Quantifying Thermal Systems: Solutions for Smarter Materials, Energy Use, and Design

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ABSTRACT

Optimizing the materials efficiency and energy security of mechanical, electrical, and thermal systems like 'heating, ventilation and air conditioning' is critical towards advancing robust buildings systems. Despite these systems' importance, the market lacks a consistent methodological framework across manufacturers for understanding supply chain impacts, critical materials and U.S. manufacturing, limiting the comparability and actionable insights derived from data-driven decision-making evaluations. This paper highlights recent advancements in data-driven supply chain mapping methodologies for thermal system equipment that is ubiquitous in residential, commercial, and industrial buildings.

Through a collaborative working group approach involving rooftop unit manufacturers, the team developed product data inventory templates that intuitively collect information related to materials, use phase energy profiles, and end of life pathways - which, in turn, can streamline data collection, identify design hotspots, and provide actionable areas for improvement (e.g., operational efficiency gains). These templates enhance manufacturers' ability to benchmark and innovate more efficiently, while also supporting decision-making that aligns with the goals of cost-effective performance. The data template, which is an Excel template that captures all necessary product inventory data over the life and use of the product or material, expands capabilities for assessing supply chain robustness, critical material selection, and compliance with domestic procurement priorities such as Build America, Buy America requirements.

By bridging systemic gaps with available methodologies, this work not only drives innovation in building design, but also establishes a flexible template that promotes reliability, affordability, and comparability in energy-efficient technologies across the thermal systems industry and beyond to other sectors.

Introduction

Regardless of design, most modern buildings have some type of thermal system, such as a rooftop unit (RTU), to maintain and control internal thermal and humidity conditions (ASHRAE, 2023b; DOE, 2020). However, like the buildings they are incorporated into thermal systems (i.e. heating, ventilation, and air conditioning) can vary significantly in both material and energy demands (Alassaf, 2024; Allen & CaraDonna, 2024). When coupled with fragmented data availability and modeling approaches, many building managers find it difficult to compare systems across products, suppliers, and markets. For example, existing guidelines define testing and reporting requirements but do not provide a unified data architecture capable of integrating lifecycle, supply chain, and domestic content information across manufacturers. All of which minimizes a building manager's ability to select the best system for their construction, especially under new and emerging domestic content requirements like Build America, Buy America (BABA) (DOC, 2021).

Domestic content requirements, such as BABA, have expanded and clarified expectations for iron/steel, manufactured products, and construction materials for federally funded projects, ensuring truthful advertising of products claiming to be made in America. BABA requires that buildings thermal system equipment, classified as manufactured products, contain at least 55% U.S.-sourced component and material costs, ensuring the domestic production of key inputs used in federally funded infrastructure projects. Compliance is demonstrated by calculating the share of U.S.-mined, -produced, or -manufactured content in the bill of materials, excluding assembly labor, and verifying that the resulting domestic content percentage meets or exceeds the federal threshold. To maintain compliance, building planners increasingly need auditable documentation to evidence domestic content, making consistent and transparent product data inventories essential for procurement and risk management.

Thermal systems such as RTUs are governed by an evolving landscape of test and code minimums (ASHRAE, 2022; Maddox et al., 2024). Together, these references define how cooling capacity and efficiency are measured and reported across part-load conditions, yet industry experience shows a disconnect between rating-condition data and real-world duty cycles needed for planning and benchmarking (ASHRAE, 2023a). This introduces variability in use-phase energy modeling and complicates cross-manufacturer comparisons, making a unified intake structure for performance inputs a practical prerequisite for credible analysis. These inconsistencies begin upstream, during construction, where manufacturers differ in how materials, assemblies, and subcomponents are documented and disclosed, leading to gaps in baseline comparability. Operational data introduces additional variability, because equipment is tested under uniform conditions that do not fully represent real-world cycling, ambient ranges, control strategies, or degradation patterns, limiting transparency around performance interpretations.

Beyond operations, end-of-life (EoL) pathways for thermal systems equipment remain under-characterized in most product documentation, even though whole-building and product input-output assessment methods call for explicit modeling of lifecycle modules (CEN, 2025; ISO, 2006, 2017). For mechanical & electrical (M&E) systems, multiple studies have shown gaps in refrigerant leakage accounting, replacement cycles, and recyclability constraints (Hu et al., 2024; Muradi et al., 2024; Purohit et al., 2024). This has motivated a design-for-disassembly (DfD) and materials-recovery perspective alongside operational efficiency, especially for RTUs with sizable metallic content and complex subassemblies. Together, these construction-, operation-, and EoL-stage gaps explain why data inconsistencies and transparency limitations persist across the sector, and they highlight the need for a unified structure that can represent all lifecycle stages in a consistent and comparable method.

