Energy Cost Accounting:

Linking Literature, Organizational Practice, and Carbon Emissions

Zur Erlangung des akademischen Grades eines
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Introduction

Energy is indispensable to organizational activity, but it is rarely valuable in itself. Rather, organizations require energy because it enables production processes, services, infrastructure, and products (Davis et al., 2018). This makes energy an unusual object of accounting. It is simultaneously a physical input, a cost driver, an operational constraint, and a source of environmental impact. As organizations face energy price volatility, changing procurement arrangements, decarbonization pressures, and expanding reporting requirements, it becomes increasingly important to understand how energy is measured, allocated and used in decision-making. Accounting research has long emphasized that environmental issues create demands for new information flows (Hopwood, 2009), while environmental management accounting highlights the relevance of integrating physical and monetary information for managerial purposes (Burritt et al., 2002, 2021). This doctoral thesis is situated at this intersection and examines how accounting systems can better capture energy consumption, energy costs, and electricity-related carbon emissions in organizations.

The central concern of this thesis is not energy management in a technical engineering sense, but the accounting problem of making energy-related consequences visible, attributable, comparable, and actionable. Energy cost accounting can be understood as a partial cost accounting concept designed to support decisions on energy efficiency, internal generation, and cost control by providing information on energy consumption, losses, and performance (Bierer and Götze, 2012). Such information can direct managerial attention, support problem-solving, and enable scorekeeping for energy-related objectives (Burritt et al., 2021). Yet, energy costs are often treated as overhead or period expenses rather than being systematically traced or allocated to cost centers, products, services, or activities (Aflaki et al., 2013; Mickovic and Wouters, 2020). This may suffice for financial reporting or rough budgeting, but limits decision-usefulness for operations, energy efficiency, investment appraisal, procurement, and accountability.

The literature offers several conceptual starting points. Conventional energy cost accounting differentiates energy costs by cost types, cost centers, and cost objects (Bierer and Götze, 2012). Material flow cost accounting (MFCA) and related approaches connect physical and monetary flows to make inefficiencies, losses, and unintended outputs visible (Christ and Burritt, 2015; Walz and Guenther, 2021). Material and energy flow cost accounting (MEFCA) extends this logic to energy flows and losses (Bierer and Götze, 2012; Burritt et al., 2021;

Sygulla et al., 2014), while input-output-based approaches point to indirect energy costs embedded in processes and overhead structures (Kaltenegger et al., 2017). However, empirical research on organizational energy practices remains fragmented, especially regarding how organizations measure, allocate, and use energy-related information in managerial decision-making (Mickovic and Wouters, 2020; Schulze et al., 2016). Existing studies often emphasize energy efficiency, audits, or technical energy management practices (Andersson and Thollander, 2019; Bunse et al., 2011; Thollander and Ottosson, 2010; Trianni et al., 2013), while the accounting dimension is underdeveloped. Consequently, the accounting treatment of energy is still insufficiently understood.

This accounting problem is intensified by the fact that energy is not a homogeneous accounting object. Different energy carriers and sources pose different measurement and allocation problems. Fuels such as diesel, heating oil, or gas can often be purchased, stored, and consumed in ways that resemble material inputs, whereas electricity is a flow-like input that must be consumed when it is generated and is measured and billed over time (Kirschen and Strbac, 2004). Its price can fluctuate with market conditions, demand patterns, and the electricity generation mix (Blizniukova et al., 2023; Cludius et al., 2014; Lu and Suthaharan, 2023; Wang et al., 2024; Wozabal et al., 2016), while its carbon intensity varies with the grid mix (Aboumahboub et al., 2012; Blizniukova et al., 2023; Schaber et al., 2012). Therefore, conventional cost accounting assumptions of input homogeneity, price stability, and time-independent cost assignment (Bhimani et al., 2015; Drury, 2018; Horngren et al., 2012) are challenged by energy and especially electricity. Energy cost accounting is also linked to carbon accounting, because purchased electricity, steam, heat, and cooling are reported as Scope 2 emissions under the Greenhouse Gas Protocol (2004). Carbon accounting research has examined emissions trading (Chen et al., 2021), carbon management (Ascui and Lovell, 2012; Kolk et al., 2008), effects of carbon footprints on decision-making (Beyer et al., 2024) and novel frameworks for handling carbon emissions (Easton et al., 2025; Kaplan and Ramanna, 2021; Letmathe, 2025; Penman, 2025; Reichelstein, 2024, 2025). Yet, conventional Scope 2 accounting often relies on aggregated emission factors or contractual instruments and does not fully reflect the timing of electricity consumption (Brander et al., 2018; Glenk, 2024; Stachelscheid and Dutzi, 2025). This limits the ability of accounting information to show when electricity consumption creates higher or lower costs and emissions.

This thesis addresses these gaps by placing energy cost accounting within management accounting and contingency theory. Management accounting research argues that accounting systems should not be evaluated independently of their organizational context. Contingency theory rejects the idea of a universally appropriate accounting system and instead emphasizes that system design and usefulness depend on contextual conditions (Chenhall, 2003; Gordon and Miller, 1976; Hayes, 1977; Otley, 1980, 2016; Waterhouse and Tiessen, 1978). Accounting systems differ in characteristics that affect how information can support managerial work (Bouwens and Abernethy, 2000; Chenhall and Morris, 1986; Gordon and Narayanan, 1984; Hall, 2010). Energy cost accounting is well suited to this perspective because its relevance and required sophistication differ across organizations. Where energy is strategically material and prices are volatile, highly aggregated energy cost information may obscure relevant decision signals. Where energy costs are immaterial or operations are rigid, the same granularity may be costly without being useful. Thus, the central issue is not whether organizations should always maximize the granularity of energy cost accounting, but how accounting systems can be designed so that energy-related information fits the economic, environmental, and organizational conditions under which it is used.

This contingent understanding structures the three complementary chapters of this thesis, which move from literature synthesis to empirical explanation and analytical improvement. The first chapter asks what is known about corporate energy practices. The second chapter asks how energy cost accounting systems are designed and used in organizational practice. The third chapter asks how temporally granular electricity cost and carbon information can be incorporated into accounting systems and what consequences such granularity has for decision-usefulness.

Taken together, the three chapters make four overarching contributions. First, the thesis contributes to the conceptualization of energy cost accounting by showing that it should not be reduced to the technical allocation of utility invoices. Rather, energy cost accounting comprises a broader set of practices through which organizations connect energy quantities, energy costs, operational activities, investment decisions, and environmental consequences. Second, the thesis contributes to empirical knowledge on corporate energy practices by combining a systematic literature review with qualitative field evidence. This shifts the discussion from normative claims about how energy should ideally be accounted for to an empirically grounded understanding of how organizations make energy cost information workable. Third, the thesis contributes to contingency-based accounting research by showing that energy cost accounting systems vary because organizations face different information problems and possess different capacities to address them. Importantly, the thesis does not equate better accounting with more detail. Instead, it shows that the usefulness of energy cost accounting depends on fit, as information must be sufficiently granular, timely, trusted, integrated, and actionable for the decision problems at hand. Fourth, the thesis contributes to carbon accounting and sustainability-related management accounting by showing how electricity-related carbon information can be linked to energy cost accounting. The energy cost and carbon accounting model demonstrates how temporally granular cost and carbon information can provide a more decision-useful basis for understanding the consequences of electricity consumption, thereby connecting internal decision-making and carbon accounting in a setting where the boundaries between disclosure-oriented reporting and internal carbon management are increasingly blurred (Jona and Soderstrom, 2023).

Methodologically, the thesis combines three complementary approaches. The systematic literature review synthesizes dispersed knowledge and identifies research gaps, following the logic that literature reviews can consolidate fragmented research and guide future scholarly and practical developments (Snyder, 2019; Tranfield et al., 2003). The qualitative field study uses cross-functional workshops to examine energy cost accounting as an organizational practice, consistent with the role of qualitative field research in understanding accounting practices in context (Ahrens and Chapman, 2006; Vaivio, 2008). The analytical simulation study formalizes and tests the implications of temporal granularity, drawing on the value of simulations for examining cost system design under conditions that are difficult to observe or manipulate empirically (Anand et al., 2019; Balakrishnan et al., 2011; Labro, 2015). This methodological combination allows the thesis to address energy cost accounting conceptually, empirically, and analytically.

The remainder of the doctoral thesis is structured as follows. Chapter 1 *How do companies manage energy? A systematic literature review on energy cost accounting, energy efficiency, and energy management,* presents the systematic literature review. Chapter 2, Energy cost accounting in practice: *A qualitative study of selective and contingent system design*, presents the qualitative empirical study. Chapter 3, *Better together: Temporal granularity of energy costs and carbon accounting*, develops and simulates the energy cost and carbon accounting model. The final chapter provides a summary of the doctoral thesis.

1. How Do Companies Manage Energy? A Systematic Literature Review on Energy Cost Accounting, Energy Efficiency, and Energy Management

Abstract[1]

It is imperative to recognize the indispensable role energy plays in sustaining business operations. Nevertheless, energy and topics associated with energy are often neglected, despite the crucial nature of information on energy consumption for the needs of managers in decision-making and the act of managing a company. As energy and its application are interdisciplinary topics, information is scattered throughout the literature. Consequently, the absence of a comprehensive study systematically collecting, describing and analyzing the current state of knowledge is striking. To address this deficiency, this systematic literature review synthesizes information from 39 papers published in 19 journals. The extracted contents of the papers were categorized, summarized, and analyzed according to their contribution toward first and second stage allocation of energy costs, energy measurement, energy efficiency, energy strategy, and energy-related investment decisions. The results of the study indicate a significant research gap in empirical investigations. The interdisciplinarity of the investigated topics leads to scattered information and frameworks for a structured analysis of corporate energy cost practices are lacking. To address this gap, this paper develops a framework for the collection of information on corporate energy practices based on the findings. This article puts forth the proposition that empirical investigations of corporate energy practices warrant scholarly attention. Such empirical studies need to find out what practice is doing, as the depth of the current state of literature is inadequate.

KEYWORDS: *energy cost accounting, energy efficiency, energy management, energy information, systematic literature review*

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1.1. Introduction

"People do not want energy itself, but rather the services that energy provides and the products that rely on these services" (Davis et al., 2018, p. 1). In their innovative study on future net-zero emissions energy systems, Davis et al. (2018) outline the importance of the often implicit relevance of accounting for and managing energy to achieve more sustainable corporate practices. This special relationship between sustainable corporate practices, carbon emissions, energy costs, and energy management emphasizes that interdisciplinary approaches are necessary to tackle these topics. Research on these topics is dispersed across various streams in the literature, however. The key to this literature review is to bring together complementary insights from various disciplines. Energy management requires data that builds on energy cost accounting, which captures the financial dimension of energy efficiency.

One pillar of this systematic literature review is *energy cost accounting*. For environmental management purposes, information on energy and its association with costs and products are of particular relevance in both the short- and long-term perspective (Burritt et al., 2023). To address these purposes, energy cost accounting information can be considered relevant to three different needs of managers (Burritt et al., 2021; Hall, 2010; Simon, 1987): attention directing, problem-solving, and scorekeeping. Information on energy consumption and energy costs draws management attention to opportunities and problems, provides information about potential solutions, and informs about whether the company is moving in the right direction or not (Burritt et al., 2021). To tackle this information need, the literature covers straightforward (conventional) energy cost accounting approaches on the one hand (Bierer and Götze, 2012). On the other hand, methods like Material Flow Cost Accounting (MFCA) (Bierer and Götze, 2012; Sygulla et al., 2011) enlighten additional perspectives. Most often, significant energy costs are part of the overhead cost and hence, recorded as indirect costs (Kaltenegger et al., 2017), leaving energy as a large unmanaged potential (Zolkowski and Nichols, 2013). A central topic for energy cost accounting is the allocation of energy costs to cost centers (1st stage allocation) and cost objects (2nd stage allocation). This allocation can be observed on several allocation bases, mainly addressing organizational considerations (Backlund et al., 2012a) or physical circumstances (Backlund et al., 2012a; Brunke et al., 2014). While several contributions to the literature describe 1st stage energy cost allocation (Fernandes et al., 1997; Kannan and Boie, 2003; Ozturk, 2005; Tunc et al., 2016), 2nd stage allocation is underdeveloped (Mickovic and Wouters, 2020). However, allocating consumed energy is never as accurate as a correct measurement. Such energy measurements are often done in a rather simple manner by utility companies and other suppliers for invoicing purposes (Mickovic and Wouters, 2020). Nevertheless, more or less sophisticated approaches to sub-metering are described (Bunse et al., 2011; Christoffersen et al., 2006; Dobes, 2013; Rohdin and Thollander, 2006).

As the second pillar, this review investigates *energy efficiency*. The usage of energy in a comparable and measurable way is needed, so improvements in energy efficiency practice are quantifiable. Energy efficiency has been investigated in different settings and industries (Thollander et al., 2013; Trianni et al., 2013; Venmans, 2014; Worrell et al., 2009). This was often explored in the form of case studies, which either focus on one specific industry (Aflaki et al., 2013; Thollander et al., 2013; Trianni et al., 2013) or cover several industries (Apeaning and Thollander, 2013; Venmans, 2014; Worrell et al., 2009). Moreover, drivers and barriers to energy efficiency have been investigated and described (De Groot et al., 2001; Fleiter et al., 2011; Palm and Thollander, 2010; Sorrell et al., 1999; Thollander et al., 2013; Thollander and Ottosson, 2008). Furthermore, the literature provides significant advances for measuring energy efficiency through metrics (Abeelen et al., 2019; Bosseboeuf et al., 1997; Boyd et al., 2008; Boyd and Pang, 2000; Eichhammer and Mannsbart, 1997; May et al., 2015; Menghi et al., 2019; Phylipsen et al., 1997). For a systematic and sustainable implementation of energy efficiency metrics, a long-term energy strategy is a necessity (Gordić et al., 2010; Rudberg et al., 2013). The incorporation of energy strategies is the subject of investigation in the literature (Backlund et al., 2012a; Hildreth and Oh, 2014; Johansson, 2015; Rohdin and Thollander, 2006). Nevertheless, in prior studies (Brunke et al., 2014; Thollander and Ottosson, 2010) even companies in energy-intense industries did not always have an energy strategy.

The third pillar of this review is *energy management*, which generally aims to improve the handling of energy in companies toward a more efficient and ecological usage of energy without neglecting productivity. Around this topic, a body of literature (e.g., Ates and Durakbasa, 2012; Jalo et al., 2021a; Muller et al., 2007; Shrouf et al., 2017; Sivill et al., 2013) has developed. The application of energy management to manufacturing systems promotes energy savings (An et al., 2022). Subsequently, energy-related investment decisions are crucial for ensuring such sustainable growth. Hence, the question of how to assess and compare different investment opportunities arises. The literature knows about straightforward methods like payback time (DeCanio and Watkins, 1998; Johansson, 2015; Venmans, 2014), but also more sophisticated approaches like the internal rate of return (Brunke et al., 2014; Thollander et al., 2015) or net present value (Bunse et al., 2011; Sandberg and Söderström, 2003).

Given the diversity of approaches identified across these three pillars, this review draws on contingency theory (Cadez and Guilding, 2008; Chenhall, 2003; Covaleski et al., 1996; Hayes, 1977; Otley, 1980, 2016; Tiessen and Waterhouse, 1983; Waterhouse and Tiessen, 1978) from the management accounting literature to conceptually frame this variation. Contingency theory states that the design and effectiveness of management accounting systems depend on contextual factors like industry, organizational structure, regulatory environment, and technological infrastructure. This appears to be a valid assumption for our context of corporate energy practices and may explain differences between organizations and sectors. While this review does not apply contingency theory empirically, acknowledging its relevance helps to interpret the scattered empirical findings, it maps this review into the literature, and supports more targeted recommendations for future research.

Although prior research significantly increased the knowledge of companies' energy management practices and energy cost accounting information availability, several aspects are still not addressed sufficiently. For instance, the question arises, which impact technological innovations (such as the internet of things or artificial intelligence) in the past few years, have on energy cost accounting, energy metering, or energy management more broadly. In addition, while studies often investigate the underlying phenomena in (sector-)specific settings, a comprehensive investigation without restrictions to certain areas, which enables the identification of clear patterns, is still missing. Moreover, only little is known about energy-related investment decisions and how information on energy costs is utilized for that purpose. Subsequently, a comprehensive overview of energy cost accounting, energy efficiency, and energy management in practice is lacking, calling for a systematic literature review.

This review fills this gap by systematically reviewing studies from a wide range of literature, synthesizing information on how companies allocate, measure, assess, or more broadly quantify energy costs and energy efficiency. The objectives of this systematic literature review are threefold: First, to systematically synthesize empirical findings on corporate energy practices regarding energy cost accounting, energy efficiency, and energy management. Second, to critically evaluate existing methodologies, metrics and frameworks.

Third, to identify and clarify gaps in the literature that future research should address. This systematic literature review fulfills these objectives, as it consolidates and critically evaluates the current state of knowledge and identifies key trends, methodologies, and research gaps. Further, systematic literature reviews analyze and synthesize existing contributions, delivering clear and conclusive insights for future research and managerial practice (Denyer and Tranfield, 2009). Moreover, literature reviews synthesize knowledge that can foster advancements in practice and policymaking to address societal challenges (Kunisch et al., 2023). Hence, the insights of this review contribute to a deeper understanding of organizations' approaches toward the management of energy and its associated costs. Additionally, this study investigates how investments in energy and energy efficiency are assessed and how energy strategies are incorporated. For this purpose, the review is guided by the following research questions:

RQ 1: "What is known in the literature on empirical investigations on energy management and energy cost accounting?"

RQ 2: "What is known in the literature on methodologies and concepts of energy cost accounting in industry and manufacturing environments?"

This paper presents a systematic literature review of empirical studies on energy cost accounting, energy efficiency, and energy management in manufacturing companies. Two reviews conducted previously are most closely related to this review. The review by Mickovic and Wouters (2020) highlights limited empirical research, insufficient detail on energy costs measurement and allocation, and a lack of cost information. Further, the review by Schulze et al. (2016) emphasizes key elements of energy management, suggest future research for this evolving research field, and criticize a shortage of company-level studies. Both Mickovic and Wouters (2020) and Schulze et al. (2016) summarize research in the fields of energy management, energy cost accounting, or more broadly, companies' energy practices. However, the review at hand is more than an update as it extends the discussion in several directions. Besides the difference in the investigated timeframe, the focus of the previous reviews differ from this as they have a single focus on either energy cost information (Mickovic and Wouters, 2020) or energy management (Schulze et al., 2016), while this review combines both fields alongside additional facets to gather a comprehensive overview of corporate energy practices. Moreover, this review is the first to systematically combine the topics of energy measurement, energy cost allocation, energy efficiency, energy strategies, and energy-related investment decisions. Hence, presenting this comprehensive overview provides in-depth information for practitioners, policymakers and scholars.

This review contributes to the literature in several ways: Firstly, it provides an overview of the latest developments in the literature. The results lay the foundation for future research or change in organizational settings by providing information on what companies are doing in practice and hence, best practices are identified. Secondly, this review is the first to tackle the topics of energy efficiency and energy efficiency metrics in detail without focusing on narrow industries (Bernabé-Custodio et al., 2023; Lawrence et al., 2018; Schulze et al., 2018) or sectors (Cunha et al., 2020; Schützenhofer, 2021; Trianni et al., 2021). This provides an understanding of how metrics are defined, measured, and applied. Furthermore, it ensures consistency and comparability toward energy efficiency metrics for practitioners and may lay the foundation for developing more robust energy efficiency metrics in the future, which will improve energy efficiency assessment. Thirdly, the results of this review point out avenues for future research. For instance, no paper in the sample provided information on energy cost centers, even though they have been described and applied in prior literature (Bierer and Götze, 2012; Dobes, 2013; Sucic et al., 2016). Moreover, while not excluding them by design, there were no papers in the final sample that specifically investigated corporate energy practices in the North American or Australian continent, although these are areas of interest for energy topics in the corporate context. This geographic bias in the sample of papers may affect the generalizability of this review's findings. However, this absence does not automatically indicate a lack of researchers' interest as it also could be linked to a certain maturity as there are papers investigating these areas prior to the timely scope of this review (Beecroft, 2007; Blass et al., 2014; Fernandes et al., 1997; Hildreth and Oh, 2014; e.g., Zolkowski and Nichols, 2013). Nevertheless, future research should address these geographical areas specifically. Additionally, there are still not enough studies describing energy cost allocation practices, energy measurement, or energy strategies in detail, providing opportunities for future research. Fourthly, this review highlights the absence of a comprehensive framework for systematically and clearly detailing and describing a company's energy practices. This lack of clarity hinders reliable comparisons between companies and complicates effective benchmarking, which subsequently impedes a sustainable improvement of a company's energy efficiency.

The systematic literature review is structured as follows: Section 1.2 outlines the methodological approach for constructing the sample of papers, including search strategy, selection criteria and the framework for the analysis. Section 1.3 synthesizes empirical findings from the sample of papers, focusing on energy cost center, energy cost allocation, energy cost measurement, energy efficiency, energy strategy, and energy-related investment decisions. Section 1.4 discusses these findings and maps them to the literature. Finally, section 1.5 concludes and provides specific recommendations for future research.

1.2. Research Method

This paper performs a systematic literature review following the guidelines of Tranfield et al. (2003), which involves a structured and replicable process to identify, evaluate, and synthesize relevant publications on energy cost accounting, energy efficiency, and energy management. The research is building on prior reviews by Mickovic and Wouters (2020) and Schulze et al. (2016), but is more than a simple update. First, this section describes the method for identifying and selecting sample of papers, while subsequently introducing the content analysis.

1.2.1. Constructing the sample of papers

The search is conducted using an adequate search string that includes combinations of terms related to energy cost accounting, energy efficiency, and energy management, which is summarized in Figure 1-1. The databases *Scopus* and *Web of Science* are used for this literature search. The final search terms include "*energy measur**", "*energy management*", "*energy metering*", "*cost accounting*" in the title and "*industry*", "*manufacturing*", "*empirical*", and "*energy cost accounting*" in the title, abstract, or keywords. The asterisk (*) is used to include different variants of the word stem "*measur*", such as measuring, measurement(s), or measure. The search was limited to articles and reviews, as this systematic literature review focuses on the current state of empirical information on corporate energy practices in peer-reviewed academic literature. Consequently, gray literature such as books or reports, though potentially informative, is outside the scope. To capture the dynamic landscape of new developments, the review includes publications since 2018, covering the period after the most recent review by Mickovic and Wouters (Mickovic and Wouters, 2020). This allows us to assess how previously identified research gaps and limitations have been addressed and whether they remain relevant. There is no limit for the search process to specific journals as results from a vast amount of research areas are relevant. Concluding, the specific search string is defined as follows: *((TITLE (energy measur*) OR TITLE (energy management) OR TITLE (energy metering) OR TITLE (cost accounting)) AND (TITLE-ABS-KEY (industry) OR TITLE-ABS-KEY (manufacturing) OR TITLE-ABS-KEY (empirical*) OR TITLE-ABS-KEY (energy cost accounting)) AND (DOCTYPE (ar OR re)) AND (PUBYEAR > 2017) AND (LIMIT-TO (LANGUAGE, "English")))*. This search string is run on both databases with minor (technical) adjustments due to the different search engines and yielded 1,430 publications in *Scopus* and 1,064 publications in *Web of Science*. As indicated in Figure 1-2, this leads to 2,494 publications in total.

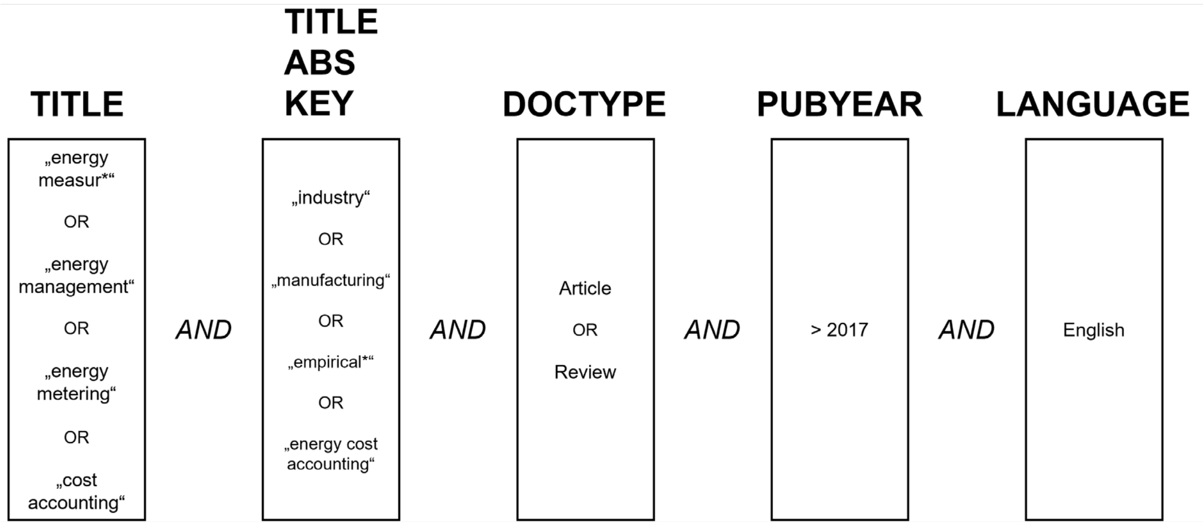

Figure 1-1: Construction of the search string for the systematic literature review

This literature review follows the steps proposed by Tranfield et al. (2003) and is illustrated in Figure 1-2. After removing duplicates using an Excel query and the DOI as primary key, 1,495 papers remain. All subsequent steps were performed manually. In the next step, the title analysis, 1,199 papers are removed, which results in 296 papers. A huge share of papers are excluded as they for example, deal with very technical topics like batteries in electric vehicles (e.g., Altun and Kutlar, 2024), topics concerning energy grids (e.g., Rezaei et al., 2024), or topics associated with natural science like biology (e.g., Wolaver et al., 2018). 105 papers remain after the abstract-keyword analysis, which marks the next step of the systematic literature review. This reduction happens after eliminating papers focusing on a country-level instead of a company-level point of view (e.g., Lu et al., 2019), theoretical considerations or frameworks that are not applied in industry or a manufacturing environment (e.g., Choi, 2021), or topics being more about technical aspects of energy (for example, its generation) (e.g., Chong et al., 2024). After the penultimate step, the full-textual analysis, 37 papers remain. Papers are excluded as they do not provide relevant information on a company level, although they initially seemed promising (e.g., Marchi et al., 2022; Rzazade et al., 2023), focus on the description of methods without an empirical component sufficient enough for the scope (e.g., Bleyl et al., 2024), or simply do not match the focus of this review as they, for example, deal with things like energy efficiency metrics in the public sector (e.g., Mulyaningsih et al., 2024). Additionally, by evaluating the references (backward) and using Google Scholar to identify more recent publications citing a specific paper (forward), 2 additional papers are included, which leads to the final set of 39 papers, displayed in Figure 1-2.

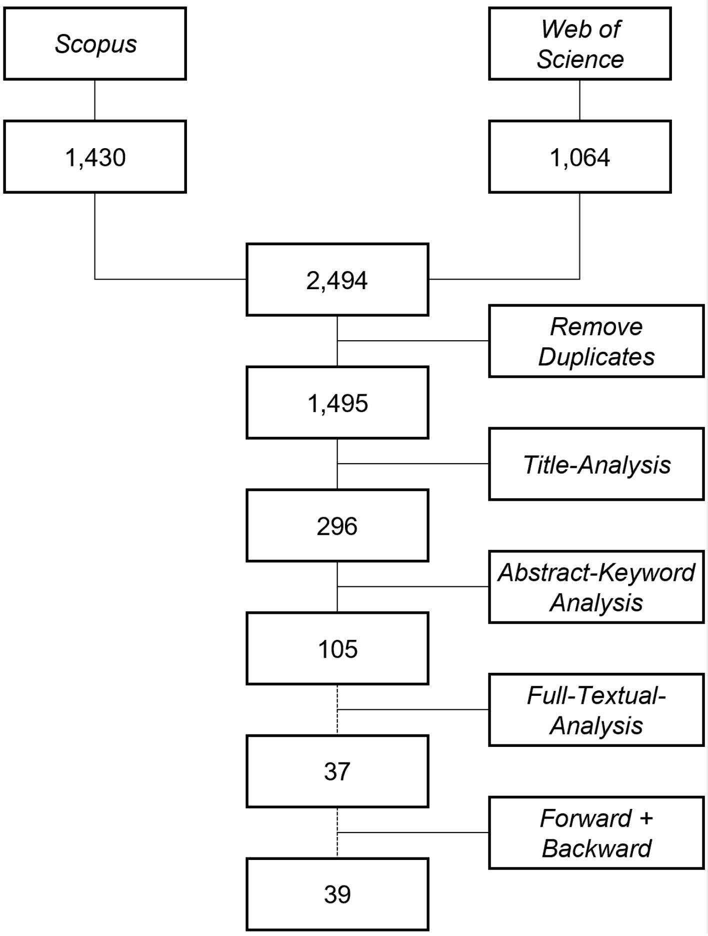

Figure 1-2: Literature search process for the systematic literature review using Elsevier's Scopus database and Web of Science

1.2.2. Content analysis

In the next step, the content of the final set of 39 papers is analyzed. Table 1-1 shows the attributes defined for the investigation, while Table 1-2 provides a detailed description of these attributes. The attributes concern characteristics of the company investigated in the paper, as well as the corresponding energy cost accounting, energy efficiency, and energy management practices.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions
		[O] Description of energy cost center													
		[P] Description of allocation of energy costs													
		[Q] Description of energy measurement													
		[R] Description of energy efficiency													
		[S] Description of energy strategy													
		[T] Description of investment and criteria													
		[U] Description of application of Specific Energy Consumption (SEC)													
		[V] Summary of quantitative information on energy costs													

Table 1-1: Literature review table

Attribute	Description
Research Method	The research methodology applied in the paper.
# of Companies	The number of companies investigated in the empirical analysis of the paper.
Industry	The industry in which the focal company/companies is/are operating.
Company Size	The size of the focal company/companies investigated.
Energy Intensity	An economic indicator of whether energy consumption and its corresponding costs are critical for a company or not.
Energy Mix	The composition of the mix of energy sources and energy carriers used by the focal company/companies.
Energy Cost Center	A cost center that is specifically established to manage tasks like energy generation and/or supply for other cost centers.
1st Stage Allocation	The allocation of energy costs from a central point of measurement (i.e. invoice) to cost centers using a specified allocation base.
2nd Stage Allocation	The allocation of energy costs from cost centers to final cost objects (i.e. products or services) using a specified allocation base.
Measurement of Energy	The practice of quantifying and tracking energy consumption and its corresponding energy costs based on direct measurements.
Energy Audit	The systematic assessment of energy use within a company, aimed at identifying inefficiencies and opportunities for improvement.
Energy Efficiency	The systematic reduction of energy consumption relative to the output, represented through metrics.
Energy Strategy	The development and articulation of specific targets and actionable plans for improving energy efficiency and energy management.
Investment Decisions	Investment decisions related to capital expenditures aimed at reducing energy consumption (i.e., improving energy efficiency through the purchase of a new machine) and criteria and evaluation methods used for assessing these investment decisions.

Table 1-2: Description of attributes used in the literature review table and analysis

The extensive literature review table consists of 22 different attributes covering three domains and bibliographical data. This table provides all available information on each paper of the sample and can be found in the appendix. It aims to suit various readers with different information needs by presenting information in the three different domains. These three domains deal with descriptive information, categorized information, and detailed information. For instance, readers striving for a fast overview of their particular field of interest could use the categorized information, which is also summarized in the condensed Table 1-5 at the end of section 1.3.1. On the other hand, readers interested in specific details in their particular field of interest can dive deep into the detailed information in the appendix.

Information on the bibliographic data (authors and year) can be found unnumbered in the upper left corner of the literature review table. This is followed by descriptive information in attributes **[A]** to **[F]**. These attributes are filled without restriction and enable the reader to find information describing the paper's case and empirical information. Attributes **[G]** to **[N]** are categorized to provide a fast overview to readers. Hence, only predetermined entries are possible. These categorized entries are ***YES***, ***y***, ***n***, and ***NO***, with each indicating a different meaning, where ***YES*** depicts the strongest category**,** indicating a very detailed description of an attribute's representation. A less detailed description is represented by ***y***, indicating an explanation in some detail. A sole mention of an attribute's representation without any detailed description is indicated by ***n***. Total absence of an attribute and its representation is indicated by ***NO***. Consequently, ***YES*** and ***y*** represent a recommendation to read up the paper if the readers are interested in the attribute, while ***n*** and ***NO*** represent that the paper is not recommended if readers want to be informed about this attribute. Attributes **[O]** to **[V]** are filled without restriction and provide detailed descriptions of the attributes, with each referring to one (or two in case of **[P]**) of the categorized attributes. The last two attributes are exceptions, as they focus on the application of Specific Energy Consumption (SEC) **[U]** and summarize the quantitative information on energy costs **[V].**

Following this approach enables the representation of an organized presentation of the literature and hence, answering the research questions. By providing information at different levels of detail, various information needs are addressed, and a transparent overview of the literature is provided. Hence, a literature review's aims of mapping and assessing the literature set by Tranfield et al. (2003) are satisfied. Moreover, the categorized attributes enable readers to rapidly identify papers worthwhile to read, while the detailed information enables them to filter on a deeper level on whether this paper is addressing their specific information needs.

1.3. Results

This section presents the findings and results of the systematic literature review. After presenting descriptive results, the subsequent section covers the results of the content analysis.

1.3.1. Descriptive analysis

The 39 papers of the final sample are distributed across 19 journals as listed in Table 1-3. One journal published the largest number of papers: The *Journal of Cleaner Production,* with 9 publications accounting for almost a quarter of all studies in the sample.

Journal	Number of papers
Applied Energy	2
British Food Journal	1
Chemical Engineering & Technology	1
Cleaner Energy Systems	1
Cleaner Environmental Systems	1
EAI Endorsed Transaction on Energy Web	1
Energies	3
Energy	5
Energy Efficiency	2
Energy Policy	2
Energy Reports	1
Energy Strategy Reviews	2
Environmental Science and Pollution Research	1
International Journal of Computer Integrated Manufacturing	1
International Journal of Energy Economics and Policy	2
Journal of Cleaner Production	9
Journal of Industrial Ecology	1
Proceedings of the Estonian Academy of Sciences	1
Sustainability (Switzerland)	2
Total	**39**

Table 1-3: Sample of 39 papers published in 19 journals

Figure 1-3 and Table 1-4 both illustrate the geographical distribution of the companies investigated, while a paper can investigate more than one country. Except for North America and Australia, these companies are spanning all over the world, showing a global interest in these topics. Nevertheless, a regional emphasis can be seen in Europe and Asia, with a very dominant focus on Sweden (seven) and Italy (five). Most studies were conducted in Europe (22). It is worth mentioning that the United States as the world's largest economy and North America per se are not represented.

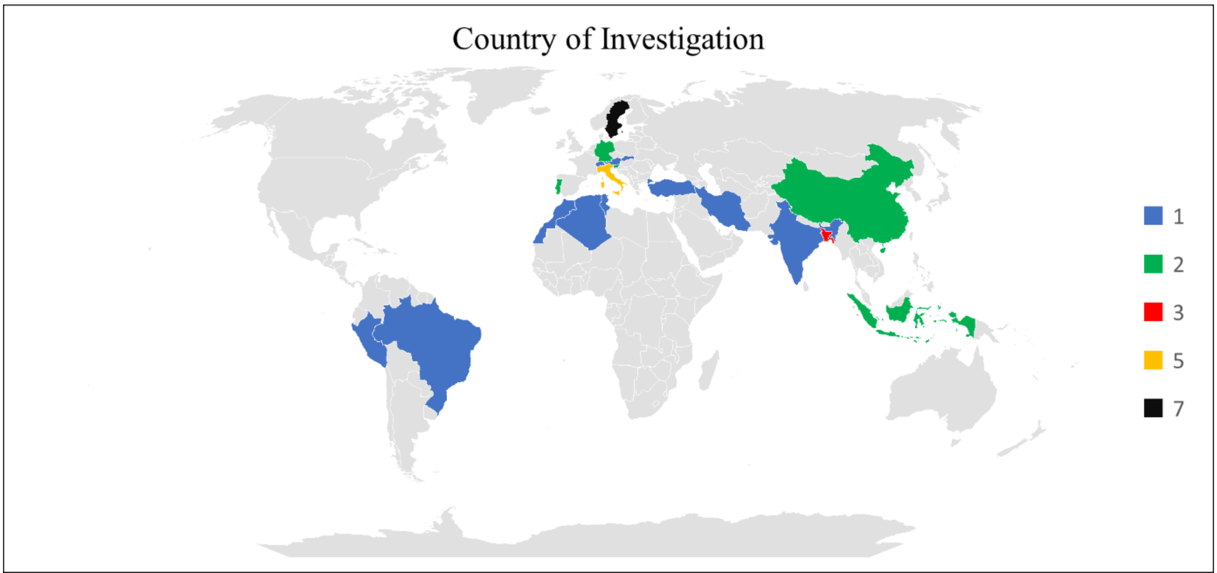

Figure 1-3: Number of studies investigating each country

Country	Number of papers
Algeria	1
Austria	1
Bangladesh	3
Brazil	1
China	2
European Union	1
Germany	2
India	1
Indonesia	2
Iran	1
Italy	5
Morocco	1
Peru	1
Portugal	2
Slovakia	1
Slovenia	2
Sweden	7
Switzerland	1
Tunisia	1
Turkey	1
Unknown	4
Worldwide	1

Table 1-4: Number of studies investigating each country. Note that studies can take place in more than one country

Figure 1-4 displays the distribution of the papers in the sample over time, from 2018 onwards. Although 2019 led by providing eight published papers, a clear trend is not recognizable. However, it should be noted that the search was conducted in August 2024 and hence, publications for 2024 are incomplete.

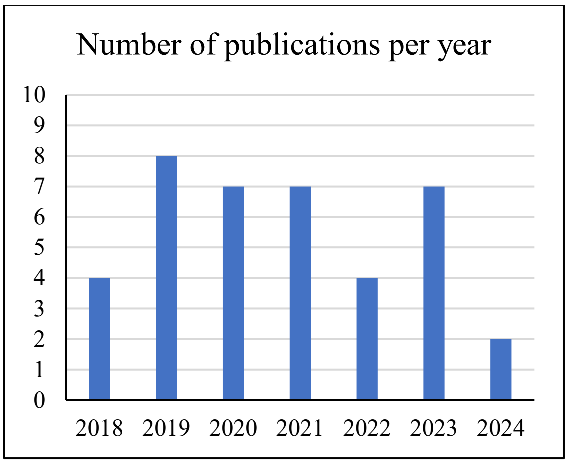

Figure 1-4: Distribution of the sample papers by year

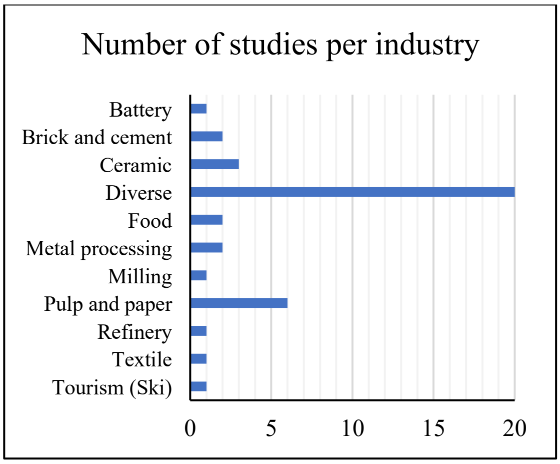

Figure 1-5: Distribution of the sample papers by industry

The research method is addressed referring to attribute [A], while each paper can be labelled with more than one research method. Hereby represents *archival data*, data gathered from sources as for instance publicly available data provided by the European Union or the United Nations. The term *case study* is defined as an in-depth investigation of company practices and procedures within one company, while *interviews* are referring to the collection of qualitative data, basically through the usage of open questions and potentially guided by interview guides. A *multiple case study* follows the definition of a case study but is executed in several companies. Lastly, the label *questionnaire* was assigned if empirical data was collected through the usage of questionnaires and surveys, whereby most questions had closed answer possibilities, such as multiple choice or Likert-scale questions. As displayed in Figure 1-6, most papers are based on single case studies (12) or questionnaires (12).

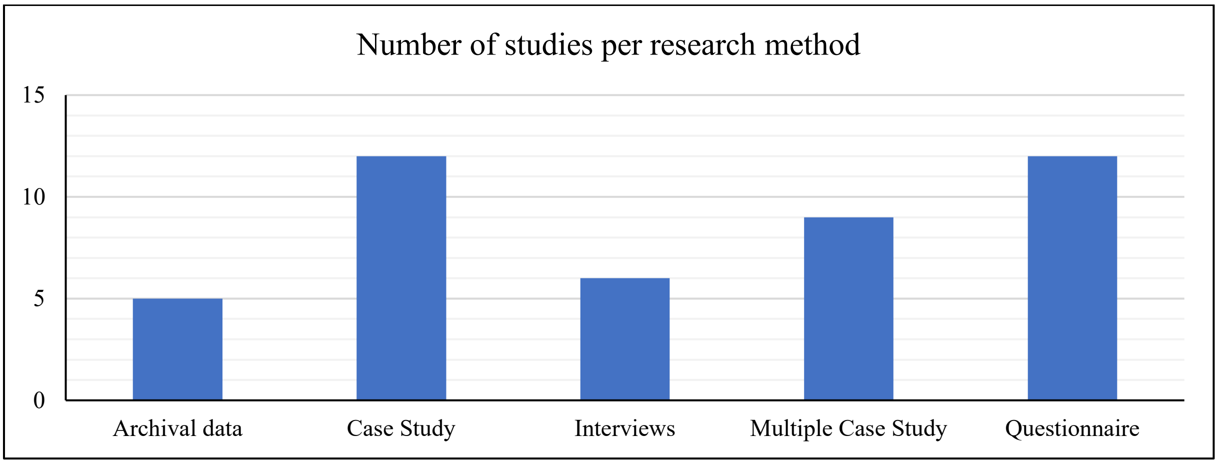

Figure 1-6: Distribution of the sample papers by research method

Strongly related to the research method is the question of how many companies a single paper is studying, which refers to attribute [B] and ranges from 1 to 12,087. As shown in Figure 1-7, most papers study either one company (10) or fewer than ten (8), while one outlier (Caporale et al., 2023) is even analyzing 12,087.

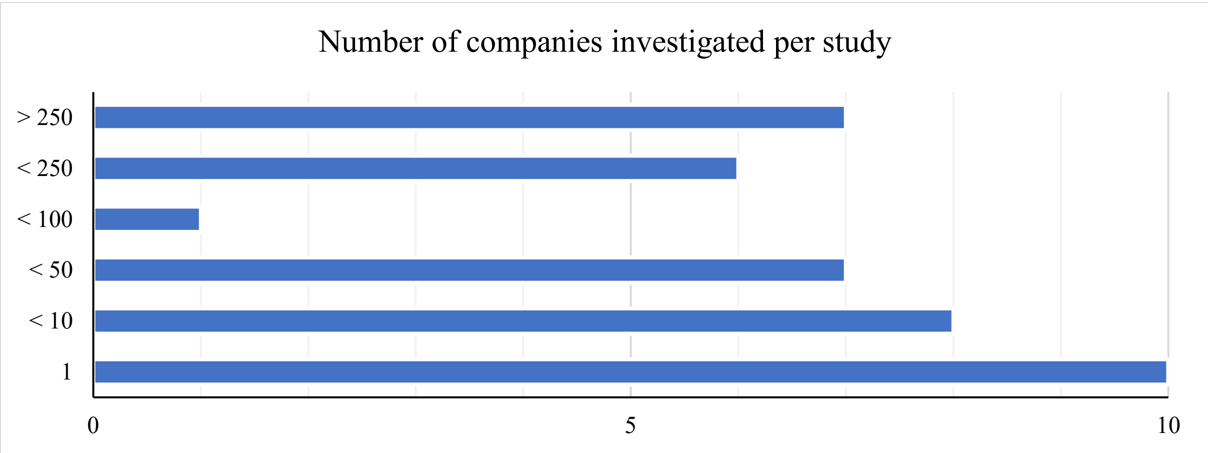

Figure 1-7: Distribution of the sample papers by number of companies investigated in the study

Addressing attribute [C], Figure 1-5 is offering information on the number of studies conducted in each industry, while each paper can be labelled with more than one industry. It is striking that more than half of the papers (20) are addressing several industries, are not stating which industry they are investigating, or simply have a sample size that does not pay attention to a homogeneous industry composition. Those papers dealing with a certain industry or addressing one are most often investigating the pulp and paper industry (6).

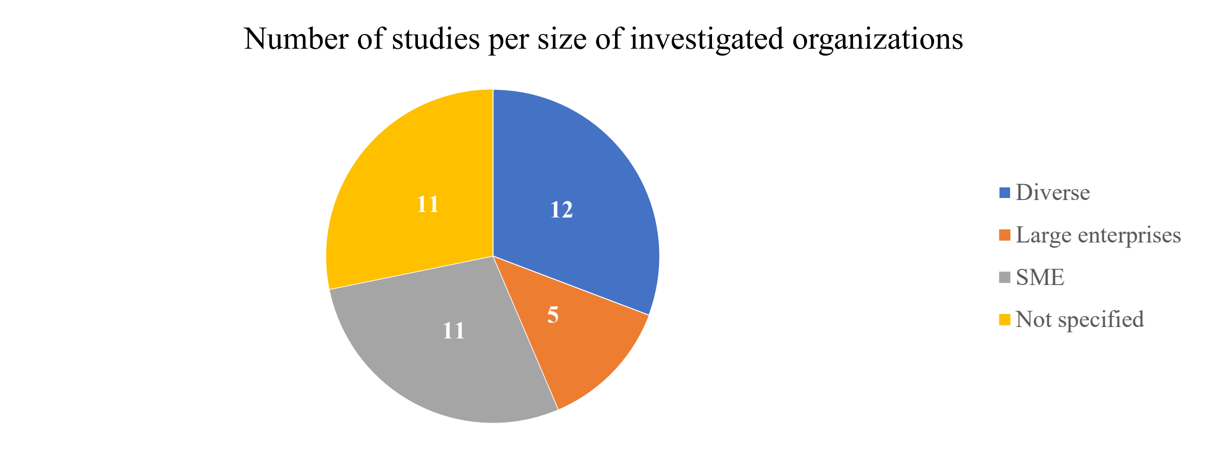

Figure 1-8: Distribution of the sample papers by size of the investigated organizations

The size investigated is addressed in attribute [D]. Figure 1-8 highlights that in contrast to the results of Mickovic and Wouters (2020), the focus has shifted away from solely investigating large enterprises. However, many papers (11) do not even address the size of the investigated company. Most papers (12) are investigating a diverse peer group of small, medium-sized and large enterprises.

