. The international diffusion of the ISO 50001 standard, published in 2011 and revised in 2018, gave these efforts a common normative backbone (Fuchs et al., 2020; Gallego et al., 2022). Yet empirical evidence consistently shows that industrial energy efficiency remains below its economic potential. Surveys of small and medium-sized enterprises in Europe highlight that a large share of profitable energy efficiency measures is never implemented, suggesting a structural "energy efficiency gap" rather than a technological shortfall (Cagno & Trianni, 2014; Trianni et al., 2012, 2015). Scholarship over the past two decades has identified

a complex web of economic, informational, organisational, behavioural, competence-related, technology-related and awareness-related barriers that explains this gap (Cagno & Trianni, 2014; Trianni et al., 2015).

The research community has responded with parallel advances. One stream has focused on the technical design of EnMS, data standards and energy key performance indicators (e-KPIs) (May et al., 2015; Vikhorev et al., 2012). Another has examined the organisational antecedents of energy performance, particularly top management commitment and energy culture (Arinaitwe et al., 2023; May et al., 2015; Rotzek et al., 2018). A third stream has explored the impact of digital technologies—the Internet of Things, big data analytics, artificial intelligence and simulation—on energy awareness and decision-making (Cagno et al., 2025; Shrouf & Miragliotta, 2015; Zhang et al., 2018). A fourth has built practice-based assessment models and maturity matrices that allow firms to benchmark their energy management capabilities (Sa et al., 2017; Trianni et al., 2018).

These streams have largely developed in isolation. A unified conceptual framework that integrates strategic, organisational, practice-based and digital dimensions is missing in the literature, despite repeated calls for "holistic perspectives" on corporate sustainability and energy (Cagno & Trianni, 2014; Ren et al., 2018; Schulze et al., 2015). This paper responds to that gap. Its objective is to develop a conceptual framework that synthesises the strands above into a coherent architecture for industrial energy management. Three research questions guide the work:

What is the existing evidence base on operating energy management in industrial companies?

What conceptual elements and detailed activities must be considered in an industrial company's energy management?

How can this evidence be synthesised into an integrative conceptual framework?

The paper proceeds as follows. Section 2 situates energy management as a corporate support function and clarifies its definition. Section 3 describes the methodological approach. Section 4 reviews the relevant evidence on energy management practices, organisational enablers, barriers, the ISO 50001 standard, maturity assessment and the digital transformation of energy management. Section 5 develops the integrative conceptual framework. Section 6 discusses implications and limitations, and Section 7 concludes.

2. Energy Management as a Corporate Support Function

2.1 Definition and scope

Energy management can be defined as the set of coordinated policies, structures, practices and information systems through which an organisation plans, controls and reduces its energy consumption while maintaining or enhancing production output (Schulze et al., 2015). It is not limited to monitoring and targeting; rather, it requires the deep integration of technical, organisational and informational dimensions across the factory floor and the firm as a whole (Vikhorev et al., 2012).

Three definitional shortcomings have limited progress in the field. First, "energy management" is often conflated with "energy efficiency", although the former denotes an organisational capability and the latter an outcome variable. Second, the scope of the function is sometimes reduced to the activities of a dedicated energy manager, whereas research shows that effective energy management requires distributed responsibility across operations, maintenance, engineering and top management (Arinaitwe et al., 2023; May et al., 2015). Third, definitional boundaries regarding whether EnMS, energy programmes and energy practices are nested or overlapping constructs remain unsettled (Trianni et al., 2018).

2.2 The strategic importance of industrial energy management

The strategic importance of energy management has grown for three reasons. First, energy is a significant component of operating cost for many manufacturers; in non-energy-intensive SMEs the ratio of energy expenditure to turnover can already approach 1% (Cagno et al., 2018). Second, regulatory pressure has expanded: carbon pricing, emissions trading schemes and energy audits under directive frameworks have institutionalised the function (Cagno & Trianni, 2014; Stede, 2017). Third, the expectations of financial institutions, customers and supply chains increasingly link energy performance with access to capital, contract eligibility and reputational standing (Fuchs et al., 2020).

