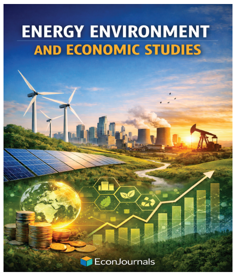

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Prioritization of Industrial Energy Efficiency Actions using Multicriteria Decision Aid

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ABSTRACT

Industrial firms frequently face the challenge of selecting among multiple energy efficiency actions under limited budgets and competing operational priorities. This study proposes a multicriteria decision-making approach to prioritize industrial energy efficiency alternatives using the ELECTRE III method. The analysis is based exclusively on real and published data extracted from the U.S. Department of Energy Industrial Training and Assessment Centers (ITAC) database, ensuring the empirical relevance and traceability of the alternatives and their performance scores. Eight actual industrial actions were selected and characterized according to four criteria: Total yearly savings, implementation cost, electricity usage savings, and electricity demand-charge savings. These criteria capture both the economic and operational dimensions of energy-efficiency investments and provide a suitable basis for an outranking analysis under imperfect preference structures. ELECTRE III is especially appropriate in this context because it allows for the incorporation of preference, indifference, and veto thresholds, thereby reflecting the uncertainty and gradual preference patterns that typically arise in real industrial decision environments. The study contributes a replicable framework for ranking energy efficiency projects using reliable secondary data and offers practical support for decision-makers seeking to improve resource allocation in manufacturing settings. The proposed approach also demonstrates how publicly available industrial assessment data can be transformed into a robust decision model for sustainable operations and energy management.

Keywords: Multicriteria Decision-making, Industrial Energy Efficiency, Project Prioritization, Sustainable Operations
JEL Classifications: C44, Q41, Q48

1. INTRODUCTION

Improving industrial energy efficiency remains one of the most practical levers for reducing operating costs, lowering emissions, and supporting industrial competitiveness. Recent international assessments continue to treat energy efficiency as a central pillar of the broader energy transition, while also noting that progress remains slower than what is required to meet long-term climate and productivity objectives. In parallel, the manufacturing sector continues to attract strong scholarly attention because of its substantial energy use and its strategic role in decarbonization and economic development. Recent reviews emphasize that energy efficiency in manufacturing is no longer a purely technical issue; it is increasingly a managerial and decision-analytic problem involving competing economic, operational, and environmental objectives (Ibn Batouta et al., 2023; International Energy Agency, 2024).

For industrial firms, and especially for small and medium-sized manufacturers, the challenge is rarely the absence of improvement opportunities. The more difficult task is deciding which actions should be implemented first. In practice, firms must choose among alternatives such as compressed-air improvements, lighting retrofits, variable-frequency drives, lubrication changes, and process-control adjustments, all of which differ in implementation cost, expected savings, payback, technical complexity, and operational risk. Evidence from recent SME-focused studies shows that the adoption of energy-efficiency measures is shaped not only by financial constraints, but also by knowledge gaps, organizational capabilities, training needs, and decision context. European evidence likewise indicates that SMEs often prioritize low-risk and short-payback measures, even when broader portfolios might generate larger strategic benefits over time (Agrawal et al., 2023; Dolšak et al., 2024). This context makes multicriteria decision-making (MCDM) especially relevant. Energy-efficiency investments cannot be adequately assessed through a single metric such as payback or annual savings alone, because attractive financial performance may coexist with higher implementation barriers, and technically superior projects may require capital or organizational readiness that firms do not possess. Recent work on energy-efficiency evaluation confirms that multicriteria approaches are increasingly used to structure such trade-offs and to support more transparent, evidence-based prioritization. More broadly, systematic reviews show that MCDA/MCDM methods have expanded substantially across engineering and industrial applications, reflecting their usefulness in settings characterized by conflicting criteria and incomplete preference information (Basílio et al., 2022; Kshanh and Tanaka, 2024; Peneva and Popchev, 2025).

Within that family of methods, ELECTRE is particularly suitable when the decision problem is not simply to identify a mathematically optimal option, but to establish a robust ordering among alternatives under imperfect knowledge and non-compensatory preferences. The ELECTRE family was developed precisely to address situations in which strong performance on one criterion should not automatically offset weak performance on another. As summarized by Figueira et al. (2016), ELECTRE methods are grounded in outranking logic and are designed for choosing, ranking, and sorting problems in the presence of heterogeneous criteria and partial preference structures. ELECTRE III is especially appropriate for ranking problems because it incorporates pseudo-criteria through indifference and preference thresholds, thereby allowing small differences between alternatives to be treated as negligible when they are not meaningful from a managerial standpoint. That feature is highly relevant in industrial energy-efficiency decisions, where minor differences in savings or costs may not justify a clear preference once uncertainty, estimation error, and operational contingencies are considered (Fernández et al., 2025; 2026; Figueira et al., 2016).

The suitability of an outranking approach becomes even clearer when the nature of industrial decision-making is considered. Recent research on energy-efficiency project evaluation has highlighted the need for frameworks that move beyond simple cost-benefit reasoning and incorporate multiple dimensions of performance. For example, comparative analyses of MCDM methods for energy-efficiency project evaluation stress that project appraisal aligned with energy-management practice requires explicit treatment of trade-offs among technical, economic, and sustainability-related criteria. Likewise, data-driven decision-support tools for energy-efficiency investments have shown that combining performance indicators and multicriteria logic can reduce uncertainty and improve the quality of investment decisions (Fernández et al., 2023; Kshanh and Tanaka, 2024; Sarmas et al., 2022).