Attribute [E] addresses the energy intensity of the investigated companies. Figure 1-9 highlights that in a majority of cases (23), there was no specification on whether the companies dealt with are energy intense or not. However, due to the circumstances (e.g., the industry) outlined in the paper, nine of them appear to likely study energy intense companies, while two of them appear to likely study non energy intense companies. Nevertheless, it is intriguing that only two papers actively investigate non energy intense companies.

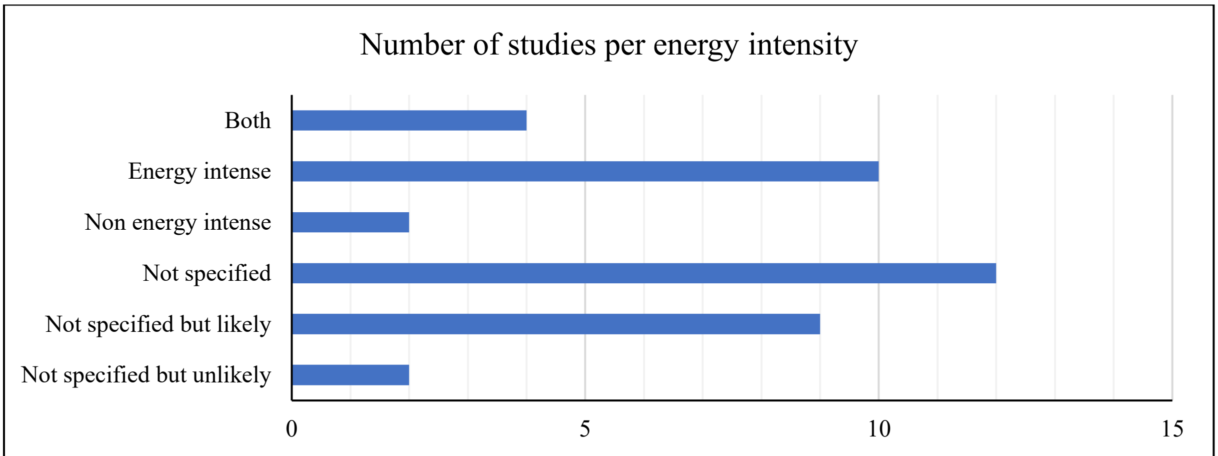

Figure 1-9: Distribution of the sample papers by the energy intensity of the investigated companies

Attributes [G] to [N] in Table 1-6 (Appendix A) are addressing the Energy Cost Center, 1st and 2nd Stage Allocation, Energy Measurement, Energy Efficiency, Energy Audit, Energy Strategy, and Energy-related Investment Decisions. These findings are classified, with the dominant classification being *NO* and *n*, which represents no finding and denotes scattered information in the literature. Hence, many papers focus on detailed aspects and only very few papers focus on broader concepts. However, taking a closer look at the different categories reveals that especially the field of allocation is quite underdeveloped, while on the other hand, every paper at least mentions the concept of energy efficiency. Nevertheless, most papers (5) go into further detail on energy measurement and energy efficiency. Table 1-5 is summarizing the occurrence of categorized attributes in the sample of papers to provide an overview.

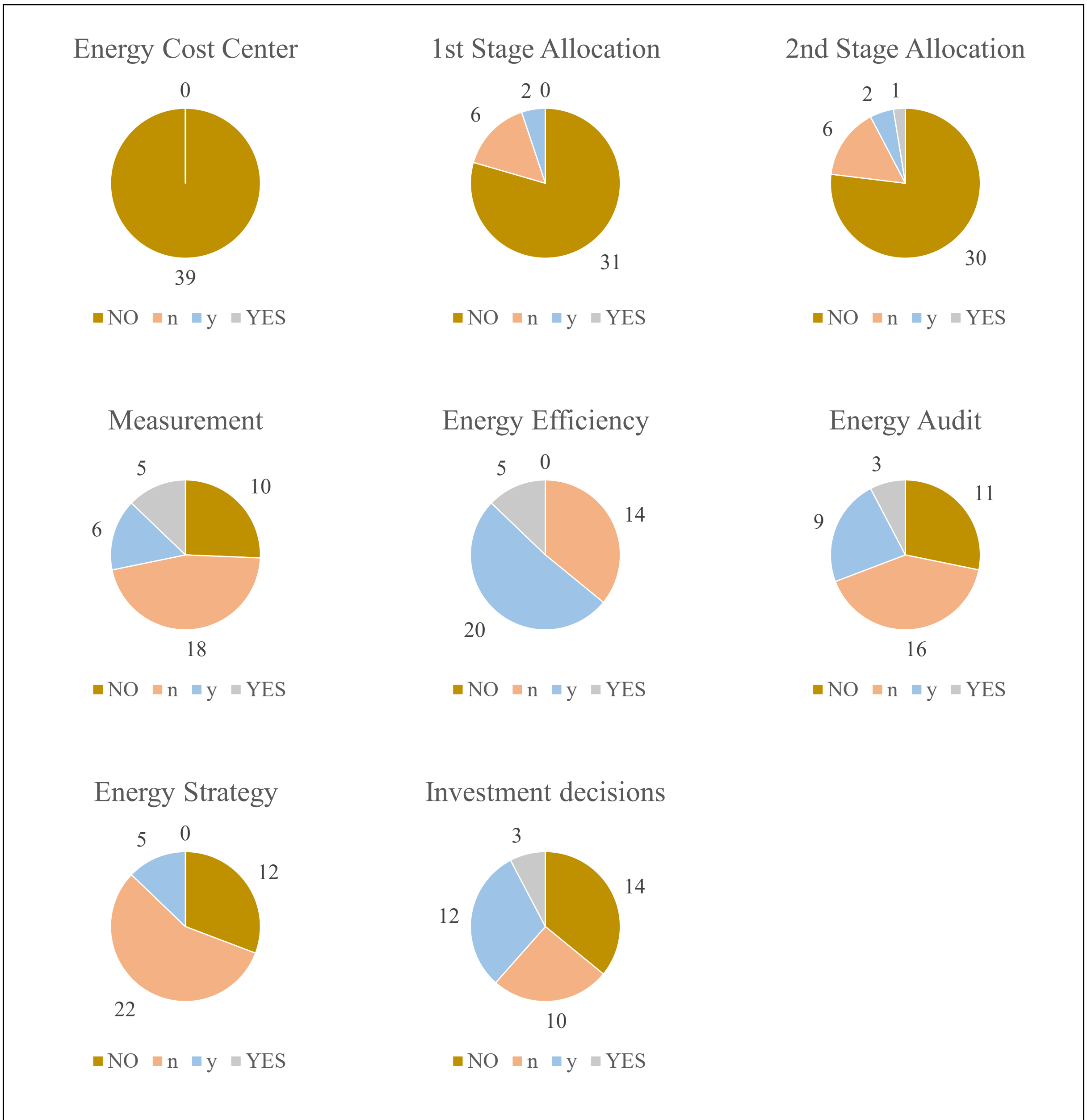

Figure 1-10: Occurrence of categorized attributes in the sample of papers by attributes. In this figure 'YES' indicates a very detailed explanation, 'y' a less detailed explanation in some detail, 'n' a sole mention without any detailed explanation, and NO the total absence of an attribute

Authors	Year	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions
Andersson and Thollander	2019	NO	n	n	YES	n	y	NO	NO
Andersson et al.	2021	NO	NO	NO	n	n	n	n	NO
Bernabé-Custodio et al.	2023	NO	NO	NO	y	n	y	n	NO
Cabello Eras et al.	2020	NO	NO	NO	YES	n	YES	n	NO
Cagno et al.	2019	NO	NO	NO	n	NO	y	NO	n
Cagno et al.	2022	NO	NO	NO	NO	y	YES	n	NO
Caporale et al.	2023	NO	NO	NO	NO	y	y	n	n
Cooremans and Schönenberger	2019	NO	NO	NO	n	y	y	n	YES
Cunha et al.	2020	NO	NO	NO	NO	y	n	NO	n
Dahlqvist and Söderholm	2019	NO	NO	NO	n	y	y	n	y
Dekamin et al.	2022	NO	y	y	n	NO	y	n	NO
Hasan and Trianni	2023	NO	NO	NO	NO	y	YES	NO	NO
Hasan et al.	2018	NO	n	n	n	n	y	y	NO
Hasan et al.	2019	NO	NO	NO	NO	y	y	n	y
Herce et al.	2021	NO	NO	NO	n	YES	y	n	y
Hossain et al.	2020	NO	n	n	n	y	YES	n	y
Hrovatin et al.	2021	NO	NO	NO	NO	n	y	NO	n
Janošovský et al.	2020	NO	NO	NO	n	NO	n	NO	y
Knayer and Kryvinska	2023	NO	NO	NO	n	n	y	NO	n

Authors	Year	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions
Kumalawati et al.	2023	NO	n	n	NO	NO	n	n	n
Lawrence et al.	2018	NO	NO	NO	n	n	n	n	n
Lawrence et al.	2019	NO	n	n	YES	n	n	y	y
Luken and Saieed	2023	NO	NO	NO	NO	n	n	NO	YES
Ma et al.	2019	NO	NO	NO	y	NO	n	NO	NO
Ma et al.	2021	NO	NO	NO	YES	NO	y	n	NO
Onjewu et al.	2022	NO	NO	NO	y	n	y	y	n
Patel et al.	2022	NO	NO	NO	NO	YES	y	n	y
Ruivo et al.	2021	NO	NO	NO	y	NO	n	n	n
Sa et al.	2018	NO	NO	NO	NO	NO	n	n	YES
Sarvestani et al.	2024	NO	NO	NO	y	NO	n	NO	NO
Schulze et al.	2018	NO	NO	NO	n	n	y	y	NO
Schützenhofer	2021	NO	NO	NO	n	YES	y	NO	y
Sola and Mota	2020	NO	NO	NO	y	NO	y	n	y
Solnørdal and Nilsen	2020	NO	n	n	n	n	n	y	y
Trianni et al.	2019	NO	y	y	n	y	y	n	y
Trianni et al.	2020	NO	NO	NO	n	n	YES	n	y
Trianni et al.	2021	NO	NO	NO	n	n	y	n	n
Viesi et al.	2023	NO	NO	YES	n	NO	n	n	NO
Yandri et al.	2024	NO	NO	NO	YES	n	n	NO	NO

Table 1-5: Summary of the occurrence of categorized attributes in the sample of papers by paper. In this table 'YES' indicates a very detailed explanation, 'y' a less detailed explanation in some detail, 'n' a sole mention without any detailed explanation, and NO the total absence of an attribute.

1.3.2. Content analysis

1.3.2.1. Energy Cost Center

Energy costs are not treated in a special cost center. Although initially described by Bierer and Götze (2012) and later on applied by Dobes (2013) and Sucic et al. (2016), no paper in the sample is describing or even referring to an energy cost center.

1.3.2.2. Energy Cost Allocation

Detailed descriptions of energy cost allocation practices are still lacking in the literature. Although not specifically providing information on energy cost allocation, several papers mention the importance of allocation (Andersson and Thollander, 2019; Hasan et al., 2018; Hossain et al., 2020; Kumalawati et al., 2023; Solnørdal and Nilsen, 2020). Dekamin et al. (2022) for instance, do not provide further information but allocate their energy costs according to their application of MFCA.

The application of both 1st and 2nd stage energy cost allocation is seldom described in detail. Trianni et al. (2019) provide a framework for benchmarking energy management practices and list energy cost allocation as one. They classify four levels of energy cost allocation, ranging from 'no energy-specific cost allocation' to 'process specific energy cost allocation'. However, they do not go in detail on how they assess the energy cost allocation practice of their case companies. Viesi et al. (2023) describe 2nd stage allocation of energy consumption in their case study of an Italian skiing resort by allocating the measured energy from each cost center (ski lift) to the final KPIs on the basis of skier-days (1 person skiing 1 day). Moreover, Dekamin et al. (2022) describe energy cost allocation to final products according to MFCA. Besides these occurrences – and they are not 2nd stage cost allocation in the traditional way – no description of 2nd stage allocation could be observed, leaving very high demand for future empirical studies.

1.3.2.3. Energy Cost Measurement

The methods and granularity of energy measurement are central in advancing both the practice of energy cost accounting and the effectiveness of energy management initiatives. Examining recent empirical studies reveals significant variation in measurement approaches, underscoring the ongoing need for standardized protocols.

Insights into energy measurement practices reveal three key dimensions of energy measurement granularity: the energy carrier, the frequency, and the unit of measurement. The literature reports detailed measurements for various energy carriers, including gas (Ma et al., 2019, 2021; Ruivo et al., 2021; Yandri et al., 2024), electricity (Andersson and Thollander, 2019; Bernabé-Custodio et al., 2023; Cabello Eras et al., 2020; Ma et al., 2019; Ruivo et al., 2021; Yandri et al., 2024), heat (Andersson and Thollander, 2019), compressed air (Cabello Eras et al., 2020), coal (Ma et al., 2019), diesel (Yandri et al., 2024) as well as total energy consumption (Lawrence et al., 2018; Trianni et al., 2019). Simultaneously, frequency of measurement varies considerably, ranging from minutely intervals (Ma et al., 2021), to daily (Cabello Eras et al., 2020; Sarvestani et al., 2024), weekly (Cabello Eras et al., 2020), monthly (Bernabé-Custodio et al., 2023; Ruivo et al., 2021; Yandri et al., 2024), and yearly intervals. (Cagno et al., 2019; Cooremans and Schönenberger, 2019; Janošovský et al., 2020; Lawrence et al., 2018; Trianni et al., 2019) Some studies even provide measurement information for the duration of specific processes (Ma et al., 2019) or custom intervals (Andersson and Thollander, 2019). Finally, the units of measurement include kWh (Bernabé-Custodio et al., 2023; Cabello Eras et al., 2020; Yandri et al., 2024), Nm^3 (Ma et al., 2021), GJ (Sarvestani et al., 2024), m^3 (Cabello Eras et al., 2020), and toe (tonnes of oil equivalent) (Herce et al., 2021; Ruivo et al., 2021) alongside functional units tailored to the specific contexts (Yandri et al., 2024).

The level of aggregation in measurement is another key aspect, which varies across the studies. While some studies focus on low-tier level energy consumption like machines (Ma et al., 2021; e.g., Viesi et al., 2023), production lines (e.g., Bernabé-Custodio et al., 2023), or multiple entities along the production process (e.g., Ma et al., 2019), many studies aggregate energy consumption data at higher levels like the entire company (e.g., Schützenhofer, 2021; Trianni et al., 2020). Ma et al. (Ma et al., 2021) state that the implementation of modern measurement and metering technologies allows for both machine-level but also aggregated monitoring, enhancing the potential for process-specific optimization. Additionally, such usage of smart metering allows for the provision of energy consumption information for every desired level (Ma et al., 2019; Viesi et al., 2023) but is described rather as a potential for energy efficiency than the status quo in companies' practice (Cagno et al., 2019). Moreover, the study by Herce et al. (2021), reports industry-wide energy consumption rather than providing information at company level, which supports broad sectoral analyses but limits process-specific insights. Papers like the case study by Solnørdal and Nilsen (2020), emphasize general trends in energy consumption monitoring and measuring rather than describing operational metering in granularity.

Although measurement is acknowledged as a necessity for energy cost accounting, the description often lacks detail, relying instead on generalized statements about energy consumption. Various studies (Dekamin et al., 2022; Hasan et al., 2018; Hossain et al., 2020; Knayer and Kryvinska, 2023) simply state the importance of energy measurement without going into further detail on how the measurement was actually conducted. Additionally, studies like Trianni et al. (2019) and Lawrence et al. (2018), report on overall energy use without elaborating on measurement specifics. Concluding, while empirical studies on energy management have made strides in measurement practices, a considerable gap in methodological consistency and detail remains. A standardized framework to discuss energy measurement would not only improve the comparability of studies but also strengthen the field’s contribution to advancing energy efficiency practices across industries.

1.3.2.4. Energy Efficiency

A consistent theme is the emphasis on energy efficiency as an essential component of energy management, though vague definitions, limited metrics and the presence of drivers and barriers. Several studies (Andersson and Thollander, 2019; Cagno et al., 2019; Lawrence et al., 2018; Luken and Saieed, 2023; Ruivo et al., 2021; Schulze et al., 2016; Solnørdal and Nilsen, 2020; Trianni et al., 2019; Viesi et al., 2023) emphasize the importance of energy efficiency, yet often do so without detailing energy efficiency metrics. Consequently, Lawrence et al. (2019) underline the significance of energy efficiency metrics but note that implementation remains very limited. Echoing this common theme of recognizing the need for efficiency without specifying concrete metrics, Sarvestani et al. (2024) describe the undeniable necessity of improving energy efficiency but do not provide concrete metrics. Similarly, Yandri et al. (2024) call for enhanced energy efficiency as long term goal and Kumalaweti et al. (2023) talk about ways of achieving energy efficiency, both without elaborating on their concept of energy efficiency or providing measurable metrics. In contrast, Cagno et al. (2022) provide a framework for assessing the impact from the adoption of energy efficiency metrics. Moreover, studies like Schützenhofer (2021) note, that while many organizations aim to improve energy efficiency, challenges in implementing practical energy efficiency metrics persist. More generally, studies (Cooremans and Schönenberger, 2019; Hasan et al., 2018, 2019; Hossain et al., 2020; Hrovatin et al., 2021; Sola and Mota, 2020; Trianni et al., 2021) explore such barriers hindering but also drivers facilitating the implementation of energy efficiency metrics in different settings.

The exploration of sector-specific practices, particularly within energy-intensive industries, is another recurring aspect. This is evident in the studies by Hossain et al. (2020), identifying eleven distinct energy efficiency metrics tailored to the cement industry and Cabello Eras et al. (2020), describing 27 for providing compressed air. Similarly, Andersson et al. (2021) provide insights into energy efficiency in the pulp and paper industry. Sector-specific energy efficiency metrics are also investigated among small and medium sized enterprises (SMEs) (Trianni et al., 2020) and in Italian energy audits (2021). In very specific settings, Bernabé-Custodio et al. (2023) elaborate on energy efficiency management based on ISO 50001 and Dekamin et al. (2022) use MFCA and more specifically the comparison of input energy and energy content of the output as an energy efficiency metric. Such customized solutions highlight the growing recognition of the industry-specific nature of energy efficiency needs. Notably, Hasan and Trianni (2023) categorize energy efficiency metrics across industries, offering a more structured approach.

Studies investigate the factors that influence energy efficiency and energy efficiency's reciprocal impact on organizational outcomes and other usages of energy efficiency. On the one hand, the influence of energy management systems (Knayer and Kryvinska, 2023; Patel et al., 2022) and additional technologies (Knayer and Kryvinska, 2023) on energy efficiency is subject of investigations. On the other hand, the effect of energy efficiency on economic performance (Cooremans and Schönenberger, 2019), environmental performance (Patel et al., 2022), and sales performance (Onjewu et al., 2022) is investigated. Moreover, there are descriptions of other usages for energy efficiency, like Ma et al. (2021) depicting the comparison of machines based on energy efficiency. Another application scenario is improving process efficiency, leading to energy savings more or less by the way (Janošovský et al., 2020). Dahlqvist and Söderholm (2019) even investigate energy efficiency as criteria for investment decisions.

1.3.2.5. Energy Strategy

Explicit discussions on energy strategies remain limited, with few studies articulating structured formalized energy strategies. While many studies focus on energy management, energy cost savings, or energy efficiency improvements as a goal, they stop short of detailing strategies or simply state the importance of strategies (Andersson et al., 2021; Cabello Eras et al., 2020; Cagno et al., 2022; Caporale et al., 2023; Cooremans and Schönenberger, 2019; Dahlqvist and Söderholm, 2019; Dekamin et al., 2022; Herce et al., 2021; Ma et al., 2021;

Onjewu et al., 2022; Patel et al., 2022; Sa et al., 2018; Sola and Mota, 2020; Trianni et al., 2020, 2021). Ruivo et al. (2021) for example discuss sector-specific strategies to achieve energy savings, without talking about energy strategies in detail. Accordingly, Viesi et al. (2023) observe that energy efforts are often implemented without a cohesive, overarching strategy and summoned as part of a broader environmental strategy. Kumalawati et al. (2023) attest a positive influence of strategic aspects on economic growth, still without talking about explicit energy strategies. This lack of formal energy strategy contrasts with the emphasis placed on energy efficiency, suggesting a gap between organizational intentions and structured energy planning.

Energy management strategies are sometimes embedded within broader frameworks. Supporting this perspective, Bernabé-Custodio et al. (2023) indicate that implementing ISO 50001 implicitly incorporates strategic elements, as the standard requires systematic energy efficiency improvements. Similarly, Schulze et al. (2018) state that organizations adopting ISO 50001 indirectly adopt a strategic approach to energy. Such frameworks provide a structure that can substitute a formal strategy by aligning organizational practices with energy management objectives. However, this reliance on standard-based structures may limit the development of customized strategies that address specific organizational needs or (sector-)specific challenges.

Few studies explicitly focus on comprehensive energy strategies, pointing to a broader research gap in this area. Hasan et al. (2018) provide one of the limited examples, examining how long-term energy strategy is one of the most important drivers for energy efficiency. Long- and short-term energy reduction targets are seen as strategic targets in a case study by Solnørdal and Nilsen (2020), while Caporale et al. (2023) specify the implementation of internal monitoring systems as an energy strategy. Lawrence et al. (2019) represent one of the few exceptions, exploring energy strategies in more detail by analyzing long-term energy strategies. However, such studies remain, as most research focuses on operational practices or efficiency improvements, often without addressing alignment with long-term strategic objectives.

1.3.2.6. Energy-related Investment Decisions

The literature mainly relies on simple financial metrics for evaluating energy-related investment decisions. In a more general manner, Patel et al. (2022) state that financial assessment is necessary for energy-related investment decisions. Across several studies

(Hasan et al., 2019; Herce et al., 2021; Hossain et al., 2020; Janošovský et al., 2020; Luken and Saieed, 2023; Sa et al., 2018; Schützenhofer, 2021; Sola and Mota, 2020; Solnørdal and Nilsen, 2020; Trianni et al., 2020), the payback period emerges as the most commonly used criterion, reflecting a focus on short-term financial returns. Adding to that, studies like Sola and Mota (2020), Solnørdal and Nilsen (2020), and Lawrence et al. (2019) highlight that organizations prioritize investments that provide quick financial returns, with preferred payback periods ranging between half a year and up to three years. Similarly, Trianni et al. (2019) and Lawrence et al. (2019) find that although companies consider alternative financial metrics like return on investment (ROI), net present value (NPV) or the internal rate of return (IRR), simple payback remains the dominant choice due to its straightforward calculation and immediate applicability.

Although simple approaches dominate, some studies explore the application of more advanced decision-making criteria. In this context, Sa et al. (2018) investigate a range of criteria including: payback time, IRR, cost-benefit analysis, and combinations of those, while Patel et al. (2022) propose the usage of ROI for energy-related investment decisions. Cooremans and Schönenberger (2019) report a relatively low number of usages for NPV, IRR, compared to a high number for payback periods, with most organizations relying on one method, although some organizations use a combination of two or even all three criteria. This suggests a gap in the adoption of comprehensive financial models that account for long-term benefits and risks associated with energy projects. Trianni et al. (2020) further underline this by observing that while IRR is sometimes used, this is typically secondary to payback periods. Their study highlights a need for increased awareness within organizations to adopt more sophisticated methods that provide a better understanding of the investment's impact.

Although financial metrics remain central, studies recognize the growing relevance of non-financial factors, drivers, barriers and broader strategic considerations in energy-related investment decisions. Illustrating this point, both Dahlqvist and Söderholm (2019) and Cagno et al. (2019) report energy efficiency as criterion for investment decisions, while Onjewu et al. (2022) point out that more emphasis should be placed on energy efficiency for investment decisions. Similarly, Kumalawati et al. (2023) emphasize that companies increasingly acknowledge the importance of aligning energy investments with broader sustainability goals, even if these factors are not formally integrated into decision-making processes. Moreover, studies discuss barriers that hinder investments in energy efficiency, like high investment costs and investment priorities (2020) or specific firm characteristics (2018). In contrast, Sola and Mota (2020) discuss potential drivers that facilitate investments in energy efficiency.

1.4. Discussion

The analysis of the results of the systematic literature review leads to the conclusion that managing energy costs consists of several related sub-disciplines that influence the energy cost accounting and that several aspects are influenced by the application of energy cost accounting. These facets are discussed in this section and summarized in Figure 1-11.

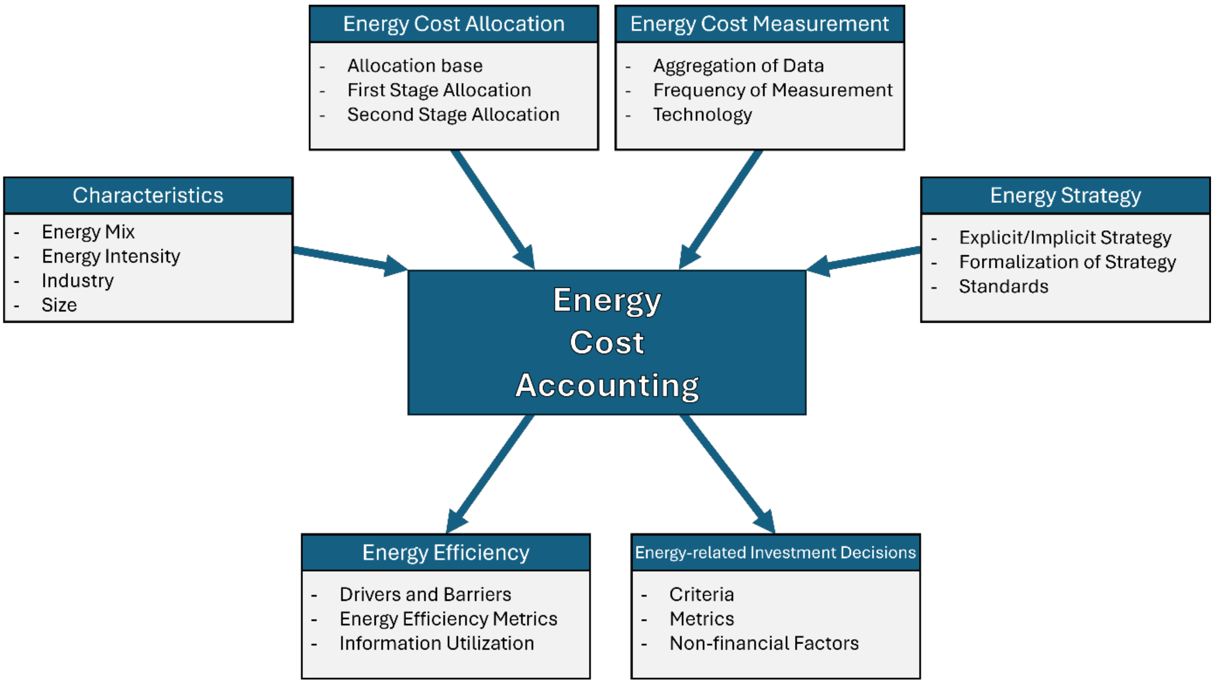

Figure 1-11: Framework for a company's energy practice

1.4.1. Energy Cost Allocation

The results underline a significant gap in the literature regarding the detailed description and application of energy cost allocation practices. As pointed out in the framework in Figure 1-11, investigating a company, it is essential to understand how energy costs are allocated for both the 1st and 2nd stage cost allocations and on which basis this allocation took place.

The lack of theoretical frameworks for energy cost allocation reveals significant gaps in practical implementation, highlighting the need for approaches to connect conceptual models with industry-specific applications. Although studies acknowledge the importance of energy cost allocation (Andersson and Thollander, 2019; Hasan et al., 2018; Hossain et al., 2020;

Kumalawati et al., 2023; Solnørdal and Nilsen, 2020), explicit descriptions of energy cost allocation in practice remain scarce, which confirms prior findings of Mickovic and Wouters (Mickovic and Wouters, 2020). The limited attention in the literature toward 1st stage energy cost allocation suggests a tendency to overlook this foundational aspect or overlook the importance of addressing energy costs on the level of cost centers. A valuable starting point towards energy cost allocation is provided through different levels of energy cost allocation (Trianni et al., 2019), addressing both 1st and 2nd stage allocation. While some studies (Dekamin et al., 2022; Viesi et al., 2023) offer case-specific insights into 2nd stage allocation, these instances deviate from traditional definitions of 2nd stage allocation. The absence of robust examples of both 1st and 2nd stage allocation points to a critical research gap, emphasizing the need for empirical studies that explore practical applications and industry-specific challenges.

Methodologies or frameworks for an efficient allocation of energy costs are absent. This absence highlights the need for more comprehensive research to establish standardized practices. Moreover, the findings underscore an urgent demand for not only empirical studies that describe energy cost allocation practice but also provide insights into their implementation. Additionally, cross-industry studies could uncover best practices and lead to standardization of energy cost allocation. By addressing these gaps, companies are better supported in achieving accurate cost allocation, improved energy information, and hence, better decision-making.

Emerging technological innovations in energy metering demonstrate the confluence of engineering advancements and economic efficiency in reducing energy consumption and energy costs. The usage of smart metering devices (Cagno et al., 2019; Ma et al., 2019, 2021) raises an important question: to what extent is energy cost allocation still relevant in modern accounting systems, if all energy costs could be traced? Addressing this question could refine the role of energy cost allocation in energy management practices and clarify its application in different organizational contexts.

1.4.2. Energy Cost Measurement

The findings reveal a lack of detailed understanding of how energy cost measurement is done in practice. As indicated in Figure 1-11, inspecting a company, understanding how frequently energy costs are measured, on which level energy cost information is aggregated and which technological solutions are used for these measurements is crucial.

Energy is measured in an incoherent way. The studies in the sample exhibit a range of intervals used for energy measurement. Energy measurements with high frequency (Andersson and Thollander, 2019; Ma et al., 2019, 2021; Sarvestani et al., 2024), provide detailed insights into energy consumption patterns, enabling adjustments and optimizations, while low frequency measurements or aggregated data (Cagno et al., 2019; Cooremans and Schönenberger, 2019; Janošovský et al., 2020; Lawrence et al., 2018; Trianni et al., 2019), offer broader overviews but lack specificity required for detailed analysis. The diversity of measurement intervals reflects the tension between the need for precision and the challenges of data collection, analysis, and reporting in practical settings.

Variations in energy measurement practices highlight the integration of modern metering technologies to combine granular data with scalable insights. This variation ranges in the level of aggregation from process-specific data (e.g., Bernabé-Custodio et al., 2023; Ma et al., 2021), to plant- or company-level data (e.g., Schützenhofer, 2021; Trianni et al., 2020). Aggregated data can facilitate sector-wide analysis (Herce et al., 2021), but sacrifices details as a trade-off. More flexible data aggregation, tailored to the specific information need, is supported by the adoption of modern metering technologies such as smart meters and sensors, but their application in practice (Cagno et al., 2019; Ma et al., 2019, 2021) remains limited. Hence, the literature only hints at the potential of technical innovations, which underscores the need for balanced approaches that combine granularity with scalability to support both operational and strategic goals.

The findings emphasize a critical need for frameworks on companies' energy practices to address energy measurements. It is essential that standardized frameworks for energy practices integrate granular insights with broader sustainability efforts to enable advancements in energy measurement and its applicability. Such frameworks should be able to accommodate both granular, process-level insights and aggregated, sector-level analyses, bridging the gap between operational precision and strategic applicability. Future research should focus on developing and testing such frameworks, drawing on advanced metering technologies and transparent reporting practices. By addressing these gaps, the field can foster more consistent comparisons across studies and companies, enhance the utility of energy data, and support more effective energy efficiency practices.

1.4.3. Energy Efficiency

The literature highlights energy efficiency as a central topic, yet it frequently lacks specificity in defining metrics and methodologies. The framework in Figure 1-11 indicates that studying a company, it is essential to examine how energy efficiency metrics are defined, how they are applied in practice, which drivers and barriers they face, and which influence they unfold.

The general importance of energy efficiency is acknowledged but concrete energy efficiency metrics are still underdeveloped. However, prior literature made notable efforts to measure energy efficiency (Abeelen et al., 2019; Bosseboeuf et al., 1997; Boyd et al., 2008; Boyd and Pang, 2000; Eichhammer and Mannsbart, 1997; May et al., 2015; Menghi et al., 2019; Phylipsen et al., 1997). Still, while the necessity of improving energy efficiency is emphasized (Sarvestani et al., 2024; Yandri et al., 2024), measurable metrics for achieving it are rare. Similarly, the importance of energy efficiency is often highlighted (Andersson and Thollander, 2019; Cagno et al., 2019; Lawrence et al., 2018; Luken and Saieed, 2023; Ruivo et al., 2021; Schulze et al., 2016; Solnørdal and Nilsen, 2020; Trianni et al., 2019; Viesi et al., 2023) without offering practical metrics to measure it. At the same time, sector-specific approaches to energy efficiency (Andersson et al., 2021; Cabello Eras et al., 2020; Herce et al., 2021; Hossain et al., 2020; Trianni et al., 2020) acknowledge sector-specific needs but the lack of standardized metrics challenges universal methodologies. Studies using standardized frameworks like MFCA to quantify energy efficiency (Dekamin et al., 2022) or providing frameworks for the assessment of energy efficiency (Cagno et al., 2022), represent steps toward more structured methodologies but remain the exception rather than the rule. This aligns with prior findings emphasizing the need for clear and meaningful metrics and methodologies to compare energy efficiency (Abeelen et al., 2019; Bosseboeuf et al., 1997; Eichhammer and Mannsbart, 1997; Phylipsen et al., 1997). Moreover, the adoption of energy efficiency metrics often encounters significant drivers and barriers, which are frequently mentioned (Cooremans and Schönenberger, 2019; Hasan et al., 2018, 2019; Hossain et al., 2020; Hrovatin et al., 2021; Lawrence et al., 2019; Schützenhofer, 2021; Sola and Mota, 2020; Trianni et al., 2021). The general lack of specificity limits the applicability, as practitioners and researchers require actionable energy efficiency metrics to effectively implement energy efficiency improvements.

Energy efficiency's dual-direction relationships with other organizational aspects highlight its multifaceted impacts and underline the complexity and the need for empirical research. The demonstration of energy efficiency improvement's positive impact on environmental and sales performance (Cooremans and Schönenberger, 2019; Onjewu et al., 2022; Patel et al., 2022) aligns with prior findings demonstrating energy efficiencies' positive influence on productivity (Boyd and Pang, 2000). In contrast, energy management systems' influence on energy efficiency (Knayer and Kryvinska, 2023) adds to prior findings that the employment of standards influences energy efficiency assessment (Boyd et al., 2008). This highlights the interdisciplinarity of energy efficiency, suggesting that its impact extends beyond mere energy cost savings to broader organizational benefits. Moreover, the diverse applications of energy efficiency as a concept, ranging from machine comparisons (Ma et al., 2021) to investment decisions (Dahlqvist and Söderholm, 2019), shows its flexibility but reveal fragmented interpretation, urging structured foundations for comparisons. Structured categorizations of energy efficiency metrics (Cagno et al., 2022; Hasan and Trianni, 2023) provide such foundations for comparisons but future research needs to provide more detailed empirical investigations.

The findings of this review reveal the need for adaptable yet comparable energy efficiency metrics, emphasizing their role in enabling insights and fostering sustainable practices. This echoes earlier findings (Eichhammer and Mannsbart, 1997; Menghi et al., 2019; Phylipsen et al., 1997), that underline the importance of sector-specific but harmonized metrics to ensure applicability and meaningful comparisons. Future research should focus on energy efficiency metrics that are adaptable to different sectors and organizational contexts but still enable comparisons. Additionally, exploring the interconnected benefits of energy efficiency could further solidify its role as a strategic goal.

1.4.4. Energy Strategy

The notable lack of explicit, formalized energy strategies reflects a significant gap in both academic research and practical application. This is outlined in the framework in Figure 1-11, as investigating a company, understanding how explicit but also to what extent an energy strategy is formalized and how standards are addressed is vital.

The absence of detailed energy strategies suggests a disconnect between high-level intentions and actionable plans. While the importance of energy strategies is often mentioned (Andersson et al., 2021; Cooremans and Schönenberger, 2019; Dahlqvist and Söderholm, 2019; Hossain et al., 2020; Ma et al., 2021), linked to economic growth (Kumalawati et al., 2023), or energy-related efforts and targets are seen as components of broader environmental strategies (Viesi et al., 2023), structured approaches or cohesive plans are lacking. In a similar manner, sector-specific strategies for energy savings (Ruivo et al., 2021) or energy management systems aligned to ISO 50001 acting as a de facto strategy (Bernabé-Custodio et al., 2023; Schulze et al., 2018) are acknowledged but stop short of offering detailed strategic frameworks. Only few studies (Hasan et al., 2019; Lawrence et al., 2019) offer valuable insights by directly addressing the formulation and impact of energy strategies. Despite these contributions, the broader literature leaves the strategic dimension of energy untouched, although the potential of energy strategies is apparent. This highlights the reliance on implicit strategic approaches, leaving organizations without clear and actionable roadmaps to fully address unique needs or challenges but providing avenues for future research.

The lack of explicit energy strategies underlines the need for frameworks that integrate energy objectives with corporate goals, promoting sustainability, competitiveness, and continuous improvement. Moreover, the absence of explicit energy strategies calls for efforts to bridge this gap. Developing and documenting formal energy strategies can provide organizations with practical roadmaps or milestones to integrate energy objectives into broader strategic goals, fostering long-term competitiveness and sustainability. The literature points to a need for more comprehensive, long-term energy strategies that align with corporate goals and provide structure for continuous improvement. Future research should aim to establish frameworks for creating, implementing, and evaluating energy strategies. Furthermore, exploring the interplay between standards and energy strategies could offer additional insights. By addressing these gaps, researchers and practitioners can enhance the strategic foundations of corporate energy practices, driving both economic and environmental benefits.

1.4.5. Energy-related Investment Decisions

Investment decisions regarding energy are made in a simplistic manner, without fully utilizing non-financial information. As stated in the framework in Figure 1-11, studying a company, identifying which criteria are used for energy-related investment decisions and which metrics are used to assess them is as essential as understanding the role of non-financial factors and non-energy benefits.

The prioritization of simple financial metrics to evaluate energy-related investment decisions highlights both strengths and weaknesses. While simpler metrics like the payback period offer clarity and ease of calculation, they often fail to capture long-term benefits and broader sustainability goals. The recurring finding of the prioritization of short-term financial returns (Hasan et al., 2019; Herce et al., 2021; Hossain et al., 2020; Janošovský et al., 2020; Luken and Saieed, 2023; Sa et al., 2018; Schützenhofer, 2021; Sola and Mota, 2020; Solnørdal and Nilsen, 2020; Trianni et al., 2020) underlines a conservative approach to investment decisions, emphasizing low-risk options with clear economic benefits. Moreover, this prioritization reflects tendencies to favor investments with immediate financial returns, aligning with constraints such as limited budgets and high competition for internal funding. Although alternative (more sophisticated) metrics like ROI, NPV, and IRR are mentioned (Lawrence et al., 2019; Trianni et al., 2019), they are secondary choices and the prioritization of simpler over more complex metrics can limit the scope of investments to projects with fast returns. Potentially, this excludes long-term energy initiatives with high impact. Furthermore, this lack of more complex metrics may stem from lack of familiarity, lack of resources, or organizational cultures that favor immediate outcomes. Despite this prioritization of simpler metrics, more sophisticated approaches also combine criteria like IRR and cost-benefit analyses (Sa et al., 2018) or NPV, IRR, and payback periods (Cooremans and Schönenberger, 2019). However, the low usage of comprehensive models incorporating several metrics reveals a gap in awareness and capability to assess energy-related investment decisions in depth, highlighting the need for better education and tools to support more nuanced decision-making processes.

While financial factors dominate, the scarce consideration of non-financial criteria and non-energy benefits highlights the need for their systematic integration into decision-making processes. Although the literature mentions non-financial criteria for decision-making (Cagno et al., 2019; Dahlqvist and Söderholm, 2019; Kumalawati et al., 2023), they are rarely formalized. In a similar manner, non-energy benefits are scarce (Cagno et al., 2019; Kumalawati et al., 2023; Onjewu et al., 2022), though prior literature pointed out that a broader set of operative implications has to be considered for decision making (Cagno et al., 2018). Nevertheless, such findings indicate that both non-financial criteria and non-energy benefits are part of the consideration but often rather informal and secondary, than systematically incorporated into decision-making processes. Consequently, this suggests an opportunity for future research to systematically integrate both aspects into the evaluation and decision-making process.

The adoption of more comprehensive investment evaluation methods is associated with organizational size. High investment costs upfront and competing investment priorities are significant obstacles (Cunha et al., 2020; Lawrence et al., 2018), which is especially an issue for smaller companies. In addition, the complexity and data requirements of metrics like NPV or IRR may act as deterrents for smaller companies or those in resource-constrained settings. This could explain why simple financial metrics are more common among small companies (Hasan et al., 2019; Patel et al., 2022; Sa et al., 2018; Trianni et al., 2020). For large companies at the same time, regulatory incentives, government agencies and stakeholder pressure (Sa et al., 2018; Sola and Mota, 2020) could foster the adoption of more sophisticated metrics for energy-related investment decision-making. Additionally, the process of decision-making differentiates between SMEs and large companies due to aspects such as process maturity, number of process participants, and access to funding.

The reliance on simple financial metrics for energy investment decisions highlights the need for strategies to integrate long-term objectives and non-financial factors. This prioritization of simple financial metrics points to ongoing issues in balancing short-term financial priorities with long-term strategic objectives. Future research should therefore explore strategies to enhance the adoption of comprehensive evaluation frameworks and metrics, emphasizing the integration of non-financial factors. Tools and methodologies simplifying the application of more sophisticated metrics could further support organizations in making informed but at the same time balanced decisions, regardless of their size. Addressing these gaps aligns energy-related decision-making with broader goals of economic and environmental sustainability.

1.5. Conclusion

The overarching objective of this systematic literature review is synthesizing the knowledge on corporate energy practices in empirical studies. This review provides a comprehensive overview of the topic as well as of the subtopics of energy cost centers, energy cost allocation, energy measurement, energy efficiency, energy strategy, and energy-related investment decisions. In summary, this review yields 39 papers in 19 peer-reviewed journals, highlighting the broad relevance of energy-related topics. Nevertheless, two of the main important findings are a lack of detail and emphasis across all energy-related topics. Additionally, the scattered information and obvious absence of guiding frameworks are apparent.

This paper contributes in multiple ways. First, this review offers a structured overview of the literature on corporate energy cost practices by systematically integrating previously disconnected areas, laying foundations for future research. Second, this review provides the most comprehensive investigation of the literature on energy efficiency metrics. By avoiding limitations related to specific industries or other biases, the analysis ensures consistency and comparability across findings. This enables practitioners to critically check their own energy efficiency metrics, offers scholars a base for comparisons, and equips policymakers with empirical findings to develop guidelines for the implementation and reporting of energy efficiency metrics. Third, this review points to several avenues for future research, including energy cost centers, energy cost allocation, and energy strategy as most studies lack depth and fail to explore interconnections between these topics. Consequently, this review provides researchers with a clear call to further pursue empirical research on these overlooked aspects. Fourth, this review reveals the lack of a clear framework for describing corporate energy cost practices. Without such a framework, organizations cannot systematically analyze their energy practices or compare themselves to benchmarks or competitors, which impedes the improvement of corporate energy practices and ultimately, corporate energy efficiency.

Subsequently, these contributions support the relevance of contingency theory (Cadez and Guilding, 2008; Chenhall, 2003; Covaleski et al., 1996; Hayes, 1977; Otley, 1980, 2016; Tiessen and Waterhouse, 1983; Waterhouse and Tiessen, 1978) in guiding future research. The observed diversity in corporate energy practices echoes the core idea of contingency theory that there is no universal best system but rather, systems must fit their context. Future studies should therefore adopt contingency-based perspectives to investigate how contextual variables such as industry characteristics (e.g., competitive dynamics, energy intensity), organizational structure (e.g., energy strategy, energy cost allocation), regulatory environment (e.g., reporting standards, mandatory audits), and technological infrastructure (e.g., energy measurement, energy monitoring) influence the design and effectiveness of corporate energy practices. Addressing these dimensions in future research offers avenues for explaining heterogeneity in corporate energy practices.

Nevertheless, there are limitations to this review. First, the sample of papers itself is a limitation. Although based on a careful and considerate process for identifying and selecting papers published in peer-reviewed academic journals, other sources including gray literature (books, reports, etc.) may provide more detailed empirical information on corporate energy practices. Second, the sample's regional focus – primarily on Europe, especially Sweden and Italy – hinders generalizability. The absence of North America, particularly the United States, represents a notable gap. Additionally, studies from less developed countries are also missing, despite their reliance on carbon intense energy sources and hence, potential to benefit from improved energy practices. Therefore, future studies should focus on these underrepresented regions to utilize the underlying potential. This includes conducting case studies, cross-country comparative analyses, leveraging international datasets or collaborating with local institutions to close these gaps. Third, the selection of subtopics in this review represents a limitation. Despite careful consideration, additional subtopics could have been selected. For instance, the impact on carbon emissions, tax implications arising from energy cost practices, or externality costs could have been included and subsequently lead to opportunities for future research.