2.3 ISO 50001 as the central benchmark

ISO 50001, published in June 2011 by the International Organization for Standardization, has become the dominant reference model for energy management systems (Chiu et al., 2012; Fuchs et al., 2020). It specifies the requirements for establishing, implementing, maintaining and improving an EnMS, and is built on the Plan-Do-Check-Act cycle familiar

from quality and environmental management standards (Gallego et al., 2022; Hashim et al., 2022). Certified organisations have reported energy savings typically in the 10–30% range over multi-year horizons, alongside non-energy benefits such as improved maintenance, reduced emissions and enhanced safety (Fuchs et al., 2020). Importantly, ISO 50001 positions continuous improvement as a binding obligation: organisations must define an energy policy, conduct energy reviews, set measurable objectives, monitor performance, conduct management reviews and act on deviations (Gallego et al., 2022; Rotzek et al., 2018).

3. Methodology

The framework was developed through a structured review of the academic literature on industrial energy management. Searches were performed across peer-reviewed journals indexed in major academic databases, focusing on systematic reviews, empirical studies and conceptual contributions published between 2000 and 2025. Search terms combined "energy management", "energy efficiency", "industrial", "manufacturing", "ISO 50001", "PDCA", "energy performance indicators", "barriers", "drivers", "energy culture", "maturity models", "Industry 4.0" and "digitalisation".

Inclusion criteria required that sources (a) addressed industrial or manufacturing firms; (b) discussed energy management as an organisational, technical or strategic concept, not solely as a single technology; and (c) provided either empirical evidence, systematic synthesis or conceptual structures. Foundational systematic reviews provided conceptual elements and detailed activities (Schulze et al., 2015); studies on the ISO 50001 standard provided structural anchors (Chiu et al., 2012; Fuchs et al., 2020; Gallego et al., 2022; Mkhaimer et al., 2017); research on barriers and drivers provided the dimensions of the enabling context (Cagno & Trianni, 2014; Stede, 2017; Trianni et al., 2012, 2015; Vučković & Džunić, 2023); work on energy culture and top management commitment populated the organisational layer (Arinaitwe et al., 2023; May et al., 2015; Rotzek et al., 2018); maturity models provided measures of internal capability (Sa et al., 2017; Trianni et al., 2018); and studies on digital technologies and big data populated the data and analytics layer (C. & Ocampo-Martínez, 2019; Cagno et al., 2025; Ren et al., 2018; Shrouf & Miragliotta, 2015; Vikhorev et al., 2012; Zambetti et al., 2019; Zhang et al., 2018). Case studies grounded the framework in observed practice (Ats-Tsauri et al., 2022; Cagno et al., 2018; Ketenci & Wolf, 2024).

Synthesis followed a thematic-construct approach: recurring conceptual elements (objectives, content, structure, actors, practices, indicators, context) were extracted, mapped against the PDCA cycle, and progressively aggregated into a multi-layered framework. The framework was iteratively refined against the empirical literature for completeness, parsimony and construct validity.

4. Review of the Evidence Base

4.1 Energy management practices

Empirical research reports an extensive catalogue of practices that organisations use to manage energy. Trianni, Cagno, Bertolotti and others (Trianni et al., 2018) propose a taxonomy that distinguishes practice dimensions along three axes:

Type of energy efficiency improvement: direct practices that influence the energy flow (on the supply side or the demand side) versus indirect practices that shape contextual factors conducive to future action.

Target of the practice: internal stakeholders (firm-level, production processes, technology processes, ancillary processes, non-production processes) versus external stakeholders (suppliers, regulators, financial institutions, technology manufacturers, partners, customers).

Position in the industrial energy management setting: strategy/planning, implementation/operation, controlling, organisation, or culture.

Development stage: initial, testing, fully operational, or revision.