Another important issue concerns data quality. A recurrent weakness in the MCDM literature is that many applications rely heavily on hypothetical cases, expert judgment alone, or datasets that are difficult to reproduce. In contrast, the U.S. Department of Energy's ITAC program provides a particularly valuable empirical base for decision modeling. According to the U.S Department of Energy, ITAC assessments generate plant-specific recommendations accompanied by estimates of costs, performance, and payback, and the public ITAC database contains tens of thousands of assessments and more than 150,000 recommendations for energy-efficiency improvements in small and medium-sized industrial facilities (Industrial Training and Centers, 2025a; 2025b; U.S. General Services Administration, 2024). This makes the database well suited for building transparent and replicable decision matrices grounded in real industrial practice rather than synthetic examples (U.S. Department of Energy, 2024; U.S. General Services Administration, 2024).

Against this background, the present study applies the ELECTRE III method to prioritize real industrial energy-efficiency actions using published ITAC recommendations as decision alternatives. The analysis focuses on alternatives characterized by four observable criteria derived from the source records: yearly savings, implementation cost, electricity usage savings, and electricity demand-charge savings. This design responds to two needs in the literature. First, it provides a ranking framework that is consistent with the non-compensatory and threshold-sensitive nature of industrial investment decisions. Second, it demonstrates how publicly available assessment data can be translated into a rigorous multicriteria model for sustainable operations and energy management. By combining a real-world dataset with an outranking methodology tailored to ranking problems, the study seeks to offer both methodological and practical value for researchers, energy managers, and industrial decision-makers (Figueira et al., 2016; Kshanh and Tanaka, 2024; Solares et al., 2025; U.S. General Services Administration, 2024).

2. LITERATURE REVIEW

2.1. Industrial Energy Efficiency as a Decision Problem

Industrial energy efficiency has evolved from a narrowly technical concern into a broader managerial and strategic issue. Recent syntheses of the manufacturing literature show that research on industrial energy efficiency now spans diagnostics, metering, optimization, technology adoption, strategic paradigms, and the analysis of barriers and drivers. This shift is important because energy-related decisions in manufacturing are rarely made on the basis of engineering performance alone; they are also shaped by organizational capabilities, investment constraints, operational priorities, and implementation risk. At the macro level, the continuing policy emphasis on energy efficiency reflects its role in reducing energy demand, improving competitiveness, and supporting decarbonization across industry.

This problem is especially acute for small and medium-sized manufacturers. Recent studies show that SMEs often face persistent barriers such as limited awareness, lack of know-how, restricted financial and human resources, and weak internal routines for evaluating improvement opportunities. Research based on European projects has also found that training, energy audits, policy support, and supply-chain collaboration are important mechanisms for increasing the uptake of efficiency measures. Similarly, recent case-based work on non-energy-intensive manufacturing SMEs indicates that even when energy-saving opportunities exist, firms may struggle to identify, compare, and implement them systematically. These findings suggest that the challenge is not only to discover efficiency measures, but also to prioritize them under real organizational constraints.

For this reason, the literature increasingly treats industrial energy efficiency as an investment and resource-allocation problem. Firms typically confront multiple feasible actions (such as compressed-air improvements, lighting retrofits, variable-frequency drives, lubrication changes, and motor-system upgrades) that differ in implementation cost, annual savings, operational disruption, and technical uncertainty. As a result, relying on a single economic indicator, such as simple payback, may produce rankings that are too reductive for practical decision-making. Recent analysis in energy management confirms that the evaluation of energy-efficiency projects aligned with industrial management frameworks such as ISO 50001 cannot be based on cost-benefit analysis alone.

2.2. Multicriteria Decision-Making in Energy-Efficiency Evaluation

The expansion of multicriteria decision-making (MCDM) in engineering and industrial research is a direct response to such complexity. Broad reviews show sustained growth in the use of MCDM methods across industrial environments, with applications in process selection, manufacturing optimization, sustainability assessment, and investment analysis. The appeal of these methods lies in their ability to structure trade-offs among economic, technical, environmental, and organizational criteria when no single measure is sufficient to represent decision quality. In manufacturing settings, this is particularly relevant because alternatives often perform well on some criteria and poorly on others, making purely compensatory evaluation problematic.

Within the energy domain, the case for MCDM is now well established. Sarmas et al. argued that multicriteria decision analysis can integrate financial and energy-consumption information in a way that improves confidence in energy-efficiency investments and supports financing decisions. More recently, Kshanh and Tanaka showed that the evaluation of energy-efficiency projects in industrial settings requires a systematic multicriteria framework because project attractiveness depends on several factors that cannot be collapsed into a single monetary measure. Related work in smart-factory contexts reaches a similar conclusion, emphasizing that uncertainty and vagueness are intrinsic to the assessment of energy-saving solutions and therefore call for structured decision-support methods.

Another feature of recent MCDM research is the move toward hybrid and data-driven approaches. Contemporary reviews note growing interest in combining weighting methods, outranking procedures, fuzzy sets, and data-driven modeling in order to strengthen robustness and improve adaptation to real decision contexts. This trend is relevant for industrial energy management because project evaluation often combines quantitative indicators, such as costs and savings, with decision thresholds and managerial judgments. However, despite these methodological advances, many published applications still rely on hypothetical examples, expert-only assessments, or narrowly defined case studies. That limitation increases the value of decision models built from transparent, published, and reproducible industrial datasets.

2.3. ELECTRE Methods and the Rationale for ELECTRE III

Among MCDM approaches, the ELECTRE family occupies a distinctive position because it is based on an outranking logic rather than on full aggregation into a single utility score. The comprehensive review by Govindan and Jepsen documented the breadth of ELECTRE applications and confirmed the continued relevance of the method family across multiple decision domains. Figueira et al. (2016) further clarified that ELECTRE methods are designed for three main types of problems (choice, ranking, and sorting) and that different variants are appropriate depending on the decision objective. This distinction is important in the present study because the problem is not to select a single “best” measure in isolation, but to establish a defensible ordering of industrial energy-efficiency actions.