1.6. Appendix A: Literature Review Table

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions
Andersson and Thollander	2019	Questionnaire, Interviews	28	Pulp and Paper	Not specified	Not specified but likely	Electricity Heat	NO	n	n	YES	n	y	NO	NO
Andersson et al.	2021	Multiple Case Study	3	Pulp and Paper	Not specified	Energy Intense	Electricity Heat	NO	NO	NO	n	n	n	n	NO

[O] Description of energy cost center
[P] Description of allocation of energy costs
[Q] Description of energy measurement
[R] Description of energy efficiency
[S] Description of energy strategy
[T] Description of investment and criteria
[U] Description of application of Specific Energy Consumption (SEC)
[V] Summary of quantitative information on energy costs

Andersson and Thollander (2019)

[O] -
[P] No specific information on the allocation of energy costs neither on the first nor on the second stage. However, energy cost allocation was ranked low as a driver for developing energy KPIs. One interviewee explicitly stated that simplifying energy cost allocations could be a useful indicator to motivate energy-saving, although it sacrifices accuracy.
[Q] Measurement is conducted for electricity, heat, and total energy cost on a plant, department, or process level. Plant level: 75% electricity, 64% heat, 46% energy costs. Department level: 71% electricity, 64% heat, 25% energy costs. Process level: 32% electricity, 18% heat, 7% energy costs. In addition, energy KPIs are available yearly, monthly, daily, or continuous.
[R] There are no specific energy efficiency metrics. To compare the efficient usage of energy, SEC and electricity or heat per ton output are used. In addition, the paper denotes the importance of KPIs for energy efficiency.
[S] -
[T] -
[U] Finding of the interviews is that SEC is often measured in energy use per ton of produced output (pulp and/or paper) aggregated at the plant level. However, there is no empirical data on this. In addition, electricity, heat, or energy cost per ton output was given as a measured KPI.
[V] No information on actual energy costs. Only qualitative information on energy costs is available.

Andersson et al. (2021)

[O] -
[P] -
[Q] No further elaboration on how measurement is conducted.
[R] Detailed and specific possibilities to improve energy efficiency in the specific pulp and paper setting are discussed but no information on energy efficiency metrics used.
[S] Specific energy strategies are not discussed. However, the importance of strategic energy management is mentioned.
[T] -
[U] SEC is given for electricity and heat separately for different purposes on different hierarchies. 26 different SECs (14 electricity, 12 heat) are distinguished.
[V] No information on actual energy costs.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

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Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Bernabé-Custodio et al.	2023	Case Study	1	Brick and cement	Not specified	Not specified but likely	Electricity	NO	NO	NO	y	n	y	n	NO

[O] -

[P] -

[Q] Measurement of the consumed energy in kWh per month for two distinct processes. In addition to that, hourly measurement (over the course of a day) for two production lines to establish benchmarks.

[R] Energy efficiency management based on ISO 50001. Energy efficiency was viewed as the relationship between energy required and energy used. Due to the implementation of energy efficiency management, process improvement and energy reduction was achieved.

[S] No specific energy strategy, but the implementation of ISO 50001 is named as a strategy for optimizing energy performance.

[T] -

[U] -

[V] Through the implementation of energy efficiency management according to ISO 5001, it was possible to decrease monthly energy consumption by 8% - in absolute values: 43,504 kWh. In monetary units, this was 18,067.23 S/ (Peruvian sol), which translates to roughly 5,000 $.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Cabello Eras et al.	2020	Case Study	1	Battery	Not specified	Energy intense	Compressed Air	NO	NO	NO	YES	n	YES	n	NO

[O] -

[P] -

[Q] Usage of compressed air is measured in m³ per day for four different sections (departments). In addition, electricity consumption for the compressors (aggregated) providing the compressed air was measured on a weekly basis in kWh.

[R] 27 different energy efficiency metrics based on findings in the literature are presented specifically for compressed air. Actions towards them were implemented in the case study.

[S] Specific energy strategies are not discussed. The implementation of strategies as a tool to identify energy-saving opportunities is mentioned.

[T] -

[U] The specific energy use of a compressor unit in MWh per ton was used as an energy KPI to assess the performance.

[V] No information on actual energy costs.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

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Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Cagno et al.	2019	Interviews	7	Diverse	Large (2), SME (5)	Not intense (4), Energy intense (3)	Not specified	NO	NO	NO	n	NO	y	NO	n

[O] -

[P] -

[Q] No detailed information on how measurement is conducted. Smart metering as an energy efficiency potential is explicitly mentioned. Yearly consumption data is available.

[R] There are no specific energy efficiency metrics. However, energy efficiency metrics are widely discussed and several energy efficiency potentials from prior literature were assessed in practice.

[S] -

[T] There is no information on specific investment criteria for energy-related investment decisions. Two case companies reported decisions based on energy efficiency considerations.

[U] -

[V] No information on actual energy costs.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Cagno et al.	2022	Multiple Case Study	9	Diverse	Large (3), SME (6)	Not intense (4), Energy intense (5)	Not specified	NO	NO	NO	NO	y	YES	n	NO

[O] -

[P] -

[Q] -

[R] 20 different energy efficiency metrics (4 of them sector-specific) are presented. In addition, a framework is provided building on characteristics to support decision-makers in assessing the impact of the adoption of energy efficiency metrics. The characteristics are grouped into (i) objective and type, (ii) implementation-related characteristics, (iii) personnel-related characteristics involved in the adoption, and (iv) additional requirements. Further, this framework is applied to nine companies and their energy efficiency metrics.

[S] Specific energy strategies are not discussed. Saving energy through the implementation of energy efficiency actions is labeled as a saving strategy.

[T] -

[U] -

[V] No information on actual energy costs.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

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Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Caporale et al.	2023	Archival Data	12087	Diverse	SME	Not specified	Not specified	NO	NO	NO	NO	y	y	n	n

[O] -

[P] -

[Q] -

[R] There are no specific energy efficiency metrics. Energy savings are seen as improvements to energy efficiency.

[S] Implementation of internal monitoring systems and the adoption of energy-saving technologies are named potential strategies. Also, energy efficiency is seen as a strategic goal.

[T] There is no information on specific investment criteria for energy-related investment decisions. The investment (in% of annual turnover) in being more resource-efficient was analyzed as a variable.

[U] -

[V] No information on actual energy costs.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Cooremans and Schönen-berger	2019	Questionnaire, Interviews, Case Studies	305 (Q), 27 (I) 5 (CS)	Diverse	Diverse	Not specified but likely	Electricity	NO	NO	NO	n	y	y	n	YES

[O] -

[P] -

[Q] No further elaboration on how measurement is conducted. electricity consumption is available on a yearly base.

[R] There are no specific energy efficiency metrics. Drivers and barriers to energy efficiency are investigated empirically. Further, the impact of energy efficiency investments on economic performance is investigated.

[S] Specific energy strategies are not discussed. The importance of including energy efficiency considerations in core business is mentioned and the implementation of an energy management system is considered part of the strategy.

[T] 232 companies used payback, 42 companies used NPV, and 52 companies used IRR. 179 use one criterion, 38 use two methods, and 29 use all three methods.

[U] -

[V] No information on actual energy costs. Energy costs were solely mentioned as reference values for energy intensity.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

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[P] Description of allocation of energy costs
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[S] Description of energy strategy
[T] Description of investment and criteria
[U] Description of application of Specific Energy Consumption (SEC)
[V] Summary of quantitative information on energy costs

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Cunha et al.	2020	Questionnaire	694	Diverse	SME	Not specified but unlikely	Electricity Heat	NO	NO	NO	NO	y	n	NO	n

[O] -
[P] -
[Q] -
[R] There are no specific energy efficiency metrics. The adoption of energy efficiency actions both for electricity and heat was investigated.
[S] -
[T] There is no information on specific investment criteria for energy-related investment decisions. However, investment costs and investment priorities are investigated as potential barriers to the implementation of energy efficiency actions.
[U] -
[V] No information on actual energy costs. The price per kWh of electricity was used as a control variable in a regression analysis.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Dahlqvist and Söderholm	2019	Questionnaire	101	Diverse	Large	Not specified	Not specified	NO	NO	NO	n	y	y	n	y

[O] -
[P] -
[Q] No specific information on how measurement is conducted. Costs for metering are discussed.
[R] The importance of energy efficiency as an investment criterion is empirically investigated. However, there is only aggregated information on a higher level. In addition, a variety of additional aspects related to energy efficiency is discussed but there are no specific energy efficiency metrics introduced.
[S] Specific energy strategies are not discussed. The existence of energy goals is mentioned as an important component of the overall business strategy.
[T] There is no information on specific investment criteria for energy-related investment decisions. However, energy efficiency is used as an investment criterion.
[U] -
[V] No information on actual energy costs. Rising energy costs are mentioned as motivation to be more energy efficient.

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Dekamin et al.	2022	Case Study	1	Agriculture	SME	Not specified but unlikely	Oil (Diesel)	NO	y	y	n	NO	y	n	NO

[O] -

[P] There is no separate allocation of energy costs, but the allocation of energy costs is part of the application of MFCA. Through the application of MFCA, energy is allocated to the products.

[Q] No further elaboration on how measurement is conducted. The authors simply state that measurement is conducted according to the MFCA method (following the flows).

[R] The MFCA approach compared the input energy of 30,687 MJ/ha to the (positive) output of 18,743 MJ/ha, which led to an energy efficiency ratio of 0.61. This indicates that 61% of the energy invested in coriander production was converted into useful energy output (coriander yield).

[S] No specific energy strategy, but strategies to improve energy efficiency are discussed.

[T] -

[U] Specific energy - labeled as SE - was given as the number of energy inputs necessary to produce the positive output.

[V] No information on actual energy costs. The MFCA approach accounted for costs and energy separately. Moreover, the focus of this study was on accounting for the non-cost aspects. Hence, no further focus was laid on specific energy costs.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Hasan and Trianni	2023	Interviews Case Study	9 (I) 3 (CS)	Diverse	Diverse	Not specified (I) Energy Intense (CS)	Diverse	NO	NO	NO	NO	y	YES	NO	NO

[O] -

[P] -

[Q] -

[R] Various energy efficiency metrics are identified in the literature and assessed according to a framework. In addition to that, very specific energy efficiency metrics based on industry 4.0 technologies, are examined in three case studies.

[S] -

[T] -

[U] -

[V] Industry 4.0 technologies are examined for their potential to improve energy efficiency. The three case studies led to energy cost savings through the usage of Industry 4.0 applications like sensors, artificial intelligence, and the Internet of Things. The authors do not explicitly state energy cost savings in monetary values.

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Hasan et al.	2018	Multiple Case Study	7	Milling	Large	Not specified but likely	Not specified	NO	n	n	n	n	y	y	NO

[O] -

[P] No specific information on the allocation of energy costs neither on the first nor on the second stage. Energy cost allocation and its importance is mentioned.

[Q] No further elaboration on how measurement is conducted. The necessity of monitoring energy costs is mentioned.

[R] There are no specific energy efficiency metrics. Drivers and barriers to energy efficiency are investigated empirically.

[S] One research question specifically dealt with (long-term) energy strategies. The existence of such a long-term energy strategy was found as one of the most important drivers for energy efficiency.

[T] -

[U] SEC is mentioned but there is no information on any usage of the concept.

[V] No information on actual energy costs. The necessity to work on energy cost information is mentioned.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Hasan et al.	2019	Questionnaire	8	Diverse	SME	Non intense	Not specified	NO	NO	NO	NO	y	y	n	y

[O] -

[P] -

[Q] -

[R] There are no specific energy efficiency metrics. Drivers and barriers to energy efficiency are investigated empirically.

[S] Specific energy strategies are not discussed. Long-term energy management strategies are dedicated to a research question.

[T] Payback period is used to assess energy-related investments. They range between 1 to 4 years.

[U] -

[V] No information on actual energy costs.

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Herce et al.	2021	Archival Data	> 700	Diverse	Diverse	Not specified	Not specified	NO	NO	NO	n	YES	y	n	y

[O] -

[P] -

[Q] No specific information on energy measurement at the level of a single company. However, aggregated information on industry-specific energy consumption is given in toe. Moreover, the coverage of energy monitoring systems in different industries in Italy is analyzed.

[R] Investigation of energy efficiency metrics used as reported in the underlying Energy Audits. Moreover, so-called energy performance improvement actions and their occurrence across different sectors in Italy are investigated.

[S] Specific energy strategies are not discussed. However, energy efficiency strategies are mentioned.

[T] No assessment of investments based on energy metrics but the ratio between investment and saving as well as payback time is proposed as an indicator for investment decisions related to energy.

[U] -

[V] No information on actual energy costs. The cost-effectiveness of energy-related investments and the corresponding savings were investigated.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Hossain et al.	2020	Multiple Case Study	7	Brick and cement	Not specified	Energy intense	Not specified	NO	n	n	n	y	YES	n	y

[O] -

[P] No specific information on the allocation of energy costs neither on the first nor on the second stage. However, the allocation of energy costs is recognized as a vital factor for efficient energy management.

[Q] No discussion on the measurement of energy costs but energy cost monitoring was mentioned as important for energy management.

[R] 11 different metrics for the cement industry were analyzed and explained. In addition, barriers and drivers were investigated. The potential of energy efficiency was estimated at around 10% in the investigated industry.

[S] Specific energy strategies are not discussed. However, the importance of energy management and energy efficiency strategies is mentioned.

[T] Energy-related investments are assessed using the payback period as a criterion. Typical payback time in the sample ranges between three to four years.

[U] -

[V] No information on actual energy costs. However, the investigation of energy costs was mentioned as an important aspect of energy management. Moreover, companies in this study were selected based on high energy costs of at least 6% of their turnover.

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Hrovatin et al.	2021	Questionnaire	21	Diverse	SME	Not specified	Not specified	NO	NO	NO	NO	n	y	NO	n

[O] -
[P] -
[Q] -
[R] Investigation of the adoption and the extent of energy efficiency metrics in Slovenian SMEs. Drivers and barriers are assessed and analyzed.
[S] -
[T] No assessment of investment decisions based on energy metrics However, the impact of costs in general on energy efficiency investments is discussed.
[U] -
[V] No information on actual energy costs. However, energy costs are discussed as a driver for energy efficiency investments.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Janošovský et al.	2020	Case Study	1	Pulp and Paper	Not specified	Energy intense	Electricity Heat	NO	NO	NO	n	NO	n	NO	y

[O] -
[P] -
[Q] No further elaboration on how measurement is conducted. Heat and electricity consumption is available on a yearly base.
[R] No information on energy efficiency metrics was used. Process efficiency was the main target of this paper and energy savings occurred through this improved process efficiency.
[S] -
[T] A so-called simple rate of return was used to assess the energy-related investments. The investment sum was divided by the yearly cost savings.
[U] SEC was calculated separately on a yearly base for heat and electricity. The annual heat or electricity consumption was divided by the annual paper production.
[V] No information on actual energy costs. 4 industry specific energy saving potentials were analyzed. Their combined energy cost saving would be 158,000 € per year.

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Knayer and Kryvinska	2023	Multiple Case Study	386	Diverse	Diverse	Not specified	Diverse	NO	NO	NO	n	n	y	NO	n

[O] -

[P] -

[Q] No information on the measurement of energy costs but measurement methods are mentioned.

[R] The occurrence of energy management systems and eleven additional technologies that could have been adopted and their influence on energy efficiency were investigated empirically.

[S] -

[T] No assessment of investments based on energy metrics but multiple mentions of investment decisions that could be influenced by parameters related to energy efficiency or energy consumption.

[U] -

[V] No information on actual energy cost data in the investigated companies. However, questions on energy consumption and the associated energy costs were asked in the course of the case studies.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Kumalawati et al.	2023	Questionnaire	169	Textile	Diverse	Not specified	Not specified	NO	n	n	NO	NO	n	n	n

[O] -

[P] No specific allocation of energy costs neither on the first nor on the second stage. However, the necessity of the allocation of environmental costs (including energy costs) is recognized in a measurement indicator of the analysis.

[Q] -

[R] Broadly talk about achieving energy efficiency through energy savings but no further elaboration on energy efficiency.

[S] No specific energy strategy, but a positive influence of environmental strategies like energy conservation on economic growth is mentioned.

[T] No assessment of investment decisions based on energy metrics but mention of the influence of sustainability metrics (like energy-related metrics) on investment decisions.

[U] -

[V] No information on actual energy costs. Energy cost savings are mentioned as a desired result of environmental management accounting practices.

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Lawrence et al.	2018	Archival data	48	Pulp and Paper	Not specified	Not specified but likely	Biomass, Oil Heat Electricity	NO	NO	NO	n	n	n	n	y

[O] -

[P] -

[Q] No further elaboration how measurement is conducted. Consumption information is available for all energy carriers on a yearly basis.

[R] There are no specific energy efficiency metrics. However, multiple facets of energy efficiency and its dependencies are discussed,

[S] Specific energy strategies are not discussed. On-site electricity production and investments in electricity infrastructure is mentioned as a strategic reorientation.

[T] There is no information on specific investment criteria for energy-related investment decisions. Barriers for investments in energy efficiency actions are discussed.

[U] SEC was separately measured for biofuel and fossil fuel but there were also aggregated values, indicating the total energy use. All SEC metrics were given in GWh/kton output. In addition, variables representing production, energy use, firm characteristics, time, and energy price were investigated regarding their effect on SEC.

[V] No information on actual energy costs. However, energy prices and especially electricity prices are investigated.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Lawrence et al.	2019	Questionnaire	29	Pulp and Paper	Diverse	Energy intense	Not specified	NO	n	n	YES	n	n	y	y

[O] -

[P] The allocation of energy costs is analyzed as a driver of energy management, finding a significant relationship, while the difficulty of allocation is not a significant barrier.

[Q] The companies' measurement of energy costs is classified using the following scale: (0) No measurement, [A] Invoice checking, (2) Monthly monitoring by energy-carrier, (3) weekly measurement for each process, unit, or building, (4) comprehensive measurement against targets with effective reporting to management

[R] No information on energy efficiency metrics. However, extensive mention of energy efficiency, drivers, and barriers.

[S] Specific energy strategies are not discussed. A long-term energy strategy is analyzed as a driver of energy management, finding a significant relationship. In addition, 26% of the companies do have an energy strategy for 5 years, 52% have an energy strategy for 3 to 5 years, and 22% have an energy strategy for 1 to 3 years.

[T] The companies energy-related investments are classified using the following scale: (0) No investment, (1) only low or no-cost implemented, (2) low or medium-cost considered if the payback period is short, (3) some appraisal criteria used, as for other cost-reduction projects, (4) resources routinely committed to energy efficiency supporting business objectives. However, there is no information on which criteria (besides payback) are used or how they are assessed.

[U] -

[V] No information on actual energy costs.

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Luken and Saieed	2023	Archival data	58	Diverse	Diverse	Not specified	Not specified	NO	NO	NO	NO	n	n	NO	YES

[O] -
[P] -
[Q] -
[R] No further description of energy efficiency metrics but energy efficiency is part of the resource efficiency metrics investigated. Reduced energy consumption in kWh per year is named as the only specific measure.
[S] -
[T] Payback periods for companies are given. The payback periods are classified into four categories: Less than half a year, less than one and a half years, less than three years, or more than three years. Separate specification of the number of companies for each category for each of the three investigated countries is given.
[U] -
[V] No specific information on energy costs but average energy use reductions per sector and country (Algeria, Morocco, Tunisia) and average production cost savings per sector and country are provided. However, there is no clear connection between those values. Total investments and savings in energy are given in monetary values (€) per country but not on a company specific level

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Ma et al.	2019	Case Study	1	Ceramic	Not specified	Energy intense	Coal Electricity Gas	NO	NO	NO	y	No	n	NO	NOS

[O] -
[P] -
[Q] Data on energy consumption for gas, electricity, and coal is measured using smart meters during the whole production process. Information is therefore available, at every desired level.
[R] There are no specific energy efficiency metrics. However, to compare the efficient usage of energy overall energy consumption is used.
[S] -
[T] -
[U] -
[V] No information on actual energy costs.

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Ma et al.	2021	Case Study	1	Ceramic	Not specified	Energy intense	Electricity Gas Oil (Diesel)	NO	NO	NO	YES	NO	y	n	NO

[O] -

[P] -

[Q] Smart meters, smart sensors, RFID meters, RFID tags, and additional technologies were used to collect energy consumption data. Gas consumption data is available minutely in Nm^3 but is often aggregated (e.g., monthly). Measurement for the level of specific machines but also aggregated (e.g., workshop).

[R] No information on the energy efficiency metrics used. However, the comparison of energy consumption between machines is based on their energy efficiency.

[S] Specific energy strategies are not discussed. However, the strategic importance of energy management is mentioned.

[T] -

[U] -

[V] No information on actual energy costs. However, by implementing the proposed method, the company reduced energy consumption by 3% and energy costs by 4%.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Onjewu et al.	2022	Archival data	137	Diverse	SME	Not specified	Not specified	NO	NO	NO	y	n	y	y	n

[O] -

[P] -

[Q] Labeled as energy consumption monitoring, the influence of measurements on sales performance is investigated. However, no detailed information on the occurrence of energy measurements is given, as the focus of this study is on the influence these measurements (as well as other variables) have on sales performance.

[R] The influence of energy efficiency metrics on sales performance is investigated in this study. However, no detailed information on the occurrence of energy efficiency metrics is given, as the focus of this study is on the influence these measurements (as well as other variables) have on sales performance. Nevertheless, some examples of energy efficiency enhancements are given.

[S] Specific energy strategies are not discussed. However, the influence of energy consumption targets on energy measurements and energy efficiency is investigated. Several examples of such targets are given.

[T] No assessment of investment decisions based on energy metrics. However, it is mentioned that companies can benefit from investing in energy efficiency.

[U] -

[V] No information on actual energy costs. However, energy costs are discussed in several contexts like energy cost reductions being a positive outcome of energy efficiency enhancements.

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Patel et al.	2022	Questionnaire	594	Diverse	SME	Not specified	Not specified	NO	NO	NO	NO	YES	y	n	y

[O] -
[P] -
[Q] -
[R] There are no specific energy efficiency metrics. The authors find a statistically significant positive effect of energy management practices on energy efficiency and a statistically significant positive effect of energy efficiency on environmental performance. In addition, they find a significant moderating effect of top management commitment.
[S] Specific energy strategies are not discussed. However, the necessity of integrating energy considerations into strategic planning is stated.
[T] In general, the paper states that a financial assessment is necessary for every energy-related investment. Return on investment is proposed for this purpose.
[U] -
[V] No information on actual energy costs. However, the general financial performance is assessed based on variables related to energy.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Ruivo et al.	2021	Multiple Case Study	3	Ceramic	SME	Not specified but likely	Electricity Gas	NO	NO	NO	y	NO	n	n	n

[O] -
[P] -
[Q] Monthly energy consumption in toe is available in each company for gas, electricity and in total.
[R] There are no specific energy efficiency metrics. The term energy efficiency is used to talk about potential actions that lead to energy savings.
[S] Specific energy strategies are not discussed. However, there is a discussion about strategies to achieve energy savings. The term strategy is used to propose sector-specific solutions to save energy.
[T] There is no information on specific investment criteria for energy-related investment decisions. The investigation only considered low to no investment cost energy saving potentials.
[U] SEC was estimated in kJ per kg output.
[V] Information on actual energy costs is available for each company and also per ton of output but there is no information on disaggregation for different energy carriers.

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[T] Description of investment and criteria
[U] Description of application of Specific Energy Consumption (SEC)
[V] Summary of quantitative information on energy costs

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Sa et al.	2018	Questionnaire, Interviews	10	Diverse	Large (5), SME (5)	Energy intense	Not specified	NO	NO	NO	NO	NO	n	n	YES

[O] -

[P] -

[Q] -

[R] There are no specific energy efficiency metrics. The extent of various cases for decision-making impacting energy efficiency is investigated.

[S] Specific energy strategies are not discussed. However, strategies and motives for the implementation of energy management systems are investigated. This is summoned in the environmental strategy.

[T] The application of a wide range of criteria for decision-making is investigated, including payback time, internal rate of return, cost-benefit analyses, and combinations of those.

[U] -

[V] No information on actual energy costs. Energy cost savings are found as a strong motivation for the implementation of energy management systems.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Sarvestani et al.	2024	Case Study	1	Refinery	Not specified	Not specified	Gas	NO	NO	NO	y	NO	n	NO	NO

[O] -

[P] -

[Q] Measurement of the total consumed energy in GJ per day based on 30 points of measurement. Only the total consumed energy in GJ per day is available.

[R] Vaguely mentioned as an "undeniable necessity" to improve energy efficiency.

[S] -

[T] -

[U] Detailed description of SEC and its calculation. Implemented as energy [in GJ] necessary to provide a ton of refined gas. This was used as an index to assess the efficiency of the refinery on a daily basis.

[V] No specific information on energy costs but the implemented artificial intelligence approach uncovered improvement potential to reduce energy consumption and improve energy efficiency.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

[O] Description of energy cost center
[P] Description of allocation of energy costs
[Q] Description of energy measurement
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[V] Summary of quantitative information on energy costs

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Schulze et al.	2018	Questionnaire	236	Diverse	at least 69 large	Not specified	Not specified	NO	NO	NO	n	n	y	y	NO

[O] -

[P] -

[Q] No further elaboration on how measurement is conducted. Consumption information is only available as an efficiency score.

[R] There are no specific energy efficiency metrics. However, a measurement item called 'operational controls' is used to investigate aspects regarding energy efficiency. In addition, energy efficiency is derived from energy consumption efficiency and energy cost efficiency.

[S] Specific energy strategies are not discussed. However, a measurement item called 'strategic/planning controls' is used to investigate aspects of an energy strategy.

[T] -

[U] -

[V] No information on actual energy costs. Energy costs are only available as energy cost efficiency score.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Schützen-hofer	2021	Multiple Case Study	45	Diverse	Large	Non intense	Not specified	NO	NO	NO	n	YES	y	NO	y

[O] -

[P] -

[Q] No further elaboration on how measurement is conducted. Only aggregated measurement information is available on the energy consumption of buildings, processes and transportation in GWh.

[R] No information on the energy efficiency metrics used. However, intense empirical investigation of energy efficiency potential in Austrian companies and energy savings observed through implemented energy efficiency metrics.

[S] -

[T] Energy-related investments are labeled as Energy efficiency actions. The payback period is used as a criterion to assess them.

[U] -

[V] No information on actual energy costs. However, energy cost savings for four different activities improving energy efficiency were provided in saved € per year.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

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Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Sola and Mota	2020	Questionnaire	228	Diverse	Diverse	Energy intense	Not specified	NO	NO	NO	y	NO	y	n	y

[O] -
[P] -
[Q] No specific information on the measurement of energy costs. However, in the aggregated result managers slightly agreed that their company is continuously monitoring energy use in processes and plants.
[R] 15 potential drivers for investments in energy efficiency and their perceived importance for the company were investigated. 11 of them were combined into 4 factors (production, economics, competitiveness, and environment) influencing organizational energy management.
[S] Specific energy strategies are not discussed. In the aggregated result managers were neutral on long-term strategic planning in the energy era and their participation in said planning. In addition to that, multiple factors contributing to the strategy were discussed.
[T] From the 15 potential drivers for investments in energy efficiency, 3 were criteria for energy-related investment decisions: significant energy cost reduction, a low payback time (<3 years), and a low initial investment.
[U] -
[V] No information on actual energy costs.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Solnørdal and Nilsen	2020	Case Study	1	Diverse	Large	Not specified	Not specified	NO	n	n	n	n	n	y	y

[O] -
[P] No specific information on the allocation of energy costs neither on the first nor on the second stage. However, the case company has two full-time employees responsible for the allocation of resources to energy issues,
[Q] No specific information on the measurement of energy costs. However, a systematic monitoring and measuring of energy consumption is mentioned.
[R] No information on the energy efficiency metrics used. A program deployed in the case company emphasizing energy efficiency is mentioned.
[S] The necessity for energy strategies is mentioned several times. Long- and short-term energy reduction targets are set as energy strategies.
[T] Investments in energy projects are assessed based on payback time, which should be around 2 to 3 years.
[U] -
[V] No information on actual energy costs. Energy costs were mentioned as an important input for investment decisions.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

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Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Trianni et al.	2019	Multiple Case Study	3	Metal (1) Pulp and paper (2)	Large (2) SME (1)	Not specified but likely	Electricity Gas Oil	NO	y	y	n	y	y	n	y

[O] -
[P] The energy cost allocation of a company is classified in the following levels: (0) No energy-specific cost allocation, (1) allocation per unit of output, (2) (first stage) allocation to department/division level, (3) process specific energy cost allocation.
[Q] No specific information on how measurement is conducted. Annual energy consumption of electricity (in GWh), oil (in GWh), and gas (in GWh) is available.
[R] Although energy efficiency is one of the central aspects of this paper, there are no specific energy efficiency metrics. However, the relevance of defining KPIs for energy efficiency is underlined and many energy management practices related to energy efficiency are discussed.
[S] Specific energy strategies are not discussed. The energy strategy is considered part of the approach toward energy efficiency.
[T] The companies' energy-related investments are classified using the following levels: (0) No investment differentiation, (1) payback time threshold < 3 years, (2) payback time threshold < 3 years and different thresholds based on the investment, (3) net present value, internal rate of return, or specific evaluation process for energy-related investments. However, there is no information on which criteria are actually used by the case companies or how they are assessed.
[U] -
[V] No information on actual energy costs.

Authors	Year	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]	[N]
Trianni et al.	2020	Multiple Case Study	16	Diverse	SME	Non intense (3) Energy intense (11), Not specified (2)	Not specified	NO	NO	NO	n	n	YES	n	y

[O] -
[P] -
[Q] No further elaboration on how measurement is conducted. Information is available for one example company on the total energy consumption in kW.
[R] 17 different energy efficiency metrics or actions were assessed on 22 factors based on findings in the literature. In addition to that, these energy efficiency metrics were verified in 11 interviews.
[S] Specific energy strategies are not discussed. However, a long-term energy strategy is mentioned as a benefit.
[T] Investments in energy efficiency actions are assessed using the total investment cost, payback time, and the total energy savings.
[U] -
[V] No information on actual energy costs. Energy costs were solely mentioned as reference value for the decision whether a company is energy-intense or not.

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions
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Trianni et al.	2021	Interviews	217	Diverse	SME	Non intense (113), Energy intense (104)	Not specified	NO	NO	NO	n	n	y	n	n
		[O] - **[P]** - **[Q]** No further elaboration on how measurement is conducted. **[R]** No information on the energy efficiency metrics used. Detailed information on the impact of the adoption of energy efficiency metrics and the willingness to adopt and implement them. **[S]** Specific energy strategies are not discussed. However, the necessity of energy cost information for the development of strategies is mentioned. **[T]** No assessment of investments based on energy metrics. However, the importance of energy information in investment decisions is mentioned. **[U]** No elaboration on SEC. However, increased SEC is briefly mentioned as a result of negative energy savings in Slovenia. **[V]** No information on actual energy costs. The urge to have energy cost information is mentioned.													
Viesi et al.	2023	Case Study	1	Tourism (Ski)	SME	Not specified but likely	Biomass Electricity Oil	NO	NO	YES	n	NO	n	n	NO
		[O] - **[P]** No first stage allocation of energy costs to cost centers as energy consumptions were directly measured for each ski lift (cost center). Second stage allocation based on skier days (1 person skiing 1 day) to KPIs. **[Q]** Direct measurement of the consumption of electricity for ski lifts and buildings. No measurement for oil and biomass. **[R]** No specific energy efficiency metrics, but they talk broadly about the necessity of energy efficiency improvements. **[S]** No specific energy strategy, but the improvement of energy efficiency is part of the broader environmental strategy. **[T]** - **[U]** - **[V]** Specific cost information is only available for heating purposes. Everything else is just mentioned in consumption numbers. Energy efficiency potentials that could be tackled would lead to a decrease in operating costs according to the authors, but no specific numbers are calculated or mentioned.													

Authors	Year	[A] Research Method	[B] # of Companies	[C] Industry	[D] Company Size	[E] Energy Intensity	[F] Energy Mix	[G] Energy Cost Center	[H] 1st Stage Allocation	[I] 2nd Stage Allocation	[J] Measurement of Energy	[K] Energy Audit	[L] Energy Efficiency	[M] Energy Strategy	[N] Investment Decisions

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Yandri et al..	2024	Case Study	1	Metal	Not specified	Not specified but likely	Electricity Gas Oil (Diesel)	NO	NO	NO	YES	n	n	NO	NO

[O] -

[P] -

[Q] Measurement of the consumed energy on a monthly base in kWh. Values available both in total and individual values for electricity, gas, and diesel. The values for gas and diesel are both available in kWh and the functional unit (mmBTU and liter). In addition to that, the amount of on-site generated electricity (PV) is also available in kWh.

[R] Further improvement of energy efficiency in the future is mentioned as a long-term goal.

[S] -

[T] -

[U] -

[V] No information on actual energy cost data. However, the main idea of this paper is to set energy goals based on the best-demonstrated performance (BDP). They run a simulation for this BDP in the target company, which would achieve an energy cost saving of 7%.

Table 1-6: Summarized data for the literature review on energy cost accounting in manufacturing environments

2. Energy cost accounting in practice: A qualitative study of selective and contingent system design

Abstract

Energy has become more economically consequential, strategically important, while also being increasingly exposed to volatility, decarbonization pressures, and compliance demands. Yet, accounting research still offers limited empirical insight into how organizations actually construct and use energy cost accounting systems in practice. This paper examines energy cost accounting as an organizational and managerial practice through a qualitative study of 14 cross-functional workshops with 32 experts from German companies. Drawing on contingency theory, the paper analyzes the contextual variables that help explain differences in energy cost accounting systems, the characteristics of energy cost accounting systems, and the consequences that arise from energy cost accounting systems. The findings show that energy cost accounting is best understood not as a uniform technical system, but as a selective, hybrid, and pragmatic organizational response to distinct information demands. Organizations differ in the materiality and strategic importance of energy, the complexity of their supply arrangements, the degree of external uncertainty and compliance burden they face, as well as the organizational resources available to address these issues. In response, they do not build uniformly comprehensive or maximally granular systems. Instead, they develop configurations that balance granularity, effort, interpretability, and usefulness. The consequences of these systems depend less on technical sophistication alone than on whether information becomes accessible, trusted, integrated across functions, and linked to concrete responsibilities and decisions. By providing a richer empirical account of energy cost accounting in practice, the paper contributes to research on (environmental) management accounting and extends contingency-based understandings of accounting system design in an increasingly important domain.

KEYWORDS: *energy cost accounting, management accounting, qualitative accounting research, contingency theory, environmental management accounting*

2.1. Introduction

Energy has become too economically consequential, too volatile, and too strategically relevant to remain a largely undifferentiated overhead in accounting systems. For many organizations, energy is no longer merely an unavoidable operating expense. It has become a cost driver, a source of uncertainty, and an increasingly important object of managerial attention. Because of rising price volatility, changing procurement arrangements, growing decarbonization pressures, and expanding reporting and compliance demands, it has become more important for organizations to understand not only how much energy they consume, but also where, when, why, and at what cost. This growing importance of energy-related information resonates with broader accounting research, which has emphasized that environmental issues are increasingly implicating accounting and creating demands for new flows of information within organizations (Hopwood, 2009). Hence, information on energy-consuming behavior and the management of energy as a scarce and costly resource is critical to organizational success (Burritt et al., 2021; Mickovic and Wouters, 2020). To generate such information in a decision-relevant form, organizations require some form of energy cost accounting system.

Despite this growing relevance, energy cost accounting remains surprisingly underexplored in accounting research. Existing work has shown that energy can be an economically significant production factor and that energy-related information can support decision-making on efficiency improvements, internal generation, and cost management (Bierer and Götze, 2012). At the same time, earlier studies suggest that in many organizations, energy costs are still treated in a highly aggregated manner, often as general overhead or period expense, without systematic allocation to cost objects, organizational units, or operational activities (Aflaki et al., 2013; Johansson and Söderström, 2011). More recent reviews (Dickemann, 2025; Mickovic and Wouters, 2020) indicate that empirical evidence of how organizations actually measure, allocate, and use energy cost information remains scarce and fragmented. This may be sufficient for external reporting or rough budgeting purposes, but it offers only limited support for managerial decisions in organizations where energy costs are substantial, variable, strategically relevant, or closely linked to operational choices.

More broadly, research in management accounting has long shown that accounting systems differ in their characteristics and usefulness depending on contextual conditions. Early contingency-based work argued against the idea of a universally appropriate accounting information system and instead emphasized that system design must be related to contextual conditions, organizational attributes, and managerial requirements (Gordon and Miller, 1976; Otley, 1980; Waterhouse and Tiessen, 1978). This contingency-based work was later extended and refined to show that management control systems are shaped by factors such as technology, structure, size, and strategy, and that their usefulness depends on how well they fit the organizational context in which they operate (Chenhall, 2003; Otley, 2016). Accordingly, accounting systems should not be evaluated in isolation, but in relation to the organizational settings, uncertainties, technologies, and decision problems they are meant to address (Chenhall, 2003; Gordon and Miller, 1976; Otley, 1980, 2016; Waterhouse and Tiessen, 1978).

Yet this insight has barely been applied empirically to energy cost accounting. While the broader literature offers concepts for describing accounting system characteristics (Chenhall, 2003), and environmental management accounting research has emphasized the relevance of combining monetary and physical information for different managerial purposes (Burritt et al., 2002, 2021), we still know relatively little about what energy cost accounting systems actually look like in practice (Dickemann, 2025; Mickovic and Wouters, 2020), why they take different forms across organizations, and what consequences follow from these differences. Existing research provides technical concepts for energy cost accounting and related accounting methods (e.g., Bierer and Götze, 2012; Kaltenegger et al., 2017; Schmidt et al., 2015), normative suggestions (e.g., Burritt et al., 2002, 2021; Trianni et al., 2019), and selected case-based insights into organizational-level energy management and accounting-related practices (e.g., Ma et al., 2019, 2021; Viesi et al., 2023). However, it does not yet offer a sufficiently rich empirical understanding of energy cost accounting as an organizational and managerial practice.

This omission matters because energy cost accounting is not simply a technical exercise of attaching prices to energy quantities. In practice, it requires organizations to define relevant levels of granularity, collect and connect data from different functions, decide how energy costs should be allocated, determine how timely and transparent information must be, and clarify who should use that information for which decisions. As a result, the design of energy cost accounting systems is likely to vary considerably across organizations, consistent with contingency-theoretical arguments (Chenhall, 2003; Gordon and Miller, 1976). Some organizations may rely on relatively simple and aggregated systems, while others may invest in more differentiated arrangements that support planning, control, procurement, investment, or compliance-related decisions. Without a stronger empirical understanding of these systems in use, it remains difficult to explain their characteristics, assess their organizational relevance, or derive implications for accounting research and practice.

This study addresses that gap by examining energy cost accounting systems in their organizational context. Rather than asking how energy cost accounting should ideally be designed in abstract terms, the paper investigates how it is actually organized and used by organizations. In doing so, the paper focuses on three interrelated research questions:

RQ1: "Which contextual variables help explain differences in energy cost accounting systems?"

RQ2: "Which characteristics of energy cost accounting systems can be observed and described in practice?"

RQ3: "What consequences arise from the characteristics of energy cost accounting systems?"

To answer these questions, this paper draws on qualitative evidence from workshops on energy cost accounting practices conducted with German companies. The workshop setting enables to examine energy cost accounting as a cross-functional organizational phenomenon rather than as a narrowly technical accounting routine. Across the workshops, the author engaged with experts from different functional areas involved in the generation, processing, and use of energy-related cost information. This makes it possible to capture not only formal accounting procedures, but also the organizational interfaces, interpretive challenges, and practical trade-offs that shape energy cost accounting in practice. The paper analyzes the material through a literature-informed coding approach that also allows inductive themes to emerge from the data, combining LLM-assisted transcription and coding support with researcher-led validation and interpretation.

The findings show that energy cost accounting systems are best understood neither as absent nor as uniformly sophisticated, but as selective, hybrid, and pragmatic responses to distinct organizational information problems. Organizations differ in the materiality and strategic salience of energy, the complexity of their supply arrangements, the degree of external uncertainty and compliance pressure they face, and the organizational resources available to address these issues. In response, they do not simply move toward ever more granular or technically advanced systems. Instead, they develop different forms of energy cost accounting that balance granularity, feasibility, interpretability, and actionability. Importantly, the consequences of these systems depend not only on measurement quality or allocation precision, but also on whether the resulting information is sufficiently accessible, trusted, integrated, and linked to concrete responsibilities and decisions.

The paper makes several contributions. First, it contributes to the literature on energy cost accounting and environmental management accounting (e.g., Bierer and Götze, 2012; Burritt et al., 2002, 2021; Kaltenegger et al., 2017) by providing a rich empirical account of the characteristics of energy cost accounting systems in practice. Rather than treating energy cost accounting as a singular technique, the paper shows that it consists of multiple interrelated design dimensions, including issues such as granularity, allocation logic, transparency, planning capability, and cross-functional data integration. Second, the paper contributes to contingency-based accounting research by identifying the contextual variables that help explain variation in energy cost accounting systems across organizations. In doing so, it extends contingency thinking to a domain that has become increasingly important under conditions of energy volatility, decarbonization, and organizational transformation. Third, the paper contributes to practice by showing that the value of energy cost accounting does not depend on maximal detail. Instead, its practical relevance depends on achieving a fit between contextual information demands, system design, and organizational actionability. This offers a more realistic basis for thinking about the design and implementation of energy cost accounting systems in organizations.

The remainder of the paper is structured as follows. Section 2.2 reviews the literature on energy cost accounting and related accounting system characteristics and develops the analytical basis for the study. Section 2.3 explains the research design, data collection, and coding approach. Section 2.4 presents the empirical findings on the contextual variables, characteristics, and consequences of energy cost accounting systems in practice. Finally, Section 2.5 discusses the findings, outlines their theoretical and practical implications, and concludes.

2.2. Literature Review

2.2.1. Energy Cost Accounting

Energy plays a critical role in industrial production, yet its treatment in cost accounting has traditionally lagged behind its economic significance. Although energy is not consumed in a physical sense, it is commonly described as being "used" in accounting because its transformation incurs costs. Accordingly, energy can be defined as "a production factor whose generation, supply, waste disposal etc. cause costs" (Bierer and Götze, 2012, p. 12). Energy cost accounting is thus a partial cost accounting concept designed to support decision-making on energy efficiency, internal generation, and cost control by providing relevant information on energy consumption, losses, and performance (Bierer and Götze, 2012).

Earlier research suggests that in most organizations, energy is purchased from the grid and treated as a period expense without further allocation to cost centers or products (Aflaki et al., 2013; Johansson and Söderström, 2011). This reflects a minimalist approach, which may be sufficient for financial reporting but fails to support operational decision-making, particularly in settings where energy represents a significant or volatile cost driver. As Bierer and Götze (2012) show, more advanced systems differentiate energy costs by cost type, cost center, and cost object, following established structures of conventional cost accounting. Their three-tiered model enables organizations to attribute energy costs accurately to energy-generating units, mixed-use departments, or final products, thereby enhancing cost transparency and control.

Subsequent contributions have broadened energy cost accounting in several directions. One related stream builds on material flow cost accounting (MFCA), which quantifies physical and monetary flows of materials and allocates costs to both intended products and unintended outputs such as losses or inefficiencies (Christ and Burritt, 2015; Walz and Guenther, 2021). Material and energy flow cost accounting (MEFCA) extends this logic to include energy flows and losses (Bierer and Götze, 2012; Sygulla et al., 2014), allowing organizations to assess both the financial and environmental consequences of energy inefficiency (Burritt et al., 2021). Another contribution is the input-output-based framework proposed by Kaltenegger et al. (2017), which highlights the importance of indirect energy costs, that is, costs embedded in processes or overhead. These approaches show that energy cost accounting can move beyond treating energy as a simple period expense by making energy flows, losses, and indirect cost effects more visible.

A further challenge for energy cost accounting is that energy is not a homogeneous accounting object. Some energy carriers or sources, such as diesel, heating oil, or other purchased fuels, are relatively material-like. They can be stored, inventoried, purchased in discrete quantities, and consumed later. By contrast, electricity is grid-bound and must be consumed at the time it is generated (Kirschen and Strbac, 2004), making its cost and carbon intensity temporally dependent (Dickemann et al., 2026). On-site renewable electricity, particularly from wind or solar, adds another layer of complexity, because it often has low marginal generation costs but requires the allocation of capital, operating, maintenance, or opportunity costs. Energy cost accounting therefore has to accommodate different cost logics across energy carriers and sources.

These differences make the allocation of energy costs particularly demanding. First-stage allocation (from energy sources to cost centers) may use physical indicators like specific energy consumption (SEC) or proxies such as square meters or headcount (Backlund et al., 2012b; Brunke et al., 2014). However, second-stage allocation (from cost centers to products or services) is underdeveloped in both literature and practice (Mickovic and Wouters, 2020). This gap is particularly relevant given that electricity-related carbon emissions from purchased electricity, steam, heat, or cooling are typically reported as Scope 2 emissions under the Greenhouse Gas Protocol (2004)[2] and account for a substantial share of industrial emissions (Ketenci and Wolf, 2024; Thiede et al., 2016).

While empirical evidence suggests that time-sensitive, granular energy data can support improved decision-making (Bevilacqua et al., 2017; Hall, 2010), these data often remain disconnected from cost accounting systems (Ashabi et al., 2024; Dickemann, 2025). As a result, conventional energy cost accounting practices, typically based on fixed rates and periodic aggregation, obscure temporal dynamics and limit decision usefulness in volatile markets. Advances in metering and digital infrastructure now make real-time integration technically feasible. These challenges emphasize that the design of cost accounting systems must be responsive to contextual demands, a view formalized in contingency theory.

[2] The Greenhouse Gas Protocol (2004) distinguishes between three scopes of carbon emissions. *Scope 1* emissions are direct emissions from sources owned or controlled by the organization. *Scope 2* emissions are indirect emissions from the generation of purchased electricity, steam, heat, or cooling consumed by the organization. *Scope 3* emissions comprise other indirect emissions in the organization's value chain.

2.2.2. Contextual Variables of Cost Accounting Systems

Cost accounting systems are shaped by their context. Contingency theory (e.g., Cadez and Guilding, 2008; Chenhall, 2003; Covaleski et al., 1996; Hayes, 1977; Otley, 1980, 2016; Tiessen and Waterhouse, 1983; Waterhouse and Tiessen, 1978) argues that the effectiveness of management accounting systems depends on contextual factors (Hayes, 1977; Otley, 1980) and that there is no universally superior accounting system applicable across all organizations and circumstances (Otley, 1980).