This taxonomy reveals that energy management encompasses far more than technology upgrades. Indeed, many of the most effective practices documented in case studies are indirect and organisational: awareness campaigns, internal energy teams, training programmes, integrated management system audits, and structured communication with employees (Rotzek et al., 2018; Schulze et al., 2015; Trianni et al., 2018).

4.2 The energy review and energy planning

At the core of the energy management process lies the energy review: a systematic assessment of energy sources, uses and consumption across the organisation (Gallego et al., 2022; Vikhorev et al., 2012). The energy review identifies sig-

nificant energy uses, establishes an energy baseline, determines energy performance indicators and uncovers opportunities for improvement (Hashim et al., 2022). Empirical evidence indicates that energy reviews are most effective when they combine top-down process mapping with bottom-up measurement, that EnPIs are calibrated to firm-specific production conditions, and that, even after iterative refinement, current measurement systems are frequently "inadequate for managing energy" at the operating-personnel level (Schulze et al., 2015).

The literature further distinguishes between (a) classical engineering audits focused on equipment, (b) process-integrated energy analysis aligned with mass and energy balances, and (c) big-data-driven analytical frameworks capable of handling heterogeneous, high-volume sensor data in real time (Vikhorev et al., 2012; Zambetti et al., 2019; Zhang et al., 2018).

4.3 Key performance indicators for energy

KPIs translate strategic energy objectives into operational signals. May, Barletta, Stahl and Taisch (May et al., 2015) argue that "absolute values and aggregated measures like energy consumption per year or per product fail to provide decision-making support, transparency and clear identification of action items." Their method generates firm-tailored e-KPIs across plant, line and equipment levels to identify energy drivers, expose cause-effect chains, prepare improvement actions and communicate status internally.

Bunse et al., cited in (Schulze et al., 2015), classify energy efficiency indicators as economic, physical, thermodynamic and hybrid, and argue that they should be defined at company, plant and—if necessary—process levels. Sivill et al., also cited in (Schulze et al., 2015), document that energy performance metrics in industry are too often "focused on departmental level, leaving out the sub-system and equipment levels." This mismatch between the granularity of available data and the granularity of decisions is one of the central operational problems the framework must address.

4.4 ISO 50001 and continuous improvement

ISO 50001 operationalises the PDCA cycle for energy (Gallego et al., 2022; Hashim et al., 2022). In the Plan phase, organisations establish energy policy, assign responsibilities, set objectives and targets, conduct energy reviews and define action plans. The Do phase involves implementing plans, delivering awareness and training, controlling operational processes and communicating outcomes. Check covers monitoring, measurement, analysis of energy performance, evaluation of compliance and corrective actions. Act comprises management review, recognition of achievements and feedback into future planning (Hashim et al., 2022). The same cycle is mirrored in derivative frameworks such as the Lean Six Sigma EnMS (LSS_EnMS), which embeds Define-Measure-Analyse-Improve-Control within the ISO 50001 structure to support systematic identification and exploitation of improvement opportunities (Mkhaimer et al., 2017).

Clean Energy Ministerial analyses of 72 certified case studies (Fuchs et al., 2020) identify the most frequently cited drivers as existing values and goals, environmental sustainability, and government incentives or regulations. Top benefits include cost savings, productivity and operational improvements, while the primary barrier is the absence of a culture of energy management. Obtaining and sustaining top management support emerges as a critical success factor.

4.5 Organisational drivers, culture and top management commitment

A growing body of evidence shows that the soft infrastructure of energy management is often more decisive than its technical infrastructure. Research on energy culture (Rotzek et al., 2018) demonstrates that normative beliefs, material practices and behavioural routines co-produce energy performance. Top management commitment has consistently been identified as a key driver: Blass et al., cited in (Schulze et al., 2015), show that involvement of top operations managers with a clearly operational role significantly increases the adoption of energy-efficiency initiatives, while the involvement of general top managers without operational anchoring has little effect. Arinaitwe, Bagire, Tukamuhabwa and others (Arinaitwe et al., 2023), analysing 66 Ugandan SMEs, decompose top management commitment into participation, support and beliefs, all of which significantly predict energy management, with beliefs exercising the strongest influence.