ELECTRE III is particularly appropriate for ranking problems characterized by imperfect information, threshold effects, and non-compensatory preferences. Unlike simple additive models, ELECTRE III allows the analyst to define indifference and preference thresholds so that small differences between alternatives do not automatically generate strong preference statements. This feature is valuable in industrial energy-efficiency analysis, where differences in savings, costs, or demand reduction may be numerically small but managerially insignificant. At the same time, the method limits the extent to which strong performance on one criterion can fully compensate for weak performance on another. That logic fits industrial decisions in which a project with attractive annual savings may still be difficult to justify if its cost, disruption, or uncertainty exceeds acceptable bounds.

Recent studies continue to confirm the suitability of ELECTRE III and related outranking models for complex ranking problems. New methodological developments have extended ELECTRE III to uncertain, fuzzy, and group-decision environments, while recent applications have employed ELECTRE-based frameworks for renewable energy investment and manufacturing-related selection problems. Although these studies differ in scope, they consistently underline the strength of outranking methods in contexts where preferences are gradual, heterogeneous, and not fully compensatory. This reinforces the methodological justification for using ELECTRE III in energy-efficiency project prioritization.

2.4. Research Gap

A further gap in the literature concerns empirical grounding. Many MCDM studies in energy and sustainability offer useful methodological innovations, but fewer rely on large, public, recommendation-level datasets that permit transparent reconstruction of the decision matrix. In this respect, the U.S. Department of Energy's Industrial Training and Assessment Centers program provides an unusually relevant basis for analysis. The program supports small and medium-sized manufacturers and links implementation grants to recommendations generated through industrial assessments. The associated public Industrial Assessment Centers database contains assessment-level and recommendation-level information from energy-efficiency assessments conducted at small and medium-sized industrial facilities, including details on savings and related recommendation characteristics. This makes it a strong empirical source for building reproducible multicriteria ranking models grounded in actual industrial actions rather than synthetic examples.

Therefore, the literature suggests a clear opportunity for contribution. First, industrial energy-efficiency decisions require methods that reflect multiple conflicting criteria rather than simple financial screening. Second, ELECTRE III is theoretically well aligned with ranking problems involving threshold-sensitive and non-compensatory judgments. Third, the availability of published ITAC recommendation data creates the possibility of testing this methodological fit on real industrial alternatives (Industrial Training and Centers, 2025a; 2025b; U.S. General Services Administration, 2024). The present study addresses this intersection by applying ELECTRE III to rank published industrial energy-efficiency actions using a real-data matrix based on yearly savings, implementation cost, electricity savings, and demand-charge savings. In doing so, it contributes to the literature on sustainable industrial operations by connecting a robust outranking method with a transparent public dataset and a practically relevant prioritization problem.

3. METHODOLOGY

3.1. Research Design

This study adopts a quantitative, applied, and ranking-oriented multicriteria design to prioritize industrial energy-efficiency actions using the ELECTRE III method. The methodological logic is appropriate for a problem in which several feasible actions must be ordered according to multiple conflicting criteria rather than evaluated through a single economic indicator. ELECTRE III belongs to the outranking family of multicriteria methods and is specifically intended for ranking problems under imperfect preference structures, allowing the analyst to model indifference, strict preference, and veto situations through threshold parameters. This makes it suitable for industrial decision settings in which small differences between alternatives may be negligible, while poor performance on certain criteria may substantially weaken an alternative's attractiveness (Díaz et al., 2022; Leyva et al., 2023; Solares et al., 2022).

The empirical basis of the study is the ITAC database, a public source associated with the U.S. Department of Energy. According to the ITAC program description, the database includes publicly available assessment and recommendation data for manufacturing facilities, including recommendation characteristics such as energy savings, dollar savings, implementation costs, and related information. This public availability is relevant from a methodological standpoint because it allows the decision matrix to be reconstructed from traceable, published records rather than hypothetical or simulated examples.

3.2. Selection of Alternatives

The alternatives evaluated in this study are eight real industrial energy-efficiency actions extracted from two published ITAC assessment records: AM0480 and SU0209 (Industrial Training and Centers, 2025a; 2025b). These records were selected because they contain recommendation-level data with sufficient consistency to characterize each action across the same set of criteria, namely yearly savings, implementation cost, electricity usage savings, and electricity demand-charge savings. Since all alternatives come from the same public assessment system and follow the same recommendation structure, they provide a coherent empirical basis for the ELECTRE III outranking analysis.

The use of published ITAC recommendations serves two main purposes. First, it strengthens the external relevance of the model because the alternatives correspond to actual industrial improvement actions identified in real manufacturing assessments rather than hypothetical projects. Second, it improves replicability, since the alternatives and their criterion values can be traced directly to the original assessment records (Industrial Training and Centers, 2025a; 2025b; U.S. General Services Administration, 2024). This is especially important in multicriteria research on energy management, where decision matrices are often based on stylized examples or expert-generated values that are difficult to verify independently.

The eight alternatives were not selected to represent all possible industrial energy-efficiency actions, but rather to form a comparable and data-consistent subset of recommendations that could be evaluated using the same four published criteria. The selected actions cover several common areas of industrial energy management, including compressed-air systems, lighting systems, lubrication practices, and motor-drive technologies. These actions vary substantially in cost, expected savings, and impact on electricity consumption and demand charges, which makes them suitable for a multicriteria ranking exercise.

The alternatives are described below.

(1). $A1$: Eliminate leaks in inert gas and compressed air lines/ valves (AM0480)

This alternative consists of identifying and eliminating leaks in inert gas and compressed-air distribution lines, connections, and valves. In industrial facilities, compressed-air systems frequently operate with hidden leakages that cause continuous energy waste because compressors must run longer or more intensively to maintain required pressure levels. From an energy-management perspective, this type of action is usually considered a relatively accessible operational improvement because it does not necessarily require major equipment replacement. Its attractiveness typically lies in the combination of low implementation complexity and measurable savings, especially in facilities where leakage rates are high.