External and operational contingencies are among the most extensively studied contextual variables and concern the circumstances and the nature of production and work processes. Perceived uncertainty in these external circumstances influences the scope and adaptability of accounting systems: in dynamic contexts, organizations tend to adopt broader, externally oriented, and more flexible systems to support responsive decision-making (Chenhall and Morris, 1986; Gordon and Narayanan, 1984; Khandwalla, 1972), while stable settings favor traditional, internally focused designs. Technology similarly affects system complexity, as standardized, routine processes are suited to formal tools like standard costing, whereas non-routine or interdependent operations require more nuanced, adaptive information (Chenhall, 2003; Daft and Macintosh, 1984; Thompson, 1967).

Organizational contingencies pertain to structural and strategic characteristics of organizations that shape internal control needs. The degree of centralization affects the granularity and distribution of cost information, with decentralized organizations demanding more detailed, unit-level data (Chenhall and Morris, 1986; Tiessen and Waterhouse, 1983). Organizational size is associated with increasing formalization and the adoption of structured, disaggregated systems (Bruns and Waterhouse, 1975; Merchant, 1981). Strategic orientation also plays a role as cost leadership tends to align with tight controls and efficiency metrics, while innovation strategies benefit from broader, forward-looking information (Govindarajan and Gupta, 1985; Langfield-Smith, 1997; Miles and Snow, 1978; Simons, 1990).

Finally, *cultural contingencies*, particularly national and organizational culture, shape preferences for control styles, participation, and reporting. High power-distance cultures may emphasize centralized, rigid systems, whereas collectivist contexts favor participatory and group-oriented approaches (Chow et al., 1994; Harrison and McKinnon, 1999; Hofstede, 1984; O'Connor, 1995). These cultural factors influence not only the form but also the perceived legitimacy and acceptability of cost accounting practices across contexts.

Collectively, these factors underpin contingency-based explanations for cost accounting system diversity, with alignment to context viewed as essential for relevance and effectiveness (Chenhall, 2003; Otley, 2016).

2.2.3. Characteristics of Cost Accounting Systems

While contextual variables shape the information demands placed on a cost accounting system, system characteristics determine how these demands are translated into functionality and decision usefulness. Prior literature has identified several dimensions along which cost accounting systems differ, many of which can be understood as responses to external, operational, organizational, and cultural contingencies.

Informational characteristics concern the type, breadth, and granularity of information that systems generate. A foundational distinction is information scope, the extent to which cost systems provide broad, externally oriented, future-focused data versus narrow, internally focused, historical information (Chenhall and Morris, 1986). Broader scope has been shown to support organizations in uncertain contexts or those pursuing innovation-oriented strategies (Gordon and Narayanan, 1984; Simons, 1990). Closely related is the level of aggregation or detail, which refers to how granularly cost information is disaggregated across organizational units or processes (Cohen and Kaimenaki, 2011; Feltham, 1977). Fine-grained systems allow for localized decision making, especially in decentralized organizations (Bruns and Waterhouse, 1975). A third key feature is timeliness, typically conceptualized through reporting frequency and speed (Bouwens and Abernethy, 2000; Chenhall and Morris, 1986), which is particularly critical under high volatility or when prices fluctuate at short intervals (Hall, 2010).

Design and structural characteristics shape how adaptable and institutionally embedded cost systems are. Flexibility refers to a system's ability to adjust to new metrics, reporting formats, or data sources in response to changing demands (Davila and Foster, 2007; Otley, 1999). Systems used in dynamic or innovation-oriented settings often require more flexibility to remain relevant. Integration, the extent to which the cost accounting system is connected within operational, enterprise, or control platforms, enhances system coherence and usability (Abernethy and Bouwens, 2005). Finally, formality, the degree of standardization, rule enforcement, and documentation, has been linked to organizational size and control orientation (Langfield-Smith, 1997; Merchant, 1981). Here, highly formalized systems support consistency in large or hierarchical organizations.

These characteristics rarely function in isolation. Rather, their configuration reflects how organizations align their accounting systems with broader structural and contextual demands. For instance, decentralized and innovation-driven organizations operating under high uncertainty tend to favor disaggregated, flexible, timely, and broadly scoped systems, while cost-focused organizations in stable contexts often rely on more aggregated, formalized and efficiency-driven systems (Chenhall, 2003).

Building on these insights from the literature, the empirical analysis in this paper examines how these characteristics are reflected in the domain of energy cost accounting. In particular, the paper explores how design dimensions, such as scope, aggregation, timeliness, and integration are adapted and operationalized in systems that aim to capture and control energy-related costs.

2.2.4. Consequences of Cost Accounting Systems

While contextual variables and system characteristics influence the design of cost accounting systems, their ultimate relevance lies in the consequences they produce. A central proposition of contingency theory is that these consequences depend not on individual features in isolation but on the alignment (or misalignment) between system characteristics and contextual demands (Chenhall, 2003; Otley, 2016). Prior research has identified several consequences of such alignment, including managerial decision-making, operational efficiency, accountability, and strategic responsiveness.

Managerial decision-making is among the most directly affected areas. Cost systems that are timely, disaggregated, and integrated with operational processes support more effective decisions across pricing, product mix, and investment planning (Boyd and Cox, 2002; Davila and Foster, 2007; Friedl et al., 2009). In dynamic contexts, systems with broad scope and low aggregation have been shown to enhance managers' ability to respond to uncertainty (Chenhall and Morris, 1986; Hall, 2010). Conversely, narrow or delayed data may lead to the exclusion of accounting information from strategic deliberations, reducing its practical utility.

Cost accounting systems also influence operational efficiency, particularly when granular cost information guides operational improvements. Systems that capture and allocate resource consumption at the level of cost centers or products help identify inefficiencies and prioritize corrective actions (Simons, 1990). Where cost data are outdated or poorly disaggregated, efforts to optimize energy or material consumption may falter due to insufficient feedback.

Cost accounting systems shape accountability. Disaggregated and frequently updated systems clarify lines of responsibility and enable performance monitoring at various organizational levels (Clune and O'Dwyer, 2020; Gray, 1992). However, if systems track short-term financial metrics but omit other indicators, they may create blind spots in oversight or shift attention away from long-term objectives.

Cost accounting system characteristics can support strategic responsiveness. Flexible, forward-looking systems that incorporate non-financial and predictive data have been linked to greater innovation capacity and responsiveness to change (Chenhall, 2003; Gordon and Narayanan, 1984). In such settings, an interactive use of accounting systems, where managers engage with data to explore strategic options rather than merely enforce compliance, can foster organizational learning and initiative (Simons, 1991).

In sum, the consequences of cost accounting systems are not inherent to the systems themselves but emerge from how well their characteristics align with organizational context. Prior literature suggests that systems designed with appropriate scope, aggregation, timeliness, flexibility, and integration are more likely to support managerial decision-making, improve operational efficiency, strengthen accountability, and enable strategic responsiveness. These consequences are contingent on contextual fit, particularly in dynamic or sustainability-focused settings such as energy cost accounting. Figure 2-1 summarizes the literature-based analytical structure developed in this section.

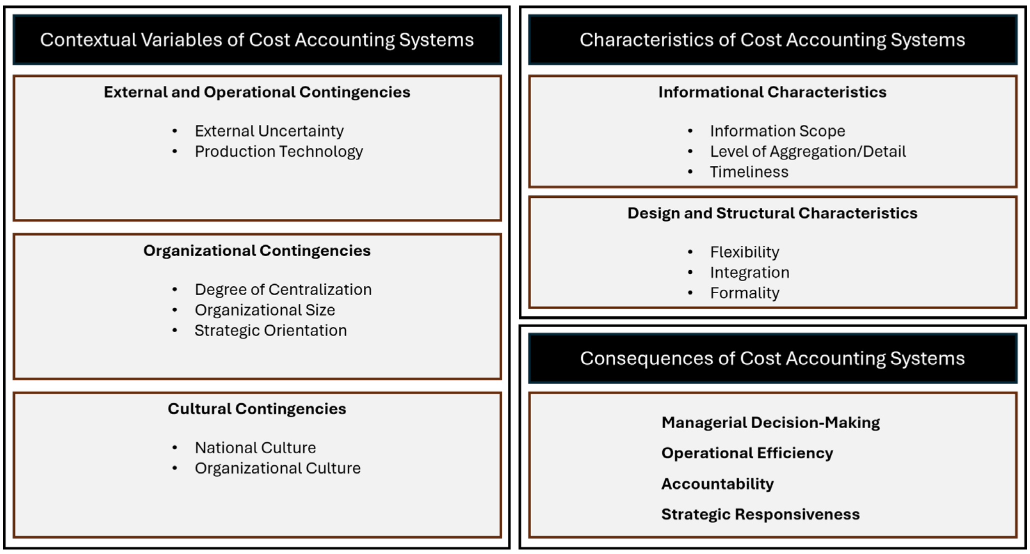

Figure 2-1: Literature overview, containing contextual variables, characteristics, and consequences of cost accounting systems.

2.3. Research Method

2.3.1. Workshops on energy cost accounting

2.3.1.1. Research design and sampling

To explore how organizations design and use energy cost accounting systems and the information they produce, the paper adopted a qualitative field-based research design. Empirical accounting research can also be descriptive in nature, and such descriptive insights play an important role in theory development by grounding conceptual advances in observed practice (Breuer et al., 2024). Qualitative methods are hence particularly suitable for examining organizational practices in context and for developing insights into emerging accounting phenomena (Ahrens and Chapman, 2006). They are specifically well suited when the aim is to understand how actors interpret and enact accounting practices in situated settings, and when existing theory provides limited guidance on specific mechanisms or design choices (Vaivio, 2008). The primary unit of analysis was the organizational-level energy cost accounting system, while individual participants provided cross-functional perspectives on the design, operation, and the use of that system.

Energy cost accounting spans several organizational domains, including management accounting, purchasing, technical operations, and energy management. This is because relevant information is distributed across functions, with cost, price, consumption, technical, and regulatory knowledge often residing in different parts of the organization. Because a single individual typically does not possess detailed knowledge of all relevant aspects, the paper uses group-based interviews in the form of workshops to capture multiple perspectives within each organization. Focus group settings enable interactional sense-making among participants and can surface forms of knowledge that do not emerge in individual interviews, as participants build on and challenge each other's input (Kamberelis and Dimitriadis, 2011). Accordingly, the workshops brought together employees from different functional areas involved in the design, operation, or use of energy cost information.

Participants for the workshops were recruited through several channels to ensure variation in organizational characteristics and to access individuals with relevant expertise. The author collaborated with professional organizations such as the *Internationaler Controller Verein* (ICV, 2025), and the *Verband der Industriellen Energie- und Kraftwirtschaft* (VIK, 2025), both of which facilitated contact with companies experienced in energy management and cost accounting. The author also approached organizations participating in regional energy efficiency networks[3] and complemented these efforts with existing industry contacts. To avoid selection biases, there were no restrictions regarding industry, size, or energy intensity. This sampling strategy resulted in a heterogeneous set of organizations and participants, allowing to capture a broad spectrum of energy cost accounting practices.

2.3.1.2. Workshop participants

The workshops included employees from various functional areas within each organization. Participants included management accountants, purchasing specialists, facility managers, and employees dedicated to energy management, such as energy managers or energy purchasers. The final composition of each workshop was agreed jointly with organizational key contacts during pre-workshop meetings to ensure that relevant functional perspectives were represented. Table 2-1 provides details on the composition and roles of the workshop participants. In total, 32 industry experts participated in 14 workshops, comprising 22 hours and 35 minutes of workshop time. This multidisciplinary composition enabled to capture cross-functional perspectives on energy cost accounting practices.

Workshop	Industry	Size	Energy Intensity	Duration	Participant	Participant ID
1	Ceramic	Large	EI	85 min	Energy Manager Energy Purchaser Management Accountant	EM1 EP1 MA1
2	Chemical	Large	EI	68 min	Energy Manager Energy Manager	EM2 EM3
3	Energy	Large	NEI	55 min	CFO	CFO1
4	Tourism & Recreation	SME	NEI	60 min	Facility Manager CFO	FM1 CFO2
5	Insurance	Large	NEI	61 min	Management Accountant	MA2
6	Mechanical Engineering	Large	EI	66 min	Quality Manager Management Accountant	QM1 MA3
7	Manufacturing conglomerate	Large	EI	101 min	Management Accountant Management Accountant Management Accountant Energy Manager	MA4 MA5 MA6 EM4
8	Pharmaceutical	Large	EI	139 min	Energy Purchaser	EP2
9	Mechanical Engineering	Large	EI	148 min	CFO Management Accountant Energy Manager	CFO3 MA7 EM5

[3] Energy efficiency networks are organized collaborations among companies with a shared interest in improving energy efficiency, typically intended to support knowledge sharing, capacity building, and the exchange of experiences on energy efficiency measures. (Jalo et al., 2021b)

Workshop	Industry	Size	Energy Intensity	Duration	Participant	Participant ID
10	Pharmaceutical Chemical	Large	EI	124 min	Energy Purchaser	EP3
					Energy Manager	EM6
					Management Accountant	MA8
					Management Accountant	MA9
					Management Accountant	MA10
11	Metal	SME	EI	111 min	CFO	CFO4
12	Consulting	SME	NEI	108 min	Energy Consultant	EC1
13	Printing	Large	EI	122 min	Energy Manager	EM7
					Management Accountant	MA11
					Management Accountant	MA12
					Management Accountant	MA13
14	Mechanical Engineering	Large	EI	107 min	Energy Manager	EM8
					Management Accountant	MA14

Table 2-1: List of workshops and workshop participants

2.3.1.3. Workshop procedure

The workshops followed a multistep procedure designed to ensure that discussions were focused, relevant, and informed by the appropriate organizational actors. The author first contacted organizations by email, providing information about the research project and outlining the purpose and structure of the workshop. After organizations agreed to participate, an online pre-workshop meeting with key contacts was held. During this meeting, the organization's broader energy cost accounting context was discussed, the focus areas for the workshop were clarified, and suitable participants from different functional areas were jointly identified. This preparatory step ensured that each workshop included the individuals best positioned to explain and discuss the organization's energy cost accounting practices.

The workshops themselves were guided by a semi-structured workshop guide developed before data collection, which covered key aspects of energy cost accounting across the energy value chain, the accounting process, and the use of energy cost information. Each workshop began with a brief introduction to the research aim, followed by an open researcher-led discussion of the organization's energy cost accounting system. Participants were encouraged to describe existing practices, provide concrete examples, and comment on challenges and ambiguities they faced. The researcher facilitated the discussion to ensure that all functional areas were heard and that relevant topics were explored in sufficient depth. The workshops varied in length, depending on the complexity and the organizational context.

2.3.1.4. Data collection and analysis

All workshops were audio-recorded and supplemented by researcher notes capturing key statements, participant interactions, and rough timecodes to revisit important moments. Immediately after each workshop, the researcher recorded a short voice memo summarizing the most salient observations and initial analytical impressions. These memos functioned as early-stage analytical notes and supported the iterative interpretation of the data. They also informed minor refinements to subsequent workshop sessions, such as sharpening prompts or probing specific topics in more depth, while the overall structure of the workshops remained constant.

The audio recordings were transcribed in German using an LLM-based transcription tool and subsequently checked and corrected manually to ensure accuracy. The resulting transcripts preserved speaker attribution and timecode information. Together with the researcher notes and post-workshop voice memos, these transcripts constituted the dataset for the analysis.

The analysis proceeded in two stages and combined a literature-informed codebook with LLM-assisted qualitative content analysis under researcher supervision. LLM assistance was used to support systematic screening and coding across a comparatively large German-language qualitative dataset, while all substantive analytical decisions remained with the researcher. As a starting point for the coding, the analysis used a literature-informed initial codebook comprising 14 codes across three overarching domains aligned with the research questions: contextual variables, characteristics, and consequences of energy cost accounting systems. This initial codebook formed the basis for the final codebook displayed in Appendix A. In a first exploratory pass, an LLM was used to identify potentially novel themes not sufficiently captured by this initial codebook. These suggestions were treated as provisional and were screened using validation rules before being reviewed manually by the researcher and either accepted, revised, or rejected. Themes were incorporated into the revised codebook only when they were conceptually distinct from existing codes, empirically grounded in the data, and relevant to the study’s research questions. In a second, deductive pass, the transcripts were coded against the revised 19-code codebook, which incorporated five additional themes identified during the exploratory stage. This combination of deductive and inductive elements allowed to link the data to established concepts in the literature, while remaining open to novel insights (Braun and Clarke, 2006; Miles et al., 2014).

To ensure analytical control, LLM outputs were restricted to verbatim transcript segments and checked against the original transcripts, notes, and timecodes. After coding individual workshops, the author compared themes across workshops to identify recurring patterns, divergent practices, and meaningful variation in energy cost accounting practices. This iterative movement between individual workshops, cross-workshop comparisons, and the evolving coding structure enabled to develop a coherent set of themes that informed the subsequent construction of the energy cost accounting framework. All coding and researcher review were conducted on the German transcripts. After the final set of quotations had been reviewed and selected, these quotations were anonymized and translated from German into English with LLM assistance. The anonymized and translated quotations were then reviewed by the researcher for accuracy, tone, and the absence of identifying information. Additional technical details on prompts, model configuration, validation rules, and processing diagnostics are reported in Appendix B. The quotations cited in the findings, including their speaker identifiers and analytical grouping, are reported in Appendix C. Additional analyzed quotations that informed the interpretation but are not cited in the main findings are provided in the supplementary material[4].

2.3.1.5. Ensuring research quality and ethics

The study received ethics approval from the Ethics Committee of the *Karlsruhe Institute of Technology*. All participants provided informed consent, and identifying information was fully anonymized. Individuals are referenced only by functional roles and numerical identifiers. Audio recordings, transcripts, and notes were stored securely on encrypted institutional servers accessible only to the research team. Research quality was ensured through triangulation of data sources (recordings, notes, memos), iterative coding, cross-workshop comparisons, and peer debriefing, supported by ongoing reflexive awareness during data collection and analysis. AI tools were used in a supportive role for transcription, coding assistance, anonymization, and translation, while all substantive coding, validation, and interpretive decisions remained with the researcher.

[4] The supplementary material is available online under the following link: https://osf.io/bj4ef/overview?view_only=8126d79e07b248b8a9bb8c6c8e6e1136

2.3.2. Crafting a framework for energy cost accounting

The themes identified during the analysis were subsequently consolidated into a framework that links contextual variables, characteristics of energy cost accounting systems, and their consequences. This framework was developed through an iterative interplay between the empirical insights from the workshops and existing research on cost accounting system design. Prior literature provided initial sensitizing concepts for understanding how contextual factors shape accounting systems, while the workshop data revealed how these factors materialize in the specific setting of energy cost accounting. By comparing emerging themes with established concepts and refining the categories accordingly, the paper distills a set of dimensions that describe how organizations design and operate their energy cost accounting systems and how these design choices affect managerial reality. For purposes of presentation, the finer-grained codes identified in the analysis were consolidated into higher-order reporting bundles that organize the findings into broader patterns of contextual variables, system characteristics, and consequences. This consolidation is reflected in the framework developed in the discussion section.

2.4. Results

The findings of the qualitative investigation show that energy cost accounting is not a uniform technical system, but a context-dependent organizational arrangement. This interpretation emerged from recurring practical concerns raised by the participants across the workshops. Participants did not describe energy cost accounting as a single coherent system designed from first principles. Instead, they spoke, among other things, about result-defining energy costs (Q011), physically constrained production processes (Q003, Q010, Q022), difficult-to-price combined heat and power (CHP) arrangements involving jointly produced energy flows (Q074, Q076, Q094), fragmented responsibilities (Q103, Q104, Q105), Excel-based workarounds and disconnected systems (Q341, Q343, Q344, Q345, Q346), uncertain regulatory and market developments (Q137, Q143, Q146, Q150, Q161), and the difficulty of turning available data into actionable information (Q067, Q068, Q069, Q070).

The findings are organized around three linked sets of higher-order analytical patterns. These patterns aggregate more fine-grained deductive and inductive codes that captured the concrete insights provided by workshop participants. First, contextual variables shaped both the perceived need for energy cost information and the feasible level of accounting sophistication. Second, organizations responded to these contextual variables not by seeking maximum granularity. Instead, workshop participants described situations in which technically available detail had to be scaled back (Q180, Q210), inaccuracy was accepted where greater precision was not considered worthwhile (Q187), and energy costs were represented through combinations of estimates, allocation keys, and existing accounting routines (Q239, Q267, Q288, Q289, Q292). Third, workshop participants described consequences of these energy cost accounting systems mainly through concrete uses of energy cost information. They pointed to budget figures and planning assumptions (Q320, Q327), forecast volumes and procurement responses (Q322, Q333), comparisons between external procurement and internal generation (Q407), subsidy and investment assessments (Q398, Q399), monitoring and improvement processes (Q360, Q397), price calculations and customer explanations (Q406, Q426, Q430), and responsibilities to explain cost spikes or procurement outcomes (Q433, Q438, Q439).

2.4.1. Contextual Variables of Energy Cost Accounting Systems

The first set of findings identifies the contextual variables that shape both the importance of energy cost accounting and the level of sophistication organizations consider feasible. Workshop participants did not describe these contextual variables in abstract terms. Rather, they surfaced them through concrete organizational problems: energy costs that directly affected profitability (Q011, Q019), production processes that could not be flexibly adjusted to electricity prices (Q003, Q010, Q022), decarbonization and sustainability targets that created additional pressure for energy-related information (Q040, Q041, Q050), energy systems in which heat, electricity, steam, and gas were technically intertwined (Q073, Q074, Q076, Q090, Q094), uncertain prices, levies, and regulatory developments that complicated budgeting and investment decisions (Q137, Q143, Q146, Q150, Q161), and organizational settings in which additional measurement or analysis was constrained by manpower and technical capacity (Q024, Q025, Q027). Across cases, these concrete problems translated into markedly different energy-related information demands. Energy cost accounting was therefore shaped not only by the energy intensity of operations, but also by the strategic importance of energy and sustainability, the complexity of the underlying energy supply, the degree of external uncertainty, and the organizational and economic feasibility of developing more sophisticated energy cost accounting systems.

"It is truly result-defining. If energy costs go up, our results are bad and if energy costs are low, our results are good." – EM7 (Q011)

A first pattern, *differentiated energy salience*, is that energy intensity and strategic relevance vary strongly across organizations and subunits. Energy mattered in almost all cases, but not to the same extent or for the same reasons. In some organizations, energy costs were described as a major cost block (Q004, Q012, Q019), a decisive competitive factor (Q047), or even a direct determinant of financial performance (Q011). This was especially evident in energy-intensive industrial settings, where workshop participants emphasized both the profitability implications of energy costs (Q011, Q019) and the limited operational flexibility of core production processes (Q003, Q010, Q022). In other organizations, energy played a smaller role in the overall cost structure (Q002, Q007, Q020), even though it had become more salient in recent years because of volatile prices (Q044, Q048), climate targets (Q040, Q050), or broader external positioning and ESG-related strategic framings (Q034, Q058). Relevance was therefore not binary, but varied across industries (Q006, Q018, Q020), organizations and sites (Q009, Q015), cost objects and products (Q008), and even subunits within the same organization (Q017).

Strategic importance, moreover, was not reducible to cost magnitude alone. For some organizations, energy had long been a routine managerial concern because of its materiality in day-to-day operations (Q037, Q038). For others, the topic had moved into strategic focus more recently because of the energy crisis following the Russian invasion of Ukraine (Q044, Q048, Q159), decarbonization targets (Q040, Q041, Q046, Q050), ESG commitments (Q053, Q058), or pressure from headquarters and group-level targets (Q041, Q051). Several workshop participants described energy strategies as increasingly embedded in a broader balancing of economic viability, supply security, and sustainability (Q042). Taken together, these accounts suggest that organizations cared about energy cost information for different strategic reasons. Some were primarily concerned with cost competitiveness (Q011, Q047), others with transformation and reporting requirements (Q040, Q041, Q058), and many with both at the same time (Q042, Q048, Q050).

“For us, it is quite difficult to determine an exact kilowatt-hour price. If someone wants to know that, I first have to sit down and analyze how much the CHP units actually produced in that month. Simply saying that we generate electricity at, say, 15 cents does not work.” – EM8 (Q074)

A second pattern, *complexity- and uncertainty-driven information demand*, is that energy supply complexity and external uncertainty broaden information requirements. The qualitative data ranged from relatively simple settings with one or two dominant energy carriers (Q084, Q085, Q086) to highly complex configurations involving multiple media (Q079, Q083), heat pumps and co-generation (Q072, Q073), internal generation and external sourcing (Q088, Q092), Power Purchase Agreements (Q091, Q095, Q096), dominant network charges (Q077, Q097), and tightly coupled heat-power-steam relations (Q073, Q090, Q094). In some cases, the same input even served both as feedstock and as energy carrier (Q082). Under such conditions, energy could not be represented as a single, stable, and easily attributable cost figure. Technically intertwined systems required organizations to separate jointly produced flows (Q076, Q094), estimate internal prices (Q074), and distinguish between purchased energy, self-generated energy, and energy embedded in complex site infrastructure (Q072, Q083, Q092). As a result, “the energy cost” often proved much harder to identify and interpret than conventional accounting representations suggest (Q074, Q077, Q078, Q097).

External uncertainty further amplified these information needs, as regulation, reporting obligations, emissions trading, network charges, political instability, and changing market conditions did not merely form a background context. Instead, they actively shaped what organizations wanted and needed from energy cost information (Q136, Q137, Q145, Q153, Q161, Q168). Many respondents emphasized that uncertainty about future prices and levies (Q137, Q146, Q150, Q151), legal requirements and regulation (Q143, Q144, Q145, Q161), and the broader regulatory trajectory (Q138, Q149, Q165) mattered at least as much as current consumption levels. This was particularly visible in budgeting contexts (Q137, Q143, Q146), investment contexts (Q147, Q148, Q151, Q165), and in the implementation of mandatory systems and reporting structures (Q135, Q144, Q157, Q168). Energy cost accounting therefore emerged not only as a means of representing past costs, but also as a response to uncertain future conditions.

"You need the manpower to do this, as well as the appropriate measurement technology. You have to implement load management, and all of that costs money. I thought I could do it myself, but it consumes too much time; it simply isn't feasible." – QM1 (Q027)

A third pattern, *feasibility-bounded system design*, is that organizational arrangements and resource constraints delimit what system designs are feasible. Even when organizations wanted more detailed information, the feasible degree of sophistication was bounded by manpower (Q024, Q025, Q026, Q027), technical infrastructure (Q027, Q031), decision rights (Q023, Q108, Q131), and fragmented responsibilities (Q103, Q104, Q105). Smaller organizations in particular stressed that improved energy cost accounting would require additional staff, measurement technology, and analytical capacity that were simply not available (Q024, Q025, Q027, Q032). Even in larger organizations in the sample, responsibilities were frequently distributed across procurement (Q100, Q130), accounting (Q111, Q127), infrastructure and maintenance (Q106, Q124), energy management (Q114, Q116), and external advisors (Q122, Q123). In some cases, this created bundled competence and short coordination paths (Q112, Q130). In others, it produced fragmentation and a lack of overall view (Q103, Q104, Q105). The findings thus suggest that the design of energy cost accounting systems depends not only on technical possibilities, but also on how expertise, authority, and coordination are organized.

Organizations also applied a clear cost-benefit logic when deciding how much granularity was worth pursuing. More detailed information was not treated as an unconditional ideal. Instead, workshop participants repeatedly assessed whether additional measurement and allocation detail would produce a meaningful managerial benefit. In many cases, they concluded that it would not. When energy costs were comparatively small (Q175, Q183), when product structures were highly variable or campaign-based (Q185), or when processes and organizational structures were too complex to trace in a meaningful way (Q174, Q186), organizations accepted a degree of inaccuracy and intentionally refrained from deeper disaggregation. Some participants also stressed that technically feasible granularity could become administratively excessive (Q180), while others noted that users often did not actually need the level of detail that was theoretically available (Q181, Q182). Granularity was therefore pursued only where expected benefits justified the organizational and technical effort (Q172, Q179, Q180, Q187). Thus, a central finding is that energy cost accounting is shaped not only by technical feasibility, but also by bounded managerial judgments about usefulness.

"The question is: what do I do with this?
Do I simply record it, or do I evaluate and analyze it?
That second step is exactly where things often stall." – EC1 (Q068)

A final pattern, *adequacy-driven redesign pressure*, is that perceived adequacy of current information shaped pressure for redesign. Perceptions of existing energy cost information varied considerably across cases. Some workshop participants reported that they had the information they needed (Q061, Q065) and were broadly satisfied with their existing systems. Others emphasized missing analyses (Q067, Q068), insufficient targeting (Q071), lack of explanatory power (Q059, Q070), delays and insufficient precision (Q062, Q066), or information that did not necessarily translate into analytical meaning (Q060, Q064). Several workshop participants pointed out that the core issue was not always the absence of data, but the difficulty of converting available information into something analytically useful (Q068, Q069, Q070). Perceived adequacy, or inadequacy, thus translates the broader contextual setting into concrete system and design problems and provides a direct bridge to the characteristics of energy cost accounting systems.

2.4.2. Characteristics of Energy Cost Accounting Systems

The second group of findings concerns the characteristics of energy cost accounting systems themselves. When participants described these systems, they rarely presented them as fully integrated or perfectly causal accounting architectures. Instead, they described a patchwork of cost centers (Q218, Q220), metering systems and estimates (Q239, Q240, Q241, Q266), allocation keys (Q267, Q268, Q289, Q290, Q292), Excel files, ERP limitations, manual transfers, and reporting routines (Q341, Q343, Q344, Q345, Q346, Q347). These accounts show that energy cost accounting systems were assembled from multiple technical, accounting, and organizational components rather than designed as coherent systems. Across the cases investigated, these systems were selective, hybrid, and pragmatic rather than fully granular and transparent. They rarely sought to produce a comprehensive, perfectly causal accounting representation of all energy-related flows and costs. Instead, organizations combined direct measurement, estimates, allocation keys, manual workarounds, and established accounting routines in ways that were considered “good enough” for managerial purposes.

“We actually need to step back somewhat from the level of technical granularity we are capable of, so as not to overdo it.” – EM1 (Q210)

A first pattern, *selective granularity*, is that energy cost information was represented with more granularity only where this additional granularity was considered useful. Energy cost accounting systems differed in the level at which energy costs were represented, but granularity typically reflected selective design choices rather than a general move toward maximum granularity. Granularity varied both across organizations and within them. Across organizations, some systems allowed energy cost information to be traced to relatively detailed objects, such as individual orders (Q219), and in some settings even at product level (Q205, Q212). Other systems represented energy costs mainly at more aggregated levels, such as electricity or gas cost centers (Q218, Q220), while further allocation to lower levels either did not occur or remained limited (Q221). Within organizations, granularity was also uneven, as production-related areas could be highly granular, whereas administrative or less decision-relevant areas remained more aggregated (Q209). Detailed technical or operational data therefore did not automatically translate into equally detailed accounting visibility. Instead, organizations chose a level of granularity that reflected perceived managerial needs, technical setup, and the cost-benefit trade-off associated with more detailed information. Granularity was thus selective and purpose-driven, not uniformly maximal (Q210).

“Given the complexity we have here, it is normal that we do not always have perfect measurement results everywhere and that we need to make proper estimates.” – MA10 (Q239)

A second pattern, *pragmatic measurement and allocation*, is that measurement and allocation combined technical sophistication with pragmatic approximation. This was particularly visible in the gap between technical measurement and accounting timeliness. Several organizations reported highly developed measurement infrastructures, including quarter-hour, hourly, or even more fine-grained technical data (Q242, Q243). Some also used additional or redundant meters where comparative measurements were considered useful (Q241). However, such infrastructure did not eliminate estimation, aggregation, or approximation. For instance, in one case, not all facilities delivered daily measurement data, and the remainder had to be estimated (Q266). In others, data were ultimately aggregated into monthly values to generate billable accounting figures (Q240). Workshop participants also emphasized that historically grown infrastructures and heterogeneous technical configurations made interpretation more demanding and prevented perfectly standardized measurement outcomes (Q239). Technically advanced measurement therefore did not automatically produce timely, complete, and fully comparable accounting information.

The same pragmatism was evident in allocation architectures, as energy cost allocation was rarely fully causal and neither purely direct nor purely indirect. Instead, organizations combined direct metering for selected areas where it was considered worthwhile with simplified keys where full causal tracing was either infeasible or not economically justified (Q288, Q290). In some cases, broad pools of energy costs were distributed via area-specific or capacity-based keys (Q267, Q268, Q292). In others, gas or heating costs were allocated by square meter, while electricity was allocated based on approximated consumption (Q289), sometimes using simplified technical assumptions such as a fraction of connected load during operation (Q290). Shared infrastructures and coupled generation technologies further complicated allocation. For instance, organizations using gas turbines to generate both heat and electricity had to separate these flows again through internal allocations, which made the process inherently more complex (Q291). Precision was therefore not absent, but negotiated against effort, feasibility, and managerial relevance.

“The same information is provided to three different places. […]
but in principle it is essentially the same information because these places do not communicate with one another.” – *EM4 (Q347)*

A third pattern, *integration-dependent transparency*, is that energy cost information became transparent only when data were accessible and could be connected across functions and systems. The main weakness in many cases was therefore not the absence of data, but the fragmentation of ownership and system logic across accounting, procurement, production, maintenance, and technical systems. Workshop participants described situations in which relevant information had to be connected manually in Excel (Q341, Q343, Q345), could not easily be transferred across systems because different ERP environments were in use (Q344), was repeatedly reported to multiple recipients that did not communicate with one another (Q347), or was not stored in detailed form in the core accounting system at all (Q346). In such settings, information existed, but it was difficult to combine it into a coherent view of energy-related costs and their causes. Where this fragmentation persisted, organizations struggled to convert information into clear managerial understanding.

At the same time, the data also suggest that stronger integration improves usability, even if it does not eliminate all problems. Where accounting, procurement, and technical functions were more closely linked, workshop participants reported more continuous exchange and shorter coordination paths. In some cases, collaboration around energy-related processes involved daily or weekly interaction among accounting, energy procurement, and technical functions (Q342). In others, deeper visibility into process control systems and technical systems was described as a prerequisite for deriving meaningful triggers and managerial interpretations from energy data (Q340). Better integration also improved internal transparency and made it easier to revisit cost assumptions in concrete cases (Q319). Integration did not solve all problems, but it clearly improved the usability of cost information.

"I cannot define my energy costs in advance. I can state roughly what I need,
but the load profile depends on weather and production levels.
That is impossible to predict." – QM1 (Q332)

A final pattern, *bounded forecasting and planning capability*, is that forecasting and planning are important, but inherently bounded by operational and external uncertainty. Organizations also used energy cost information prospectively. Forecasting and planning capabilities were particularly relevant for budgeting, procurement preparation, internal tariff setting, and investment assessments (Q320, Q326). In some organizations, forecasts for the following year explicitly informed procurement decisions (Q333), and forecast volumes from sites were required for procurement (Q322, Q327). In others, central energy management specified expected price assumptions for the coming year and combined them with plant-level consumption forecasts in a cyclical planning process (Q327), sometimes in close coordination with production planning to forecast the expected load profile (Q321, Q322). At the same time, workshop participants emphasized that these capabilities were inherently bounded. Forecasting was difficult because future consumption and price developments depended on weather, production levels, and broader market developments (Q332, Q334). Some participants stated explicitly that exact gas or electricity needs could not be forecast day by day or hour by hour with sufficient precision for procurement purposes (Q331, Q332). In some organizations, forecasts meaningfully supported procurement and planning decisions (Q327, Q333). In others, forecasting was acknowledged as approximate and only partly reliable (Q331, Q332, Q334). The key finding is therefore not simply whether organizations forecast, but how they do so under conditions of unavoidable uncertainty.

2.4.3. Consequences of Energy Cost Accounting Systems

The third set of findings concerns the consequences of energy cost accounting systems. When participants described these consequences, they did not portray them as direct steering through highly individualized control systems. Rather, they described situations in which energy cost information entered concrete organizational activities. Energy cost accounting mattered where organizations used energy cost information to budget and plan (Q320, Q327), procure and structure energy supply (Q322, Q333, Q407), assess investments (Q398, Q399, Q405), inform pricing and customer discussions (Q406, Q426, Q430), and explain and defend energy-related outcomes (Q433, Q438, Q439). In these accounts, energy cost accounting mattered less because it made all energy consumption visible in a comprehensive control system, and more because it provided a basis for planning, sourcing, explanation, justification, and selected forms of accountability. In this sense, the findings point less to a narrow control story than to a broader steering and justification story.

> *"For us, this is linked to a comprehensive economic analysis based on the cost of procuring external electricity from the grid versus generating it internally." – EM3 (Q407)*

A first pattern, *sourcing- and investment-relevant decision support*, is that energy cost information supports sourcing and renewable investment decisions. This was the clearest practical consequence in the data. Organizations used energy cost information to compare internal and external generation (Q407), evaluate the economic attractiveness of renewable investments over longer time horizons (Q375, Q376), design Power Purchase Agreements and on-site sourcing arrangements (Q383, Q384), and justify broader green sourcing strategies (Q374). In several cases, these decisions were framed not only in terms of short-term cost minimization, but also in relation to supply security, independence, and long-term strategic commitment (Q382, Q383, Q384). Energy cost information therefore did not merely document procurement outcomes after the fact. Rather, it informed how organizations structured sourcing portfolios (Q383, Q384, Q385), assessed renewable investments, and weighed alternative supply arrangements in the first place (Q390).

"Without going into detail, energy costs are part of our price calculation. Prices are adjusted accordingly depending on the product and customer." – EM2 (Q406)

A second pattern, *argumentative decision support*, is that energy cost information supported budgeting, pricing, and broader managerial decision making. Beyond sourcing and investment, workshop participants described using energy cost information to inform price calculations (Q391, Q406), support investment decisions (Q399, Q405), and justify funding applications or machinery-related subsidy decisions (Q398). In some cases, workshop participants stressed that energy cost information mattered because costs, rather than consumption data alone, entered concrete economic decisions (Q406, Q407, Q431). In others, its decision relevance lay in providing a forward-looking basis for managerial assessment, particularly where expected developments in energy and carbon costs shaped the attractiveness of investments (Q399, Q402, Q405). Therefore, the findings suggest that energy cost accounting did not operate merely as a monitoring device. It also functions as an argumentative and decision-support infrastructure through which organizations interpret economic developments and justify decisions.

"I am required to evaluate the main energy consumers and initiate improvements in these areas [...] Through this process, we carry out the optimization." – QM1 (Q360)

A third pattern, *actionability-dependent efficiency effects*, is that efficiency effects arose only when information became operationally actionable. The workshops do not permit strong causal claims about the performance effects of energy cost accounting systems. Even so, the cases consistently suggest that information alone did not improve efficiency. Efficiency consequences emerged only where organizations were able to translate information into concrete operational interventions, technical projects, or investment measures. This was visible, for instance, in projects to recover and use waste heat (Q359, Q361), in structured processes to identify and improve significant energy users (Q352, Q360, Q362), and in much smaller operational interventions ranging from process redesign and scrap reduction to eliminating unnecessary machine use (Q353, Q356, Q365). The underlying mechanism was therefore not simply the existence of more information, but the availability of information that could be turned into specific actions. Where information remained descriptive, compliance-oriented, or insufficiently connected to operational levers, its efficiency effects appeared far more limited (Q357, Q365).

"You have to explain when something is too expensive,
but you never have to explain when it is too cheap." – EP2 (Q438)

A final pattern, *selective and partly incentive-coupled accountability*, is that accountability effects were selective, collective, and only partly incentive-coupled. In some organizations, energy-related responsibility was clearly assigned and linked to explanation duties, formal accountability, or escalation to identifiable management roles (Q432, Q433, Q437, Q438). In such settings, energy cost information created a basis for holding specific actors answerable for procurement outcomes, target implementation, or cost spikes (Q432, Q433, Q438, Q439). At the same time, accountability did not emerge uniformly across cases. Some workshop participants emphasized that responsibility remained collective or case-specific rather than attached to single individuals in any straightforward way (Q434, Q446). Likewise, incentive coupling existed in some settings, for example through management bonus links to sustainability targets (Q448) or group-based rewards for relative energy performance (Q447), or personal energy-related targets at selected managerial levels (Q445, Q450). Other workshop participants, however, explicitly stated that individual incentives to save energy were absent (Q442) or that sustainability targets were not a fixed component of monetary target agreements (Q443, Q451). Energy cost accounting can therefore create accountability, but it does so unevenly, as responsibility may be clear in some domains, diffuse in others, and only partly translated into individualized incentive systems.

2.5. Discussion

The central implication of this study is that energy cost accounting systems are not best understood as systems that become more useful simply by becoming more detailed, but as selective and organizationally embedded responses to distinct energy-related information demands, whose consequences depend on whether the resulting information becomes actionable in practice. Across the workshops, organizations differed in the materiality and strategic importance of energy, the complexity of their supply arrangements, the degree of external uncertainty and compliance pressure they faced, and the organizational resources available to address these issues. In response, they did not build uniformly comprehensive or maximally granular systems. Instead, they developed selective, hybrid, and pragmatic energy cost accounting systems that balanced granularity, feasibility, interpretability, and accountability. The practical value of these energy cost accounting systems, however, depended not only on measurement quality or accounting precision, but also on whether the information was sufficiently accessible, trusted, and linked to concrete responsibilities and decisions. In that sense, the findings extend contingency-based understandings of accounting system design (Chenhall, 2003; Covaleski et al., 1996; Otley, 1980; Waterhouse and Tiessen, 1978) by showing that fit in the domain of energy cost accounting is not merely a technical alignment between contextual variables and information characteristics, but an organizational accomplishment shaped by integration, responsibility and use.

2.5.1. An integrated framework of energy cost accounting practice

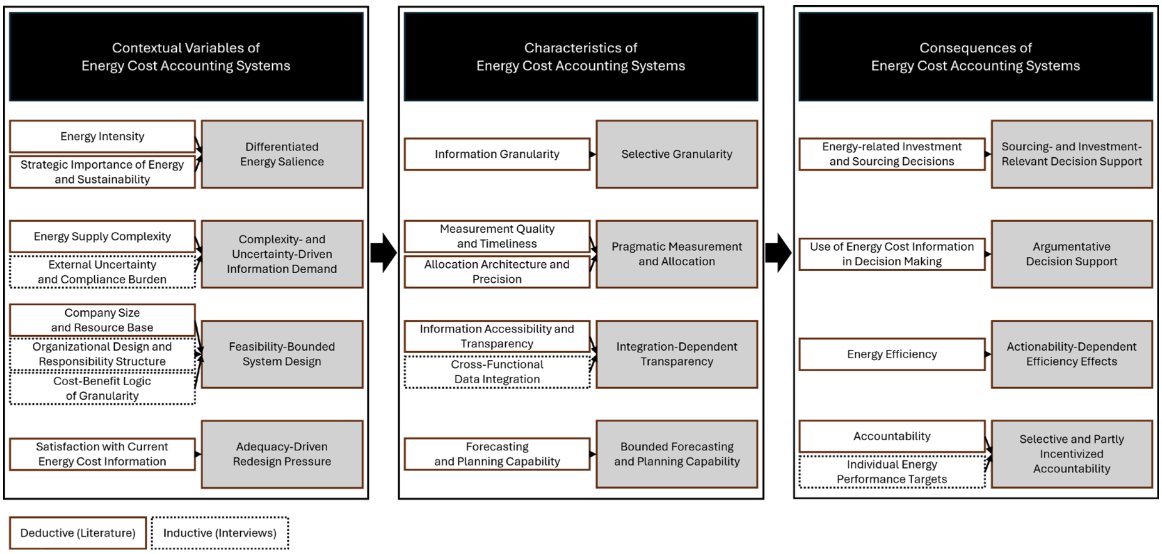

Figure 2-2: Energy cost accounting framework consisting of contextual variables, system design characteristics, and organizational uses and consequences. Solid boxes indicate deductive literature-based codes, while dotted boxes indicate inductively derived codes. Gray boxes indicate higher-order patterns derived from the analysis.

The findings suggest an integrated framework of energy cost accounting practice that links contextual variables, system design characteristics, and organizational uses and consequences, as displayed in Figure 2-2. While Figure 2-1 summarized the literature-based analytical structure, Figure 2-2 specifies how this structure materialized in the empirical setting of energy cost accounting. The framework should not be read as a taxonomy of fixed types. Rather, it is a configurational and process-oriented model that captures how contextual variables generate particular information problems, how organizations respond through specific design choices in their energy cost accounting system, and how these systems in turn shape organizational uses and consequences. This interpretation is important because the findings demonstrate that in line with contingency theory, a simple linear logic in which more detailed information automatically produces better decisions does not work (Gordon and Miller, 1976; Otley, 1980). Instead, different contingencies require different packages of organizational design responses. In this sense, the framework builds on earlier contingency work that rejected one universally appropriate information system (Gordon and Miller, 1976; Otley, 1980), while moving beyond it by showing how different contextual pressures are combined into selective packages of energy cost accounting responses.

The first part of the framework highlights that contingencies create distinct information problems. Where energy intensity is high and energy has strategic relevance, organizations have stronger incentives to observe energy in more differentiated ways. Where energy supply is more complex, for instance due to multiple energy sources, on-site generation, volatile prices, or contractual heterogeneity, organizations require more credible and attributable information. External uncertainty and compliance burden intensify these demands further, because they increase the need to justify decisions and cope with changing reporting requirements. At the same time, organizational resources, technical infrastructure, and responsibility structures influence what degree of accounting sophistication is feasible. In line with contingency theory, the information problem is therefore not uniform across organizations, and neither is the appropriate response (Gordon and Miller, 1976; Hayes, 1977; Waterhouse and Tiessen, 1978).

The second part of the framework shows that organizations respond selectively rather than comprehensively. Specifically, organizations choose where greater informational granularity is worth the effort, where measurement quality and timeliness matter, where more precise allocation is needed, where transparency and accessibility matter most, and where forecasting capability becomes essential. This finding is consistent with classic work on management accounting systems, which has long emphasized that information characteristics affect their usefulness (Chenhall and Morris, 1986; Gordon and Miller, 1976). However, the findings suggest that in the case of energy cost accounting these characteristics are not implemented as an abstract ideal. They are constructed pragmatically around specific organizational problems. What emerges is not a pure or internally uniform system, but a hybrid configuration, which is highly developed in some areas, more aggregated or manual in others, and explicitly shaped by clear cost-benefit considerations. This also resonates with arguments that management control is often better understood as a package of partially coordinated elements than as a single fully integrated system (Otley, 2016).