May, Stahl and Taisch (May et al., 2015) synthesise that "organizational barriers may refer to the firm's structure … the firm's culture and learning capacity as well as behavioral factors like values and attitudes." They further identify commitment of top management, long-term energy strategy and ambitious leadership as central organisational driving forces, together with a clearly communicated environmental strategy and managerial commitment.

Effective communication is itself a cultural lever. Christoffersen et al., cited in (Schulze et al., 2015), found that 44% of surveyed Danish industrial firms seek to actively involve employees through "passive" information channels such as notice boards, but that richer communication tools—monthly business meeting reports, monthly letters, internal websites and directed memos—are associated with stronger engagement (Schulze et al., 2015).

4.6 Barriers to energy management and energy efficiency investments

The "energy efficiency gap" stems from a layered set of barriers. Trianni, Cagno and Farné (Trianni et al., 2015), studying SMEs across manufacturing, identify seven categories—economic, informational, organisational, behavioural, competence-related, technology-related and awareness-related—and report that economic barriers dominate, with values consistently above 3 on a 4-point perception scale, while technology-related barriers are perceived as low (around 1.70). Within the foundry sector, barriers are compounded by organisational complexity and by the perception that resources must be devoted to guaranteeing business continuity, which downgrades energy efficiency to a peripheral issue (Cagno & Trianni, 2014; Trianni et al., 2012).

Stede (Stede, 2017) organises barriers relevant to the Italian industrial sector into three families:

Financial: short payback periods (firms typically adopt thresholds of 2–5 years, often stricter), limited access to capital, and reluctance of banks to lend against energy efficiency assets.

Informational/behavioural/institutional: imperfect information, low trustworthiness of sources, lack of skilled personnel, low priority of energy efficiency in decision-making (bounded rationality), and regulatory uncertainty.

External: market structure and policy framework.

Studies of energy efficiency investments consistently show that industrial firms adopt very short payback thresholds—often 2–3 years—even when internal rates of return are high. In Italy, surveys document thresholds between 2 and 3 years despite positive NPVs, with equity remaining the dominant financing route because banks are sceptical of energy efficiency projects (Chiaroni et al., 2016). The pulp and paper and foundry industries in Sweden report similar patterns, with most firms applying a three-year ceiling (Schulze et al., 2015). In developing-country projects analysed by Alcorta et al., cited in (Schulze et al., 2015), payback periods at project level range from 0.9 to 2.9 years, but these attractive metrics often fail to influence corporate decision-making.

Vučković and Džunić (2023) highlight that small and medium-sized firms without clear management responsibilities for energy efficiency invest less, and that the managerial-organisational factor has the largest direct effect on improvements in energy-intensive industries such as Indonesian steel.

4.7 Maturity models and assessment

Maturity models provide an operational bridge between qualitative practice catalogues and quantitative benchmarking. Trianni, Cagno, Bertolotti and others (Trianni et al., 2018) synthesise prior maturity models, identifying recurring patterns:

Ngai, Chau, Poon and To propose five maturity levels (initial, managed, defined, quantitatively managed, optimised) and four phases (practice establishment, practice standardisation, performance management, continuous improvement), all from an environmental-management perspective.

Antunes, Carreira and Mira da Silva derive five maturity levels following the PDCA cycle, aligned with ISO 50001 and CMMI practices, and explicitly map the challenges organisations face at each level.

Introna, Cesarotti, Benedetti, Biagiotti and Rotunno identify five levels (initial, occasional, planning, managerial, optimal) and five dimensions of success, with "awareness, knowledge and skills" identified as the most important.

Such models make explicit that maturity in energy management is not merely the adoption of more technologies but the progressive institutionalisation of practices across the PDCA cycle, supported by measurement capability and organisational learning.