In the present dataset, *A*1 is characterized by a relatively low implementation cost and moderate annual savings. It also produces relevant electricity savings and a positive, though not dominant, reduction in demand charges. These characteristics suggest that *A*1 is a practical corrective measure that can improve system efficiency without requiring a large capital outlay.

(2). *A*2: Utilize higher-efficiency lamps and/or ballasts (AM0480)

This alternative involves replacing existing lighting components with more efficient lamps and/or ballasts. Lighting upgrades are among the most common energy-efficiency actions in industrial plants because they are relatively easy to implement, generally well understood by facility managers, and usually entail limited disruption to production processes. Such actions often yield savings through lower electricity consumption and, in some cases, reduced maintenance needs.

However, compared with improvements in large motor-driven or compressed-air systems, lighting projects often produce smaller absolute savings, particularly in facilities where lighting represents only a limited share of total electricity consumption. In this study, *A*2 has a modest implementation cost, but its yearly savings, electricity savings, and demand-charge reductions are among the lowest in the set. Therefore, while it remains a valid energy-efficiency measure, it is expected to be less attractive when evaluated against alternatives that affect more energy-intensive systems.

(3). *A*3: Make a practice of turning off lights when not needed (AM0480)

This alternative represents a behavioral or procedural measure rather than a capital-intensive technological upgrade. It consists of implementing operating practices to ensure that lighting is turned off in areas or periods where it is not needed. Such measures are commonly recommended because they can be implemented quickly, require limited investment, and may generate immediate savings if current operating practices are inefficient.

From a managerial standpoint, this kind of recommendation is appealing because of its simplicity. However, its success often depends on human behavior, monitoring, and organizational discipline, which may affect the persistence of results over time. In the present dataset, *A*3 has a low implementation cost and modest savings. It performs somewhat better than *A*2 in electricity usage savings, but its demand-charge impact remains limited. Consequently, *A*3 can be interpreted as a low-cost improvement with relatively constrained strategic impact.

(4). *A*4: Reduce the pressure of compressed air to the minimum required (AM0480)

This alternative consists of adjusting the compressed-air system so that operating pressure is reduced to the minimum level necessary for production requirements. In many industrial facilities, compressed-air systems operate above the pressure actually needed, which increases electricity consumption and may aggravate leakage losses. Pressure optimization is therefore a common recommendation in compressed-air management.

*A*4 is particularly notable because it has the lowest implementation cost among all selected alternatives. This makes it highly attractive from a short-term investment perspective. However, its annual savings and electricity reductions are moderate compared with the stronger actions in the sample. Accordingly, *A*4 represents a classic case of an action that is inexpensive and operationally sensible, but whose overall ranking may depend on how strongly the decision-maker values low cost relative to larger energy and financial benefits.

(5). *A*5: Install compressor air intakes in coolest locations (SU0209)

This alternative involves relocating or redesigning compressor air intakes so that compressors draw air from the coolest available location. Since cooler intake air is denser, compressors can operate more efficiently when suction air temperature is lower. In practice, this can improve compressor performance and reduce electricity consumption without necessarily changing the fundamental production process.

Among the selected alternatives, *A*5 stands out because it combines strong yearly savings, high electricity savings, and substantial demand-charge savings, while maintaining a moderate implementation cost relative to its benefits. This gives it a well-balanced performance profile across the four criteria. Conceptually, *A*5 represents an action that is neither purely operational nor heavily capital-intensive, but rather a technically targeted intervention with strong economic returns.

(6). *A*6: Eliminate leaks in inert gas and compressed air lines/valves (SU0209)

Like *A*1, this alternative focuses on eliminating leaks in inert gas and compressed-air systems, but it comes from a different industrial assessment record and therefore reflects a different plant context. This is important because it shows that the same general type of recommendation may produce different magnitudes of savings, costs, and demand effects depending on facility conditions, operating patterns, and the extent of system inefficiency.

In the present data, *A*6 performs better than *A*1 in yearly savings, electricity savings, and demand-charge savings, although its implementation cost is also somewhat higher. This suggests that the leakage problem identified in the SU0209 assessment is larger or that the expected correction has a greater operational impact. Therefore, *A*6 can be interpreted as a stronger version of the compressed-air leak-repair strategy, with a more favorable overall benefit profile.

(7). *A*7: Use synthetic lubricant (SU0209)

This alternative recommends the use of synthetic lubricant, presumably in equipment whose operating efficiency can be improved through reduced friction, improved thermal performance, or more stable lubrication characteristics. In industrial contexts, lubricant-related recommendations may improve machine performance and decrease energy consumption, although their impact is often more indirect than that of actions targeting compressors, motors, or major electrical systems.

In the decision matrix, *A*7 occupies an intermediate position. Its electricity savings and demand-charge reductions are non-trivial, but its implementation cost is noticeably higher than that of several low-cost actions, while its yearly savings remain far below those of the leading alternatives. Thus, *A*7 represents a measure with meaningful technical merit but only moderate multicriteria attractiveness when compared with more impactful system-level interventions.

(8). *A*8: Use adjustable-frequency drive or multiple-speed motors on existing system (SU0209)

This alternative consists of installing an adjustable-frequency drive or using multiple-speed motors in an existing system. Such interventions are widely recognized as major energy-efficiency opportunities in industrial settings because they allow motor output to better match process demand, thereby reducing unnecessary electricity consumption and often lowering peak demand as well. These measures are especially effective in systems with variable loads, such as pumps, fans, and certain compressor applications.