The final part of the framework shows that the consequences of energy cost accounting systems depend on whether information becomes interpretable and actionable in organizational routines. Specifically, energy cost accounting systems matter when they support investment and sourcing decisions, operational decision making, energy efficiency initiatives, accountability structures, and performance targets. Yet these consequences are not automatic. For that reason, satisfaction with the current energy cost information is better understood as a feedback mechanism than as a classical exogenous contingency. Where actors regard existing information as sufficiently useful, system development may stabilize. Where dissatisfaction persists, further refinement becomes more likely. This introduces a dynamic element into the framework and suggests that energy cost accounting systems evolve through recurrent assessments of practical adequacy rather than through one-off design choices. This dynamic interpretation is consistent with work emphasizing that control packages evolve over time rather than being designed once and for all (Otley, 2016), and with arguments that accounting rules can become resistant to change once embedded in organizational arrangements (Tiessen and Waterhouse, 1983).

2.5.2. Energy cost accounting as contingent and selective organizational response

The core theoretical contribution of the study is therefore to refine how contingency theory is applied to energy cost accounting. Prior contingency research has shown that accounting systems should be designed in relation to contextual circumstances rather than according to universally optimal principles (Chenhall, 2003; Gordon and Miller, 1976; Otley, 1980). Yet this literature is often read as if fit could be captured through relatively discrete alignments between particular contingencies and particular system characteristics. The findings suggest a more configurational view. Multiple contingencies combine, and organizations respond through partial and situated configurations rather than through one-to-one or all-encompassing design solutions (Gordon and Miller, 1976; Otley, 1980), and system fit is mediated by organizational arrangements that shape whether information can actually travel into organizational action. This is also in line with integrated contingency work that models performance as a function of fit between context and accounting-system application rather than as a function of universally superior techniques (Cadez and Guilding, 2008).

This matters especially for how granularity is theorized. Existing work on management accounting systems generally implies that richer and more timely information can enhance decision support, particularly in uncertain and interdependent settings (Chenhall, 2003; Chenhall and Morris, 1986; Gordon and Miller, 1976). The findings extend this view by specifying how organizations determine appropriate granularity in energy cost accounting. Rather than pursuing maximum granularity as a technical ideal, organizations weigh its expected benefits against implementation effort, interpretive burden, data availability, and organizational usability. The relevant design question is therefore not how to maximize informational detail, but how to achieve appropriate granularity for the decisions at hand (Gordon and Miller, 1976). This shifts the discussion from informational sophistication to the organizational economics of accounting design.

The findings also show that organizational embedding is part of system fit. The inductively derived themes make this especially visible. Organizational design and responsibility structure shape who owns energy-related information and who is expected to act on it. Cross-functional data integration determines whether energy cost information remains technically available but practically fragmented, or whether it becomes meaningful across accounting, operations, procurement, and energy management. External uncertainty and compliance burden shape whether systems are built primarily for internal learning, for external defensibility, or for both. Finally, the cost-benefit logic of granularity makes it visible that system design itself is subject to managerial judgement. In this sense, fit is not only between context and information, but also between information and organizational responsibility. This extends more practice-oriented views of accounting by showing that the effects of accounting systems depend on how they are enacted and connected to organizational work, not merely on whether they are technically installed (Ahrens and Chapman, 2004; Covaleski et al., 1996).

2.5.3. Extending the literature on cost accounting system design and environmental management accounting

Another core contribution is to show that energy cost accounting is not a marginal overhead issue within cost accounting, but a strategically significant domain of cost accounting in many organizations. Prior literature has noted that in many organizations energy is purchased from the grid and treated largely as a period cost, with limited internal allocation or managerial visibility (Aflaki et al., 2013; Johansson and Söderström, 2011). Energy cost accounting has therefore often remained underdeveloped relative to its economic significance, despite its relevance for efficiency and decision support (Bierer and Götze, 2012). The findings suggest that this traditional view has become increasingly inadequate. In many of the organizations that participated in the workshops, energy was not merely a background overhead. It had become strategically salient, operationally variable, closely tied to procurement and sourcing, and increasingly connected to sustainability and compliance demands. In some cases, it had become central enough to shape core investment logic and broader organizational priorities.

More broadly, the findings extend the literature on accounting system design by showing that decision usefulness depends not only on information quality, but also on how information becomes accessible, interpretable, and integrated across functions. While the literature highlights information granularity, measurement quality, timeliness, allocation precision, and forecasting capability as important design dimensions, the findings confirm these characteristics, but they also show that their practical value depends on accessibility, transparency, and cross-functional integration. In other words, the issue is not only what information exists, but how it becomes usable (Gordon and Miller, 1976; Otley, 2016). This is an important shift. It suggests that decision usefulness in energy cost accounting depends not simply on better information, but on whether information is organized in ways that support coordination and effective application across organizational settings (Cadez and Guilding, 2008; Gordon and Miller, 1976). In this respect, the study also speaks to environmental management accounting research, which has long argued for better visibility of environmental and energy-related information (Burritt et al., 2002) but has less often examined the organizational conditions under which such information becomes managerially consequential.

A further insight concerns the ambiguous effects of compliance pressure. External uncertainty and compliance burden often stimulated more formalized and better documented systems (Gordon and Miller, 1976). However, they could also orient attention toward reporting, traceability, and defensibility rather than toward learning and experimentation. Once institutionalized, these more formalized accounting arrangements may also acquire stabilizing and enduring roles, which can make them useful for defensibility but less open to experimentation (Tiessen and Waterhouse, 1983). This is an important tension, as it suggests that the same pressures that improve measurement discipline may also narrow the purposes for which systems are used. This point should not be overstated, given the scope of the study, but it helps explain why technically advanced systems do not necessarily become more decision-useful in practice. The contribution here is not that compliance undermines managerial usefulness per se, but that the relationship is contingent and may pull system design in different directions.

2.5.4. From accounting information quality to organizational action

A third core contribution is to clarify how energy cost accounting becomes consequential inside organizations. Information quality alone is insufficient (Covaleski et al., 1996; Otley, 1980), as energy cost information only matters when it travels into decisions, routines, accountability structures, and organizational processes. Its effect is therefore mediated by whether the information is visible, attributable, accepted as organizationally legitimate, and linked to specific organizational responsibilities (Tiessen and Waterhouse, 1983; Waterhouse and Tiessen, 1978). Where energy is strategically important and information is sufficiently granular, energy cost accounting can inform larger investment and sourcing decisions. Under such conditions, organizations are better able to evaluate contractual arrangements, self-generation options, energy efficiency investments, and procurement choices in a more differentiated way. In addition, the findings show that energy cost information becomes consequential when it supports pricing discussions, customer explanations, investment justifications, and the defense of procurement or cost outcomes. Where measurement and allocation are sufficiently precise and timely, energy cost information can also shape day-to-day managerial judgments, for instance by making operational trade-offs visible or by clarifying the cost implications of particular activities. Where information is accessible and integrated across functions, organizations are more likely to translate accounting numbers into coordinated energy efficiency initiatives rather than leaving them as isolated technical reports. Finally, where forecasting capability is developed and information is accepted as credible, energy cost accounting can support accountability structures and target-setting at unit or individual level.

This is where the idea of selective hybridity becomes especially important. Organizations do not build pure systems. Rather, they assemble configurations that are granular in some areas but aggregated in others, technically sophisticated in some dimensions and manual in others, oriented toward some decisions but not all, and shaped by local feasibility as well as organizational politics, which is consistent with contingency arguments against a single universally appropriate system (Gordon and Miller, 1976; Otley, 1980) and package views of management control (Otley, 2016). This also extends arguments that management accounting systems should not be evaluated in isolation, but in terms of how they combine with broader organizational arrangements to produce workable overall effects (Tiessen and Waterhouse, 1983). The practical logic of energy cost accounting is therefore not optimization through comprehensiveness, but selectivity through workable compromise. That insight fits the broader spirit of contingency theory, but also sharpens it. What matters is not the existence of a single best system, but the extent to which a given configuration produces actionable information for a particular organizational setting.

2.5.5. Implications, limitations, and future research

The practical implication of this study is that managers should design energy cost accounting from decision problems outward, rather than from a general ambition for maximum detail. Managers should not primarily ask how to build the most detailed possible energy cost accounting system. Instead, they should ask which decisions require better energy cost information, where greater granularity is worth the effort, who needs access to energy cost information, and how responsibilities should be aligned with the information provided. In practical terms this means starting from decision problems rather than from data availability, investing selectively in granularity and precision where the stakes are highest, and ensuring cross-functional integration so that information can actually travel into action.

The study has several limitations that qualify the interpretation and generalizability of the findings. First, the workshop design itself captures perceptions, practices and organizational reasoning, but it does not directly measure performance effects. The paper can show how participants understand and use energy cost accounting, but not whether particular system configurations lead to superior outcomes. Moreover, because the data were generated in group settings, the discussions may have been shaped by dominant voices, cross-functional self-presentation, or social desirability, potentially suppressing more critical or sensitive views. Second, the findings are grounded in a specific institutional and regulatory context, especially the German context, where energy price dynamics, reporting requirements, and sustainability pressures may be particularly important. Third, the evidence is essentially cross-sectional and cannot fully capture how energy cost accounting systems evolve over time (Otley, 2016). Finally, although all LLM-assisted transcription, coding, anonymization, and translation outputs were manually reviewed, the use of tool-supported qualitative analysis may still have influenced how the empirical material was organized and represented.

These limitations point to several promising directions for future research. First, longitudinal studies could examine how energy cost accounting systems change after regulatory shocks, energy market volatility, or major investments in infrastructure. Second, comparative studies across industries and countries could investigate more systematically how price pressure, supply complexity, and institutional context shape the design of these systems. Third, future research could examine when compliance-oriented systems become managerially useful and when they remain primarily reporting devices. Fourth, another fruitful direction would be to link specific configurations of energy cost accounting more directly to organizational outcomes. Finally, research should connect energy cost accounting and carbon accounting more explicitly, especially as organizations increasingly face the challenge of integrating financial and emissions-related information into one coherent system.

2.6. Appendix A: Development and operationalization of the codebook

This appendix documents both the development and the operationalization of the codebook used for the qualitative analysis. Sections 2.6.1 to 2.6.3 provide the conceptual and literature-based grounding of the coding categories. These sections explain how the categories were derived and theoretically anchored, but they do not constitute the operational codebook itself. Section 2.6.4 presents the operational codebook used during coding, including inclusion criteria, exclusion criteria, and typical indicators for each code.

2.6.1. Contextual variables of energy cost accounting systems: Conceptual grounding of codes

To understand why energy cost accounting systems differ across organizations, it is necessary to examine the factors that may explain their design and development. In many organizations, existing management accounting systems were not originally built to provide detailed energy cost information. Revising such systems can therefore require substantial organizational effort, technical adaptation, and investment, while the expected benefits may initially remain uncertain. Identifying the variables that help explain current system characteristics is therefore important for understanding energy cost accounting in practice and for revealing where organizational change may be needed.

Building on prior cost accounting and contingency-based research, five literature-based variables that may explain variation in energy cost accounting systems are distinguished: **energy intensity**, **company size and resource base**, **strategic importance of energy and sustainability**, **satisfaction with current energy cost information**, and **energy supply complexity**. An overview of these variables and their relationship to related concepts in prior research is presented in Table 2-2. In addition, three variables emerged from the inductive coding and are therefore discussed separately after the literature-based variables: **organizational design and responsibility structure**, **external uncertainty and compliance burden**, and **cost-benefit logic of granularity**.

Term and Definition	Related Term	Source	Definition or Usage of Term
Energy intensity *The extent to which an organization's activities depend on energy consumption and incur energy-related costs.*	Intensity of competition	Khandwalla, 1972	The term was used to investigate the effect of intense competition. For this purpose, CEOs rated the intensity of price competition and competition in promotion and distribution on a 7-point Likert scale in a survey.
	Monitoring intensity	Simons, 1987	The term was used to name an example of control system attributes.
	Work intensity	Balakrishnan et al., 2012b	The term was used as a potential phenomenon that could change the degree of management control.
Company size and resource base *The scale of the organization and the financial, human, and technical resources available to develop and maintain energy cost accounting.*	Company size	Bjørnenak, 1997	The term referred to the number of employees and was used for an investigation of the adoption and sophistication of ABC systems.
	Size	Davila, 2005	The term referred to the number of employees and was used to investigate the influence of the emergence of management control systems in growing firms.
	Size	Innes and Mitchell, 1995	The term referred to the turnover per year and was used to classify companies. Afterwards, the usage of ABC systems among British companies was analyzed.
	Size of organization	Al-Omiri and Drury, 2007	The term referred to the annual sales turnover and was investigated as a factor influencing the choice and sophistication of product costing systems.
Strategic importance of energy and sustainability *The extent to which energy management and sustainability objectives are prioritized in the organization's strategy and decision-making.*	Importance of cost accounting information in making decisions	Boyd and Cox, 2002	The term was measured in a survey using a Likert scale (1 to 5) on how important cost information is for certain decisions.
	Importance of cost information	Al-Omiri and Drury, 2007	The term was used for an empirical investigation on factors influencing the choice and sophistication of product costing systems
	Importance of cost information to management	Hoque, 2000	The term was used as an outcome of just-in-time production systems and automated manufacturing systems.

Term and Definition	Related Term	Source	Definition or Usage of Term
Satisfaction with current energy cost information *The extent to which decision makers perceive existing energy cost information as adequate, reliable, and useful for their needs.*	Satisfaction	Chenhall, 2003	The term was used in the description outcomes of a management control system.
	Satisfaction	Friedl et al., 2009	The term was empirically investigated as 'general' satisfaction with cost accounting systems among German companies.
	Satisfaction with information	Abernethy et al., 2001	The term was used for an investigation on managerial satisfaction with the information provided by a costing system.
	User satisfaction	Chang et al., 2003	The term was used for an empirical investigation of accounting system performance. The term was measured by several measurement items using a Likert scale from 1 to 7.
Energy supply complexity *The complexity of the organization's energy supply arising from the variety of energy carriers, sources, suppliers, contracts, and self-generation arrangements.*	Energy Mix	Augutis et al., 2015	The term was used as a description for the combination of different energy sources with the goal of optimizing towards secure energy supply.
	Energy Mix	Díaz et al., 2019	The term was used as a description for the combination of different energy sources with the goal of analyzing implication on economic growth.
	Renewable Energy Mix	Agustina et al., 2023	The term was used as the fraction of the total energy supply in the case country that was generated through renewable sources.

Table 2-2: Comparison of the terminology of variables explaining the energy cost accounting systems and related concepts used in prior research. Most papers do not provide an explicit definition of the term. In such a case, the table describes how the term is used or applied or for which purpose it is used

2.6.1.1. Energy intensity

Energy intensity refers to the extent to which an organization's activities depend on energy consumption and incur energy-related costs. *Energy intensity* in the context of energy cost accounting is defined as "the extent to which an organization's activities depend on energy consumption and incur energy-related costs".

This *energy intensity* is usually measured by a denominator in economic terms (Phylipsen et al., 1997). Key figures or ratios like kWh/€ can help to identify crucial points. Therefore, access to reliable and detailed information on energy consumption and the costs occurring through this consumption is necessary. The literature provides similar approaches trying to explain cost accounting phenomena on intensity-based variables like work intensity (Balakrishnan et al., 2012a), monitoring intensity (Simons, 1987) or intensity of competition (Khandwalla, 1972). It is in the nature of things that energy intensity increases with rising energy consumption. Hence, more energy-intensive organizations experience higher incentives to engage with their energy cost accounting.

2.6.1.2. Company size and resource base

Company size and resource base refer to the scale of the organization and the financial, human, and technical resources available to develop and maintain energy cost accounting. *Company size and resource base* in the context of energy cost accounting is defined as “the scale of the organization and the financial, human, and technical resources available to develop and maintain energy cost accounting”.

This variable is relevant because more sophisticated energy cost accounting systems typically require dedicated personnel, technical infrastructure, data management capabilities, and managerial attention. In the literature, various scholars (e.g., Al-Omiri and Drury, 2007; Bjørnenak, 1997; Chenhall and Morris, 1986; Davila, 2005; Innes and Mitchell, 1995; Tregidga and Laine, 2021) explained accounting phenomena based on company size. The literature distinguishes size in terms of monetary-based values like annual turnover (Innes and Mitchell, 1995) or non-monetary-based values like the number of employees (Davila, 2005). In general, the more established a company is and the bigger its size, the more complex, detailed and implemented its cost accounting system is (Davila, 2005). In the context of energy cost accounting, size matters not only because it reflects organizational scale, but also because it often coincides with a broader resource base that makes more detailed measurement, allocation, reporting, and system maintenance feasible.

2.6.1.3. Strategic importance of energy and sustainability

Strategic importance of energy and sustainability refers to the extent to which energy management and sustainability objectives are prioritized in the organization’s strategy and decision-making. *Strategic importance of energy and sustainability* in the context of energy cost accounting is defined as “the extent to which energy management and sustainability objectives are prioritized in the organization’s strategy and decision-making”.

This variable is relevant because organizations are more likely to invest in more detailed and decision-useful energy cost information when energy and sustainability are treated as strategically important. Some scholars in the literature investigated the importance of cost information in different settings. Boyd and Cox (2002) investigated the importance of cost accounting information on decision making empirically in a survey among companies in the United States. Al-Omiri and Drury (2007) explained their concept of cost system sophistication using the importance of cost information. Hoque (2000) showed a significant impact of cost information importance on managerial decisions. Research on sustainability strategy similarly shows that sustainability goals shape organizational priorities, strategic processes, and information needs. Gosselin (1997) stated that the strategy sets the need for cost management information, especially for companies in a competitive context. In a study conducted by Unruh et al. (2016), nearly 90% of the respondents said that a sustainability strategy is essential to remain competitive. So, the specific characteristics of the energy cost accounting system, and the information it generates, should be shaped to satisfy the information needs of the strategy, as accounting information should be designed to support a chosen strategy (Baines and Langfield-Smith, 2003). Energy cost information is crucial for sustainability strategies as it can be easily monetized (Gunarathne and Lee, 2019). The literature investigated the integration of sustainability goals in corporate strategy (Peters and Simaens, 2020) and factors influencing corporate sustainability goals and their success (Rodrigues and Franco, 2019). In the context of energy cost accounting, organizations that assign greater strategic importance to energy and sustainability should therefore be more likely to develop more advanced energy-related accounting practices.

2.6.1.4. Satisfaction with current energy cost information

The *satisfaction with current energy cost information* has a pivotal role in explaining the characteristics of an energy cost accounting system, with level of satisfaction influencing the rate of change or implementation of more detailed systems. *Satisfaction with current energy cost information* in the context of energy cost accounting is defined as “the extent to which decision makers perceive existing energy cost information as adequate, reliable, and useful for their needs”.

Previous explanations in cost accounting literature dealt with the satisfaction with costing system choices (Abernethy et al., 2001), the general satisfaction with the management accounting system (Chenhall, 2003), or user satisfaction (Chang et al., 2003). Friedl et al. (2009) investigated the satisfaction with cost accounting information empirically in a survey among German companies. If people are satisfied, they are less likely to question their existing energy cost accounting system and accelerate a change of it (Anderson, 1995). So, the characteristics of an energy cost accounting system are influenced by the satisfaction of its user’s information need. The other way around, decision makers being unsatisfied can accelerate the implementation of a more detailed energy cost accounting system.

2.6.1.5. Energy supply complexity

Energy supply complexity refers to the complexity of the organization's energy supply arising from the variety of energy carriers, sources, suppliers, contracts, and self-generation arrangements. *Energy supply complexity* in the context of energy cost accounting is defined as "the complexity of the organization's energy supply arising from the variety of energy carriers, sources, suppliers, contracts, and self-generation arrangements".

This variable is relevant because organizations differ considerably in the complexity of their energy supply. Some rely on a single externally purchased energy source, whereas others operate with multiple energy carriers, several suppliers, varying procurement arrangements, and self-generation technologies. Prior literature discusses related issues under the label of energy mix, typically referring to the combination of energy sources and carriers (Augutis et al., 2015; Díaz et al., 2019; Agustina et al., 2023). In the present context, however, the explanatory issue is broader than the composition of energy sources alone. What matters is the overall complexity of sourcing, procurement, and coordination, which is likely to increase both the informational demands placed on the accounting system and the difficulty of integrating energy-related information into a coherent cost structure.

2.6.1.6. Organizational design and responsibility structure

This variable emerged from the inductive coding and is therefore not included in Table 2-2. *Organizational design and responsibility structure* is defined as "the way energy-related decision rights, responsibilities, and coordination mechanisms are distributed across organizational actors and units".

This variable captures whether energy-related responsibilities are centralized or decentralized, who holds decision rights, and how departments coordinate on energy-related issues. It is distinct from accountability as a consequence of the accounting system. The focus here is not on whether individuals are evaluated through the information produced by the system, but on how responsibility for energy-related decisions is structurally organized within the organization. This organizational design can shape what type of information is needed, at what level it is required, and how strongly energy issues are coordinated across functions. Relevant theoretical anchors can be found in contingency-based work on organizational structure, decentralization, and information needs (Chenhall, 2003; Chenhall and Morris, 1986; Tiessen and Waterhouse, 1983).

2.6.1.7. External uncertainty and compliance burden

This variable emerged from the inductive coding and is therefore not included in Table 2-2. *External uncertainty and compliance burden* is defined as “the degree to which changing external conditions and regulatory requirements create uncertainty or administrative burdens for energy-related decisions and accounting”.

This variable captures external contingencies such as changing regulation, technological uncertainty, certification requirements, reporting obligations, and compliance processes imposed by regulators, grid operators, or other external stakeholders. It is distinct from forecasting and planning capability, which refers to an internal characteristic of the accounting system. The issue here is not whether the system itself can generate forecasts, but whether external uncertainty and compliance demands shape organizations’ incentives and capacity to develop energy-related accounting practices. Such pressures may increase the need for better information while also consuming organizational resources. This logic is consistent with contingency-based work on contextual uncertainty and external contingencies (Chenhall, 2003; Otley, 2016), as well as research on barriers to energy-related organizational change (Thollander and Ottosson, 2008).

2.6.1.8. Cost-benefit logic of granularity

This variable emerged from the inductive coding and is therefore not included in Table 2-2. *Cost-benefit logic of granularity* is defined as “the extent to which the level of detail in energy cost accounting is shaped by perceived trade-offs between informational benefits and implementation costs”.

This variable reflects the idea that more detailed information is not costless. Increasing granularity often requires additional meters, interfaces, data processing, IT infrastructure, and organizational effort. Organizations therefore do not necessarily pursue the highest possible level of detail, but rather a level that appears justified by its expected usefulness. This logic is consistent with contingency theory, which treats accounting system design as dependent on context and on the balance between the benefits and costs of information (Chenhall, 2003; Otley, 2016). It also aligns with research on physical allocation and measurement choices in energy-related settings (Backlund et al., 2012b), as well as with more recent work highlighting the complexity of integrating energy data into accounting systems (Ashabi et al., 2024).

2.6.2. Characteristics of energy cost accounting systems: Conceptual grounding of codes

In this section, the focus is on the characteristics of a company's energy cost accounting, namely the **information granularity**, **measurement quality and timeliness**, **allocation architecture and precision**, **information accessibility and transparency**, **forecasting and planning capability**, and **cross-functional data integration**. Previous studies have examined characteristics of cost accounting systems in broader terms. Building on this literature, related concepts and terminology are used to describe five literature-based characteristics of energy cost accounting systems. An overview of these literature-based characteristics and their relationship to terminology used in prior cost accounting research is presented in Table 2-3. Cross-functional data integration emerged from the inductive coding and is therefore discussed separately after the literature-based characteristics.

Term and Definition	Related Terms	Sources	Definition or Usage of Term
Information granularity *The levels at which energy cost information is available.*	Level of aggregation	Chenhall and Morris, 1986	The term referred to aggregating cost information across time periods or areas such as cost centers, often summarized in formats aligned with formal decision models like discounted cash flow analysis.
	Level of detail	Cohen and Kaimenaki, 2011	The term was used for the aggregation of cost information around periods of time or areas of interest such as cost centers.
	Levels	Feltham, 1977	The term was used to describe levels on which aggregation of cost information takes place.

Term and Definition	Related Term	Source	Definition or Usage of Term
Measurement quality and timeliness *The quality, frequency, and recency of energy-related measurements and cost information.*	Accuracy	Cohen and Kaimenaki, 2011	The term was used to describe the extent of detailed information and the ability to disaggregate costs.
	Accuracy	Hilton, 1979	The term is used to indicate the degree to which cost information reflects reality.
	Timeliness	Bouwens and Abernethy, 2000	*"Timeliness is conceptualized in […] two sub-dimensions: frequency of reporting and speed of reporting. Frequency refers to how often information is provided to managers while speed pertains to the time lag between when a manager requests information and when it is made available". (p. 224)*
	Timeliness	Chang et al., 2003	The term refers to the provision of information on request and the frequency of that information provision.
	Timeliness	Chenhall and Morris, 1986	The term reflects the speed and frequency of information provision.
	Timeliness	Cohen and Kaimenaki, 2011	The term describes the frequency of cost information provision and whether it is regularly or upon request.
	Timeliness	Fong and Quaddus, 2010	*"The timeliness […] is divided into frequency and speed of reporting." (p. 158)*
	Timeliness	Hilton, 1979	The term describes the frequency of cost information provision and the time necessary to generate cost information.
	Timeliness	Pedroso et al., 2020	The term is used to describe the frequency and speed of reporting.
Allocation architecture and precision *How energy costs are structurally collected and allocated, and how accurately those allocations reflect actual consumption.*	Precision	Friedl et al., 2009	The term is named as an important factor for cost accounting systems in a survey among German companies without any further description of the concept.
	Precision	Wright, 1983	The term is used as a measure for statistical precision by looking at the difference between cost allocation and measurement.

Term and Definition	Related Term	Source	Definition or Usage of Term
Information accessibility and transparency *The extent to which energy cost information is visible, understandable, and accessible across organizational levels and stages of the production process.*	Cost Transparency	Friedl et al., 2009	The term is named as an important benefit of an elaborated cost accounting system in a survey among German companies without any further description of the concept.
	Transparency of costs	Balakrishnan et al., 2012b	The term is mentioned as a result of an increased traceability.
Forecasting and planning capability *The extent to which the energy cost accounting system supports forward-looking estimation, forecasting, simulation, or planning.*	Planning	Balachandran et al., 1997	The term is used as different simulations were held to characterize the performance of capacity planning.
	Planning	Balakrishnan et al., 2012a	The term is used as product costs are used as decision aids for planning purposes.

Table 2-3: Comparison of the terminology to describe the characteristics of an energy cost accounting system and the terminology used in previous studies on cost accounting systems. Most papers do not provide an explicit definition of the term. In such a case, the table describes how the term is used or applied or for which purpose it is used

2.6.2.1. Information granularity

Information granularity reflects the number of levels at which energy cost information is available and is a central characteristic of the comprehensiveness of an energy cost accounting system. *Information granularity* in the context of energy cost accounting is defined as “the levels at which energy cost information is available”.

Possible examples for a level that mirrors this *information granularity* of an energy cost accounting system could be a whole production site, a single department within this site, a specific machine running in the department, or a specific batch of produced units on that machine at which information on energy consumption and its corresponding cost is gathered and available. This translates to the level (Feltham, 1977), level of detail (Cohen and Kaimenaki, 2011), or level of aggregation (Chenhall and Morris, 1986) of a management accounting system described by several scholars in the literature. Their interpretation of the concept describes the number of points in an organization at which specific information aggregation occurs. Cohen and Kaimenaki (2011) conclude that a higher level of detail provides a clearer and more realistic view of costs. Moreover, the quality of cost accounting information can be improved by such an increase in the level of detail (Friedl et al., 2009).

2.6.2.2. Measurement quality and timeliness

The *measurement quality and timeliness* of the energy cost accounting reflects how reliable, frequent, and up-to-date energy-related measurements and cost information are. *Measurement quality and timeliness* in the context of energy cost accounting is defined as "the quality, frequency, and recency of energy-related measurement and cost information".

Prior cost accounting research discusses related ideas under the labels of accuracy and timeliness. Accuracy refers to the extent to which cost information reflects reality, whereas timeliness refers to the frequency and speed with which information is made available. Prior studies use both concepts when discussing the quality and availability of cost information (Chang et al., 2003; Chenhall and Morris, 1986; Cohen and Kaimenaki, 2011; Hilton, 1979; Pedroso et al., 2020). The frequency of information provision deals with the degree to which information is available on a regular basis (Cohen and Kaimenaki, 2011) and in which specific frequency or interval (Chenhall and Morris, 1986). Consequently, a higher frequency reflects a more up-to-date and reliable estimation of costs (Cohen and Kaimenaki, 2011). In addition to that, Hilton (1979) highlights the influence of measurement on a cost accounting's accuracy.

2.6.2.3. Allocation architecture and precision

Allocation architecture and precision describe how energy costs are structurally collected and allocated within the organization and how accurately these allocations reflect actual consumption. *Allocation architecture and precision* in the context of energy cost accounting is defined as "how energy costs are structurally collected and allocated, and how accurately those allocations reflect actual consumption".

Wright (1983) interpreted *precision* in a cost accounting system as statistical measure of how well an allocation base fits. First stage allocation is of importance for the *precision*, as the split incentive problem can arise, meaning that managers of cost centers are less motivated to work efficiently with energy if energy costs are allocated based on imprecise measures (Thollander and Ottosson, 2010). Such a lack of a first stage energy cost-allocation spoils the improvement of a company's energy efficiency (Backlund et al., 2012b). Moreover, an imprecise allocation can lead to costing errors (Wright, 1983). In addition to that, the precision of the second stage allocation is crucial for the meaningfulness of energy information on the level of products or services a company is offering and selling to its customers as this second-stage allocation sets the "energy-ingredient" of a product or service price. Hence, second stage allocation determines the quality of the cost information through the allocation (Fernandes et al., 1997).

2.6.2.4. Information accessibility and transparency

Information accessibility and transparency refer to the extent to which energy cost information is visible, understandable, and accessible across organizational levels and stages of the production process. *Information accessibility and transparency* in the context of energy cost accounting is defined as "the extent to which energy cost information is visible, understandable, and accessible across organizational levels and stages of the production process".

For instance, the availability of energy cost information to a certain department or responsible employees. In a survey among German companies, cost transparency for indirect costs – as energy costs are to a lot of companies – was identified as one of the main purposes a cost accounting system should fulfil (Friedl et al., 2009). Moreover, the access to information at different levels of an organization and its importance was highlighted in the literature (e.g., Burritt et al., 2021; Nielsen and Madsen, 2009). The availability of detailed information and access to them saves managers' time as they don't spend it gathering each time they have to make a decision (Cohen and Kaimenaki, 2011).

2.6.2.5. Forecasting and planning capability

Beyond documenting past energy use and costs, an energy cost accounting system can also support *forecasting and planning capability*. *Forecasting and planning capability* in the context of energy cost accounting is defined as "the extent to which the energy cost accounting system supports forward-looking estimation, forecasting, simulation, or planning".

A cost accounting system is traditionally designed to understand the available data and make use of this information (Balakrishnan et al., 2012b, 2012a). However, cost accounting systems do not solely focus on the description of events that previously happened in the production but also come up with forecasts for the future. Previous investigations dealt with such predictive capabilities for instance in the context of capacity planning (Balachandran et al., 1997; Balakrishnan et al., 2012b), the identification of unused resources (Balakrishnan et al., 2012a), or more recently carbon information (Glenk, 2024). In the context of energy cost accounting, these predictions can be used for various occasions in a company like production planning or scheduling, avoiding energy consumption peaks, or simply estimating future energy costs.

2.6.2.6. Cross-functional data integration

This characteristic emerged from the inductive coding and is therefore not included in the table at the beginning of the section. *Cross-functional data integration* is defined as "the extent to which energy-related data is linked across functions and systems such as procurement, production, ERP, accounting, and controlling". Cross-functional data integration differs from information accessibility and transparency. Whereas transparency concerns whether information is visible and usable, cross-functional data integration concerns whether relevant data from different functions and systems are technically and organizationally connected. An anchor in the literature is Ashabi et al. (2024) on the disconnection between energy data and cost accounting systems

2.6.3. Consequences of energy cost accounting systems: Conceptual grounding of codes

To understand the implications of energy cost accounting systems, it is necessary to examine the organizational consequences they may produce. Energy cost accounting not only describes energy-related costs and consumption, but may also shape decision-making, efficiency improvements, sourcing and investment choices, and accountability structures. Building on prior research, four literature-based consequences of energy cost accounting systems are distinguished: **energy efficiency**, **energy-related investment and sourcing decisions**, **use of energy cost information in decision making**, and **accountability**. An overview of these consequences and their relationship to related concepts in prior research is presented in Table 2-4. In addition, one consequence, **individual energy performance targets**, emerged from the inductive coding and is therefore discussed separately after the literature-based consequences.

Term and Definition	Related Term	Source	Definition or Usage of Term
Energy Efficiency	Energy Efficiency	Directive 2012/27/EU	*"The ratio of the output of goods or services and the input of energy" (p.10)*
The ability to optimize the use of energy to provide the same level of output.	Energy Efficiency	Schmidt et al., 2016	The term is used in an investigation of KPIs to measure the efficient use of energy.
	Energy Efficiency	Thollander and Ottosson, 2008	The term is used in a case study on measures for an efficient application of energy.
Energy sourcing and renewable investment decisions	Renewable Energy Consumption	Amri, 2019	The term is used to measure the total consumption of energy generated by renewables.
The extent to which energy cost information influences decisions on energy sourcing, self-generation, renewable energy adoption, and related energy investments	Renewable Energy Mix	Agustina et al., 2023	The term was used as the fraction of the total energy supply in the case country that was generated through renewable sources.
	Renewable Mix	Díaz et al., 2019	The term was used as a description for the combination of different sources of renewable energy.
Use of energy cost information in decision making	Decisions cost accounting information is used for	Boyd and Cox, 2002	The term was used in an empirical investigation of decisions, cost accounting information is used for making the decision.
An organization's understanding of energy cost information and the utilization of this knowledge for decision making.	Use of Cost Accounting Systems	Friedl et al., 2009	The term was used in an empirical investigation among German enterprises for application fields influenced by cost accounting information.
Accountability	Accountability	Gray, 1992	The term was used to emphasize how employees and management can be identified for companies actions.
The obligation of individuals within an organization to be answerable for their actions on energy related topics.	Environmental accountability	Clune and O'Dwyer, 2020	The term was used in an investigation of how mechanisms for environmental accountability embeds within the field of investment.

Table 2-4: Comparison of the terminology of consequences arising from the energy cost accounting system and related concepts used in prior research. Most papers do not provide an explicit definition of the term. In such a case, the table describes how the term is used or applied or for which purpose it is used

2.6.3.1. Energy efficiency

Energy efficiency refers to the ability to optimize energy use while maintaining a given level of output. *Energy efficiency* in the context of energy cost accounting is defined as "the ability to optimize energy use while maintaining a given level of output".

Energy efficiency is a relevant consequence because more developed energy cost accounting systems can make energy consumption more visible, attributable, and actionable. When energy costs are measured and allocated in a more detailed, accurate, and transparent way, managers are more likely to identify inefficiencies and respond to them. Prior literature defines energy efficiency as the relationship between energy input and the resulting output of goods or services (European Parliament, 2012; Schmidt et al., 2016; Thollander and Ottosson, 2008). Research also suggests that more detailed energy information, for example through sub-metering, can contribute to more efficient energy use by making consumption patterns visible and can create incentives for improvement (Backlund et al., 2012b; Bunse et al., 2011; Dewees and Tombe, 2011).

2.6.3.2. Energy sourcing and renewable investment decisions

Energy sourcing and renewable investment decisions refer to the extent to which energy cost information influences decisions on energy sourcing, self-generation, renewable energy adoption, and related energy investments. *Energy sourcing and renewable investment decisions* in the context of energy cost accounting is defined as "the extent to which energy cost information influences decisions on energy sourcing, self-generation, renewable energy adoption, and related energy investments".

This consequence is relevant because energy cost accounting can shape whether alternative sourcing options and energy-related investments become visible, understandable, and economically assessable to decision makers. More detailed energy cost information may increase awareness of current consumption patterns, cost structures, and the economic implications of different sourcing arrangements, including self-generation and renewable energy options. Prior literature has examined such developments in terms of renewable energy consumption, renewable energy mix, or the share of energy demand covered by renewable sources (Agustina et al., 2023; Amri, 2019; Díaz et al., 2019). In organizational settings, energy cost accounting may therefore act as either a driver or a barrier to energy-related investment and sourcing change, depending on whether it enables managers to assess the costs and benefits of such decisions (Mickovic and Wouters, 2020).

2.6.3.3. Use of energy cost information in decision making

Use of energy cost information in decision making refers to the extent to which energy cost information is used to support managerial and operational decisions. *Use of energy cost information in decision making* in the context of energy cost accounting is defined as "the extent to which energy cost information is used to support managerial and operational decisions".

This consequence is relevant because the practical value of an energy cost accounting system depends not only on what information it produces, but also on whether that information is actually used. Prior research shows that cost accounting information can support decisions such as pricing, planning, investment, and cost control (Baines and Langfield-Smith, 2003; Boyd and Cox, 2002; Friedl et al., 2009). In the context of energy cost accounting, such information may be used in areas such as internal reporting, cost analysis, production planning, energy scheduling, or investment appraisal. The extent to which energy cost information shapes such decisions is therefore an important consequence of the accounting system itself. This logic is also consistent with evidence that structured and coordinated information facilitates managerial decisions (Bloomfield et al., 2015).

2.6.3.4. Accountability

Accountability refers to the extent to which individuals or organizational units are held answerable for energy-related actions and outcomes. *Accountability* in the context of energy cost accounting is defined as "the extent to which individuals or organizational units are held answerable for energy-related actions and outcomes".

It would also be conceivable that the information an energy cost accounting system is providing is used to hold people accountable. Such accountability can increase organizational transparency as the number of information which are visible is increased (Gray, 1992). Moreover, in light of a company-wide sustainability strategy, it is easily imaginable that managers have to commit to (more or less individual) sustainability goals. Clune and O'Dwyer (2020) conducted a series of extensive interviews among practitioners in the Netherlands to investigate mechanisms for environmental accountability. In addition, individuals may translate abstract long-run goals into more concrete and immediate subgoals (Thomas, 2016), which also supports the idea of holding people accountable for their behavior towards the usage of energy. Such accountability may apply to individual managers, teams, departments, or other organizational units.

2.6.3.5. Individual energy performance targets

This consequence emerged from the inductive coding and is therefore not included in Table 2-4. *Individual energy performance targets* is defined as "the extent to which energy-related performance goals are formally assigned to individuals or organizational units and used for evaluation or incentives”.

This consequence goes beyond general accountability, which refers broadly to answerability for energy-related actions and outcomes, individual energy performance targets capture a more specific motivational mechanism: the formal assignment of measurable energy-related goals to individuals or units. These targets may, for example, be linked to cost reduction, consumption reduction, efficiency goals, or broader sustainability objectives. This logic is consistent with research on accountability, motivational control, and performance measurement in management accounting (Chenhall, 2003; Gray, 1992; Hayes, 1977). In this sense, energy cost accounting can contribute not only to making energy-related performance visible, but also to energy-related objectives in formal evaluation and incentive structures.

2.6.4. Operational codebook used for coding

2.6.4.1. Operational codebook for contextual variables of energy cost accounting systems

Variable	Include when the text refers to…	Exclude when the text refers to…	Typical indicators / examples
Energy intensity	the extent to which operations depend on energy use or incur substantial energy-related costs	efficiency outcomes or specific accounting characteristics themselves	high energy use, energy cost share, kWh per €, energy-intensive production, major energy cost exposure
Company size and resource base	organizational scale or available financial, human, and technical resources for developing energy cost accounting	the accounting system's actual sophistication itself	number of employees, turnover, budget, staff capacity, IT resources, technical capabilities, controlling capacity
Strategic importance of energy and sustainability	the degree to which energy and sustainability are prioritized in strategy and decision-making	concrete consequences such as accountability targets unless the emphasis is strategic priority	strategic priority, sustainability strategy, management attention, importance of cost information, competitive relevance, explicit energy goals
Satisfaction with current energy cost information	decision makers' satisfaction or dissatisfaction with existing energy cost information	objective information quality unless the text clearly refers to perceived adequacy/usefulness	satisfaction, dissatisfaction, perceived adequacy, usefulness, frustration with current information, unmet information needs
Energy supply complexity	complexity arising from multiple energy carriers, suppliers, contracts, sourcing arrangements, or self-generation	general energy intensity or strategic importance alone	multiple suppliers, electricity and gas, self-generation, renewable sourcing, Power Purchase Agreements, contract complexity, mixed sourcing arrangements
Organizational design and responsibility structure	how decision rights, responsibilities, and coordination for energy are distributed	accountability as an outcome of the accounting system	centralized vs decentralized responsibility, energy manager role, cross-department coordination, plant-level autonomy, ownership of energy topics
External uncertainty and compliance burden	changing regulation, certification, reporting duties, grid requirements, or external uncertainty affecting system development	internal forecasting capability or internal planning processes	regulatory change, compliance burden, reporting obligations, certification, grid operator requirements, policy uncertainty
Cost-benefit logic of granularity	explicit trade-offs between informational benefits and implementation costs of more detailed accounting	the resulting level of detail itself without reference to the trade-off	too costly to meter, effort-benefit comparison, implementation cost, IT burden, "not worth the detail," selective granularity

Table 2-5: Operational codebook for contextual variables of energy cost accounting systems

2.6.4.2. Operational codebook for characteristics of energy cost accounting systems

Characteristic	Include when the text refers to…	Exclude when the text refers to…	Typical indicators / examples
Information granularity	the level at which energy cost information is available or distinguishable within the organization	frequency of updates, measurement accuracy, accessibility, or integration across systems	site-level, department-level, machine-level, process-level, batch-level, product-level, cost center-level information
Measurement quality and timeliness	the reliability, frequency, recency, speed, or regularity of energy-related measurement or reporting	how costs are allocated, what organizational level information is available, or whether data from different systems are linked	real-time data, hourly/daily/monthly measurement, delayed reporting, outdated information, inaccurate meters, regular reporting, on-demand reporting
Allocation architecture and precision	how energy costs are collected, assigned, traced, or allocated, and how well allocations reflect actual consumption	general measurement frequency, transparency alone, or strategic importance of energy	direct tracing, allocation keys, first-stage allocation, second-stage allocation, cost center allocation, machine-hour allocation, imprecise allocation base, costing errors
Information accessibility and transparency	whether energy cost information is visible, understandable, and accessible to relevant actors or units	whether data systems are technically integrated, or whether information is very detailed but not necessarily accessible	managers can access data, dashboards, understandable reports, visibility across departments, traceability, transparent energy costs
Forecasting and planning capability	the use of energy cost information for forward-looking estimation, simulation, scenario analysis, planning, or scheduling	external uncertainty, compliance burden, or historical reporting only	forecasting future energy costs, planning production, scenario analysis, simulation, scheduling to avoid peaks
Cross-functional data integration	whether energy-related data is linked across procurement, production, ERP, accounting, controlling, or other systems/functions	simple access to reports without actual system/data integration	ERP linkages, procurement data linked to energy data, accounting-system interfaces, disconnected systems, manual merging across departments

Table 2-6: Operational codebook for characteristics of energy cost accounting systems

2.6.4.3. Operational codebook for consequences of energy cost accounting systems

Consequence	Include when the text refers to…	Exclude when the text refers to…	Typical indicators / examples
Energy efficiency	improvements or changes in energy use relative to output	high energy use as a contextual condition rather than an outcome	reduced consumption, avoided waste, efficiency gains, better energy use per unit, lower energy input for same output
Energy sourcing and renewable investment decisions	decisions on sourcing, self-generation, renewable adoption, or energy-related investments influenced by accounting information	general strategy unless tied to specific sourcing or investment choices	solar investment, CHP, supplier choice, renewable sourcing, self-generation, storage, switching contracts
Use of energy cost information in decision making	actual use of energy cost information in managerial or operational decisions	mere existence of information without evidence of use	production planning, scheduling, pricing, cost analysis, internal reporting, investment appraisal, decision support
Accountability	holding individuals or units answerable for energy-related actions or outcomes	structural distribution of responsibilities without answerability	responsibility for targets, being held accountable, performance review, departmental answerability, reporting against goals
Individual energy performance targets	formal assignment of measurable energy-related goals used for evaluation or incentives	broad accountability without explicit targets or incentives	bonus-linked energy targets, departmental reduction targets, energy KPIs in performance evaluation, incentive systems

Table 2-7: Operational codebook for consequences of energy cost accounting systems

2.7. Appendix B: Technical details of the LLM-assisted qualitative content analysis

This appendix documents the technical workflow supporting the LLM-assisted qualitative content analysis. It is intended to enhance transparency and methodological review, but not to function as a full software manual. All substantive interpretations presented in the paper are the result of researcher judgment informed by the workshop transcripts, notes, memos, and manually reviewed coding outputs.

2.7.1. Purpose and role of LLM assistance

This appendix provides additional technical detail on the LLM-assisted research process, including transcription, coding, anonymization, and translation procedures used in the qualitative content analysis. LLM tools were used in a supportive role to facilitate systematic processing of a large German-language qualitative dataset. All substantive coding, validation, and interpretive decisions remained with the researcher.

The analytical workflow combined a literature-informed codebook with a two-pass LLM-assisted coding pipeline implemented in Python. The procedure comprised transcript preparation, exploratory theme discovery, deductive coding against the revised codebook, researcher review of all provisional outputs, anonymization and translation of selected quotations, and the generation of structured analytical output files.

2.7.2. Data corpus and preprocessing

The underlying qualitative dataset comprised 14 workshop-based, semi-structured group interviews with German organizations. Audio files were transcribed in German using WhisperX, an open-source transcription system, after which all transcripts were manually checked and corrected. The workshop transcripts were in German and preserved speaker attribution and timecode markers in the format "[hh:mm:ss] Speaker:". Transcripts were stored in DOCX format for editing and review and converted into TXT format for computational processing using an automated script that preserved speaker structure and timecode information.

For the coding pipeline, each transcript was segmented into overlapping chunks of up to 5,000 characters with an overlap of 600 characters. The overlap was used to preserve local conversational context and reduce the risk that analytically relevant quotations or meaning were split across chunk boundaries. Researcher notes and post-workshop voice memos were retained as complementary material throughout the analysis.