4.8 Industry 4.0, data infrastructure and digitalisation

Industrial energy management is undergoing a structural transformation driven by the diffusion of IoT sensors, smart meters, cloud platforms and analytical tools. Shrouf and Miragliotta (Shrouf & Miragliotta, 2015) demonstrate that IoT-enabled energy management supports production-level decisions through real-time data acquisition, calibration and

visualisation, with applications ranging from new energy KPIs in trailer manufacturing to decentralised dashboards in food processing. Vikhorev, Greenough and Brown (Vikhorev et al., 2012) argue that the deep integration of factory floor and factory building requires standardisation of data collection, online data processing and visualisation techniques, and that the most significant energy consumers must be identified, monitored and analysed in real time to enable industrial energy efficiency.

Reference frameworks for energy data include (i) data standards that specify sampling period, precision, units and descriptions; (ii) on-line data processing, including event-based processing of heterogeneous sensor streams; and (iii) visualisation techniques that surface consumption patterns to plant personnel (Vikhorev et al., 2012).

Big data analytics extends this infrastructure. Zhang, Ma and Yang (Zhang et al., 2018), reporting on ball mills in a pulp workshop, document energy savings of 3% per month and energy cost savings of 4% within six months after deploying a big-data-driven framework. Ren, Zhang, Liu and others (Ren et al., 2018) argue that with continuous smart sensing across the lifecycle, "the energy waste problems in manufacturing enterprises … can be identified and quantified … and reduced or eliminated in real-time." Diaz and Ocampo-Martínez (C. & Ocampo-Martínez, 2019) propose IoT-enabled real-time monitoring combined with data envelopment analysis to detect abnormal energy patterns and quantify gaps.

The most recent integration is with the broader Industry 4.0 transformation. Cagno, Accordini, Thollander and others (Cagno et al., 2025) propose a Smart Factory framework that maps four clusters of I4.0 technologies (system, infrastructure, service, process) onto nine areas of impact on energy management practices, validating the model in two Swedish firms producing automotive components, heavy machinery and machine tool accessories. Internet of Things emerges as a critical enabler for real-time collection and analysis, while AI and big data analytics provide predictive capabilities, and simulation/virtual reality support process visualisation and design optimisation.

4.9 Sectoral and firm-size contingencies

The framework must accommodate the heterogeneity of industrial firms. Energy-intensive industries such as steel, chemicals, cement and pulp and paper face structurally different challenges from light manufacturing, food processing or electronics assembly. For steel, Ats-Tsauri, Wilarnugroho and Purba (Ats-Tsauri et al., 2022) adopt Soft Systems Methodology to derive a conceptual model that identifies actors, activities and inter-relationships in energy management, emphasising the value of soft systems thinking in fuzzy, multi-stakeholder situations. For energy-intensive industries broadly, Rebelo da Silva, Loures, Lima and others (Silva et al., 2019) develop a "Spider" conceptual map based on ISO 50001 and Business Process Management, clarifying the relationships between intra-organisational units and external stakeholders.

SMEs warrant particular attention because they account for a large share of industrial energy consumption but face resource constraints that amplify every barrier category. Ketenci and Wolf (Ketenci & Wolf, 2024) report a case-study framework for non-energy-intensive SMEs that combines greenhouse gas accounting with comprehensive energy flow analysis. Their two case studies yielded reductions of 900,000 kWh and 1,300,000 kWh respectively, corresponding to 16% and 22% energy cost drops at 2021 energy prices.

5. Toward an Integrative Conceptual Framework

5.1 Architectural principles

The framework developed in this paper rests on five architectural principles, each directly supported by the evidence reviewed in Section 4.

PDCA as temporal backbone. ISO 50001 and its derivatives operationalise energy management as a continuous-improvement cycle (Gallego et al., 2022; Hashim et al., 2022; Mkhaimer et al., 2017). The framework embeds every element in the cycle's phases.