*A*8 is the most capital-intensive alternative in the set, with the highest implementation cost. At the same time, it also exhibits the highest yearly savings, highest electricity savings, and highest demand-charge savings of all eight actions. This makes *A*8 a particularly important alternative in the multicriteria analysis, since it embodies a central trade-off in industrial energy management: A relatively high upfront investment in exchange for very strong recurring benefits. In practical terms, *A*8 represents a strategic energy-efficiency project with the potential for substantial long-term impact.

Taken together, the eight alternatives provide a useful spectrum of industrial energy-efficiency actions. Some alternatives, such as *A*2 and *A*3, are low-cost and easy to implement but offer limited absolute savings. Others, such as *A*4, are extremely inexpensive and operationally sensible, yet still moderate in impact. A different group, including *A*5, *A*6, and especially *A*8, offers much stronger energy and financial returns, though sometimes at higher implementation cost. Finally, alternatives such as *A*1 and *A*7 occupy intermediate positions and help reveal the trade-offs that ELECTRE III is designed to analyze.

3.3. Criteria Definition and Decision Matrix Construction

Each alternative was characterized using four published criteria, all extracted directly from the ITAC recommendation records:

- C1. Total yearly savings ($/year) – To be maximized
- C2. Implementation cost ($) – To be minimized
- C3. Electricity usage savings (kWh/year) – To be maximized
- C4. Electricity demand-charge savings ($/year) – To be maximized.

These criteria were selected because they are both published in the source records and decision-relevant for industrial energy-efficiency evaluation. Together, they reflect two complementary dimensions of project attractiveness. The first is the economic dimension, represented by yearly savings and implementation cost. The second is the energy-performance dimension, represented by electricity savings and demand-charge savings. In industrial practice, these dimensions are closely linked but not identical; a project may present strong electricity reductions without generating the largest total monetary savings, or it may require very low capital while yielding only modest demand-charge improvements. For that reason, a multicriteria structure is preferable to a single-metric screening rule.

The decision matrix, shown in Table 1, was therefore constructed as an $m \times n$ matrix, where $m = 8$ alternatives and $n = 4$ criteria. In Table 1, symbols ↑ and ↓ denote the optimization direction of each criterion. A criterion marked with ↑ is treated as a benefit criterion and therefore must be maximized, while a criterion marked with ↓ is treated as a cost criterion and therefore must be minimized.

Each matrix entry $g_j(a_i)$ represents the published performance of alternative a_i on criterion j. Because the source data are already numeric and recommendation-specific, no normalization was required prior to the conceptual formulation of the ELECTRE III procedure. However, the interpretation of performance differences between alternatives depends not only on raw values, but also on whether those differences are large enough to imply indifference, weak preference, strong preference, or veto. That issue is addressed through the ELECTRE III threshold structure.

3.4. ELECTRE III Procedure

ELECTRE III constructs an outranking relation by comparing each pair of alternatives on all criteria and aggregating the evidence that one alternative is at least as good as another. The method proceeds through four main stages: (1) Pairwise comparison using pseudo-criteria, (2) concordance analysis, (3) discordance and credibility analysis, and (4) descending and ascending distillation to obtain a final ranking. This sequence is consistently described in the ELECTRE literature and in computational implementations of the method.

3.4.1. Pseudo-criteria and thresholds

For each criterion g_j, ELECTRE III uses three possible discrimination thresholds:

- Indifference threshold q_j: The largest difference considered negligible by the decision-maker
- Preference threshold p_j: The smallest difference considered sufficient to establish clear preference
- Veto threshold v_j: A difference large enough to block the outranking relation, even if concordance is otherwise strong

These thresholds define a pseudo-criterion structure, which is one of the distinguishing features of ELECTRE III. Rather than treating every numerical difference as substantively meaningful, the method allows for a zone of hesitation between indifference and strict preference. This feature is particularly relevant for industrial project appraisal because the practical significance of small cost or savings differences is often uncertain.

Table 1: Performance matrix

Alternative	Decision action	C1. Yearly savings ($/year) ↑	C2. Implementation cost ($) ↓	C3. Electricity savings (kWh/year) ↑	C4. Demand-charge savings ($/year) ↑
*A*1	Eliminate leaks in inert gas and compressed air lines/valves (AM0480)	1,920	200	28,500	120
*A*2	Utilize higher-efficiency lamps and/or ballasts (AM0480)	788	384	2,450	3
*A*3	Make a practice of turning off lights when not needed (AM0480)	665	225	9,700	55
*A*4	Reduce the pressure of compressed air to the minimum required (AM0480)	380	20	5,680	20
*A*5	Install compressor air intakes in coolest locations (SU0209)	4,742	509	69,640	564
*A*6	Eliminate leaks in inert gas and compressed air lines/valves (SU0209)	2,683	418	39,312	324
*A*7	Use synthetic lubricant (SU0209)	1,072	1,000	15,725	128
*A*8	Use adjustable-frequency drive or multiple-speed motors on existing system (SU0209)	9,558	8,908	140,151	1,149

Source: Authors' compilation based on published recommendation-level data from ITAC assessment records AM0480 and SU0209 (Industrial Training and Centers, 2025a; 2025b). The arrow symbols indicate the preference direction of each criterion in the multicriteria model. ↑ means that the criterion is to be maximized (higher values are preferred), whereas ↓ means that the criterion is to be minimized (lower values are preferred).

In this study, thresholds are defined criterion by criterion. Because the present section focuses on the methodology, the thresholds are conceptually specified here, while their operational values are assigned in the model implementation stage. The general requirement is that, for each criterion *j*, the thresholds satisfy:

$$0 \leq q_j \leq p_j \leq v_j$$

for criteria where a veto is used. For some criteria, a veto threshold may be omitted if the analyst considers that poor performance should not automatically block outranking.