2.7.3. Codebook development

The analysis was guided by a structured codebook aligned with the study's three research questions. The initial codebook contained 14 codes across three overarching domains: contextual variables, characteristics, and consequences of energy cost accounting systems. During the exploratory phase of the analysis, five additional themes were identified and incorporated into the codebook, resulting in a final coding framework with 19 codes. Each code included a definition, coding guidance, inclusion and exclusion criteria, typical indicators, and related terms. The final codebook is displayed in Appendix A.

2.7.4. LLM infrastructure and model use

The coding pipeline was implemented in Python and accessed LLMs via two infrastructures: the Helmholtz Blablador API hosted by Forschungszentrum Jülich and the KIT KI-Toolbox of the Karlsruhe Institute of Technology. The primary model used for the inductive coding was MiniMax-M2.5[5] via the Helmholtz Blablador API, while the primary model used for deductive coding, anonymization, and translation was kit.qwen3.5-397b-A17b[6] via the KIT KI-Toolbox. Additional models were tested on both APIs during method development and comparison.

The final configuration prioritized stability and reproducibility rather than creative generation. The primary coding workflow used a temperature setting of 0.15, a maximum response length of 4,096 tokens, a timeout of 120 seconds, and up to three retries per request. The minimum confidence threshold used in the final selection logic was 0.80 unless otherwise noted for exploratory theme discovery.

2.7.5. Pass 1: Exploratory theme discovery

In the first pass, the pipeline was used to identify potentially novel themes not adequately captured by the initial codebook. Each transcript chunk was screened by the LLM for emerging themes. The inductive prompt included explicit classification rules to distinguish genuinely novel constructs from variations of already coded concepts.

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[5] Further information on the model can be found here: https://huggingface.co/MiniMaxAI/MiniMax-M2.5
[6] Further information on the model can be found here: https://huggingface.co/Qwen/Qwen3.5-397B-A17B

For each candidate theme, the model was required to return a verbatim German quotation of at least ten words, a confidence score, and a justification explaining why the theme was not covered by the existing codebook. Candidate themes were screened through a validation pipeline that checked schema compliance, excluded meta-research content, filtered interviewer speech, applied a confidence floor for new-category candidates, and verified quotations against the original transcript text.

The exploratory pass included several filtering and consolidation steps to ensure that candidate themes were not merely repeated, fragmented, or differently labeled versions of the same idea. Intra-document deduplication removed repeated or overlapping candidate themes within the same transcript. Cross-document aggregation grouped similar themes appearing across different workshops. Semantic merging combined closely related theme labels when they referred to the same underlying construct. Candidate themes were quality-scored based on quote quality, the strength of the gap explanation, and cross-document support, with penalties applied for generic labels, overlap with existing codes, truncation, and cross-company contamination. The outputs of the exploratory pass were treated as provisional rather than final coding decisions. The resulting candidates were therefore exported into a structured review file for manual researcher review. Researcher review focused on whether candidate themes were conceptually distinct from existing codes, empirically grounded in the workshop data, and relevant to the research questions. Themes judged to represent genuinely new analytical content were accepted directly or revised before inclusion in the final codebook.

2.7.6. Pass 2: Deductive coding against the revised codebook

In the second pass, all transcripts were coded against the revised codebook. The deductive prompt included the full category definitions, coding guidance, approved inductive themes from Pass 1, explicit coding rules, and reference segment examples. These snippet examples were developed during the deductive coding stage and expanded iteratively across development runs by incorporating high-quality retained segments from manually reviewed outputs. This process improved calibration and supported more consistent category assignment in subsequent runs.

The model was instructed to return only exact verbatim transcript segments and to avoid paraphrasing, translation, or synthesis. It also applied explicit exclusion criteria, including generic industry observations, vague confirmations, methodological comments, interviewer speech, introductory small talk, and non-answers.

The resulting outputs were subjected to post-processing validation. This included minimum segment-length requirements, transcript substring verification, category normalization, and deduplication both within and across subcategories. The final selection followed a quality-over-quantity principle. The latest full deductive run produced 1,727 provisional coded segments across the 14 transcripts. After researcher review, 451 coded segments were retained for the final analysis.

2.7.7. Researcher review and interpretive control

All candidate themes and coded transcript segments generated with LLM assistance were reviewed manually by the researcher. For each provisional output, the researcher checked whether the quoted segment appeared verbatim in the original German transcript, inspected the surrounding transcript context, and assessed whether the proposed theme or code assignment matched the code definitions and the broader analytical logic of the study. Where necessary, segments were rejected, reassigned to a different code, merged with related segments, or retained for further analysis. Researcher notes, timecodes, and post-workshop voice memos were used to support these judgments and to ensure that interpretations were not based on isolated transcript fragments alone. LLM assistance therefore supported systematic screening and coding but did not replace researcher judgment.

The reviewed outputs were then compared across workshops to identify recurring patterns, divergent practices, and meaningful variation across cases. This cross-workshop synthesis informed the consolidation of themes into the final framework in the paper.

2.7.8. Anonymization and translation

Anonymization occurred at both company and quotation level. At the company level, deterministic alphabetical pseudonyms were used. At the quotation level, LLM assistance was used to replace person names, geographic identifiers, product names, and department names with generic placeholders. Quotations were translated from German into English using explicit instructions for literal academic translation that preserved meaning and tone as closely as possible. These anonymized and translated quotations were then checked by the researcher for accuracy, tone, and the absence of identifying information.

2.7.9. Output files and diagnostics

The coding pipeline generated structured output files for both exploratory and deductive analysis. Deductive outputs included CSV files with one row per coded segment, Excel-based summaries, and diagnostic JSON files. Exploratory outputs included ranked candidate files, a manual review template, Excel workbooks summarizing theme candidates, and final recommendation files after manual review. Additional synthesis files summarized coded material by research question, subcategory prominence, and cross-document patterns. All runs were timestamped and stored in dedicated output folders together with run manifests and processing logs.

2.7.10. Iterative refinement

The pipeline was refined iteratively across several development versions to improve the substantive usefulness and methodological reliability of the LLM-assisted outputs. Prompt formulations were refined across development runs to improve category identification, reduce false positives, and strengthen coding consistency across both exploratory and deductive stages. Earlier iterations tended to overstate cross-document support by allowing overly broad enrichment rules, which risked treating weakly related statements as evidence for the same candidate theme. Later versions tightened similarity thresholds, revised support scoring, and refined the handling of meta-research language and domain assignment. The final version used more conservative enrichment logic and stricter filtering, resulting in more credible document support and better score separation among candidate themes.

2.7.11. Quality assurance

The technical pipeline incorporated several safeguards to improve reliability and traceability during processing. These included API preflight checks, checkpoint-based resume functionality, retry processing for failed documents, regex-based speaker attribution, taxonomy normalization using predefined aliases, and per-document diagnostics reporting raw, retained, and dropped coded segments. These safeguards helped ensure that processing errors, failed API calls, inconsistent category labels, and attribution problems could be identified and corrected during the analysis.

2.8. Appendix C: Quotations used for the qualitative analysis

2.8.1. Quotations used for the contextual variables of energy cost accounting

Quote ID	Speaker	Quotation
Q002	MA14	For a processing company like ours, material costs are primarily the be-all and end-all in determining the cost structure. However, energy costs, as well as wages and the employees' profit share, certainly play a role. Energy does factor in, but we are not part of the chemical industry or similar sectors where energy costs rank at the very top. That is not the case for us. While energy costs are important, they are not the single most critical factor.
Q003	EP1	In areas where we are heavily connected and consume significant amounts of energy, such as during glass melting, we have no option to say, 'The wind is blowing nicely right now; let's just start the tank.'
Q004	EP1	A great deal of energy and infrastructure is required. Thus, investments in glassmakers, among others, are necessary. The proportion of personnel costs is not particularly high; consequently, energy costs play a major role.
Q006	EM3	As an energy-intensive industry in Germany—a category to which we belong—energy costs play a prominent role.
Q007	MA2	In 2024, we incurred approximately two million in energy costs. Relative to our total operating expenses—specifically material costs alone, let me calculate... well, this amounted to roughly three percent of the total material costs.
Q008	EP2	So, on average across the group, energy costs account for between three and four percent of our COGS. However, depending on the product, this can vary between two and ten percent.
Q009	EP2	However, from the perspective of a site—which identifies these as its own cost centers—we effectively arrive directly after raw material and personnel costs. This is because, in absolute euro terms for a site, this represents a significant impact.
Q010	EP2	One hour of electrical flexibility is a death sentence for us in the chemical industry. We cannot simply shut down a plant for an hour.
Q011	EM7	“It is truly result-defining. If energy costs go up, our results are bad and if energy costs are low, our results are good.”
Q012	EM7	In principle, this is the second most important component in the overall cost structure. Personnel costs rank first, followed by a significant gap; thereafter come energy costs and then materials. These are the three primary cost drivers. Depending on the magnitude of energy costs, they may occasionally rise to second place—or conversely drop to third; this varies.
Q015	EM7	Company B accounts for 80% to 90% of the energy costs for the entire group. This is essentially related to process energy. We will likely return to the specifics of how and what this entails a bit later. However, it is indeed the case that within our production operations—we are the quintessential manufacturing division; everything else is trade or services—we operate as a manufacturing business. Consequently, we must ensure that our energy costs align appropriately.
Q017	EM4	I have the impression that this is decisive for the staff. It depends somewhat on the production; specifically, what percentage of production costs is allocated to energy. This varies considerably. There are areas that are more energy-intensive than others. For these areas, it naturally plays a central role.
Q018	CFO3	We are an iron foundry; consequently, we produce heavy metals. Iron foundries are energy-intensive everywhere in the world.
Q019	CFO3	At our company, electricity costs are significantly higher than 4% of revenue.

Quote ID	Speaker	Quotation
Q020	MA8	However, we are not classically energy-intensive in a way that would allow one to state that at Company H, the share of energy costs in manufacturing costs is greater than 20 percent or 15 percent. We do not fall into the category typically considered energy-intensive under energy regulations. Nevertheless, energy and energy costs play a role, and this role is becoming increasingly significant.
Q022	MA3	I need a certain amount of energy to melt the metal. That is physics; there is no room for manipulation.
Q023	MA14	We are a family-owned company with four managing directors. Ultimately, someone has to take responsibility for ensuring that all decisions are made promptly.
Q024	MA14; EM8	MA14: So, if one had to engage with this much more intensively—as you just mentioned—how would we control it? Would you check after, say, two hours and take another look?; EM8: No. There is quite simply no capacity for that.
Q025	EM8	Nevertheless, it is still a massive effort. We are being supported in this regard by an external firm; without their assistance, this would simply not have been feasible in terms of manpower. They will also continue to support us going forward.
Q026	QM1	The technology currently available to us is highly diverse, yet there is no personnel capable of mastering it. Nevertheless, every facility management team is now expected to master this extensive modular system.
Q027	QM1	"You need the manpower to do this, as well as the appropriate measurement technology. You have to implement load management, and all of that costs money. I thought I could do it myself, but it consumes too much time; it simply isn't feasible."
Q031	CFO4	Theoretically, one could also implement this using electricity; however, when considering the required power capacity, our current infrastructure at the site—including the existing transformer and the ring main in the industrial area—does not support it.
Q032	CFO4	Since we are a somewhat smaller company, many things ultimately converge at the top.
Q034	MA2	Certainly, the sustainability goals that we have. We want to present ourselves externally as a sustainable company.
Q037	MA7	Cost accounting is a very essential aspect, particularly regarding how important energy costs actually are for us. Accordingly, we have weekly—not daily, but weekly—touchpoints where we must engage with these issues: examining the cost rates, tracing their origins, and identifying potential savings. It was quite amusing when I first started here; we used an Excel file listing all the allocations and such. One initially gets a shock seeing what it all amounts to, especially when coming from a private background. Energy costs are certainly an important topic.
Q038	CFO3	I would say that this is not something we need to emphasize at all, as everyone in our day-to-day operations has always been aware that energy—more specifically, electricity—is extremely important. Ultimately, it comes down to electricity.
Q040	MA9	In the long term, the goal is indeed to operate the site as CO2-neutral. This extends beyond Instagram alone. However, currently, I would say, the situation is still mixed. Naturally, we have a climate protection target for Company H. We aim to achieve climate neutrality by 2040. This means slightly ahead of the EU and slightly ahead of Germany.
Q041	EM6	Perhaps as an addition, Company H has now issued its targets, specifically decarbonization targets for 2040; consequently, a new pressure has arisen within the Business Units that must ultimately be addressed.
Q042	MA8	For us, the ultimate triad is always economic efficiency, sustainability, and security of supply.
Q044	MA8	It is not the decisive factor, but especially in recent years, energy supply has been a focus, particularly from a cost perspective, within the context of the energy crisis.

Quote ID	Speaker	Quotation
Q046	EM2	There is a Plan 2030, along with further concepts aiming for climate neutrality by 2050; this is examined comprehensively, ensuring that we consider not only ecological goals but also social and governance objectives.
Q047	EM2	Energy costs are a competitive factor. In this regard, we differ from the automotive industry or less energy-intensive industries.
Q048	EM1	The output from our energy management has indeed become highly significant due to the rise in energy prices over recent years; there is now actual demand regarding efficiency measures and other matters to know the current tariff or electricity costs in order to conduct calculations. In my view, over the past few years, energy costs have become a major topic, and inquiries on this subject are coming from many different directions.
Q050	EP2	That is the authenticity: implementing sustainability within the corporation. Based on 2019 levels, we aim to continuously reduce our emissions. We intend to be climate-neutral by the end of 2029 and achieve net zero by the end of 2050. To reach climate neutrality, this means a reduction of 42 percent compared to the 2019 baseline—essentially a 42 percent reduction within ten years.
Q051	EM7	Because we are bound to the group, we have a central unit within the group that writes sustainability reports and deals with the targets. Impulses and target specifications also frequently come from there.
Q053	EM4	However, we take this seriously; it is, in fact, part of our corporate principles. The [Family] is strongly committed to sustainability, particularly environmental protection and resource conservation. Environmental protection is definitely a core component.
Q058	CFO1	I would say that every company has a strategy regarding ESG. First, I established the baseline. I believe it is beneficial for all to make few changes, but instead to report regularly, both in terms of frequency and quality. This establishes the framework. It also defines specific targets to be achieved by 2030 or 2050.
Q059	MA2	Personally, I would like to gain a slightly clearer overview. I am still working on this, specifically with the cost planner, requesting further details on exactly which information she receives from whom to justify the planned figures she ultimately provides me. Only then will I truly be able to understand why there were such significant discrepancies between actuals and plans. This remains an unresolved puzzle that I intend to investigate further.
Q060	MA14	You can have 50,000 key figures, but what meaningful insight lies behind them? It is really not that simple for us to say, as you already mentioned, that you have your values and receive an alert as soon as something does not match. However, there is no single energy efficiency key figure here. There is not one number that determines whether it is good or bad.
Q061	EM8	In principle, we are satisfied. We know where the energy is going and are working to improve the situation.
Q062	CFO3	However, we still see potential to become faster and even more precise in our reporting.
Q064	EM3	At times, do we perhaps provide too much information—essentially an information overload—depending on who the person across the table is?
Q065	EM1	I would argue that we essentially have the information we need.
Q066	EP1	The system could certainly be more performant in certain areas. By now, we also have several international sites on the system; as you can see, there is still some room for improvement at one or another location.
Q067	EC1	So there is some information here and there, yes, but there is hardly any analysis.
Q068	EC1	"The question is: what do I do with this? Do I simply record it, or do I evaluate and analyze it? That second step is exactly where things often stall."

Quote ID	Speaker	Quotation
Q069	EC1	The implementation and saving of energy, and what is stamped on an invoice somewhere in accounting and then filed away, are often two entirely different things.
Q070	EM7	This has led us—though our environmental auditors have been pointing this out for years—to conclude that this is essentially a meaningless metric. While it allows for tracking trends over time, it offers little value because it constantly requires additional explanation. For instance, when we state that a specific process step differs slightly, those nuances are simply aggregated into this metric, rendering it effectively meaningless.
Q071	QM1	By now, I feel that there is too much communication, but it lacks sufficient focus.
Q072	MA2	So, in principle, we utilize several types of energy carriers. Primarily, our building here—the headquarters—is essentially heated, or rather operated, by a heat pump that extracts energy from the air. Naturally, the heat pump is powered by electricity. However, neither the heat pump nor the building belongs to us; they are owned by the landlord, who subsequently charges us monthly via an allocation based on the billing statement. At the end of the year, there is also a final balancing payment. In total, we have four heat pumps. Additionally, there are two CHP units on the roof that can be activated as needed; these generate both heat and power using gas. Furthermore, there is a separate gas boiler that serves as a backup system, capable of operating if the other systems fail.
Q073	EM8	We have two large natural gas CHP units in the basement; these are for heating, naturally. However, on the other hand, they also generate cooling water via an absorption refrigeration machine—one could imagine it as a giant heat exchanger. The interplay is such that we require both heat and, conversely, cold to enable production, as we must quench many parts. We need the heat, and the waste product of the CHP units is essentially electricity. This means that we effectively generate electricity as a by-product from the heat—or rather, from the gas—which we then consume ourselves.
Q074	EM8	“For us, it is quite difficult to determine an exact kilowatt-hour price. If someone wants to know that, I first have to sit down and analyze how much the CHP units actually produced in that month. Simply saying that we generate electricity at, say, 15 cents does not work.”
Q076	MA8	For example, in the context of combined heat and power processes involving natural gas: how much natural gas is allocated to heat generation, and how much to electricity generation? We must consider which allocation key or approach to use. Various approaches exist; ultimately, one was selected.
Q077	MA9	Alongside the actual procurement of electricity and natural gas commodities, there are associated ancillary procurement costs, including network charges, network surcharges, taxes, other state levies, and allocations. These naturally represent a very significant portion and are traditionally included within our procurement or external cost categories.
Q078	MA8	Since we do not source from a single supplier but from multiple ones, the process is significantly more complex. We are not dealing with a single invoice, but rather hundreds of invoices.
Q079	EM6	I believe we have a total of 20 or 22 different media—quite a significant number. However, not all of these are energy carriers in the classical sense; logically, they also include technical gases, which are delivered directly to us.
Q082	EM3	As previously mentioned, natural gas is procured both as a feedstock, i.e., a raw material, and as an energy carrier.
Q083	EM3	Electricity is the second major form of energy we procure. Looking at our other sites—particularly Wesseling and Hanau—we are integrated within the respective locations. This means we source various forms of cooling energy from the chemical park, ranging from cooling water and well water to brine. Additionally, we procure steam across different energy levels.

Quote ID	Speaker	Quotation
Q084	EP1	We purchase approximately 600 GWh of electricity in Germany and just under one terawatt-hour of gas. After that, there is a long gap. We also still use heating oil—quite a few million liters, in fact.
Q085	EC1	In principle, electricity and gas are the main energy carriers; diesel, gasoline, and heating oil are hardly discussed at all.
Q086	CFO2	What we have not addressed at all is fuels. While that is relevant for us, it is insignificant in terms of cost magnitude. When we discuss energy sources, we focus primarily on electricity and district heating; these are by far the two largest categories for us.
Q088	EP2	We do have our own power plants, so we are considering whether to utilize them by firing up the gas turbine or to purchase external electricity.
Q090	EP2	We mostly start up the gas turbine because we require steam; we operate within a cogeneration (CHP) process where electricity is merely a by-product. Our primary objective is not to generate electricity, but solely to produce steam.
Q091	EP2	We structure the Power Purchase Agreement so that the portfolio ultimately consists of 80 percent wind and solar energy, with the remainder purchased on the stock exchange.
Q092	MA11	We have the option to generate our own electricity at two sites using cogeneration plants; specifically, we operate gas turbines to heat a boiler. When the ratio is favorable and the plant is economical, we naturally increase gas usage to simultaneously produce the process steam—which is absolutely essential—and electricity. However, if the plant is uneconomical due to an unfavorable electricity-to-gas price ratio, we purchase electricity from external sources and generate the required process steam in the heating boiler.
Q094	MA4	Because, among other things, we generate heat and electricity via a gas turbine. This means we have coupled production, which we then have to separate again during internal allocations. This naturally makes the process somewhat more complex.
Q095	EM4	When it comes to electricity, this is already done through Power Purchase Agreements.
Q096	EM4	The Power Purchase Agreements have a relatively long duration, spanning several years. The terms are typically 5 to 10 years, I believe, indicating a strong long-term orientation.
Q097	CFO4	However, nowadays, depending on the federal government's approach to compensation regarding network charges, I might end up having to pay a gross price of 30 cents. Of that, only 10 cents represents actual labor costs that I can negotiate. This means that components such as performance prices and network charges are immensely important and constitute a very large portion. This is something we can no longer control at all. In discussions with our customers, we ultimately have to convey this reality. We talk about the electricity price, but 60% is beyond our influence, while only 40% can be influenced. Even if we manage to reduce the controllable portion by two cents, this does not result in a 10% reduction overall. I find that this nuance is often missing in terms of understanding and transparency.
Q100	EP2	Cost controlling takes place within our procurement department, as we need to determine how to structure the energy supply contracts, along with the energy manager who must approve the monthly invoices. This forms the duo present at each site.
Q103	MA2	Regarding sustainability management, I consulted with the two real estate departments here in [Location] and [Location]. At the real estate department in [Location], I spoke with several different contacts: one regarding electricity procurement, another who serves as the building manager for the new executive building and maintains contact with the landlord, and local staff familiar with technical infrastructure, such as electricity meters and heat pumps. I also spoke with another individual in the real estate division at [Location] responsible for cost planning. In total, three or four people there dealt with these topics from various perspectives; each offered a slightly different view, but none had an overall perspective.

Quote ID	Speaker	Quotation
Q104	MA2	So I would rather view it as somewhat painful, particularly regarding the information that I had to assemble quite laboriously on the subject—specifically, how widely this information is distributed across companies and individuals.
Q105	MA2	There are various individuals who each oversee a specific sub-area, yet they often have little to no understanding of what the others actually do.
Q106	EM8	The person responsible in that area is the Managing Director for Production, [Person]. We report directly to him as a staff unit. Our role as energy experts is essentially the next level down. Then we have what I would call the members of the energy team, but most importantly, the Head of Maintenance, since they ultimately must ensure that operations continue running smoothly if any issues arise. Therefore, [Person] holds primary responsibility, and all matters are escalated to him.
Q108	CFO3	Based on the structure of our group and its parent company, there are no directives in this regard; therefore, our managing director operates relatively autonomously.
Q111	MA8	So, ultimately, we are organized here at Company H such that we naturally have various business units. We are all active here at the Darmstadt site. Operationally, regarding production, we are organized into separate companies at the site. This means that alongside Company H as the site operator, there are Company H Division A, Company H Division B, and Company H Division C; Company H ultimately supplies all entities at this site. This includes production units as well as what are known as 'Enabling Functions'—that is, supporting processes for production. If I say we are under Site Management within Company H, specifically in the Infrastructure division, our role is to provide energy supply and act as a service provider for the entire site, delivering all our services within this framework.
Q112	MA10	I think it helps that we have bundled expertise on the beneficiary side. We are closely coordinated from data collection through to controlling across the entire process, and more recently, even including energy generation—meaning the technical side is now within the same department. This means that even there, decisions can be made quickly via short communication channels, providing the necessary insights.
Q114	MA8	This means that our department is divided into various groups and ultimately handles everything ranging from energy procurement to energy distribution and energy refinement. We are also responsible for and ultimately consolidate all regulatory, commercial, and technical matters concerning energy supply and billing.
Q116	EM2	The department is called Energy Management. Within the Energy Management department, all regulatory matters concerning the company in Germany are handled, including energy procurement, European and national emissions trading, central network access issues, and the energy and electricity taxes.
Q122	EC1	In principle, we coordinate this with them. As such, we are frequently appointed as the external energy management officer. We moderate these energy team meetings and ensure that the documentation is established appropriately.
Q123	EC1	There are companies that handle a great deal in-house, in which case we do less and focus more on legal norm requirements and similar matters. However, there are companies that simply lack the desire or time, and in some cases also the necessary expertise, to address these issues themselves; in those instances, we are more deeply involved.
Q124	EC1	I believe that operational responsibility usually lies with someone from the maintenance and infrastructure department; in fact, there is almost always someone who oversees this area.
Q127	EM7	So, we three are essentially the controlling team at Company B. However, we are not part of Company B; legally, we are housed within a shared-service unit. Ultimately, we also provide controlling services for other sub-groups. At Company B, these functions are consolidated within a single legal entity, but we subsequently recharge our services to the individual subsidiaries.

Quote ID	Speaker	Quotation
Q130	EM4	What should be said, which in turn is favorable, is that at least in the area of energy procurement, it was possible to bundle everything within Business Services. There is now a position filled—I believe there are three of them—who handle the global energy purchasing.
Q131	MA4	Because we have many business groups that are able—and indeed expected—to operate quite independently, the decision largely rests with the respective business group. To put it simply, outside of Weinheim, the business group effectively has the authority to determine whether this is implemented.
Q135	EM8	So, the final step was the implementation of ISO 50001, which we were required to introduce due to our company size.
Q136	MA14	At some point, driven in part by the pandemic and the war in Ukraine, a situation arose where energy providers no longer offered long-term agreements—or even annual contracts—to companies of our scale.
Q137	CFO3	There is zero planning security. Currently, there is a draft law regarding subsidies for transmission network charges involving 6.5 billion euros for one year. I do not know what will reach our level or what will happen thereafter. That represents the greatest uncertainty of all.
Q138	CFO3	Then it moves on to the European emissions trading system. We do not know what will happen from 2030 onwards. We do not know when our products will be added to the CBAM list. We also do not know whether CBAM will actually work. These are the major uncertainties.
Q143	MA10	For instance, one could say that the budgeting for 2026 is largely complete; we are truly in the final stages. This means, returning to the issue of regulations, we are currently establishing an internal electricity tariff—or generally an internal tariff for utilities. However, the legislation on many fronts is not yet clear for the coming year.
Q144	MA8	As a large company, we are partially legally obligated to do this. For instance, based on our energy consumption, once it exceeds a threshold of 2.5 gigawatt-hours, a company in Germany is required to implement an energy management system. This constitutes one aspect. We require this level of detail to meet both legal and normative requirements.
Q145	EM6	Regulatory pressure is constantly increasing; this is an ongoing issue that brings additional requirements.
Q146	MA10	Or also other surcharges and network charges; we tend to face some difficulties in that, at the time of budgeting, we often do not know all the price components.
Q147	MA8	Regulatory issues. Many aspects remain unclear, even for investment decisions.
Q148	EP3	Then there is a secretary from the EU who says: 'If you want low interest rates and later secure external financing, you must be green.' Consequently, there is external pressure to act. These are not direct investment decisions based on an economic feasibility analysis; rather, they are external factors that naturally play a decisive role, which is precisely why we undertake them. Otherwise, many initiatives would not be pursued.
Q149	EM2	We use natural gas as a feedstock; this material use of natural gas necessitates natural gas rather than hydrogen in the pipeline, since that is how we utilize it. These uncertainties and insecurities currently constitute impediments to transformation, decarbonization, and establishing a clear direction regarding our future path.
Q150	EM2	The key issue is uncertainty. This is not about the political situation; rather, there is a lack of predictability for the energy-intensive industry. Where will electricity costs, CO_2 costs, and energy costs head in the future?
Q151	EM2	There is a major unknown: where will the electricity price stand in ten years? Consequently, I cannot plan for my investment to be economically viable in ten years, as I do not know what the electricity price will be.

Quote ID	Speaker	Quotation
Q153	EP1	Uncertainty regarding the political framework conditions is certainly one factor. Things tend to swing back and forth quite a bit. That is indeed difficult.
Q157	EC1	The reason we are engaged is often not that companies say, 'Okay, we need help reducing energy or implementing energy-saving projects.' Rather, it is because they are legally required to do so or have been asked by customers to implement ISO 50001, which also allows them to benefit from a reduction in levies. This is frequently the primary entry point for us; it is not specifically about saving energy initially, but rather about establishing the system first, with energy savings being a positive side effect.
Q159	EP2	However, this issue has unfortunately gained incredible momentum due to the Ukraine war. This must be stated openly; it is hardly a secret.
Q161	EP2	Indeed, the regulatory framework is overwhelming, including the Energy Efficiency Act and the Building Energy Act. The federal government sometimes has funding, sometimes none. Then the coalition collapses. Trump is present. I believe our challenge is not internal; our challenge is always external.
Q165	EM7	The legislature does not make things easy. Fundamentally, it is the network charges that cause this, thereby worsening the situation. Is economic viability fundamentally assured over more than ten years even with higher network charges? That is always a matter of weighing the pros and cons.
Q168	EM4	What really pains us is external reporting—specifically, the multitude of entities demanding information from us, which places a significant burden on our operations. This results in a loss of working hours, forcing us to divert focus from other priorities. The requirements begin with the State Statistical Office, the Main Customs Office, the Federal Network Agency, various regulatory authorities, gas platforms, and the Gas Security Platform. The sheer volume of required reporting has become unmanageable; it is immense. We even employ a dedicated staff member solely for this task, whose role is otherwise non-existent.
Q172	EM8	For example, we have presses with a connected load of 5 kW; these are not individually measured because the meter... It would be too much effort for too little energy. Then there are specific areas. For instance, regarding the presses, only the entire hall is metered, and we allocate this based on the connected load. [...] Because the cost-benefit ratio would no longer make sense.
Q174	MA10	It is simply not feasible otherwise; given our structure at this site, we often have up to ten cost centers within a single building or office complex. Consequently, in the worst-case scenario involving twenty media types—the most complex case—it is impossible to measure every single medium for each individual office.
Q175	MA3	And energy costs are simply not a major expense large enough to make it worthwhile.
Q179	EM3	We are currently on a major journey, and I believe this is truly a significant undertaking because it is extremely elaborate. Starting from the analysis phase, we determine where we can meet the standard requirements using simple metrics in areas that are less relevant to the company as they involve smaller energy consumers. Conversely, we explore how we can derive actual benefits for plant optimization from the KPIs associated with our large energy consumers.
Q180	EM1	The effort is enormous. Both the administrative and technical efforts are already substantial; to go into detail, we conduct approximately 2,000 measurements at the site in [Location] covering electricity, gas, and water. If we were to continuously apply different pricing schemes and bill on a more granular basis than monthly, we would essentially torture the system—and naturally, the staff managing it—as well. Therefore, despite our capability for such technical granularity, we actually need to scale back somewhat to avoid overdoing it.
Q181	EP2	Because ultimately, one simply does not examine things in detail through a cost center.

Quote ID	Speaker	Quotation
Q182	EP2	And that is somewhat due to the fact that we have so many people in this organization; it serves different needs. But ultimately, no one actually requires this level of granularity. Some want to understand it, while others do not care and simply input a number.
Q183	EP2	And this effort is not justified in comparison to our average costs, which are simply energy costs.
Q185	EP2	Yes, the effort required does not justify doing that; it would be futile. Above all, one must consider that we do not produce the same product throughout the entire year—we operate in campaigns. This means, for example, Campaign A runs from April to May, a period of two months, followed by another campaign. Consequently, different consumers are utilized with varying intensities. Evaluating this at such a detailed level is nonsense.
Q186	EP2	We are often part of a network. This means that site A performs process step 1, then it continues at site B. It may also return or even go overseas. It is too complex to allocate energy types in such a fine-grained manner. Therefore, the site acts as a sort of 'cheese dome'.
Q187	EM4	But in principle, we live with this inaccuracy. On one hand, it is not worth the effort; on the other hand, we do not have a classic product costing system where we would need to be precise in order to calculate our products.

Table 2-8: Quotations used for the contextual variables

2.8.2. Quotations used for the characteristics of energy cost accounting

Quote ID	Speaker	Quotation
Q205	EM2 + EM3	EM3: The cost center is the lowest level when looking at this.; EM2: Yes, well, you convert it down to the product level. That is done at the product level—every product has its own energy costs. The products have their own energy costs.
Q209	EM1	It is quite production-like and very granular, whereas in the administration building it is less so.
Q210	EM1	So, we actually need to step back somewhat from the level of technical granularity that we are capable of, so as not to overdo it.
Q212	EP1	From an energy management perspective: production units that track live key performance indicators within the system. This means the feed systems incorporate energy values, including SAP data. They can indicate, in principle, the energy costs per unit sold or produced. Some systems can even perform this online, i.e., live.
Q218	MA12	We have electricity cost centers and a gas cost center; we would have—no, we do not have the individual ones. For gas, we have rather the CHP cost center, not the energy center.
Q219	MA12	A booklet order—that is, a booklet constitutes an order—we can then determine the energy costs incurred for that specific order and report them accordingly. From there, I can break the costs down further.
Q220	MA3	In that department [the energy cost center], essentially only the costs for the individual energy carriers are collected. We have a cost center for electricity—specifically the [Location] electricity supply here—and gas.
Q221	MA3	No, they are distributed to cost units. [Person]: Okay, so that means they would simply be... [Person 2]: That is then a period expense.
Q239	MA10	So, I think given the complexity we have here, it is normal that we do not always have perfect measurement results everywhere and that we need to make proper estimates or similar, which of course is always more resource-intensive than if, for instance, I had a hundred instances of the same measurement type all set up according to standard. Here, the standard is also very old; that is, much has evolved over time, the structures differ slightly across locations, and the methods of connection and the technologies employed vary. Consequently, it is naturally necessary in certain areas to understand how to interpret the data, how to make sense of a specific peak, or other such issues.
Q240	MA8	Exactly, these measurements are aggregated into a monthly value to provide a corresponding billing figure.
Q241	EM6	However, we often also have our own meters in addition; not always, but in cases where we say it makes sense to have a comparative measurement, we then also have redundant meters.
Q242	EM6	For electricity, the interval is a quarter-hour; for natural gas, it is an hour.
Q243	MA10	We measure the recording systems at quarter-hour intervals, but can achieve significantly higher resolution for internal measurements if required. In the upstream systems, this extends down to one- or two-second values.
Q266	CFO1	As I mentioned earlier, not 100% of the facilities provide measurement data on a daily basis; the remainder is estimated.
Q267	MA2	Initially, we consolidate various expenses—including energy costs, personnel costs, training costs, external consulting, and other miscellaneous items—onto specific cost centers. Subsequently, these cost centers are allocated to functional areas through what is known as functional area accounting, utilizing distinct area-specific allocation keys.
Q268	MA2	This constitutes the main pool, which is then allocated monthly based on this capacity allocation key.

Quote ID	Speaker	Quotation
Q288	MA3	I only calculate the machine hour rates; the variable portion includes a significant share of electricity costs. These costs are subsequently allocated to the cost carriers. While I track processing time in minutes, this is processed indirectly through the machine hour rate rather than being recorded explicitly as specific kilowatt-hour consumption.
Q289	MA3	For gas in particular, we allocate based on area; specifically, heating costs are allocated per square meter. For electricity, we allocate based on approximated consumption wherever possible.
Q290	MA3	This approach is accepted: the connection value multiplied by 0.5 during operation.
Q291	MA4	There is also a relatively large amount of internal allocation involved, because, among other things, we generate heat and electricity via a gas turbine. In other words, we have this coupling there. We then have to separate all of this again during internal allocations. Naturally, this makes things somewhat more complex.
Q292	EM4	In practice, however, these items are booked to an apportionment cost center alongside rental and ancillary costs, and are subsequently allocated to individual cost centers using a square-meter allocation key. The measurement points—i.e., the individual meters that appear on the billing statement—are not otherwise taken into account in the analysis.
Q319	CFO4	Aside from energy management—where I naturally first need to establish reviews, major consumers, and so on—how do I improve in this area? This is certainly a key factor for us; however, it is also crucial for our internal transparency. When discussing with a customer whether energy costs account for x or y percent of a particularly costly large order, I have the opportunity to examine what the actual figures are and what assumptions I made during my initial calculation.
Q320	EP2	They ask me, whether I can provide a budget figure for the electricity price in 2026. Yes, I can do that.
Q321	EP2	The energy manager identifies our major consumers and collaborates with production planning to generate forecasts, enabling us to understand our load profile.
Q322	EP2	This means we require the forecasted volumes from our sites to procure natural gas. We hedge up to 50 percent, while the remainder floats at market prices.
Q326	MA8	Of course, we also attempt to look into the future, meaning not only current energy costs and the energy information situation, but we are also interested in: what forecasts can we rely on? This means, how will energy costs evolve? How will CO2 costs evolve? This is very important for our decision-making: the status quo today is one aspect, but looking into the future is also essential for us. A long-term outlook on this topic is crucial for making investment decisions.
Q327	EM2	Prior to each year, every plant knows precisely—down to the plant level—the production volumes required. Consequently, energy costs are incorporated into the respective budget planning, with differentiation across all energy carriers. Centralized energy management, specifically our department, issues the projected price assumptions for the current year; this process is centralized and governed by a central directive. We define the anticipated energy prices for the upcoming year, while consumption levels are typically determined at the plant level. However, this constitutes a cyclical process: procurement can only occur once the exact consumption volume is known. Thus, it is a bidirectional process.
Q331	QM1	It is impossible to predict exactly by the day and hour how much gas I will need. If I procure it on a quarterly basis, I cannot know; for instance, if I were to procure it today, I would have to specify that in three months, on a specific day at a specific time, I will need a certain amount of gas.

Quote ID	Speaker	Quotation
Q332	QM1	I cannot define my energy costs in advance; while I can state that I need approximately a certain amount of kW, perhaps getting within plus or minus five percent, the shape of the load profile [bathtub profile] depends on the weather and on production levels here. Whether I have high or low production volume—that is impossible to predict.
Q333	EM4	This means that we always assess the situation—at the moment, we are once again at that stage. We create a forecast for the following year regarding our electricity position, and procurement then responds somewhat accordingly.
Q334	EP1	Regarding the forecast direction, it becomes somewhat difficult. One can purchase external expertise, but that is also prone to arbitrary errors.
Q340	EM6	Visualizing such data or deriving triggers from it is only possible if I have the ability to delve deeper into process control systems or other, let's say, more technical systems that are not energy management systems.
Q341	EP1	Integrating this with our procurement portfolio—that is, regarding suppliers, prices, and so on—would actually be desirable if it were somehow included. Currently, we handle this somewhat ad hoc using Excel.
Q342	EM1	However, I believe the collaboration—so to speak, within this group—is characterized by daily exchanges and weekly meetings with controlling, energy procurement, and others. Thus, there is a certain number of individuals who are not individually responsible but rather share responsibility for the process.
Q343	EP2	We use Excel, which is the problem; we monitor prices weekly—forward, futures, and daily prices—but we do not yet integrate this data very effectively into the procurement process for these items.
Q344	EP2	In addition, we operate using different SAP systems. Consequently, I cannot simply transfer and allocate costs from CropScience to Pharma.
Q345	EP2	The pain points for me are that we still rely so heavily on Excel. I would prefer a unified system. We are moving toward obtaining pricing information via Power BI, but it remains a case of 'shit in, shit out.' Excel continues to be the definitive source data that feeds the system.
Q346	EM4	So, we do not store detailed information per meter in SAP here. Instead, I believe you receive it via Excel and then import it as a batch mapper.
Q347	EM4	The same information is provided to three different locations. It is always slightly modified, but in principle it is essentially the same information because these locations do not communicate with one another.

Table 2-9: Quotations used for the characteristics

2.8.3. Quotations used for the consequences of energy cost accounting

Quote ID	Speaker	Quotation
Q352	EM5	Since 2011, we have been addressing this issue by establishing key performance indicators, which enabled us to improve the total energy consumption in the casting area by 20 percent.
Q353	CFO3	These were initiatives that always originated internally. How can I save the most energy? By, for instance, reducing scrap. Or, crucially for us, by increasing the proportion of the casting within the molding box relative to our expansion quantity—that is what we call it. Specifically, by reducing the gates. This allowed me to achieve significant energy savings. The iron fed back into the cycle as sprue must be re-melted; this process consumes precisely that amount of energy.
Q356	FM1	Then we considered and discussed: 'Well, just consider—of course in consultation with the zoology—what would happen if, for example, we lowered the temperature by half a degree or by one degree? Does this affect the animal? Does it even notice, or not? Does it work?' Yet, I could save energy. What would that look like? We occasionally tested this in between, which explains these downward fluctuations; if the zoology then stated that it was too cold, I would raise the temperature again. But we simply try out such things.
Q357	EC1	This is primarily the case because the standard explicitly requires saving kilowatt-hours rather than euros.
Q359	MA11	When compressed air is generated, warm air or waste heat is produced; we utilize this waste heat only partially. However, we measure it and can calculate it, which is part of a project examining how this waste heat can actually be used and, specifically, where it can be used.
Q360	QM1	And this is precisely the difference compared to the ISO 50001 standard, as it is consumption-oriented rather than cost-oriented. Consequently, I am required to evaluate the SEUs—that is, the main energy consumers—and initiate improvements in these areas. We have corresponding measures in place, including an energy circle where we discuss what actions can be taken to ensure that these consumers are either reconfigured, reassessed, optimized, refurbished, or otherwise improved in the future. Through this process, we carry out the optimization.
Q361	EM4	Unused waste heat is recovered for the heating network, thereby saving natural gas.
Q362	EM4	So we examine that closely. What are the network losses? Who are the significant energy consumers? Is there potential for further savings? Then there is the Plan-Do-Check-Act cycle; accordingly, we conduct an audit every year.
Q365	CFO4	In terms of energy costs, this is certainly an area where we need to do some more work, as we observe that certain machines could easily be left unused—something we have mentioned about twenty-five times. Perhaps we simply need to install a lock in front of the switch.
Q374	EP1	Furthermore, we meet our entire global electricity demand through green energy backed by certificates of origin.
Q375	EP1	For new buildings, this is technically feasible of course; however, in principle, there comes a point where economic viability is calculated, and then [...] it is usually more economical to pursue an alternative approach. When discussing rooftop installations, relying solely on the savings from electricity costs makes implementation impossible.
Q376	EP1	However, when calculated over ten or even more years, do I actually save that much in electricity costs, or is the electricity price already at zero anyway?
Q382	EC1	I believe we currently have companies that are installing PV systems with the explicit goal of generating their own energy and thereby becoming more independent.
Q383	EP2	We approach our properties—open spaces or land that belongs to us—and then sign a Power Purchase Agreement, which is usually referred to as a 'behind-the-meter' or 'on-site' Power Purchase Agreement. This means we seek a third party who plans, builds, operates, and supplies us with kilowatt-hours.

Quote ID	Speaker	Quotation
Q384	EP2	We prefer to seek partners who commit to us on a long-term basis. We are prepared to sign contracts for 5, 10, 15, or even 25 years, because our commitment does not end in 2029. After all, the earth will continue to rotate in 2030 as well. For this reason, we can also sustain a base-load supply contract for ten years.
Q385	EP2	We fix up to 50 percent, and the remainder floats in the market. We examine market data from the stock exchange and then negotiate the corresponding surcharges and markups that such a supplier typically includes in its contracts.
Q390	QM1	The goal was self-sufficiency; we aimed to feed in as little as possible, since there is no compensation for it. Purchasing electricity is expensive, whereas selling it yields nothing. Furthermore, feed-in typically occurs when everyone else is also feeding in, resulting in negative prices; in such cases, one even has to pay for the electricity fed into the grid.
Q391	MA2	This yields certain cost blocks that appear in the profit and loss statement. From these, mathematicians derive cost surcharges, which are then added to the insurance product. Consequently, these energy costs naturally contribute, albeit in a relatively small proportion, to the calculation of a comprehensive insurance tariff or supplementary insurance.
Q397	EM8	It is monitored. I essentially configure alarm notifications within the energy software—the module is named accordingly—and if a figure deviates significantly, I receive a notification, and we respond accordingly.
Q398	MA14	However, this also applies to subsidies. For instance, we occasionally receive grants for acquiring new machinery when we achieve energy savings. In such cases, we utilize our existing data.
Q399	MA8	How are energy costs evolving? How are CO2 costs evolving? This is very important for us when making decisions: the status quo today is one aspect. However, looking into the future is also essential for us. We need a long-term outlook on this issue specifically to be able to make investment decisions.
Q402	EM6	I believe that the economic efficiency assessment is always incorporated here. Our overarching goal is to achieve Net Zero by 2040. The question then becomes: which projects are feasible? Which of these offers the potential to reach this target? This represents the most efficient approach. I believe this aspect carries greater weight here. Otherwise, if we were to oppose investment decisions made by the business units regarding products and so on, we would lose ground.
Q405	EM3	[Person]: Are there other investment decisions affected by this? Essentially site planning, production planning, and similar matters—does that occur?; EM3: Absolutely. I could go into detail, but it clearly plays a significant role.
Q406	EM2	Without going into detail, energy costs are part of our price calculation. Prices are adjusted accordingly depending on the product and customer.
Q407	EM3	For us, this is linked to a comprehensive economic analysis based on the cost of procuring external electricity from the grid versus generating it internally.
Q426	CFO4	I simply need to know where the limits lie—both in terms of what is feasible and what is not—and equally important, I need to determine how far I can raise my prices based on arguments regarding rising energy costs. At what point does a customer tell me that this approach is excessively focused on sustainability?
Q430	CFO4	Apart from energy management, where I naturally first need to establish reviews and identify major consumers, how do I improve in this area? This is certainly a decisive factor for us, and it is also crucial for our internal transparency. When discussing with a client whether energy costs account for x or y percent of a particularly costly large order, I have the opportunity to examine what the actual reality is versus what I assumed during my initial calculation.