Layered architecture. Energy management is simultaneously a strategic, organisational, operational and informational phenomenon. The framework explicitly separates these layers to avoid the conflation that has hampered prior conceptual work (Cagno & Trianni, 2014; Schulze et al., 2015).

Contextualisation. External drivers (policy, energy prices, market structure, supply chain pressure) and internal culture (beliefs, communication, leadership) jointly condition the achievable maturity. Leaving these as exogenous variables would reduce explanatory power (Rotzek et al., 2018; Stede, 2017; Trianni et al., 2015).

Information fluency. Energy-relevant data must flow from the shop floor, through operational systems, to managerial decision layers, and back to the shop floor as guidance; the framework treats this loop as a first-class element rather than an auxiliary capability (May et al., 2015; Vikhorev et al., 2012; Zhang et al., 2018).

Practice–metric coupling. Every meaningful practice should be paired with at least one measurable indicator and one owner; this principle operationalises the energy KPI literature (May et al., 2015; Schulze et al., 2015).

5.2 The framework: three domains and seven building blocks

The framework consists of three domains—the external context, the internal architecture and the practice portfolio—organised into seven building blocks connected by two cross-domain flows: the energy information flow and the performance feedback loop. Figure 1 (described textually below) depicts the integrated view.

Domain A — Enabling context

A1. External drivers and policy environment. Energy prices, climate and energy policy, carbon pricing, supply chain pressure and customer requirements condition the strategic motivation for energy management (Cagno & Trianni, 2014; Fuchs et al., 2020; Stede, 2017).

A2. Market and technological environment. Availability of energy-efficient technologies, BATs (best available techniques), digital solutions and external service providers shapes the feasible practice portfolio (Cagno et al., 2015, 2025).

Domain B — Internal architecture

B1. Strategy and policy. Long-term energy strategy and explicit energy policy aligned with corporate objectives, derived from ISO 50001 planning activities (Gallego et al., 2022; Sa et al., 2017).

B2. Organisational structure and governance. Defined roles, coordination mechanisms and spans of responsibility for energy-related decisions (May et al., 2015; Schulze et al., 2015).

B3. People and culture. Top management commitment, beliefs, communication routines, training programmes and the broader energy culture that supports distributed energy stewardship (Arinaitwe et al., 2023; Rotzek et al., 2018; Schulze et al., 2015).

Domain C — Practice portfolio and operations

C1. Energy review and planning activities. Energy baselines, identification of significant energy uses, EnPIs, target setting and action planning (Gallego et al., 2022; Hashim et al., 2022; Vikhorev et al., 2012).

C2. Implementation and operation. Execution of projects, operational control of significant energy uses, training programmes, motivation and awareness campaigns (May et al., 2015; Schulze et al., 2015; Trianni et al., 2018).

C3. Monitoring, checking and improvement. Measurement and verification, audits, management review, corrective and preventive actions (Fuchs et al., 2020; Hashim et al., 2022; Mkhaimer et al., 2017).

Cross-domain flows

Energy information flow. Connects shop-floor sensors, operational systems and decision-support platforms; powered by IoT, data analytics, e-KPIs and visualisation tools (Cagno et al., 2025; May et al., 2015; Shrouf & Miragliotta, 2015; Vikhorev et al., 2012; Zhang et al., 2018).

Performance feedback loop. Closes the PDCA cycle, feeding lessons from checking and acting back into strategy, organisation and planning.

5.3 Mapping practices to the framework

The framework accommodates the practice taxonomy of (Trianni et al., 2018) by positioning each practice according to (a) its target (internal vs external stakeholder), (b) its type (direct supply/demand vs indirect contextual) and (c) the framework block it primarily serves. Indirect practices targeting internal stakeholders and the organisational/cultural dimension populate block B3, while direct supply-side practices (e.g. combined heat and power, on-site renewables) and demand-side practices (e.g. equipment upgrades, process optimisation) populate C2. Practices aimed at external stakeholders—engaging suppliers on embodied energy, regulators in policy dialogue, financial institutions to unlock capital—span A1 and B1, mediating the boundary between external drivers and internal strategy (Stede, 2017; Trianni et al., 2018).