3.4.2. Partial concordance

For every pair of alternatives (*a,b*), a partial concordance index $c_j(a,b)$ is computed for criterion *j*. This index measures the degree to which the statement "*a* is at least as good as *b*" is supported on that criterion. The value of $c_j(a,b)$ varies between 0 and 1 depending on the position of the observed difference relative to the indifference and preference thresholds. When the performance difference is within the indifference zone, concordance is complete; when it exceeds the preference threshold in the unfavorable direction, concordance becomes null; and between these two thresholds concordance changes gradually.

3.4.3. Global concordance

The global concordance index *C*(*a,b*) aggregates the partial concordance indices using criterion weights:

$$C(a,b) = \sum_{j=1}^{n} w_j \, c_j(a,b)$$

where w_j is the weight assigned to criterion *j*, with $\sum_{j=1}^{n} w_j = 1.$ The index *C*(*a,b*) expresses the collective evidence in favor of the outranking statement *aSb*. In substantive terms, it captures the degree to which the criteria, taken together, support the idea that alternative *a* is at least as good as alternative *b*.

3.4.4. Discordance and credibility

A high global concordance is not sufficient by itself to establish outranking. ELECTRE III also tests whether one or more criteria provide strong evidence against the outranking relation. This is done through discordance indices $d_j(a,b)$, which measure the extent to which criterion *j* opposes the assertion that *a* outranks *b*. When the disadvantage of *a* relative to *b* on a given criterion exceeds the veto threshold, that criterion can substantially reduce or even cancel the credibility of the outranking relation.

The credibility index *S*(*a,b*) combines concordance and discordance into an overall strength of outranking. Its value ranges from 0 to 1 and reflects the degree to which the relation *aSb* is credible after accounting for criteria that may veto or weaken the favorable concordance coalition. This formulation is particularly useful in industrial decision-making because it prevents an alternative with very strong performance on some criteria from automatically compensating for serious weaknesses on another criterion.

3.5. Ranking Procedure

Once the credibility matrix is obtained, ELECTRE III produces a ranking through descending and ascending distillation procedures. In descending distillation, the method progressively identifies the most supported alternatives and assigns them to the top positions. In ascending distillation, it identifies the least supported alternatives and assigns them to the bottom positions. The final preorder is obtained by combining both distillations. This process allows the method to produce a ranking that reflects pairwise outranking strength without forcing a fully compensatory ordering. For the present study, the final result is interpreted as an ordering of industrial energy-efficiency actions according to their overall desirability under the four published criteria. Because ELECTRE III permits incomparability or weak separation when evidence is insufficient, the final ordering is understood as a robust preference structure rather than as a precise cardinal ranking. This is consistent with the nature of the decision problem, where managerial judgments often involve zones of hesitation and partial dominance rather than exact trade-off equivalence.

Criterion weights represent the relative importance assigned to the four evaluation dimensions. In this study, weights are treated as exogenous model parameters specified by the analyst or decision-maker. This choice is consistent with standard ELECTRE III applications and allows the model to accommodate different strategic perspectives. For example, a financially constrained decision-maker may emphasize implementation cost and yearly savings, whereas an energy-management perspective may assign greater importance to electricity savings and demand-charge reduction. Since ELECTRE III is sensitive to the relative strength of criteria through global concordance, weight specification is a critical part of model construction.

To preserve transparency, the weighting scheme should satisfy three principles:

1. Weights must sum to one;
2. Weights must be explicitly reported; and
3. The results should be tested through sensitivity analysis.

This last point is especially important because changes in weights can alter the balance of support among alternatives even when the underlying data remain unchanged. Recent literature on multicriteria energy-efficiency evaluation similarly emphasizes the need for transparent weighting and robustness checks in project-prioritization models.

To improve the credibility of the findings, the ELECTRE III application should be complemented by sensitivity analysis. In this study, robustness is assessed by varying three classes of model parameters:

1. Criterion weights,
2. Threshold values (q_j,p_j,v_j), and
3. The use or non-use of veto thresholds on selected criteria.

This procedure is consistent with the ELECTRE literature, which recognizes that outranking results depend on value judgments embedded in thresholds and weights. A stable ranking across reasonable parameter variations would indicate that the prioritization is robust rather than driven by a narrow parameter specification.

The methodology is designed to be reproducible because all alternatives and criterion values come from publicly available ITAC assessment records. A researcher can reconstruct the decision matrix by retrieving the same recommendation records, assigning the selected criteria, specifying weights and thresholds, and running the ELECTRE III procedure in an MCDA-compatible environment. Publicly documented implementations of ELECTRE III, including software documentation that returns concordance, discordance, credibility, dominance, and scoring tables, further support reproducibility of the analytical workflow.

4. RESULTS

This section presents the results of the ELECTRE III application for the eight industrial energy-efficiency actions. The section first reports the overall outcome and then interprets the role of each criterion in explaining the final ordering.

For the baseline specification, the four criteria were weighted as follows: Yearly savings (0.35), implementation cost (0.20), electricity usage savings (0.30), and electricity demand-charge savings (0.15). Preference and indifference thresholds were defined as fixed fractions of the observed range of each criterion, using 5% for q and 15% for p. Because the purpose of the application is exploratory and because the alternatives include both low-cost housekeeping actions and large-impact capital-intensive actions, the veto threshold was not activated in the baseline run. Under this specification, the credibility matrix coincides with the global concordance matrix, and the ranking is obtained through the usual ELECTRE III distillation logic.

4.1. Overall Ranking Results

Table 2 reports the results of the descending distillation, ascending distillation, and final combined preorder.