Quote ID	Speaker	Quotation
Q431	MA3	I am hardly concerned with consumption; if the cost is low, I essentially do not care.
Q432	MA8	For example, I am personally liable for energy-law-related reports in my capacity as group leader.
Q433	MA8	Ultimately, our department head is the person who must explain major issues and bear responsibility when energy procurement goes awry, when cost spikes are excessive, when we failed to factor in certain reimbursement criteria, or when something went wrong.
Q434	EM1	From the production side, that is difficult to say. It is, after all, a large process, and I do not know whether specific responsible individuals were designated; however, it is often the case that several parties collaborate and share overall responsibility for the energy process, with each contributing their part. There is no single person—for instance, the CEO of Company J—who is solely responsible for energy, such that if something goes wrong, it would be considered their problem.
Q437	EP2	We are also responsible for certain topics; one would call us accountable. For instance, we are responsible for implementing our strategy to procure green electricity. We must achieve climate neutrality by the end of 2029. This means that our procured electricity—specifically, only the electricity we purchase—must originate entirely (100%) from renewable sources.
Q438	EP2	You have to explain when something is too expensive, but you never have to explain when it is too cheap.
Q439	EP2	And the other person entered something and noticed the following year: 'Damn, I was completely off.' Then he called me and said: 'The gas price you negotiated is too high.' 'No, it is fixed now; actually, your budgeting was terrible.'
Q442	MA2	Well, of course, there is also no individual incentive whatsoever to save energy.
Q443	CFO3	There are target agreements, including some with monetary implications. However, it is explicitly not mandated that sustainability targets must be established. Instead, these agreements consistently align with the corporate strategy on an annual basis, focusing on planned projects. Sustainability targets are not a fixed component of this framework.
Q445	EM6	The energy efficiency managers working at Company H have exactly these kinds of targets assigned. And these are linked to compensation, yes. So, it is not directly applicable to every one of us, but in my case, for example, it certainly is.
Q446	EP1	So it is truly a case-by-case assessment; one cannot simply say: 'Well, dear Manager [Person], your consumption has increased by 10% over time per square meter, so I must regrettably dismiss you.'
Q447	CFO2	As [Person] mentioned earlier, rankings are naturally established as part of the annual controlling process. The most energy-efficient site receives a nice reward for the company outing.
Q448	EP2	The seriousness with which this is pursued is quite simply due to the fact that the executive board's bonus depends on our achievement of the sustainability targets. To put it another way: Company A ties the achievement of sustainability targets to the payment of management bonuses. This naturally provides a strong motivation.
Q450	EM4	That depends on whether one is an employee outside the collective agreement or not. From a certain management level onwards, there are personal goals that must be pursued; these are evaluated by a corresponding committee. [Person]: For example, requiring the saving of a specific amount of energy. EM4: Yes, that can be included; there are indeed personal goals. For us energy specialists, these are usually energy targets, though sometimes other objectives as well, but they are always part of the set.
Q451	CFO1	As far as I know, this has not yet been universally implemented regarding certain variable salary components. Of course, if I am currently running a project such as the ESG implementation and so on, it is included in that context.

Table 2-10: Quotations used for the consequences

3. Better together: Temporal granularity of energy costs and carbon accounting

Abstract

This paper introduces a model that integrates temporally granular electricity cost data and carbon intensity data to account for energy costs and Scope 2 CO_2 emissions. Existing approaches to carbon accounting often rely on aggregated data, obscuring temporal variability in energy-related emissions and costs. The proposed model aligns electricity consumption with temporally granular grid characteristics, generating temporal-granular cost and carbon information at the level of cost objects and timeslots. We simulate four scenarios based on electricity market data, systematically varying electricity pricing structures and consumption patterns from hourly to yearly aggregation levels. Our findings show that temporal granularity substantially impacts both energy costs and carbon emissions, particularly in environments characterized by fluctuating electricity prices, electricity consumption, and carbon intensities. This suggests that temporally granular modelling of energy costs and carbon intensity is relevant to enhance operational decision-making, drive behavioral change, and support effective regulatory frameworks. While implementation depends on data availability and organizational flexibility, recent advances in smart metering and energy management systems enhance feasibility. The paper contributes to the literature by conceptualizing temporal granularity and volatility of electricity prices and electricity consumption as critical contingency factors in the design of energy cost and carbon accounting systems.

KEYWORDS: *energy cost accounting, scope 2 carbon emission, Greenhouse Gas Protocol, temporal granularity, carbon accounting, contingency theory*

3.1. Introduction

In the face of anthropogenic global warming, businesses are increasingly mindful of the linkages between energy, environmental impacts, and costs (Burritt et al., 2021). Prioritizing these aspects is not just a choice but a compelling necessity for companies striving to maintain competitiveness. For many organizations, Scope 2 emissions (indirect emissions from purchased electricity, steam, heating, and cooling) represent the major share of their total carbon emissions (Ketenci and Wolf, 2024; Thiede et al., 2016). Importantly, neither these Scope 2 emissions nor the costs due to electricity consumption are static over time. However, when accounting systems summarize these in temporally aggregated measures for costs and carbon emissions, they obscure *when* costs and emissions actually arise and thereby reduce the decision-usefulness of the resulting information. This paper therefore examines temporal granularity as a design issue in accounting for electricity costs and Scope 2 carbon emissions.

Accounting research has increasingly examined carbon accounting. Carbon accounting is a prerequisite for a system of tradable emission rights (Bebbington and Larrinaga-González, 2008; Chen et al., 2021; Clarkson et al., 2015), it is a way to make organizations accountable for carbon emission (Griffin et al., 2017; Phang et al., 2025) and it supports them in managing those emissions (Reichelstein, 2025). Research has addressed novel frameworks for carbon accounting (Easton et al., 2025; Kaplan and Ramanna, 2021; Reichelstein, 2024), organizational-level competencies for carbon accounting (Ascui and Lovell, 2012), and limitations in quantifying and commensurating carbon emissions (Kolk et al., 2008).

Although the GHG Protocol is the leading standard to account for carbon emissions (Green, 2010) and a key research topic in environmental management research (e.g., Diniz et al., 2021; Garcia and Freire, 2014; Stachelscheid and Dutzi, 2025), it has received surprisingly little attention in accounting research. This is notable as the GHG Protocol is not only a standard for emissions reporting but it can also serve as the basis for internal decision-making, blurring the lines between disclosure and internal carbon management (Jona and Soderstrom, 2023). Some recent accounting research has started to examine Scope 2 accounting under the GHG protocol (Jenkins et al., 2025) but the role of temporal aggregation remains underexplored. The current study examines temporal granularity as an accounting design choice, thereby complementing prior research on several dimensions of aggregation (Anand et al., 2019; Arya et al., 2004; Balakrishnan et al., 2011; Datar and Gupta, 1994; Labro and

Vanhoucke, 2007; Şabac and Yoo, 2018). This issue is also policy relevant for the current GHG Protocol revision process (GHG Protocol, 2026).[7]

The temporal variation in both carbon intensity and cost of electricity is substantial. Electricity prices are highly dynamic (Mickovic and Wouters, 2020) due to fluctuations in supply and demand, while the carbon intensity of the grid varies with the generation sources available at any given time (Blizniukova et al., 2023). Carbon intensity concerns the amount of carbon emissions caused by a specific amount of electricity generation, usually expressed in kg of CO_2-eq per MWh. Solar generation and electricity demand patterns both typically peak during daytime in regions with a large share of solar electricity-generation, which increases the variation in the grid's carbon intensity throughout the day (Frantzen and Hauser, 2012). For example, on 10 August 2024 in Germany, carbon intensity ranged from 125.96 to 386.56 kg CO_2-eq per MWh, while electricity prices ranged from –40.77 (negative prices) to 133.00 € per MWh. The timing of electricity consumption can therefore drastically affect both carbon emissions and costs. Electricity prices are highly volatile (e.g., Clò et al., 2015; Cludius et al., 2014; Rintamäki et al., 2017; Tashpulatov, 2013) with lower costs and emissions when renewables dominate and higher costs and emissions during fossil-fuel-intensive periods (e.g., Gelabert et al., 2011; Keeley et al., 2020; Quint and Dahlke, 2019; Sáenz De Miera et al., 2008; Weigt, 2009; Würzburg et al., 2013).

Yet, current accounting methods for estimating Scope 2 emissions do not account for this dynamic behavior of carbon intensity. According to the Greenhouse Gas Protocol (2004), Scope 2 emissions are calculated using either the location-based method that reflects the average local grid mix, or the market-based method that reflects contractual instruments (Brander et al., 2018; Stachelscheid and Dutzi, 2025). However, both methods do not capture temporal variation of Scope 2 carbon emissions and thereby merely approximate real-world conditions, which limits their decision usefulness (Glenk, 2024). Energy cost accounting systems also hardly incorporate the joint dynamics of cost and carbon intensity over time. This misalignment suggests that the decision-usefulness of energy cost accounting information may be hampered, because it would depend on contextual factors such as volatility in

[7] The GHG Protocol is currently in the process of updating its documents of standards and guidance, including its Scope 2 Guidance. The proposed revisions for the location-based method for Scope 2 emissions include the use of temporally granular data to align emissions claims more closely with the point in time when electricity is consumed. Drawing on our research, we also provided feedback as part of the public consultation, which was completed on 31 January 2026. See the website GHG Protocol Public Consultations, https://ghgprotocol.org/ghg-protocol-public-consultations (accessed 25 February 2026).

electricity prices and carbon intensity. This view is consistent with contingency theory (e.g., Cadez and Guilding, 2008; Chenhall, 2003; Covaleski et al., 1996; Hayes, 1977; Otley, 1980, 2016; Waterhouse and Tiessen, 1978) and aligned with recent calls for more actionable carbon information in energy cost accounting systems (Dickemann, 2025). Hence, this paper investigates the following research questions: *(1) How can temporally granular information on electricity consumption and prices be incorporated in energy cost and carbon accounting systems? (2) What are the effects of such temporal granularity on the accuracy and decision-usefulness of cost and emission information?*

We investigate an accounting model that integrates temporally granular data on electricity consumption, pricing, and carbon intensity to provide fine-grained estimates of both costs and emissions at the timeslot and unit level. This information allows organizations to evaluate the design implications of different temporal granularities. We investigate the model through a series of simulations based on real-world data on electricity generation, carbon intensity, and spot market prices for Germany, California (USA), Greece, New South Wales (Australia), and Ontario (Canada). The simulations vary three core contingency factors: (1) temporal granularity, (2) electricity pricing structure (constant vs. variable), and (3) electricity consumption patterns (constant vs. time-varying) to isolate the effects of temporal alignment between consumption, prices, and emissions. This simulation-based design allows us to assess how different accounting system designs affect the decision-usefulness of cost and emissions information across different organizational and environmental conditions.

Simulations are well-suited for this purpose, as they offer many advantages for addressing research questions in accounting that are otherwise difficult to analyze empirically (Labro, 2015). For instance, simulations allow researchers to manipulate structural conditions (such as temporal granularity, electricity consumption, and electricity prices) which is not feasible with real-world data due to informational constraints and practical limitations (Balakrishnan et al., 2011). Anand, Balakrishnan, and Labro (2019) further highlight that simulation experiments allow for precise manipulation of factors like resource costs, consumption patterns, and the availability of temporally granular information, thereby providing insights into complex interactions that shape cost system accuracy and decision support. Taken together, simulations can overcome empirical barriers and yield insights into accounting system design and its implications for decision support systems. In our study, simulations allow us to systematically explore how different temporal granularities, pricing structures, and managing consumption patterns affect the alignment between accounting information and underlying environmental-economic conditions.

Our findings demonstrate the effect different temporal granularities have on both electricity costs and associated Scope 2 carbon emissions. The results show how electricity costs and associated carbon emissions diverge, even under constant consumption patterns, when accounted with different temporal granularities. Furthermore, the analysis demonstrates the decision-usefulness of this temporally granular information by simulating moderate shifts of electricity consumption to cheaper or less carbon-intensive timeslots. We show that this results in materially lower costs and lower Scope 2 carbon emissions, compared to the baseline.

Based on the simulations and findings, this paper contributes to the accounting literature in several ways. First, it illustrates how carbon intensity can be integrated into energy cost accounting systems at high temporal granularity. Second, it shows that higher temporal granularity can improve the accuracy and usefulness of both cost and carbon information, especially in volatile settings. Third, it conceptualizes temporal granularity as a design choice in accounting systems, advancing contingency-theoretical thinking in the area of energy cost and carbon accounting. Finally, it highlights the potential for implementation of temporal granular accounting for Scope 2 emissions without significant additional investment or major changes to current energy monitoring and management systems.

3.2. Literature review

3.2.1. Dynamic electricity costs and Scope 2 emissions

Accurate energy cost information supports managerial decisions on investment planning, operational efficiency, and responsiveness to dynamic pricing. It enables long-term investment decisions that affect future energy consumption (Bierer and Götze, 2012), directs managerial attention to operational inefficiencies, supports problem-solving, and facilitates performance tracking (Burritt et al., 2021). Energy costs are substantial in energy-intensive industries (Andersson and Thollander, 2019; Bui and De Villiers, 2017; Quinteiro et al., 2012) but still relevant in less energy-intensive industries (Gunarathne and Lee, 2015). Similarly, electricity-related carbon emissions, classified as Scope 2 under the Greenhouse Gas Protocol (2004), are important for decision-making and the other purposes mentioned above. These are a major source of industrial carbon emissions (Quinteiro et al., 2012) and for many organizations, Scope 2 emissions account for the largest share of their overall carbon footprint (Ketenci and Wolf, 2024; Thiede et al., 2016).

We focus on electricity, as this form of energy bridges energy costs and Scope 2 emissions. Both electricity prices and Scope 2 emissions fluctuate significantly over time. Electricity price fluctuations are especially high under grid stress conditions (Lu and Suthaharan, 2023; Wang et al., 2024) due to variations in the underlying electricity generation mix (Blizniukova et al., 2023; Khan, 2018; Miller et al., 2022). Renewables lower day-ahead prices via the merit-order effect (Sánchez De La Nieta and Contreras, 2020) and carbon emissions vary with the changing electricity generation mix (Aboumahboub et al., 2012; Schaber et al., 2012). Since renewables typically have low marginal cost and displace fossil-based generation, periods of high renewable supply are usually associated with both lower prices (or even negative prices) and lower carbon intensity. Reversely, (very) high electricity prices occur during demand peaks, especially under grid stress conditions (Lu and Suthaharan, 2023; Wang et al., 2024). Moreover, electricity prices and carbon intensity are not only volatile over time but also interdependent across regions due to the grid infrastructure (Li et al., 2018).

3.2.2. Electricity challenges for conventional cost accounting systems

While energy is sometimes referred to as a production material (Ketenci and Wolf, 2024; Trianni et al., 2021), its properties more closely resemble a flow than a stock. As Burritt et al. (2021) note, energy resembles a process input, which is measured and billed by time (Chan et al., 2008; Wozabal et al., 2016) and accounted for accordingly (Thiede et al., 2016). Although methods like Material Flow Cost Accounting integrate resource data into cost systems, they typically focus on physical flows and material efficiency, not temporal variation (e.g., Burritt et al., 2021; Christ and Burritt, 2015). For most manufacturing companies, electricity is the dominant energy input and thus the main focus of energy-related cost and carbon accounting.

Electricity must be consumed at the time it is generated (Kirschen and Strbac, 2004), making its sourcing fundamentally different from other inputs. Especially small and medium-sized organizations typically rely on grid-supplied electricity, whereas self-generation is more common among large (Aflaki et al., 2013) and energy-intensive organizations (Johansson and Söderström, 2011). Since consumption must match real-time demand, electricity prices and carbon intensity are linked to grid conditions. During peak periods, prices often spike (Lu and Suthaharan, 2023; Wang et al., 2024), and both prices and carbon intensities fluctuate over time due to volatile markets influenced by global conditions (Hammoudeh et al., 2014). Consequently, organizations are incentivized to shift consumption to lower-cost periods and adopt measures such as peak avoidance (Bevilacqua et al., 2017). However, such operational responses remain disconnected from cost accounting systems.

Energy cost accounting systems do not yet capture this dynamic behavior of electricity costs because conventional cost accounting assumes input homogeneity, price stability, and time-independence (Bhimani et al., 2015; Drury, 2018; Horngren et al., 2012), assumptions that electricity systematically violates. As a result, cost accounting for electricity fails to incorporate the temporal electricity price and carbon intensity volatility into formal accounting logic. Even when granular data are collected (i.e., smart metering (e.g., Ma et al., 2021) or electricity dashboards (e.g., Ashabi et al., 2024)), such information remains decoupled from core costing logic (Bevilacqua et al., 2017). A recent review confirms that conventional energy cost accounting systems fail to reflect this temporal complexity (Dickemann, 2025), limiting their usefulness for dynamic decision-making. Taken together, these features challenge the representation of electricity within traditional cost accounting.

3.2.3. Accounting for electricity-related carbon emissions

Similarly, systems that account for Scope 2 emissions do not yet capture the dynamic behavior of the electricity generation mix and the resulting carbon intensity. The GHG Protocol (2004) outlines the location-based or market-based method for calculating Scope 2 emissions. Neither of these captures temporal variability, which limits the decision-usefulness of reported emissions data (Howard-Grenville et al., 2014). The location-based method multiplies total electricity consumption by an average emission factor for the regional or national grid to calculate emissions of grid-supplied electricity (Kemper et al., 2025). The market-based method attributes emissions according to contractual instruments (i.e., renewable energy certificates), allowing organizations to report lower emissions for certified "green" electricity purchases (Brander et al., 2018) independent from the physical reality of the grid-delivered electricity.

Both methods are indirect allocation methods in that they assign emissions generated at power plants to end-users, but they represent different perspectives and both face criticism (Ballentine and Falwell, 2025; Kemper et al., 2025; Roston et al., 2024). The market-based method may allow double-counting when multiple entities claim credit for the same renewables (Ballentine and Falwell, 2025), while the location-based method suffers from unclear grid boundaries and weak decarbonization incentives (Kemper et al., 2025). Moreover, using both methods simultaneously introduces inconsistencies, where renewably generated electricity is sold to individual organizations while being included in the average grid emissions (Holzapfel et al., 2023, 2024; Khan, 2018). This effectively accounts for renewable energy twice. Furthermore, both methods have additional accounting challenges such as related to boundary choices (Ascui, 2014; Haslam et al., 2014) and data quality (Gipper et al., 2025).

3.2.4. Decision-usefulness of energy cost and carbon information

The situation that accounting systems for energy costs and Scope 2 carbon emissions often rely on aggregated information (Miller et al., 2022) limits their relevance for managerial activities such as benchmarking, investment prioritization, or operational control. Contingency theory highlights that the decision-usefulness of accounting systems depends on their alignment with organizational and environmental conditions (Luft and Shields, 2003; Otley, 1980). The decision-usefulness of energy cost and carbon information would depend on how well it reflects temporal variation. Prior work has shown that timeliness and granularity of accounting information affect how managers allocate attention, interpret performance, and make decisions in complex environments (Hall, 2010). Volatile and fast-changing contexts demand accounting systems that match temporal dynamics (Otley, 1999). Thus, organizations should adopt energy-aware decision-making (Bevilacqua et al., 2017) since empirical evidence suggests that energy prices can act as an effective regulatory tool to reduce carbon emissions (Li et al., 2020). The benefits of granular accounting information are especially large where managers can influence the timing of energy loads (Phang et al., 2025).

In sum, existing accounting models do not account for the fine-granular temporal volatility of energy prices and carbon intensity. Tools like smart metering (e.g., Ma et al., 2021) or energy dashboards (e.g., Ashabi et al., 2024) exist, but they remain disconnected from formal accounting logic. This paper investigates an accounting model grounded in contingency theory that demonstrates how accounting systems can reflect the actual volatility faced by managers in real-time decision environments.

3.3. Research method

We propose and simulate a model for estimating energy costs and carbon emissions from electricity consumption. Section 3.4.1 presents this model and formalizes the relationships between electricity consumption, prices, and carbon intensity over time. The model enables a more accurate assessment of the cost and carbon implications of organizational electricity consumption by incorporating temporally granular data on electricity generation and electricity costs. Using publicly available information on the electricity generation mix and emission factors, the carbon intensity of the grid can be derived and, if available, primary data on the carbon intensity from specific grid operators can be used.

In section 3.4.2, we evaluate how different levels of temporally granular information influence the results of both energy cost accounting and carbon accounting. This matters, because if aggregation toward less temporal granularity influences accounting results, it would also affect the usefulness of those accounting results for managerial decisions. To this end, we present simulation results for electricity consumption and the resulting electricity cost and Scope 2 carbon emission outcomes. The simulation incorporates five levels of temporal granularity: hourly, daily, weekly, monthly, and yearly. It draws on data from the German power grid. We replicate the simulations with data from four other regions (California, Greece, New South Wales, and Ontario) that have comparable electricity generation mixes.

The underlying dataset comprises the electricity generation mix and spot market prices for 2024, sourced from official government bodies. Data is available at five levels of temporal granularity, with hourly data (8,784 hours in one year) providing the highest granularity. Carbon intensity for each time slot is calculated as a weighted average of source-specific emission factors, with weights corresponding to each generation source's share in the electricity generation mix of the respective grid. The Appendix (section 3.6.4) provides more details on the carbon intensity calculation.[8]

We simulate two demand patterns: one with constant electricity consumption and another with time-varying consumption that reflects a manufacturing organization operating seven days a week in a two-shift system with reduced weekend activity. In the time-varying case, electricity consumption is highest during the day (06:00 – 20:00) and significantly lower during night hours (20:00 – 06:00), corresponding to reduced activity outside production

[8] All the data and the Python code files are made available at https://osf.io/43ngt/overview?view_only=2f136c57c60f47d19ba5908745e10b64. We used OpenAI's GPT-5.4 to assist with explaining and debugging parts of the Python scripts, and to draft the replication package documentation (README and execution instructions).

hours. Electricity consumption also decreases on weekends, reflecting a limited production schedule. The data incorporates seasonal variation and fluctuations in hourly and daily usage, yielding a dynamic and plausible consumption profile over the year. In all scenarios, the total amount of electricity consumed over the investigated year 2024 is held constant.

Moreover, we illustrate the potential decision-usefulness of temporally granular accounting information by modeling stylized but transparent managerial adjustments to the intra-day timing of electricity consumption. Temporally granular information would support managers to shift electricity consumption across hours within a day, subject to predefined operational constraints, while total daily consumption remains unchanged. We simulate this by allowing to shift some of the electricity consumption during the next day to either minimize cost or emissions, within particular operational constraints. The results of the simulation provide a benchmark of the potential value of temporally granular accounting information.

3.4. Results

3.4.1. Energy cost and carbon accounting model

The model for energy cost and carbon accounting (ECCA) integrates temporally granular electricity cost and carbon intensity data into management accounting systems to provide a more accurate and decision-relevant representation of electricity-related carbon emissions. It relies on two core data streams. First, data on the electricity generation mix in the grid, including total generation and the share of individual sources (e.g., wind, solar, coal) obtained from national or regional databases such as SMARD (Germany) or CAISO (California). These data are used to calculate the carbon intensity of grid electricity per functional unit as a weighted average of source-specific emission factors (expressed in kg of CO_2-eq per MWh) based on each source's share in the electricity generation mix. Second, data on organizational electricity consumption (expressed in MWh), covering both grid-supplied and self-generated electricity from renewable or conventional sources. By combining carbon intensity and consumption data, the model provides detailed, timeslot- and unit-specific calculations of electricity-related energy consumption, carbon emissions, and associated costs for an organization. This information can support decisions on electricity sourcing, cost allocation, carbon management, and process optimization (e.g., scheduling, identification of critical processes), thereby facilitating targeted efficiency improvements, emissions reductions, and more accurate information about both costs and real-world emissions.

3.4.1.1. Dimensions of electricity-related carbon emissions

Accurately calculating electricity-related carbon emissions requires information across three key dimensions: *electricity consumption* (MWh), *carbon intensity* (kg CO_2-eq/MWh), and e*lectricity purchase price* (€/MWh), as well as the corresponding *timeslot* in which the electricity is used. Let T denote the set of all timeslots in the focal period, indexed by t.

3.4.1.1.1. Electricity consumption

The electricity consumption in a given timeslot t, denoted as E_t, consists of E_t^p, electricity purchased from the grid in timeslot t, and E_t^s, electricity self-generated in timeslot t. Throughout this model, we assume that electricity demand and electricity consumption are always equal, with no grid supply interruptions. Self-generated electricity may originate from renewable (e.g., solar or wind) and non-renewable (e.g., coal or gas) sources. Let J denote the set of all self-generation sources, indexed by j. In this model, electricity storage (e.g., batteries or conversion into heat storage) is treated as an additional self-generated source when discharging, while charging for storage is part of the electricity consumption. The total self-generated electricity in timeslot t originates from a set of $j \in J$ sources and can be expressed as $E_t^s = \sum_{j \in J} E_{tj}^s$. The total electricity consumption in timeslot t is displayed in *Equation (I)*.

$$\text{(I)} \qquad E_t = E_t^p + \sum_{j \in J} E_{tj}^s$$

3.4.1.1.2. Electricity costs

The electricity purchase price in a given timeslot t, denoted as P_t, consists of P_t^p, the price for electricity purchased from the grid in timeslot t; and a set of $j \in J$ prices P_{tj}^s , where each price reflects the variable price of energy carriers or operational costs associated with a specific self-generation source j in timeslot t.

The electricity costs in a timeslot t are denoted as C_t and consist of fixed electricity costs in timeslot t C_t^f , and variable electricity costs in timeslot t C_t^v, displayed in *Equation (II)*. Fixed electricity costs in timeslot t (C_t^f), represent those costs that do not vary with the quantity of electricity consumed. They are calculated as the sum of the fixed costs attributable to assets from the company's general electricity infrastructure in timeslot t FC_t^a, fixed costs associated with electricity purchases from the grid in timeslot t FC_t^p, and fixed costs from self-generation in timeslot t FC_t^s, displayed in *Equation (IIa)*.

Variable electricity costs in timeslot t (C_t^v), represent those costs that vary directly with the quantity of electricity consumed. These are calculated as the sum of the electricity purchased from the grid in timeslot t (E_t^p) multiplied by the variable grid price (P_t^p), and the electricity consumed from each source j of self-generated electricity in timeslot t (E_{tj}^s) multiplied by its respective price (P_{tj}^s), summed across all sources j, displayed in *Equation (IIb)*.

$$\text{(II) } C_t = C_t^f + C_t^v$$

$$\text{(IIa) } C_t^f = FC_t^a + FC_t^p + FC_t^s$$

$$\text{(IIb) } C_t^v = E_t^p \times P_t^p + \sum_{j \in J}(E_{tj}^s \times P_{tj}^s)$$

3.4.1.1.3. Carbon Emissions

The carbon intensity in a given timeslot t, denoted as I_t, consists of I_t^p, the carbon intensity for electricity purchased from the grid in timeslot t; and a set of $j \in J$ carbon intensities I_{tj}^s for self-generated electricity in timeslot t.

The carbon emissions in a timeslot t are denoted as G_t and consist of the fixed carbon emissions in timeslot t G_t^f, and variable carbon emissions in timeslot t G_t^v, displayed in *Equation (III)*. Fixed carbon emissions in timeslot t (G_t^f), represent those carbon emissions that do not change with the quantity of electricity consumed. They are calculated as the sum of the carbon emissions attributable to assets associated with the electricity infrastructure in timeslot t FG_t^a, fixed carbon emissions associated with electricity purchases from the grid in timeslot t FG_t^p, and fixed carbon emissions from self-generation in timeslot t FG_t^s, displayed in *Equation (IIIa)*.

Variable carbon emissions in timeslot t (G_t^v), represent those carbon emissions that vary directly with the amount of electricity consumed. These are calculated as the sum of the electricity purchased from the grid in timeslot t (E_t^p) multiplied by the carbon intensity for electricity purchased from the grid in timeslot t (I_t^p), and the electricity consumed from each source j of self-generated electricity in timeslot t (E_{tj}^s) multiplied by its respective carbon intensity (I_{tj}^s), summed across all sources j, displayed in *Equation (IIIb)*.

$$\text{(III) } G_t = G_t^f + G_t^v$$

$$\text{(IIIa) } G_t^f = FG_t^a + FG_t^p + FG_t^s$$

$$\text{(IIIb) } G_t^v = E_t^p \times I_t^p + \sum_{j \in J}(E_{tj}^s \times I_{tj}^s)$$

3.4.1.2. Allocation to units of analysis

To generate actionable insights, the electricity consumption, electricity costs, and carbon emissions for each timeslot t must be assigned to the relevant units of analysis (UoA). For example, allocating consumption to individual production lines or departments enables process-level efficiency monitoring and supports more targeted managerial decisions. At any given timeslot t, let N denote the set of all UoA, indexed by n. The total value for a timeslot t can be disaggregated to each UoA n using an allocation factor α_{nt}[9], which represents the share assigned to UoA n in timeslot t. By definition, the allocation factors for a given timeslot t across all UoA n sum to one ($\sum_{\{n \in N\}} \alpha_{nt} = 1$).

Allocation is done separately for each dimension using a distinct allocation factor α for each UoA n in timeslot t. The electricity consumption in timeslot t (E_t) is allocated to each UoA n using the allocation factor α^e_{nt}, displayed in *Equation (IV)*. The electricity costs in timeslot t (C_t) are allocated to each UoA n using the allocation factor α^c_{nt}, displayed in *Equation (V)*. The carbon emissions in timeslot t (G_t) are allocated to each UoA n using the allocation factor α^g_{nt}, displayed in *Equation (VI)*. The allocation to a UoA can (and often should) reflect the underlying cost or emission structure, with fixed and variable components allocated on different bases. These fixed and variable components together determine the final allocation factor α.

$$\text{(IV) } u^e_{nt} = E_t \times \alpha^e_{nt}$$
$$\text{(V) } u^c_{nt} = C_t \times \alpha^c_{nt}$$
$$\text{(VI) } u^g_{nt} = G_t \times \alpha^g_{nt}$$

3.4.1.3. Aggregation across time or units of analysis

Aggregating information enables analysis across extended time periods or organizational scopes. For example, aggregating electricity consumption across all hours of a day (for a particular unit of analysis) captures the daily electricity consumption, or aggregation across all production lines (within a single timeslot) provides an overview of total plant demand. Such data may enable operational adjustments such as load balancing or rescheduling energy-intensive tasks. For each UoA n in timeslot t, u^e_{nt}, u^c_{nt}, and u^g_{nt} respectively denote the

[9] The literature provides various proposals for the allocation of electricity costs (e.g., Brunke et al., 2014; Fernandes et al., 1997; Phylipsen et al., 1997) and carbon emissions (e.g., Kellner and Otto, 2012; Moretti et al., 2017; Peereboom et al., 1998).

electricity consumption, electricity costs, and carbon emissions allocated according to section 3.4.1.2. These allocated values form the basis for the aggregation described below.

3.4.1.3.1. Aggregation over time (per unit of analysis)

For a given UoA n, the total electricity consumption for the period T ($UoAE_n$) is obtained as the sum of u_{nt}^{e} across all timeslots $t \in T$, displayed in *Equation (VII)*. The total electricity costs for the period T ($UoAC_n$) are similarly calculated as the sum of u_{nt}^{c} across all timeslots $t \in T$, displayed in *Equation (VIII)*. Finally, the total carbon emissions for the period T ($UoAG_n$) are determined as the sum of u_{nt}^{g} across all timeslots $t \in T$, displayed in *Equation (IX)*.

$$\text{(VII) } UoAE_n = \sum_{\{t \in T\}} u_{nt}^{e}$$
$$\text{(VIII) } UoAC_n = \sum_{\{t \in T\}} u_{nt}^{c}$$
$$\text{(IX) } UoAG_n = \sum_{\{t \in T\}} u_{nt}^{g}$$

3.4.1.3.2. Aggregation over units of analysis (per timeslot)

For a given timeslot t, the total electricity consumption (E_t) is obtained as the sum of u_{nt}^{e} across all UoA $n \in N$, displayed in *Equation (X)*. The total electricity costs for the timeslot t (C_t) are similarly calculated as the sum of u_{nt}^{c} across all UoA $n \in N$, displayed in *Equation (XI)*. Finally, the total carbon emissions for the timeslot t (G_t) are determined as the sum of u_{nt}^{g} across all UoA $n \in N$, displayed in *Equation (XII)*.

$$\text{(X) } E_t = \sum_{\{n \in N\}} u_{nt}^{e}$$
$$\text{(XI) } C_t = \sum_{\{n \in N\}} u_{nt}^{c}$$
$$\text{(XII) } G_t = \sum_{\{n \in N\}} u_{nt}^{g}$$

3.4.1.3.3. Aggregation over time and units of analysis

For the entire organization over the period T, the total electricity consumption (E_{Total}) is obtained as the sum of u_{nt}^{e} across all UoA $n \in N$ and all timeslots $t \in T$, displayed in *Equation (XIII)*. The total electricity costs (C_{Total}) for the organization are similarly calculated as the sum of u_{nt}^{c} across all UoA $n \in N$ and all timeslots $t \in T$, displayed in *Equation (XIV)*. Finally, the total carbon emissions (G_{Total}) for the organization are calculated as the sum of u_{nt}^{g} across all UoA $n \in N$ and all timeslots $t \in T$, displayed in *Equation (XV)*.

$$\text{(XIII) } E_{Total} = \sum_{\{t \in T\}} \sum_{\{n \in N\}} u_{nt}^{e}$$

$$\text{(XIV) } C_{Total} = \sum_{\{t \in T\}} \sum_{\{n \in N\}} u_{nt}^{c}$$

$$\text{(XV) } G_{Total} = \sum_{\{t \in T\}} \sum_{\{n \in N\}} u_{nt}^{g}$$

3.4.2. Simulating the effects of the ECCA model

3.4.2.1. Simulating the influence of temporal granularity

The ECCA model incorporates temporal granularity and the influence of this would depend on how much variables fluctuate over time. To explore these relationships, we conduct simulations that systematically vary three dimensions: (1) temporal granularity of data on electricity consumption and grid carbon intensity, (2) electricity prices being constant or fluctuating, and (3) electricity consumption being constant or varying. The model posits that aligning electricity consumption, carbon intensity, and electricity costs at a high temporal granularity improves the decision usefulness of both energy cost accounting and carbon accounting. This logic reflects the contingency-theoretical view in which the usefulness of accounting information depends on its alignment with the underlying volatility of organizational environments. The simulations evaluate how this temporal alignment affects accounting outcomes under varying conditions.

	Constant consumption	Time-varying consumption
Constant price	Scenario 1	Scenario 3
Fluctuating price	Scenario 2	Scenario 4

Table 3-1: Simulation design overview showing scenario combinations of pricing and consumption variation. Within each scenario, five different levels of temporal granularity are simulated.

We vary electricity consumption patterns (constant vs. time-varying) and pricing structures (constant vs. fluctuating), resulting in four scenarios summarized in Table 3-1. Within each scenario, we simulate accounting outcomes for a whole year at five levels of temporal granularity: hourly, daily, weekly, monthly, and yearly. These levels represent increasingly coarse aggregations of electricity consumption, pricing, and carbon intensity. For instance, the monthly granularity aggregates data into twelve average values for one year, whereas the hourly granularity preserves all temporal fluctuations (i.e., 8,784 separate hours for one year). Because hourly data retain the highest available granularity across all input dimensions, they provide the closest approximation to real-world variation and thus serve as the benchmark. Deviations from this hourly benchmark are treated as distortions in accounting outcomes caused by information loss through aggregation. This temporal granularity is reflected in the five columns of Table 3-2, which report simulation results for both electricity costs and carbon emissions, along with the deviation (delta) from the hourly benchmark.

Temporal Granularity	Hourly	Daily	Weekly	Monthly	Yearly
Panel A: Scenario 1 (constant consumption and constant price)					
Costs	3,448,786 €	3,448,786 €	3,448,786 €	3,448,786 €	3,448,786 €
Emissions	15,693 t CO_2-eq	15,119 t CO_2-eq	14,980 t CO_2-eq	14,877 t CO_2-eq	14,970 t CO_2-eq
Delta Costs		0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)
Delta CO_2		574 t CO_2-eq (3.66 %)	713 t CO_2-eq (4.55 %)	816 t CO_2-eq (5.20 %)	723 t CO_2-eq (4.61 %)
Panel B: Scenario 2 (constant consumption and fluctuating prices)					
Costs	3,448,786 €	3,448,786 €	3,448,786 €	3,448,786 €	3,448,786 €
Emissions	15,693 t CO_2-eq	15,119 t CO_2-eq	14,980 t CO_2-eq	14,877 t CO_2-eq	14,970 t CO_2-eq
Delta Costs		0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)
Delta CO_2		574 t CO_2-eq (3.66 %)	713 t CO_2-eq (4.55 %)	816 t CO_2-eq (5.20 %)	723 t CO_2-eq (4.61 %)
Panel C: Scenario 3 (time-varying consumption and constant price)					
Costs	3,448,786 €	3,448,786 €	3,448,786 €	3,448,786 €	3,448,786 €
Emissions	15,583 t CO_2-eq	15,375 t CO_2-eq	14,974 t CO_2-eq	14,869 t CO_2-eq	14,970 t CO_2-eq
Delta Costs		0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)
Delta CO_2		208 t CO_2-eq (1.34 %)	609 t CO_2-eq (3.90 %)	714 t CO_2-eq (4.58 %)	613 t CO_2-eq (3.93 %)
Panel D: Scenario 4 (time-varying consumption and fluctuating prices)					
Costs	3,558,366 €	3,562,148 €	3,451,072 €	3,449,580 €	3,448,786 €
Emissions	15,583 t CO_2-eq	15,375 t CO_2-eq	14,974 t CO_2-eq	14,869 t CO_2-eq	14,970 t CO_2-eq
Delta Costs		3,782 € (0.11 %)	107,294 € (3.02 %)	108,786 € (3.06 %)	109,580 € (3.08 %)
Delta CO_2		208 t CO_2-eq (1.34 %)	609 t CO_2-eq (3.90 %)	714 t CO_2-eq (4.58 %)	613 t CO_2-eq (3.93 %)

Table 3-2: Simulating the influence of temporal granularity on electricity cost and carbon emission accounting outcomes. Note: Table 3-2 reports electricity costs and carbon emissions for the entire year 2024. The five columns refer to using hourly, daily, weekly, monthly or yearly temporal granularity for electricity consumption and carbon intensity data. Constant consumption is 4.87 MWh per hour in these scenarios, and details on the varying consumption pattern are provided in Table 3-4 in the Appendix; the constant electricity price is 78.51 €/MWh (average price in Germany 2024), and fluctuating prices mirror hourly electricity prices at the German spot market in 2024. Totals are rounded; delta values and percentages are calculated from unrounded values, so minor differences may occur.

In all scenarios, carbon intensity fluctuates hourly based on real-world grid generation data, ensuring that temporal aggregation effects are always evaluated against a fluctuating carbon baseline. Electricity is purchased exclusively from the grid and the total annual electricity consumption is held constant. Fluctuating pricing scenarios rely on hourly spot market prices from the German electricity market in 2024. Further modeling assumptions and parameters are provided in Appendix A.

Building on the logic of the ECCA model, we show that different temporal granularities influence the accounting outcomes, but it works differently for costs than for emissions. Aggregating temporal granularity only influences costs if prices are fluctuating and there is time-varying consumption (Scenario 4). However, temporal granularity influences emissions in all scenarios. The reason is that fluctuating carbon intensities can only be aggregated over time at the grid level, whereas consumption data are measured at the company level.

Scenario 1 serves as the baseline scenario. It assumes both constant electricity consumption and a constant price, thereby isolating the effect of temporal granularity. Since neither consumption nor pricing varies over time, any differences in calculated carbon emissions across the five aggregation levels arise solely from the temporal aggregation. As expected, electricity costs remain identical across temporal granularities. In contrast, emissions diverge up to 5.2 percent at lower granularities, despite identical total electricity consumption and costs. This effect stems from the way carbon emissions are calculated in the ECCA model (section 3.4.1), where emissions in a timeslot (G_t) are the product of electricity consumption (E_t) multiplied by carbon intensity (I_t) in the same timeslot. When the electricity consumption (E_t) is constant, the hourly benchmark sums these products across all timeslots (hours), fully preserving hourly fluctuations in carbon intensity (I_t). Coarser aggregations replace hourly values I_t with an average carbon intensity for the longer period, which is then multiplied by total consumption in that period. However, this average carbon intensity is based on the total electricity consumption of the region and not of the individual organization. Hence, the organization's calculated carbon emissions are different. Averaging carbon intensity before multiplication systematically misstates total emissions when carbon intensity (I_t) varies over time. Tables 3-6 and 3-7 in the Appendix (Section 3.6.4) illustrate this effect in detail for 10 August 2024, comparing calculations based on hourly and daily data, showing that daily aggregation substantially misstates total carbon emissions for that day by 3.28 t CO_2-eq (11.54 percent). These results demonstrate that even in the absence of variation in consumption and price, temporal aggregation can significantly distort carbon accounting outcomes.

Scenario 2 builds on the baseline by introducing fluctuating electricity prices, while holding consumption constant, to assess how price volatility affects accounting outcomes. Since carbon intensities are the same in all scenarios and electricity consumption data are the same as in Scenario 1, total carbon emissions are identical to those in Scenario 1. Interestingly, costs are also the same in Scenario 1 and 2, although prices are different: these are constant in Scenario 1 but hourly fluctuating in Scenario 2. Why are costs the same in both scenarios? The average price is calculated as the mean of all hourly prices, whereby each hour has the same weight. This is the constant price in Scenario 1. As a result, multiplying this constant price with all the hourly consumption data to calculate total costs in Scenario 1 mathematically gives the exact same total cost as multiplying all the fluctuating hourly prices with all the hourly consumption data in Scenario 2. Therefore, the constant price used in Scenario 1 corresponds exactly to the arithmetic mean of the hourly spot market prices used in Scenario 2. Consequently, aggregating time-varying electricity prices over constant consumption yields total electricity costs.

This result reflects a fundamental asymmetry between cost accounting and carbon accounting outcomes. As explained above in Scenario 1 (and it is the same for Scenario 2), aggregation of carbon accounting is not done by multiplying the arithmetic mean of an organization's carbon intensity with the organization's electricity consumption, but by multiplying the arithmetic mean of the grid's carbon intensity by the organization's electricity consumption. Therefore, temporal aggregation affects carbon emissions. However, temporal granularity does not affect cost accounting outcomes in Scenario 2—moving from hourly to coarser data yields identical cost outcomes—because of the way the data is aggregated.

Scenario 3 builds on the baseline of Scenario 1 by introducing a time-varying electricity consumption pattern, while keeping electricity prices constant (as in Scenario 1). The varying electricity consumption interacts with fluctuations in carbon intensity, causing discrepancies in emissions at coarser temporal granularities of up to 4.58 percent under monthly granularity compared to the hourly benchmark. This distortion arises because coarser aggregations replace the hour-by-hour multiplication of consumption with, for example, monthly average grid carbon intensity multiplied with monthly total consumption. This aggregation does not anymore reveal short-term consumption peaks that coincide with periods of high carbon intensity, such as night hours when renewable energy sources like solar are unavailable. However, the distortions of emission are smaller than in Scenarios 1 and 2, which may seem puzzling at first. In the time-varying consumption pattern, electricity consumption is higher during the day, which usually coincides with lower carbon intensity in the German electricity grid during the day due to a higher share of renewable electricity generation, especially solar. The time-varying consumption profile is thus more aligned with low-carbon intensity hours, which makes the effect of aggregation smaller compared to the constant electricity consumption (Scenarios 1 and 2).

Importantly, electricity costs remain the same across all temporal granularities in Scenario 3 due to constant electricity pricing, as in Scenario 1. This highlights the critical asymmetry identified earlier: carbon accounting outcomes are always sensitive to temporal granularity (even if electricity consumption is constant), because carbon intensity varies over time. Yet, cost accounting outcomes remain unaffected by temporal granularity, unless electricity consumption and prices simultaneously vary (as Scenario 4 will illustrate). Consequently, detailed temporal information is particularly crucial in carbon accounting, as managerial decisions such as production scheduling can significantly affect carbon emissions.

Scenario 4 combines time-varying electricity prices with a time-varying consumption pattern, making it the most decision-relevant and empirically grounded scenario. It reflects a realistic interaction of all three dimensions of the ECCA model. This scenario reveals the full extent to which temporal granularity affects accounting outcomes: both electricity costs and carbon emissions differ substantially from the hourly baseline when the temporal granularity decreases. While the carbon emission results resemble those of Scenario 3, the cost deviations are only now emerging and these are economically meaningful, reaching up to 3.08 percent compared to the hourly benchmark.

The contrast with Scenario 2 is instructive: there, prices also varied, but consumption was constant, so aggregation had no effect on total costs. Here, the boundary condition identified earlier is met, substantial temporal variation occurs in both prices and consumption, and cost outcomes become sensitive to aggregation in the same way carbon outcomes have been in all scenarios. This makes Scenario 4 a “full interaction” case in which the combined volatility of input variables magnifies the consequences of temporal granularity.

To assess the robustness and generalizability, we replicated all four scenarios for Greece, New South Wales (Australia), California (United States), and Ontario (Canada), using hourly electricity generation and spot market price data. These additional analyses test whether the main results also hold under different electricity price dynamics and grid carbon intensity patterns. Across all four regions, the qualitative conclusions remain unchanged: temporal aggregation distorts electricity costs and carbon emissions. While the magnitude of these distortions differs across markets, reflecting differences in electricity price volatility and carbon intensity patterns, the results remain robust beyond the German context. Full results are provided in Appendix B.

Together with the systematic patterns seen in all scenarios, these results confirm that temporal granularity is not a mere technicality, but a foundational design choice in energy cost and carbon accounting with significant implications. From a contingency theory perspective, this design choice determines how well the system aligns with the temporal complexity of the underlying environment. Across all scenarios, coarse temporal aggregation systematically distorts outcomes relative to the hourly benchmark, resulting in over- or underaccounting of both electricity costs and carbon emissions. These distortions for carbon emissions emerge even under constant electricity consumption and intensify when pricing and consumption vary over time. For instance, carbon emissions computed with hourly data exceed monthly values by up to 4.60 percent (Scenarios 1 and 2), while cost differences in realistic settings surpass 3 percent of the electricity costs (Scenario 4). In energy-intensive sectors, a 3 percent deviation in annual electricity costs could translate into millions in costs, highlighting the materiality of these distortions. These discrepancies have direct implications for managerial decisions and Scope 2 emissions accounting. The results further reveal that conventional accounting practices may obscure emissions that the ECCA model makes visible, particularly those linked to consumption during carbon-intensive periods. Potentially, this can lead to underreporting Scope 2 emissions or missed opportunities for cost and emissions reductions through temporal load shifting. These findings confirm the decision-relevance of the ECCA model and demonstrate the importance of temporal granularity: this is grounded in contingency theory and empirically consequential.

3.4.2.2. Simulating the decision-usefulness of managerial discretion

So far, we addressed the impact of temporal granularity on cost and emissions outcomes without explicitly differentiating between different users of the information. In this section, we address decision relevance and focus specifically on internal users who may use temporal granular information for short-term decisions on their timing of energy consumption.[10] Thereby, we answer the call for research by Jona and Soderstrom (2023) to develop effective carbon accounting tools that can be used internally and externally.