In response to these systemic barriers, this work advances a manufacturer-friendly, Excel-based input-output data inventory template for thermal systems that improves consistency and alignment of the construction, operation, EoL stages, and domestic content/supply-chain attributes across lifecycle phases A1–D (Unger et al., 2024). This approach builds directly on prior input-output template development on luminaires which was fit to the thermal systems industry through an M&E working-group collaboration to define minimum required fields, lifecycle boundaries, and shared vocabulary for hotspot identification and benchmark comparability (Feraldi et al., 2023).

Within the context of thermal systems, the template addresses several practical needs. First, it harmonizes materials inventory at the part and subassembly level (e.g., material class, mass, supplier, country of origin, criticality flags), improving screening of impacts from production and manufacturing, and enabling report or declaration data handoff under ISO 21930 and related product category rules (PCRs). Second, it structures use-phase energy inputs consistent with AHRI 340/360 and ASHRAE 90.1 paths, capturing load vs. capacity (i.e., part load) curves, duty cycles, climate-zone profiles, and control strategies to reduce uncertainty in modeling. Third, it codifies EoL pathways by subsystem, documenting disassembly steps, recyclability, and recovery potential to support reshoring of U.S. manufacturing, and re-manufacturing. Fourth, it integrates a BABA-aware domestic content workflow that emphasizes bill of material (BOM) supplementation and provides a costing track, yielding an auditable documentation package without forcing premature cost disclosures (Bixler & Hickcox, 2026).

Methods

Working Group and Industry Collaboration

The development of the thermal systems data inventory template began with an existing template previously developed for the luminaire industry. This earlier structure served as a starting point for identifying transferable data fields and life cycle boundaries that could be adapted for thermal systems.

To align this template with real-world manufacturing practices and downstream analytical needs, the team engaged with industry partners through two industry groups that included manufacturers, building owners, specifiers, research organizations, trade associations, and universities. The first group was a focused advisory group that provided strategic guidance, scope definition, and methodology oversight. The second group was a working group focused on discussing the unique needs of the industry and how these can be represented in the template. This second group aided in aligning the evolving template to address practical implementation needs across the industry.

The working group meetings identified the key barriers that limit consistent product data collection and comparison. These included the need for a unified BOM schema, which incorporated origin and mass data, inputs for harmonized operational performance for energy modeling, subsystem level EoL routing information, and auditable domestic content documentation workflows. With these priorities, the research team developed an initial draft template that mapped each field to lifecycle modules across A1 to D.

This draft template was then fielded with the industry working group which tested it with their RTU data collections. Manufacturers supplied product structures and sample RTU BOMs with material and origin information, allowing the team to assess how well the proposed schema aligned with existing manufacture data systems. Through this testing, specifiers and building owners contributed perspectives related to procurement comparisons and lifecycle planning, emphasizing the importance of consistent operation data and clear EoL documentation.

Together, these iterative discussions informed revisions to field definitions, validation rules, and subsystem classifications, which resulted in a template that balanced analytical rigor with practical reporting requirements.

Input-Output Inventory Template Development

Building on insights from the working groups, the team developed an Excel-based template designed to consolidate thermal system product information into a single, analysis-ready source. The template was designed to be model-agnostic so that the resulting data could be used across multiple assessment tools and procurement workflows. Fields are mapped to subsystem codes representing major thermal system components, including heat exchange assemblies, compressors, fans, electronics, and control systems. This subsystem structure enables both detailed component-level analysis and higher-level system comparisons.
The five modules that have been integrated into the template include: input materials, use phase energy, EoL, domestic content, and supply chain. The materials module allows the documentation of part-level BOM information including material, class, mass, supplier, and country of origin. These then fill into the use phase inputs which document operational characteristics such as part load performance curves, weather profiles, and control strategies. The EoL module expands on the materials and use phase energy modules to evaluate the disassembly steps, recyclability, and recovery potential at the subsystem level. Lastly, these modules inform the domestic content and supply chains module by enabling the users to document supplier locations, sourcing attributes, and operational cost information to provide domestic and supply chain metrics.

To improve data consistency, the template includes controlled terminology, validation rules, and uniform units for key parameters. Subsystem tags and lifecycle module indicators accompany each record, allowing exported data to be ingested by multiple analytical tools without additional formatting. Furthermore, the template supports structured data exports in formats such as CSV and JSON, enabling straightforward integration with modeling tools and internal data pipelines.

Results

Insights from Manufacturer Collaboration

Engagement with manufacturers during the working group process provided several insights that influenced the template design. When manufacturers began mapping their existing BOMs and supplier records into the proposed schema, it became clear that early versions of the template did not fully capture the hierarchical structure used in internal product documentation.