The baseline ELECTRE III model yields the following preorder:

$$A8 \succ A5 \succ A6 \succ A1 \succ \{A2, A3, A4, A7\}$$

The result indicates a clear separation between the first four actions and the remaining four. At the top of the ranking, *A*8 is the most preferred action. It is followed by *A*5, then *A*6, and then *A*1. The last four alternatives form a weakly differentiated group, meaning that the available criteria and thresholds do not provide enough discriminatory power to justify a strict ordering among them.

This pattern is substantively meaningful. The best-ranked actions are those that combine strong yearly savings, large electricity savings, and substantial demand-charge reductions. By contrast, the lowest group contains actions that are either low-cost but modest in impact, or moderately beneficial but not strong enough across several criteria to dominate the others in a robust outranking sense.

4.2. Interpretation of the Leading Alternatives

The first-ranked alternative, *A*8, corresponds to the use of an adjustable-frequency drive or multiple-speed motors on the existing system. Its leading position is explained by its exceptional performance on the three benefit-type criteria. It has the highest yearly savings, the highest electricity usage savings, and the highest demand-charge savings of all alternatives. Its main weakness is implementation cost, which is also by far the highest in the set. Nevertheless, under the baseline ELECTRE III specification, the magnitude of its benefits is sufficient to outweigh that disadvantage. In other words, although *A*8 is expensive, its benefit profile is strong enough to support a robust first-place position.

The second-ranked alternative, *A*5, is the installation of compressor air intakes in the coolest locations. This action presents a highly balanced profile: strong yearly savings, large electricity reductions, and substantial demand-charge benefits, while maintaining an implementation cost that is moderate relative to its returns. Compared with *A*8, *A*5 offers lower absolute benefits, but it is penalized far less on cost. This balance explains why it occupies a stable second position rather than falling into the middle of the ranking.

Table 2: ELECTRE III ranking results

Alternative	Decision action	Descending distillation	Ascending distillation	Final preorder
*A*8	Use adjustable-frequency drive or multiple-speed motors on existing system	1	1	1
*A*5	Install compressor air intakes in coolest locations	2	2	2
*A*6	Eliminate leaks in inert gas and compressed air lines/valves (SU0209)	3	3	3
*A*1	Eliminate leaks in inert gas and compressed air lines/valves (AM0480)	4	4	4
*A*2	Utilize higher-efficiency lamps and/or ballasts	5	5	5–8
*A*3	Make a practice of turning off lights when not needed	5	5	5–8
*A*4	Reduce the pressure of compressed air to the minimum required	5	5	5–8
*A*7	Use synthetic lubricant	5	5	5–8

Source: Authors' creation

The third-ranked alternative, *A*6, which also concerns eliminating leaks in inert gas and compressed-air lines and valves, performs well on all criteria without becoming dominant on any one of them. Its yearly savings and electricity reductions are clearly above those of the lower-ranked group, and its implementation cost remains manageable. However, it does not match the magnitude of benefits observed in *A*5 and *A*8, which prevents it from entering the top two positions.

The fourth-ranked alternative, *A*1, involves the same type of action as *A*6 but from a different assessment record. It remains a desirable option because of its low implementation cost and positive benefit profile. Even so, it is placed below *A*6 because its yearly savings, electricity reductions, and demand-charge effects are materially smaller.

4.3. Interpretation of the Weakly Differentiated Group

The alternatives *A*2, *A*3, *A*4, and *A*7 form the last preorder level. This does not mean that they are equivalent in a strict cardinal sense, but rather that, under the ELECTRE III thresholds and weights adopted in the baseline model, the evidence is insufficient to support a stable strict ranking among them.

*A*2 and *A*3 are inexpensive and operationally simple actions, but both generate relatively low annual savings and small demand-charge effects. They therefore remain attractive as low-risk measures, yet they do not accumulate enough multicriteria support to outrank the leading actions.

*A*4 is a particularly interesting case. It has the lowest implementation cost of all alternatives, which gives it a strong position on the cost criterion. However, its yearly savings and electricity-saving effects are modest. ELECTRE III treats this as a non-compensatory trade-off: outstanding performance on one criterion does not automatically offset weaker performance on the others. As a result, *A*4 does not climb above the lower tier despite its very favorable cost profile.

*A*7 offers better benefits than some of the other lower-ranked alternatives, especially in electricity savings and demand-charge savings, but its implementation cost is much higher than that of *A*2, *A*3, and *A*4. This cost disadvantage weakens its outranking strength and keeps it within the same final group.

4.4. Credibility Structure and Outranking Pattern

To facilitate interpretation, Table 3 summarizes the strong outranking pattern under a credibility cut level of 0.70.

Table 3: Summary of strong outranking relations ($\sigma(a, b) \geq 0.70$)

Alternative	Alternatives strongly outranked	Count
*A*8	*A*1, *A*2, *A*3, *A*4, *A*5, *A*6, *A*7	7
*A*5	*A*1, *A*2, *A*3, *A*4, *A*6, *A*7	6
*A*6	*A*1, *A*2, *A*3, *A*4, *A*7	5
*A*1	*A*2, *A*3, *A*4, *A*7	4
*A*2	*A*3, *A*4, *A*7	3
*A*3	*A*2, *A*4, *A*7	3
*A*4	*A*2, *A*3, *A*7	3
*A*7	*A*2, *A*3, *A*4	3

This table confirms the general ranking pattern. *A*8 strongly outranks all other alternatives, which reinforces its position as the top action in the baseline run. *A*5 strongly outranks six of the seven remaining alternatives, and *A*6 strongly outranks five. In contrast, the last four alternatives show a much denser and more symmetric pattern of mutual outranking, which explains why the distillation procedures do not separate them into distinct final ranks.

4.5. Criterion-level Interpretation

The final preorder can be understood more clearly by considering the role of the four criteria.