The preceding simulations treated electricity consumption patterns as exogenous, although a central implication of temporally granular accounting systems is that they enable managerial intervention. Managers can adjust the timing of electricity consumption to reduce electricity costs and Scope 2 carbon emissions. For instance, intelligent production scheduling could simultaneously reduce electricity costs and carbon emissions, revealing a potential complementarity between environmental and financial performance. Therefore, the economic value of temporal granularity depends not only on data accuracy but also on the degree of managerial discretion over the timing of electricity consumption.

To examine this mechanism, we simulate discretionary load shifting under stylized but transparent constraints. We modeled managerial discretion by allowing up to 10 percent of total daily electricity consumption to be reallocated within the same day, and hourly consumption may increase or decrease by up to 20 percent relative to the baseline profile, while total daily and annual consumption remain unchanged. Managers are assumed to be able to shift a limited share of daily electricity consumption, relative to the baseline presented in section 3.4.2.1, subject to hourly adjustment bounds and constant daily totals. Consumption decisions are made for each following day under perfect foresight of hourly electricity prices and carbon intensities.

Because discretionary load shifting requires information on intra-day fluctuations in electricity prices and carbon intensities, the managerial discretion simulation is implemented at hourly temporal granularity, which preserves these hourly fluctuations in both. This simulation is therefore intended as a benchmark of the potential value of temporally granular accounting information, not as a behavioral prediction. We implement this simulation for the German setting, which serves as the baseline market throughout the paper. Table 3-3 reports the baseline outcomes (Panel A) for the four scenarios without managerial intervention and the resulting changes under two shifting rules. For the cost-oriented rule (Panel B), managers rank hours within each day by electricity price and shift the permitted share of load from the most expensive to the cheapest hours, subject to the hourly adjustment limits. For the carbon-

[10] Information on how a firm might reduce carbon emissions may also be relevant for external stakeholders if they see operational changes to reduce such emissions differently than purchasing offset (Johnson et al., 2020).

oriented rule (Panel C), the same procedure is applied using hourly carbon intensity instead of electricity prices.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Panel A: Baseline				
Costs	3,448,786 €	3,448,786 €	3,448,786 €	3,558,366 €
Emissions	15,693 t CO_2-eq	15,693 t CO_2-eq	15,583 t CO_2-eq	15,583 t CO_2-eq
Panel B: Cost optimization				
Costs	3,448,786 €	3,244,271 €	3,448,786 €	3,350,342 €
Emissions	15,693 t CO_2-eq	15,290 t CO_2-eq	15,583 t CO_2-eq	15,169 t CO_2-eq
Saving Costs	0 € (0.00 %)	204,516 € (5.93 %)	0 € (0.00 %)	208,023 € (5.85 %)
Saving CO_2	0 t CO_2-eq (0.00 %)	403 t CO_2-eq (2.57 %)	0 t CO_2-eq (0.00 %)	414 t CO_2-eq (2.66 %)
Panel C: Emissions optimization				
Costs	3,448,786 €	3,309,609 €	3,448,786 €	3,409,694 €
Emissions	15,129 t CO_2-eq	15,129 t CO_2-eq	15,021 t CO_2-eq	15,021 t CO_2-eq
Saving Costs	0 € (0.00 %)	139,177 € (4.04 %)	0 € (0.00 %)	148,672 € (4.18 %)
Saving CO_2	564 t CO_2-eq (3.60 %)	565 t CO_2-eq (3.60 %)	562 t CO_2-eq (3.61 %)	562 t CO_2-eq (3.61 %)

Table 3-3: Simulating the effects of discretionary within-day electricity consumption shifting. Note: Table 3-3 reports electricity costs and carbon emissions for the entire year 2024 with an hourly temporal granularity. The four columns refer to the Scenarios defined in Table 3-1. The costs and emissions for these scenarios are the same as in Table 3-2. To simulate the effects of consumption shifting, the algorithm reallocates up to 10% of daily consumption within the day, subject to ± 20% hourly adjustment constraints, with the goal to either reduce costs or emissions.

Results show that in the cost-optimization setting (Panel B), cost savings arise only in Scenarios 2 and 4, where electricity prices are fluctuating (spot market). In these settings, discretionary load shifting reduces annual electricity costs by almost 6 percent. Importantly, emissions also decline as a by-product, reflecting that low-cost periods tend to coincide with low-carbon periods in the German grid. The manager would often also shift consumption to low-carbon periods when they deliberately shift to low-cost periods. In contrast, no savings occur in Scenario 1 and 3, where prices are constant. Therefore, managerial discretion creates cost savings only when electricity prices vary temporally.

In the emissions-optimization setting (Panel C), total carbon emissions decline across all scenarios because carbon intensity varies temporally in each scenario and therefore managers would have the possibility to shift consumption to low-carbon periods. Emission reductions of more than 3.6 percent are achievable under the modeled discretion constraints.

In Scenarios 2 and 4, cost savings also emerge although they deliberately shift to low-carbon periods, again illustrating complementarity between environmental and financial objectives in this case.

These simulations demonstrate that temporal granularity matters for the decision relevance of energy cost and carbon emission information. When volatility exists in electricity prices or carbon intensities, temporally granular information enables economically and environmentally meaningful managerial adjustments. From a contingency-theory perspective, the value of temporal granularity depends on two interacting conditions: the volatility of the underlying data and managerial discretion over consumption timing. Temporal granularity in energy cost and carbon accounting thus operates as both an accounting design choice and an enabler of insights and adjustments to optimize electricity costs and Scope 2 carbon emissions. Without temporally granular accounting information, these potential electricity cost and Scope 2 carbon emission savings would neither be measurable nor managerially actionable, as they would remain invisible within the accounting system.

3.5. Discussion and conclusion

Electricity prices and grid carbon intensity vary over time, yet accounting systems often aggregate them into time-invariant measures, limiting what organizations can know and do about energy costs and Scope 2 carbon emissions. By aggregating time-varying inputs into coarse averages, accounting systems can misstate measured outcomes and blur when costs and emissions actually arise. This aggregation affects the signals managers receive and which opportunities for cost reduction and carbon emissions mitigation become visible and actionable. We therefore develop and simulate the ECCA model to demonstrate how temporal aggregation can distort electricity costs and Scope 2 carbon emission information, and how temporally granular information can generate decision-useful information.

The ECCA model provides a framework that links electricity consumption with corresponding electricity prices and carbon intensities at a temporally granular level. This enables the allocation of electricity costs and electricity-related carbon emissions at the unit and timeslot level. By formalizing these relationships, ECCA makes temporal alignment of energy costs and carbon emissions an explicit design dimension of accounting systems. The formalization accommodates different sourcing constellations, including electricity purchased from the grid and self-generation. It can also represent settings with intermittent or unavailable grid supply (e.g., outages or off-grid operations in remote areas).

By modelling temporal granularity of Scope 2 carbon emissions, this study adds to the accounting literature on granularity of carbon emission information. Extant, recent research addresses ways to provide granular carbon emissions data and addresses granularity in the sense of detailed emissions data toward separate cost centers, products, services, customers, and other such relevant cost objects (Asam et al., 2025). We conceptualize granularity along a different dimension: time. Temporal granularity complements prior research by moving beyond the question of “where emissions occur” to also capture “when emissions occur”.

Relatedly, this study contributes to the accounting literature on aggregation in cost systems by addressing temporal aggregation. Prior research shows that aggregation across heterogeneous resource or activity cost pools can generate aggregation error when a single allocation rate is applied to non-homogeneous cost structures (Labro and Vanhoucke, 2007). We extend this logic to the aggregation dimension of time by showing that temporally aggregating volatile inputs (electricity prices and grid carbon intensity) can systematically distort electricity cost and Scope 2 carbon emissions outcomes. Temporal aggregation constitutes an additional source of aggregation error in accounting systems when underlying conditions vary over time.

This study also contributes to ongoing debates on Scope 2 carbon accounting and standard setting, including discussions in the Greenhouse Gas Protocol ecosystem that increasingly recognize the timing of electricity consumption and temporal granularity. While the GHG protocol currently gives considerable discretion when choosing emission factors and activity measures (Glenk, 2025), the ECCA model illustrates how accounting information can incorporate not only how much electricity is consumed but also when it is consumed . This addresses known limitations in prevailing Scope 2 methods, which often obscure the consequence of consumption decisions (Downar et al., 2021). While electricity prices can encourage consumption shifting (Bevilacqua et al., 2017), they do not always align with carbon intensity or reflect full environmental costs. Temporally granular cost and carbon information can therefore complement market-based signals and inform disclosure rules, voluntary standards, and policy discussions aimed at aligning electricity consumption with periods of lower carbon intensity. In this sense, temporal granularity can support both carbon mitigation and grid efficiency, aligning with policy recommendations proposed by Khan (2018). In addition, the ECCA model can strengthen transparency and traceability by linking consumption, pricing, and emissions at a temporally granular level.

The numerical simulations show that temporal granularity is a consequential design choice: temporal aggregation can systematically distort Scope 2 carbon emission and (when prices and consumption fluctuate jointly) electricity cost outcomes. Importantly, the effects differ for costs and emissions. Because carbon intensity varies over time and is measured at the grid level, aggregated carbon intensity data can distort carbon emissions outcomes even when total consumption is held constant, whereas cost distortions arise only when both prices and consumption fluctuate.

Beyond accounting outcome distortions, temporally granular information can reshape what becomes managerially actionable. Our managerial discretion simulations illustrate that hourly information provides an informational basis for within-day load shifting by making electricity cost and carbon emissions implications of consumption timing visible. Under the stylized discretion constraints, shifting consumption toward low-price hours yields economically meaningful cost savings when prices vary, while shifting toward low-carbon hours yields emissions reductions when carbon intensity varies. In the German setting, these effects mostly coincide because low-price and low-carbon periods often overlap, suggesting a contingent complementarity between financial and environmental objectives. However, in other settings, price-carbon divergence can create tradeoffs.

Our simulation results show that temporal granularity is a consequential design choice in energy cost and carbon accounting systems. This extends prior work on environmental accounting systems that rely on aggregated data (Burritt et al., 2011) and complements management accounting research on how accounting information affects operational and strategic decision-making (Balakrishnan et al., 2014). Contingency-based research argues that accounting system design should fit the informational demands of the environment (Chenhall, 2003; Otley, 1980, 2016; Waterhouse and Tiessen, 1978). From this perspective, temporal volatility in electricity prices and grid carbon intensity constitutes a salient environmental condition, and temporal granularity represents an accounting system design response that determines how well accounting measures align with time-variant environments. Importantly, temporally granular information can increase the visibility of when and where costs and emissions arise, which aligns with research showing that accounting systems can influence organizational attention and behavior in sustainability contexts (Maas et al., 2016). Moreover, the simulations demonstrate that, when managers have discretion over consumption timing, temporally granular accounting information improves the underlying informational basis for intervention by making potential efficiency gains and emissions reductions calculable and comparable, thereby increasing the decision-usefulness of electricity cost and Scope 2 carbon emission information.

The implications of temporally granular energy cost and carbon accounting are subject to several conditions. The decision-usefulness of temporally granular accounting information depends on organizational discretion and flexibility to adjust electricity consumption timing. For organizations with rigid schedules, uninterrupted processes, or limited technological capacity, the scope for within-day shifting may be constrained, limiting the actionability of temporally granular information. Temporally granular information may also surface tradeoffs when electricity prices and grid carbon intensity diverge. In such settings cost optimization can increase emissions, while carbon optimization can increase costs, requiring explicit prioritization between financial and carbon objectives. Furthermore, effective implementation of the ECCA logic further requires access to temporally granular data and the ability to integrate these operational data streams into accounting routines. While smart metering and energy management systems increasingly generate temporally granular consumption data, aligning these data with accounting information systems remains a socio-technical challenge involving interfaces, data ownership, and accountability for measures.

A first avenue for future research concerns attribution under energy storage, where temporal decoupling between charging and use raises new accounting questions. While ECCA already incorporates storage into the accounting logic, future work could develop timestamp mechanisms that track the source and time-specific carbon intensity of stored electricity. Such an extension would enable more precise emissions attribution when stored electricity is later used and would clarify how storage decisions interact with carbon mitigation objectives, particularly in volatile grid conditions where charging and discharging choices can materially reshape both cost and emissions outcomes.

A second avenue for future research concerns how temporally granular electricity cost and carbon emission information becomes institutionalized in organizations. Empirical studies could examine how metering and energy-management data are integrated into accounting routines and enterprise systems (e.g., ERP), how data ownership and accountability for measures are assigned across functions, and how these arrangements shape the interpretation and use of temporally granular information in operational and investment decisions. Such work could also explore organizational frictions that mediate whether temporally granular information changes action, including coordination costs or competing priorities (cost vs. carbon). Relatedly, future research could test temporal volatility as a contingency factor, examining when temporal granularity is consequential and when it is not. Although we replicate patterns across multiple grids, field-based evidence is needed to assess whether the benefits of temporal granularity materialize under real-world constraints, including limited managerial discretion to shift loads, adjustment costs, and contractual restrictions. In particular, future research could examine how electricity pricing structures (e.g., peak-load fees, tiered tariffs) and organizational consumption profiles influence the value of temporally granular accounting information.

Finally, future research should examine how organizations govern cost-carbon tradeoffs when price and carbon signals diverge, and how incentives shape the resulting decisions. When low-carbon periods coincide with high electricity prices (and vice versa), temporally granular information makes tradeoffs explicit and can shift attention toward one objective at the expense of another. Understanding how organizations prioritize objectives, design incentive systems, and avoid unintended consequences (e.g., cost optimizations that actually increase costs via carbon taxes) would deepen knowledge of how accounting information structures sustainability-related decision-making.

Concluding, this paper shows that temporal granularity is an important design choice in energy cost and carbon accounting. The simulations demonstrate that temporal aggregation can systematically distort accounting outcomes, with asymmetric effects across costs and emissions, and that the decision-usefulness of temporally granular information depends on the joint presence of temporal volatility in prices and carbon intensity and managerial discretion over consumption timing. From a contingency-theory perspective (e.g., Cadez and Guilding, 2008; Chenhall, 2003; Covaleski et al., 1996; Hayes, 1977; Otley, 1980, 2016; Waterhouse and Tiessen, 1978), this positions temporal volatility as a salient environmental condition and temporal granularity as a design response that shapes what becomes visible and actionable in accounting systems. By formalizing temporal alignment at the unit and timeslot level, the ECCA model extends prior work on aggregation (Datar and Gupta, 1994; Labro, 2019) and carbon accounting (Bjørn et al., 2025; Brander et al., 2018; Diniz et al., 2021). More broadly, the ECCA model highlights that accounting conventions about time are not mere technicalities but determine how organizations govern costs and carbon in increasingly volatile electricity grids.

3.6. Appendix A: Specification of the model

3.6.1. Model parameters

Parameter	Description	Constant consumption (Scenario 1 +2)	Varying Consumption (Scenario 3 +4)
FC_t^a	Annual fixed cost for providing general electricity infrastructure.	43,920	43,920
FC_t^p	Annual fixed cost for purchasing electricity from the grid	43,920	43,920
FC_t^s	Annual fixed cost for self-generation of electricity	0	0
FG_t^a	Annual fixed carbon emissions for providing general electricity infrastructure.	87,840 t CO_2-eq	87,840 t CO_2-eq
FG_t^p	Annual fixed carbon emissions for purchasing electricity from the grid	87,840 t CO_2-eq	87,840 t CO_2-eq
FG_t^s	Annual fixed carbon emissions for self-generation of electricity	0	0
E_t^p	Electricity consumption from the grid *(values used with more decimal spots)*	4.87 MWh	Varying consumption
E_t^s	Electricity consumption from self-generation	0	0
P_t^p	Price per MWh electricity from the grid *(values used with more decimal spots)*	78.51 € [GER] 100.88 € [GRE] 131.01 A$ [NSW] 35.02 $ [CA] 32.19 CAD [ON]	Volatile spot market prices
P_t^s	Price per MWh self-generated electricity	0	0
I_t^p	Carbon intensity for electricity purchased from the grid *(values used with more decimal spots)*	Time-varying with the electricity generation mix of the grid	Time-varying with the electricity generation mix of the grid
I_t^s	Carbon intensity for electricity self-generated	0	0

Table 3-4: Parameter values used in the simulation. Monetary values are in Euro (€) for Germany (GER). In Appendix B, monetary values are in Euro (€) for Greece (GRE), US dollars ($) for California (CA), Australian dollars (A$) for New South Wales (NSW), and Canadian dollars (CAD) for Ontario (ON).

The parameters in Table 3-4, together with the temporally granular electricity generation mix and price data for each region, form the core inputs to the ECCA model. They establish the link between empirical electricity market conditions and organizational consumption patterns in the simulations.

Fixed parameters (FC_t and FG_t) represent annual non-variable costs and carbon emissions allocated to specific organizational functions (e.g., administration, production) and, where applicable, to on-site generation. These parameters remain constant across all scenarios, ensuring that observed differences in simulation outcomes are driven by temporal variations in variable costs and carbon intensity rather than by changes in fixed-cost allocation.

Generation and consumption parameters (E_t) define the total annual electricity purchased from the grid or generated on-site. In these simulations, all on-site generation parameters are set to zero to focus on grid-purchased electricity. Combined with each scenario's temporal consumption profile, these totals determine the hourly and aggregated load profiles used by the model. The static profile allocates identical consumption to each timeslot, while the volatile profile reflects realistic operational scheduling in manufacturing, with peaks and troughs in demand. This affects how consumption aligns with periods of high or low prices and high or low carbon intensities.

Carbon intensity parameters (I_t) are calculated for each timeslot as the weighted average of source-specific emission factors, with weights corresponding to the share of each generation source in the electricity generation mix of the grid at that timeslot. This approach captures short-term fluctuations in grid carbon intensity and reflects the actual environmental impact of electricity consumption timing. Electricity generation mix data of the grid are drawn from official 2024 market datasets for each region.

Electricity price parameters (P_t) are sourced from official 2024 market data for each region and aggregated to hourly, daily, weekly, monthly, and yearly levels to match the temporal granularity of each simulation run.

3.6.2. Emission factors

Source	**Biomass**	**Hydro**	**Wind**	**Solar**	**Nuclear**	**Coal**	**Gas**	**Misc. Conv.**
Carbon Intensity [kg CO_2-eq/MWh]	230	10.70	12.20	35.40	5.13	1,023.00	434.00	700.00
Reference	IPCC, 2014	UNECE, 2022	UNECE, 2022	UNECE, 2022	UNECE, 2022	UNECE, 2022	UNECE, 2022	EMBER, 2023

Table 3-5: Emission factors used to calculate the carbon intensity values in the simulations of the ECCA model and their respective sources.

The emission factors in Table 3-5 form the basis for calculating temporally granular carbon intensity values in the simulations. Most values are taken directly from the United Nations Economic Commission for Europe's (UNECE), *Life-Cycle Assessment of Electricity Sources* report (UNECE, 2022). Missing categories are supplemented with data from the IPCC (2014) for biomass and EMBER's *European Electricity Review* for miscellaneous conventional generation (EMBER, 2023).

The solar emission factor represents the median of available UNECE values, covering different types of solar generation. The "miscellaneous conventional" category represents a residual mix of coal, gas, geothermal, and biomass generation not separately reported in the primary data. For the California dataset, geothermal electricity generation is reported separately; its corresponding emission factor of 38 kg CO_2-eq/MWh is sourced from the IPCC (2014) and applied analogously to the other source-specific factors in the model.

3.6.3. Data adjustments and modeling simplifications

Several data adjustments were necessary for the simulations. In the *German dataset*, an additional category dealt with "miscellaneous renewables". However, this was an insignificant amount of electricity generated, and we could not determine a reliable emission factor. Therefore, we excluded it from the analysis. For the *California dataset*, a small number of hourly values were missing or erroneous due to grid interruptions or database errors. Missing values were addressed either by interpolation (for single missing values) or by setting the values to zero (for longer periods). These adjustments do not affect the study's conclusions, as results are compared on an aggregated basis according to each temporal granularity. Consequently, any effect of missing data is applied equally across all scenarios and temporal granularities, influencing total values but not the relative comparisons between them. For the *Greece dataset*, two consecutive hourly values were missing in the electricity generation mix. These values were filled by duplicating the preceding and subsequent hourly values, respectively.

In addition, modeling simplifications were applied. *Storage technologies*, including batteries and pumped hydro, were excluded from the set of electricity generation sources, as storage is not classified as an energy source according to the IPCC (2012). Including storage would substantially complicate the simulations without contributing to the primary focus of the study.

3.6.4. Exemplary calculation of carbon emissions at two levels of temporal granularity

Table 3-7 illustrates how hourly carbon intensity is calculated using the example for the German dataset on 10 August 2024, using the method applied throughout the simulations. For each hour, carbon intensity is calculated as the generation weighted average of the source-specific emission factors provided in Table 3-5 in this Appendix using the following formula:

$$CI_t = \frac{\sum Electricity\ generated\ in\ t_{Source} * Emission\ Factor_{Source}}{Total\ electricity\ generated\ in\ t}$$

Hour / Day	Electricity consumption E_t (MWh)	Carbon intensity I_t (kg CO_2-eq/MWh)	Carbon Emissions (t CO_2-eq)
Panel A: Hourly values for electricity consumption and carbon intensity			
00:00 – 01:00	4.87	318.70	1.55
01:00 – 02:00	4.87	326.84	1.59
02:00 – 03:00	4.87	336.40	1.64
03:00 – 04:00	4.87	343.63	1.67
04:00 – 05:00	4.87	340.06	1.66
05:00 – 06:00	4.87	324.11	1.58
06:00 – 07:00	4.87	301.64	1.47
07:00 – 08:00	4.87	247.03	1.20
08:00 – 09:00	4.87	186.06	0.91
09:00 – 10:00	4.87	152.18	0.74
10:00 – 11:00	4.87	142.00	0.69
11:00 – 12:00	4.87	133.43	0.65
12:00 – 13:00	4.87	126.17	0.61
13:00 – 14:00	4.87	127.30	0.62
14:00 – 15:00	4.87	129.69	0.63
15:00 – 16:00	4.87	132.32	0.64
16:00 – 17:00	4.87	135.44	0.66
17:00 – 18:00	4.87	143.51	0.70
18:00 – 19:00	4.87	183.91	0.90
19:00 – 20:00	4.87	276.53	1.35
20:00 – 21:00	4.87	329.33	1.60
21:00 – 22:00	4.87	349.41	1.70
22:00 – 23:00	4.87	365.66	1.78
23:00 – 24:00	4.87	378.55	1.84
TOTAL	116.96		28.41
Panel B: Daily values for electricity consumption and carbon intensity			
10 August 2024	116.96	214.87	25.13

Table 3-6: Exemplary calculation of electricity-related carbon emissions in Scenario 1 on 10 August 2024, using hourly (Panel A) and daily (Panel B) electricity consumption at the organization level and carbon intensity data of the grid.

Hour	Total Gen.	Bio	Hydro	Wind	Solar	Coal	Gas	Misc. Conv.	CI
00:00 – 01:00	**32,146**	3,892	1,989	15,067	9	6,712	3,060	1,306	**318.70**
01:00 – 02:00	**31,120**	3,823	1,926	14,195	6	6,643	3,106	1,312	**326.84**
02:00 – 03:00	**30,254**	3,814	1,953	13,376	7	6,720	2,962	1,313	**336.40**
03:00 – 04:00	**29,389**	3,784	1,884	12,710	4	6,687	2,908	1,305	**343.63**
04:00 – 05:00	**29,515**	3,805	1,815	12,947	6	6,617	2,908	1,308	**340.06**
05:00 – 06:00	**29,848**	3,868	1,852	13,589	18	6,276	2,832	1,306	**324.11**
06:00 – 07:00	**31,280**	3,999	1,784	14,261	1,046	5,991	2,780	1,311	**301.64**
07:00 – 08:00	**34,332**	4,046	1,809	13,285	6,362	5,065	2,350	1,309	**247.03**
08:00 – 09:00	**39,618**	3,936	1,863	11,144	15,268	3,796	2,203	1,302	**186.06**
09:00 – 10:00	**48,814**	3,805	1,881	10,787	25,131	3,518	2,302	1,283	**152.18**
10:00 – 11:00	**55,008**	3,710	1,927	9,830	32,046	3,479	2,360	1,549	**142.00**
11:00 – 12:00	**59,198**	3,645	1,822	10,067	36,264	3,460	2,269	1,565	**133.43**
12:00 – 13:00	**61,000**	3,564	1,811	10,388	38,204	3,442	2,242	1,245	**126.17**
13:00 – 14:00	**59,259**	3,517	1,700	8,781	38,408	3,400	2,200	1,149	**127.30**
14:00 – 15:00	**57,581**	3,512	1,670	8,157	37,470	3,400	2,119	1,150	**129.69**
15:00 – 16:00	**56,390**	3,498	1,746	9,290	34,941	3,418	2,246	1,147	**132.32**
16:00 – 17:00	**54,293**	3,585	1,844	11,682	30,253	3,422	2,263	1,143	**135.44**
17:00 – 18:00	**50,261**	3,708	1,887	14,946	22,740	3,426	2,198	1,256	**143.51**
18:00 – 19:00	**42,521**	3,895	1,903	16,124	12,634	4,217	2,349	1,297	**183.91**
19:00 – 20:00	**34,385**	4,162	2,065	13,765	4,201	5,871	2,912	1,306	**276.53**
20:00 – 21:00	**29,635**	4,339	2,318	11,858	513	6,169	3,024	1,309	**329.33**
21:00 – 22:00	**27,829**	4,380	2,414	10,469	30	6,197	2,924	1,310	**349.41**
22:00 – 23:00	**26,388**	4,199	2,347	9,334	9	6,189	2,893	1,311	**365.66**
23:00 – 24:00	**25,587**	4,101	2,028	8,763	6	6,166	3,106	1,311	**378.55**
10 August 2024	**975,646**	92,584	46,234	284,811	335,573	120,277	62,512	31,101	**214.87**

Table 3-7: Exemplary calculation of the carbon intensity on 10 August 2024 in Germany, used in Table 3-6, for both hourly aggregation (Panel A) and the daily aggregation (Panel B).

3.7. Appendix B: Simulations in peer regions

In this online appendix with supporting information, we replicate the simulations using data from four additional regions California (United States of America), Greece, New South Wales (Australia), and Ontario (Canada) to assess the robustness and generalizability of the results across different electricity grids. The selected peer regions differ in electricity price volatility and grid carbon intensity profiles, allowing us to test whether the effects of temporal aggregation generalize across heterogeneous market environments.

Results are reported in Tables 3-8 to 3-11. Across all four regions, the qualitative pattern mirrors that observed for Germany: temporal aggregation systematically distorted both cost and emission outcomes relative to the hourly benchmark. Cost deviations only arise when electricity prices and consumption vary simultaneously (Scenario 4). The magnitude of the distortions differs across regions, reflecting differences in time-varying carbon intensity and electricity price volatility. In Greece (Table 3-8), Scenario 1's carbon emission deviations reached 4.38 percent at the daily level, slightly below Germany's 4.60 percent, while Scenario 4's cost deviations remained comparatively modest at up to 2.04 percent. In New South Wales (Table 3-9), Scenario 1's carbon emission deviation was 3.50 percent at the daily level, lower than in Germany, whereas Scenario 4's cost deviations rose to 6.40 percent at the weekly level. California (Table 3-10) showed similarly large daily emissions deviations in Scenario 1 at 4.41 percent, but substantially higher cost deviations in Scenario 4 of up to 7.99 percent. Ontario (Table 3-11) provides a useful contrast case: despite its comparatively low-emission grid, temporal aggregation still produced relevant distortions, with Scenario 1 emission deviations reaching 2.70 percent and Scenario 4 cost deviations reaching 4.27 percent. Notably, the direction of the distortion differs across regions, indicating that temporal aggregation can either overstate or understate accounting outcomes depending on the alignment of consumption timing, electricity prices, and grid carbon intensity. Overall, these replications confirm that the materiality of temporal aggregation effects depends on regional variation in grid carbon intensity dynamics and electricity price volatility, but the underlying logic of the ECCA model remains robust across diverse market and grid contexts.

Temporal Granularity	Hourly	Daily	Weekly	Monthly	Yearly
Panel A: Scenario 1 (constant consumption and constant price)					
Costs	4,406,197 €	4,406,197 €	4,406,197 €	4,406,197 €	4,406,197 €
Emissions	11,950 t CO_2-eq	11,426 t CO_2-eq	11,443 t CO_2-eq	11,471 t CO_2-eq	11,547 t CO_2-eq
Delta Costs		0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)
Delta CO_2		524 t CO_2-eq (4.38 %)	507 t CO_2-eq (4.24 %)	478 t CO_2-eq (4.00 %)	403 t CO_2-eq (3.37 %)
Panel B: Scenario 2 (constant consumption and fluctuating prices)					
Costs	4,406,197 €	4,406,197 €	4,406,197 €	4,406,197 €	4,406,197 €
Emissions	11,950 t CO_2-eq	11,426 t CO_2-eq	11,443 t CO_2-eq	11,471 t CO_2-eq	11,547 t CO_2-eq
Delta Costs		0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)
Delta CO_2		524 t CO_2-eq (4.38 %)	507 t CO_2-eq (4.24 %)	478 t CO_2-eq (4.00 %)	403 t CO_2-eq (3.37 %)
Panel C: Scenario 3 (varying consumption and constant price)					
Costs	4,406,197 €	4,406,197 €	4,406,197 €	4,406,197 €	4,406,197 €
Emissions	11,700 t CO_2-eq	11,627 t CO_2-eq	11,489 t CO_2-eq	11,510 t CO_2-eq	11,547 t CO_2-eq
Delta Costs		0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)	0 € (0.00 %)
Delta CO_2		73 t CO_2-eq (0.62 %)	211 t CO_2-eq (1.81 %)	190 t CO_2-eq (1.62 %)	153 t CO_2-eq (1.31 %)
Panel D: Scenario 4 (varying consumption and fluctuating prices)					
Costs	4,498,182 €	4,514,212 €	4,423,192 €	4,420,591 €	4,406,197 €
Emissions	11,700 t CO_2-eq	11,627 t CO_2-eq	11,489 t CO_2-eq	11,510 t CO_2-eq	11,547 t CO_2-eq
Delta Costs		16,030 € (0.36 %)	74,990 € (1.81 %)	77,591 € (1.72 %)	91,985 € (2.04 %)
Delta CO_2		73 t CO_2-eq (0.62 %)	211 t CO_2-eq (1.81 %)	190 t CO_2-eq (1.62 %)	153 t CO_2-eq (1.31 %)

Table 3-8: Simulation results using grid data from Greece Note: Table 3-8 reports electricity costs and carbon emissions for the entire year 2024. The five columns refer to using hourly, daily, weekly, monthly or yearly temporal granularity for electricity consumption and carbon intensity data. Constant consumption is 4.87 MWh per hour in these scenarios, and details on the varying consumption pattern are provided in Table 3-4 in Appendix A of the paper; the constant electricity price is 100.88 €/MWh (average price in Greece 2024) and fluctuating prices mirror hourly electricity prices at the Greek spot market in 2024. Totals are rounded; delta values and percentages are calculated from unrounded values, so minor differences may occur.

Temporal Granularity	Hourly	Daily	Weekly	Monthly	Yearly
Panel A: Scenario 1 (constant consumption and constant price)					
Costs	5,696,257 $A	5,696,257 $A	5,696,257 $A	5,696,257 $A	5,696,257 $A
Emissions	29,470 t CO_2-eq	28,438 t CO_2-eq	28,421 t CO_2-eq	28,433 t CO_2-eq	28,493 t CO_2-eq
Delta Costs		0 $A (0.00 %)	0 $A (0.00 %)	0 $A (0.00 %)	0 $A (0.00 %)
Delta CO_2		1,032 t CO_2-eq (3.50 %)	1,049 t CO_2-eq (3.56 %)	1,037 t CO_2-eq (3.52 %)	977 t CO_2-eq (3.32 %)
Panel B: Scenario 2 (constant consumption and fluctuating prices)					
Costs	5,696,257 $A	5,696,257 $A	5,696,257 $A	5,696,257 $A	5,696,257 $A
Emissions	29,470 t CO_2-eq	28,438 t CO_2-eq	28,421 t CO_2-eq	28,433 t CO_2-eq	28,493 t CO_2-eq
Delta Costs		0 $A (0.00 %)	0 $A (0.00 %)	0 $A (0.00 %)	0 $A (0.00 %)
Delta CO_2		1,032 t CO_2-eq (3.50 %)	1,049 t CO_2-eq (3.56 %)	1,037 t CO_2-eq (3.52 %)	977 t CO_2-eq (3.32 %)
Panel C: Scenario 3 (varying consumption and constant price)					
Costs	5,696,257 $A	5,696,257 $A	5,696,257 $A	5,696,257 $A	5,696,257 $A
Emissions	28,359 t CO_2-eq	28,481 t CO_2-eq	28,424 t CO_2-eq	28,438 t CO_2-eq	28,493 t CO_2-eq
Delta Costs		0 $A (0.00 %)	0 $A (0.00 %)	0 $A (0.00 %)	0 $A (0.00 %)
Delta CO_2		122 t CO_2-eq (0.43 %)	65 t CO_2-eq (0.23 %)	79 t CO_2-eq (0.28 %)	134 t CO_2-eq (0.47 %)
Panel D: Scenario 4 (varying consumption and fluctuating prices)					
Costs	6,059,887 $A	5,926,812 $A	5,671,771 $A	5,683,985 $A	5,696,257 $A
Emissions	28,359 t CO_2-eq	28,481 t CO_2-eq	28,424 t CO_2-eq	28,438 t CO_2-eq	28,493 t CO_2-eq
Delta Costs		133,075 $A (2.20 %)	388,116 $A (6.40 %)	375,902 $A (6.20 %)	363,629 $A (6.00 %)
Delta CO_2		122 t CO_2-eq (0.43 %)	65 t CO_2-eq (0.23 %)	79 t CO_2-eq (0.28 %)	134 t CO_2-eq (0.47 %)

Table 3-9: Simulation results using grid data from New South Wales (Australia) Note: Table 3-9 reports electricity costs and carbon emissions for the entire year 2024. The five columns refer to using hourly, daily, weekly, monthly or yearly temporal granularity for electricity consumption and carbon intensity data. Constant consumption is 4.87 MWh per hour in these scenarios, and details on the varying consumption pattern are provided in Table 3-4 in Appendix A of the paper; the constant electricity price is 131.01 A$/MWh (average price in New South Wales 2024) and fluctuating prices mirror hourly electricity prices at the New South Welsh spot market in 2024. Totals are rounded; delta values and percentages are calculated from unrounded values, so minor differences may occur.

Temporal Granularity	Hourly	Daily	Weekly	Monthly	Yearly
Panel A: Scenario 1 (constant consumption and constant price)					
Costs	1,586,937 $	1,586,937 $	1,586,937 $	1,586,937 $	1,586,937 $
Emissions	7,574 t CO_2-eq	7,240 t CO_2-eq	7,268 t CO_2-eq	7,266 t CO_2-eq	7,248 t CO_2-eq
Delta Costs		0 $ (0.00 %)	0 $ (0.00 %)	0 $ (0.00 %)	0 $ (0.00 %)
Delta CO_2		334 t CO_2-eq (4.41 %)	306 t CO_2-eq (4.03 %)	308 t CO_2-eq (4.07 %)	326 t CO_2-eq (4.30 %)
Panel B: Scenario 2 (constant consumption and fluctuating prices)					
Costs	1,586,937 $	1,586,937 $	1,586,937 $	1,586,937 $	1,586,937 $
Emissions	7,574 t CO_2-eq	7,240 t CO_2-eq	7,268 t CO_2-eq	7,266 t CO_2-eq	7,248 t CO_2-eq
Delta Costs		0 $ (0.00 %)	0 $ (0.00 %)	0 $ (0.00 %)	0 $ (0.00 %)
Delta CO_2		334 t CO_2-eq (4.41 %)	306 t CO_2-eq (4.03 %)	308 t CO_2-eq (4.07 %)	326 t CO_2-eq (4.30 %)
Panel C: Scenario 3 (varying consumption and constant price)					
Costs	1,586,937 $	1,586,937 $	1,586,937 $	1,586,937 $	1,586,937 $
Emissions	7,415 t CO_2-eq	7,372 t CO_2-eq	7,336 t CO_2-eq	7,333 t CO_2-eq	7,248 t CO_2-eq
Delta Costs		0 $ (0.00 %)	0 $ (0.00 %)	0 $ (0.00 %)	0 $ (0.00 %)
Delta CO_2		43 t CO_2-eq (0.58 %)	79 t CO_2-eq (1.07 %)	82 t CO_2-eq (1.10 %)	167 t CO_2-eq (2.25 %)
Panel D: Scenario 4 (varying consumption and fluctuating prices)					
Costs	1,501,907 $	1,599,600 $	1,621,872 $	1,620,682 $	1,586,937 $
Emissions	7,415 t CO_2-eq	7,372 t CO_2-eq	7,336 t CO_2-eq	7,333 t CO_2-eq	7,248 t CO_2-eq
Delta Costs		97,693 $ (6.50 %)	119,965 $ (7.99 %)	118,775 $ (7.91 %)	85,031 $ (5.66 %)
Delta CO_2		43 t CO_2-eq (0.58 %)	79 t CO_2-eq (1.07 %)	82 t CO_2-eq (1.10 %)	167 t CO_2-eq (2.25 %)

Table 3-10: Simulation results using grid data from California (United States of America) Note: Table 3-10 reports electricity costs and carbon emissions for the entire year 2024. The five columns refer to using hourly, daily, weekly, monthly or yearly temporal granularity for electricity consumption and carbon intensity data. Constant consumption is 4.87 MWh per hour in these scenarios, and details on the varying consumption pattern are provided in Table 3-4 in the Appendix of the paper; the constant electricity price is 35.02 $/MWh (average price in California 2024) and fluctuating prices mirror hourly electricity prices at the Californian spot market in 2024. Totals are rounded; delta values and percentages are calculated from unrounded values, so minor differences may occur.

Temporal Granularity	Hourly	Daily	Weekly	Monthly	Yearly
Panel A: Scenario 1 (constant consumption and constant price)					
Costs	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD
Emissions	3,394 t CO_2-eq	3,446 t CO_2-eq	3,457 t CO_2-eq	3,465 t CO_2-eq	3,485 t CO_2-eq
Delta Costs		0 CAD (0.00 %)	0 CAD (0.00 %)	0 CAD (0.00 %)	0 CAD (0.00 %)
Delta CO_2		52 t CO_2-eq (1.52 %)	63 t CO_2-eq (1.86 %)	71 t CO_2-eq (2.08 %)	91 t CO_2-eq (2.70 %)
Panel B: Scenario 2 (constant consumption and fluctuating prices)					
Costs	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD
Emissions	3,394 t CO_2-eq	3,446 t CO_2-eq	3,457 t CO_2-eq	3,465 t CO_2-eq	3,485 t CO_2-eq
Delta Costs		0 CAD (0.00 %)	0 CAD (0.00 %)	0 CAD (0.00 %)	0 CAD (0.00 %)
Delta CO_2		52 t CO_2-eq (1.52 %)	63 t CO_2-eq (1.86 %)	71 t CO_2-eq (2.08 %)	91 t CO_2-eq (2.70 %)
Panel C: Scenario 3 (varying consumption and constant price)					
Costs	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD	1,465,674 CAD
Emissions	3,545 t CO_2-eq	3,520 t CO_2-eq	3,471 t CO_2-eq	3,482 t CO_2-eq	3,485 t CO_2-eq
Delta Costs		0 CAD (0.00 %)	0 CAD (0.00 %)	0 CAD (0.00 %)	0 CAD (0.00 %)
Delta CO_2		25 t CO_2-eq (0.71 %)	74 t CO_2-eq (2.08 %)	63 t CO_2-eq (1.77 %)	60 t CO_2-eq (1.67 %)
Panel D: Scenario 4 (varying consumption and fluctuating prices)					
Costs	1,531,003 CAD	1,492,369 CAD	1,474,487 CAD	1,475,071 CAD	1,465,674 CAD
Emissions	3,545 t CO_2-eq	3,520 t CO_2-eq	3,471 t CO_2-eq	3,482 t CO_2-eq	3,485 t CO_2-eq
Delta Costs		38,634 CAD (2.52 %)	56,516 CAD (3.69 %)	55,931 CAD (3.65 %)	65,329 CAD (4.27 %)
Delta CO_2		25 t CO_2-eq (0.71 %)	74 t CO_2-eq (2.08 %)	63 t CO_2-eq (1.77 %)	60 t CO_2-eq (1.67 %)

Table 3-11: Simulation results using grid data from Ontario (Canada) Note: Table 3-11 reports electricity costs and carbon emissions for the entire year 2024. The five columns refer to using hourly, daily, weekly, monthly or yearly temporal granularity for electricity consumption and carbon intensity data. Constant consumption is 4.87 MWh per hour in these scenarios, and details on the varying consumption pattern are provided in Table 3-4 in Appendix A of the paper; the constant electricity price is 32.19 CAD/MWh (average price in Ontario 2024) and fluctuating prices mirror hourly electricity prices at the Ontarian spot market in 2024. Totals are rounded; delta values and percentages are calculated from unrounded values, so minor differences may occur.

Summary

The doctoral thesis examines how accounting systems can better capture energy consumption, energy costs, and electricity-related carbon emissions in organizations. The thesis uses a systematic literature review, a qualitative empirical field study, and an analytical simulation study as complementary research methods. Together, the thesis aims to improve our understanding of how organizations currently manage energy-related information on costs and carbon emissions, how energy cost accounting systems are designed in practice, and how temporally granular accounting information can improve managerial decision-making.

The first paper is a systematic literature review on energy cost accounting, energy efficiency, and energy management in companies. It synthesizes 39 papers published in 19 journals and focuses on energy cost allocation, energy measurement, energy efficiency, energy strategy, and energy-related investment decisions. The paper shows that empirical knowledge on corporate energy practices is still fragmented, especially regarding detailed energy cost allocation and measurement practices, and it develops a framework for describing and analyzing these practices more systematically.

The second paper is a qualitative empirical field study of energy cost accounting practices in organizations. Based on 14 workshops with 32 industry experts from different functional areas, the study investigates how energy cost accounting systems are designed and used in practice. The paper develops an empirically grounded framework linking contextual factors, the design characteristics of energy cost accounting systems, and their organizational consequences.

The third paper develops the energy cost and carbon accounting model, which integrates time-specific electricity consumption, price, and carbon intensity data into accounting calculations. Methodologically, this paper combines formal modeling with simulation. Using electricity market and grid data, it simulates accounting outcomes under different combinations of consumption patterns, pricing conditions, and temporal aggregation levels. The results show that coarse temporal aggregation can systematically distort both electricity cost and Scope 2 carbon emission information. This paper contributes a novel accounting model and demonstrates that temporal granularity is a fundamental design choice for decision-useful energy cost and carbon accounting.

Overall, the dissertation contributes to management accounting and sustainability accounting research by showing how energy-related accounting information can be better

conceptualized, empirically understood, and analytically improved. It combines literature synthesis, qualitative field evidence, and model-based simulation to address a common research problem: how can organizations design accounting systems that reflect the economic and environmental implications of electricity consumption.

In sum, the thesis contributes to management accounting, sustainability accounting, and environmental management accounting research by showing how energy-related accounting information can be better conceptualized, empirically understood, and analytically improved. The thesis combines literature synthesis, qualitative field evidence, and model-based simulation to address a shared research problem: how organizations can design accounting systems that reflect the economic and environmental implications of energy consumption. In doing so, the thesis positions energy cost accounting as an important bridge between conventional cost accounting, environmental management accounting, energy management, and carbon accounting.

This thesis also opens several avenues for future research. First, further empirical studies are needed to systematically examine how organizations measure, allocate, and use energy cost information across different industries, countries, and institutional settings. Such work could extend the European focus of much existing research and investigate organizational practices in underrepresented regions. Second, longitudinal studies could examine how energy cost accounting systems evolve in response to energy market volatility, regulatory change, decarbonization requirements, and investments in metering or energy management infrastructure. Third, future research could investigate how energy management data are integrated into accounting routines, ERP systems, and decision-making processes, and how responsibilities for energy-related costs and emissions are assigned across functions. Fourth, field-based studies could assess whether the benefits of temporally granular energy cost and carbon information materialize under real-world organizational constraints, such as limited flexibility to shift electricity loads, contractual restrictions, competing priorities, or adjustment costs. Finally, future research should examine how organizations govern cost-carbon trade-offs when low-cost and low-carbon signals diverge. Understanding how accounting systems make these trade-offs visible, and how organizations design incentives, responsibilities, and decision processes around them, is essential for developing energy cost accounting systems that support both economic and environmental objectives.

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Summary of the doctoral thesis

Energy Cost Accounting: Linking Literature, Organizational Practice, and Carbon Emissions

by

Philip Dickemann

This doctoral thesis examines how accounting systems can better capture energy consumption, energy costs, and electricity-related carbon emissions in organizations. It develops and combines conceptual, empirical, and analytical approaches to improve energy cost and carbon accounting.

The premise of this thesis is that energy is an important production factor but is often treated as an aggregated overhead cost in conventional accounting systems. At the same time, volatile electricity prices, decarbonization pressures, and carbon reporting requirements increase the need for more detailed and decision-useful energy-related accounting information.

The thesis consists of three studies. First, a systematic literature review synthesizes research on energy cost accounting, energy efficiency and energy management. It shows that existing knowledge on corporate energy practices remains fragmented, especially regarding detailed energy cost allocation and measurement. Second, a qualitative field study examines how energy cost accounting systems are designed and used in practice. Based on 14 workshops with 32 industry experts, it develops a framework linking contextual factors, system characteristics, and organizational consequences. Third, an energy cost and carbon accounting model is developed and evaluated through simulation. The model integrates temporally granular electricity consumption, price, and carbon intensity data. The simulations show that coarse temporal aggregation can distort both electricity cost and Scope 2 carbon emission information.

Overall, the doctoral thesis contributes to management accounting, sustainability accounting, and environmental management accounting by positioning energy cost accounting as a bridge between conventional cost accounting, energy management, and carbon accounting.

This thesis was supervised by *Prof. Dr. Marc Wouters* at the Institute of Management. It is *written in English*. The pursued degree is *Dr. rer. pol.*