5.4 Maturity as a property of the framework

The maturity models reviewed in Section 4.7 can be reinterpreted within the proposed framework as a description of how filled each building block is and how robust the cross-domain flows are. At Level 1 (initial), organisations typically have some energy monitoring but no strategy, no defined KPIs and ad hoc responses. At Level 2 (managed), an energy policy, an energy manager and some practices exist, but information flows operate intermittently. At Level 3 (defined), KPIs are routinely calculated, training programmes are structured and external stakeholder engagement begins. At Level 4 (quantitatively managed), the information flow is near-real-time, big-data analytics support root-cause analysis, and PDCA loops are short. At Level 5 (optimising), predictive analytics, AI-assisted decision-making and proactive cultural reinforcement become standard features (Sa et al., 2017; Trianni et al., 2018).

5.5 Mapping to ISO 50001, Industry 4.0 and SME contexts

The framework is explicitly compatible with ISO 50001: block C1 corresponds to the "Plan" phase activities, block C2 to "Do", block C3 to "Check" and the closure into strategy and organisation corresponds to "Act". The framework's emphasis on information fluency positions it as a natural host for Industry 4.0 extensions: smart sensors and IoT platforms expand the energy information flow, while AI and big-data analytics strengthen the feedback loop and enable earlier detection of inefficiencies (Cagno et al., 2025; Shrouf & Miragliotta, 2015; Zambetti et al., 2019; Zhang et al., 2018). For SMEs, the framework allows a minimalist configuration—strategy (B1), review (C1), low-cost monitoring (cross-domain flow) and the actors who use it (B2, B3)—consistent with the practitioner frameworks documented by Ketenci and Wolf (Ketenci & Wolf, 2024) and validated in non-energy-intensive case studies.

5.6 Worked illustration: hypothetical deployment

Consider a mid-sized metal-forming firm pursuing an energy efficiency programme. The framework guides the work as follows. A1: rising electricity prices and supply-chain Scope 2 reporting requirements motivate the programme. A2: assessment of available technologies (e.g. variable-speed drives, heat recovery) and service providers (e.g.ESCOs, IoT vendors) defines the feasible set. B1: top management signs an energy policy, sets a 10% reduction target over three years and reorients capital allocation to align with this target. B2: a part-time Energy Manager, supported by a cross-functional team, is appointed. B3: a communication plan combining shift-level briefings, monthly dashboards and a recognition scheme is rolled out to address cultural barriers. C1: an energy review identifies SEUs (compressor network, heat-treatment line, HVAC), establishes baselines and defines EnPIs (kWh/tonne). C2: investments in variable-speed drives, compressed-air leak reduction and an operator-led switch-off campaign are implemented. C3: IoT metering at major loads enables daily e-KPI tracking; monthly management review evaluates deviations and triggers corrective actions. The information flow yields actionable insights (e.g. off-hour peaks revealed by dashboards), and the feedback loop updates strategy (e.g. tighter controls after night-shift deviations). This configuration corresponds to a Level 3 maturity and represents a realistic three-year trajectory consistent with reported SME outcomes (Ketenci & Wolf, 2024).

6. Discussion

6.1 Theoretical contributions

The framework contributes to theory in three respects. First, it integrates previously parallel research streams—techno-economic, organisational-behavioural, digital and maturity-assessment—into a single architecture, responding to the explicit call in the literature for "integrative" and "holistic" treatments (Batouta et al., 2023; Cagno et al., 2025; Cagno & Trianni, 2014). Second, by locating practices, indicators, culture and information infrastructure on the same canvas, the framework makes the interdependencies between them analytically tractable: changes in B3 (culture) influence the realised benefit of investments in C2 (operations), and the strength of the cross-domain information flow mediates that relationship (May et al., 2015; Zhang et al., 2018). Third, the PDCA backbone preserves compatibility with ISO 50001 and its derivatives (Gallego et al., 2022; Hashim et al., 2022; Mkhaimer et al., 2017), making the framework directly translatable into practitioner languages.