First, the two benefit criteria with the greatest practical discriminatory power are yearly savings and electricity usage savings. The top-ranked actions dominate on these dimensions, especially *A*8 and *A*5. These criteria therefore play a major role in structuring the upper part of the preorder. Second, implementation cost moderates the ranking but does not fully determine it. This is evident in the case of *A*4, which is the cheapest action but remains in the lowest preorder level, and in the case of *A*8, which is the most expensive but still ranks first because of its outstanding benefits. This result illustrates one of the main strengths of ELECTRE III: It avoids the overly compensatory logic of simple additive models while still allowing strong performance on several criteria to justify a high ranking. Third, electricity demand-charge savings provides an additional layer of discrimination among high-impact actions. It helps differentiate alternatives that may have similar yearly savings but different effects on peak demand. This is one reason why *A*5 and *A*6 remain clearly above the lower-ranked actions.

The ranking suggests that interventions aimed at major compressor and motor systems should be prioritized before smaller operational or lighting improvements when the decision-maker simultaneously values financial return, energy reduction, and peak-demand relief. A limited sensitivity analysis was conducted by varying the criterion weights within moderate ranges while preserving the same preference-threshold structure. The resulting preorder was stable at the top: *A*8 and *A*5 consistently remained in the first two positions, although their internal order may become closer when greater emphasis is placed on implementation cost. Likewise, *A*6 and *A*1 remained in the middle positions in most runs, and the lower group {*A*2, *A*3, *A*4, *A*7} continued to exhibit weak internal discrimination. This result is important because it indicates that the overall message of the model is robust: the most attractive actions are not simply the cheapest ones, but those capable of generating substantial recurring savings and system-level electricity benefits. At the same time, the persistence of ties in the lower tier suggests that a decision-maker seeking finer discrimination among *A*2, *A*3, *A*4, and *A*7 may need either additional criteria or more demanding threshold settings. All these results indicate that the ELECTRE III application produces a coherent and interpretable ranking of the eight industrial energy-efficiency actions. The method identifies *A*8 and *A*5 as the most attractive alternatives, followed by *A*6 and *A*1, while *A*2, *A*3, *A*4, and *A*7 remain in a lower, weakly differentiated cluster. The ranking reflects the non-compensatory logic of the method and shows that the best actions are those that combine strong annual savings with high electricity and demand-charge reductions, even when their implementation costs are not the lowest.

5. CONCLUSIONS AND POLICY IMPLICATIONS

This study shows that the prioritization of industrial energy-efficiency actions is not a trivial cost-minimization exercise, but a genuinely multicriteria decision problem. When yearly savings, implementation cost, electricity savings, and demand-charge reductions are considered jointly, the most attractive actions are not simply the cheapest ones, nor necessarily the ones with the highest isolated technical impact. Instead, the best-performing actions are those that achieve a strong balance between economic return and system-level energy benefits.

A first relevant conclusion is that large-impact interventions aimed at major electrical systems dominate low-cost housekeeping measures when the decision context is evaluated holistically. In the present application, actions related to adjustable-frequency drives, multiple-speed motors, and compressor optimization occupied the highest positions in the ELECTRE III preorder because they combine substantial yearly savings with strong electricity and demand-charge reductions. By contrast, lighting-related and behavioral measures, although operationally simple and inexpensive, remained in a lower and weakly differentiated tier. This suggests that firms seeking strategic energy gains should look first at high-leverage systems, especially motors and compressed-air infrastructure. A second important conclusion is that implementation cost alone is a poor guide for prioritization. One of the most interesting findings of the study is that the lowest-cost action did not emerge as the best alternative, while the highest-cost action was ranked first. This result is analytically important because it illustrates the risk of relying on simplistic screening rules such as minimum investment or short-term affordability. In real industrial decision settings, low-cost actions may be attractive for quick wins, but they do not necessarily generate the highest overall value. Conversely, more capital-intensive actions can be justified when their combined financial and operational benefits are strong enough. A third conclusion concerns the usefulness of the non-compensatory logic embedded in ELECTRE III. The method proved especially valuable because it avoids the excessive compensation typical of additive models. In practical terms, this means that a very low implementation cost does not automatically outweigh weak savings performance, and very high savings do not become unquestionable if accompanied by serious disadvantages. This feature is particularly relevant for industrial energy management, where managers rarely evaluate projects through a single metric and often face trade-offs that are not fully reducible to monetary terms alone. The results therefore support the view that outranking methods provide a more realistic decision framework for industrial energy planning than purely compensatory approaches. A fourth conclusion is methodological: public recommendation-level databases can be transformed into robust multicriteria decision models. By using published ITAC recommendations, this study demonstrates that it is possible to build a transparent and reproducible ranking model from real industrial data rather than hypothetical examples. This is a meaningful contribution, because a persistent weakness in applied multicriteria studies is the reliance on stylized or non-verifiable datasets. The present application shows that publicly available industrial assessment data are not only useful for descriptive analysis, but can also support formal decision-aiding models with clear managerial relevance.

The results also suggest an important managerial implication. Firms should not interpret lower-ranked actions as useless; rather, they should view them as secondary or complementary measures within a broader energy-efficiency portfolio. In that sense, the study supports a layered strategy: first prioritize the high-impact system interventions, then complement them with low-cost operational and behavioral actions that may still contribute incremental improvements. This portfolio logic is more realistic than treating all recommendations as direct substitutes. Finally, the study highlights that priority is context-dependent, but not arbitrary. Although the exact preorder may vary with weights and thresholds, the top of the ranking remained structurally associated with actions capable of producing major recurring savings and significant energy-system improvements. This indicates that, even under imperfect preference structures, some industrial actions are consistently more attractive than others. Therefore, the main value of ELECTRE III in this context is not merely to produce a ranking, but to reveal which recommendations remain strong under multicriteria scrutiny and which ones are more sensitive to decision-maker preferences.

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