6.2 Implications for practice

For practitioners, the framework carries four implications.

Diagnose before you invest. Block C1 must be functional before costly C2 investments are made; otherwise the firm cannot measure the savings it is seeking (May et al., 2015; Vikhorev et al., 2012).

Treat culture as a primary asset, not a by-product. Cultural development in block B3 has a higher expected return in early maturity stages than additional technology investment (Arinaitwe et al., 2023; Rotzek et al., 2018).

Plan for the information flow, not just the sensors. Digitalisation efforts that collect data without protocolled pathways to decisions will underperform (Cagno et al., 2025; Shrouf & Miragliotta, 2015).

Sequence investment to the firm's maturity. Mismatches—as when SMEs acquire AI tools before establishing roles, baselines or KPIs—end in abandoned projects (Guo et al., 2022; Ketenci & Wolf, 2024).

6.3 Implications for policy

For policymakers, the framework reframes the energy efficiency gap. If the binding constraints on industrial energy performance are organisational and informational rather than technological, then policy support should target capability building: subsidising EnMS implementation along ISO 50001 lines, funding energy manager training, supporting e-KPI development and lowering barriers to external financing (Cagno & Trianni, 2014; Stede, 2017). In this sense the broadly observed under-implementation of profitable EEMs is as much a governance gap as an economics gap.

6.4 Limitations and future research

Three limitations should be acknowledged. First, the framework is conceptual and grounded in literature synthesis rather than empirical hypothesis testing; subsequent research should validate its structure through survey-based structural equation modelling or system dynamics. Second, although the framework is developed to be sector-agnostic, some blocks (notably C2 and the granularity of A2) will have very different content in energy-intensive versus light manufacturing, and contingencies require quantitative sector studies. Third, the role of emerging digital tools—generative AI for energy knowledge management, edge AI for shop-floor optimisation—remains insufficiently captured in the empirical literature and will require framework updates. Promising directions include quantifying cross-domain information elasticity (the marginal improvement in C3 outcomes from additional investment in the information flow), applying the framework in longitudinal impact evaluations of ISO 50001 implementations, and extending it to assess how blockchain-enabled energy attribute tracking reshapes the A1–B1 interface.

7. Conclusions

Industrial energy management has matured into a multi-dimensional discipline in which technological, organisational, cultural and informational dimensions interact. Despite the richness of the empirical literature, conceptual integration has lagged behind empirical accumulation. This paper has presented an integrative conceptual framework that organises the evidence around three domains—enabling context, internal architecture, and practice portfolio—embedded in the PDCA cycle and bound together by an energy information flow and a performance feedback loop.

The framework delivers three core messages. First, energy efficiency is governed as much by soft infrastructure (strategy, organisation, culture) as by hardware (technologies, meters), and this is consistent with the seven-category barrier taxonomy that has emerged across multiple empirical studies. Second, ISO 50001 remains the dominant normative architecture, but when complemented with e-KPIs, maturity diagnostics and Industry 4.0 digital infrastructure it can support a continuous improvement trajectory up to predictive, optimising levels. Third, the recurring shortfall between economically attractive and actually implemented energy efficiency projects can be reframed as a governance gap, and addressing it requires deliberate framework-aware capability building rather than technology-only interventions.

For researchers, the framework supplies a common analytical lens for future studies; for practitioners, it provides a planning scaffold for energy programmes; and for policymakers, it clarifies where capability-building investments are likely to yield the largest returns. The persistence of the energy efficiency gap, despite decades of effort, suggests that the next generation of progress will depend less on discovering new technologies and more on building the organisational and informational scaffolding that allows existing technologies to be deployed, measured, learned from and improved upon. The framework proposed here is offered as one step in that direction..

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