Manufacturers typically organized product data across multiple levels of assemblies and subassemblies, including cabinets, heat exchangers, compressors, fans, electronics, and control components. Incorporating subsystem tags and module indicators into the template increased clarity by providing a link to the product hierarchy and the lifecycle context (see Figure 1).

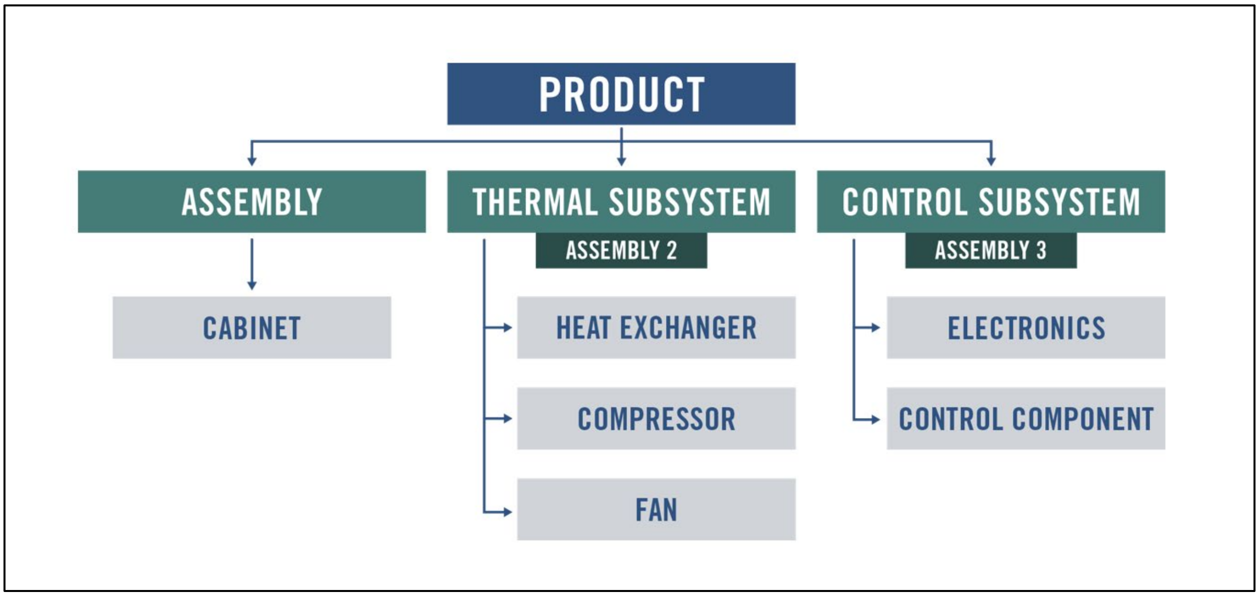

Figure 1. Typical RTU system hierarchy. Incorporating subsystem tags and module indicators into the template increased clarity by providing a link to the product hierarchy and the lifecycle context.

Industry collaboration also revealed differences in how operational performance data was recorded across manufacturers. When part load performance curve and control sequences were translated into the harmonized template format, variations in data representation highlighted the importance of capturing operational behavior rather than solely relying on nameplate ratings (see Figure 2).

B6: Operational Energy Usage		
Includes the electrical consumption of HVAC as reported in the Info and Spec's Tab. Additional power draw of management functions may be included if they are known, otherwise select N/A.		
Energy Usage of HVAC Only		
Power Draw (watts)	3,200	
Lifetime HVAC Power Draw (kWh)	38,400	
Management Systems		
	Included	**Energy Draw (watts)**
Thermostat Control	Yes	3
Occupancy Sensor	Yes	1
Demand Response Function	Yes	2
Variable Speed Control	Yes	15
Scheduling	Yes	1
Energy Management System	Yes	1
Lifetime management power draw (kWh)	276,000	
Lifetime system power draw (kWh)	314,400	

Figure 2. Screenshot of operational energy usage (B6) template inputs. When part load performance curve and control sequences were translated into the harmonized template format, variations in data representation highlighted the importance of capturing operational behavior rather than solely relying on nameplate ratings.

Lastly, this collaborative process highlighted that this template was applicable not only to RTUs but to any equipment category. This is predominantly because many thermal systems share similar assemblies and lifecycle characteristics and thus the same core data structure could be applied across the sector without compromising analytical consistency.

Template Validation and Structure

Subsystem tags and lifecycle module indicators enabled exported data to be maintained especially when transferred between internal systems or modeling structures. This was achieved by developing the template to cover not only production through installation (A1-A5) but also operation and maintenance (B), EoL management (C) and beyond (D) (see Figure 3).

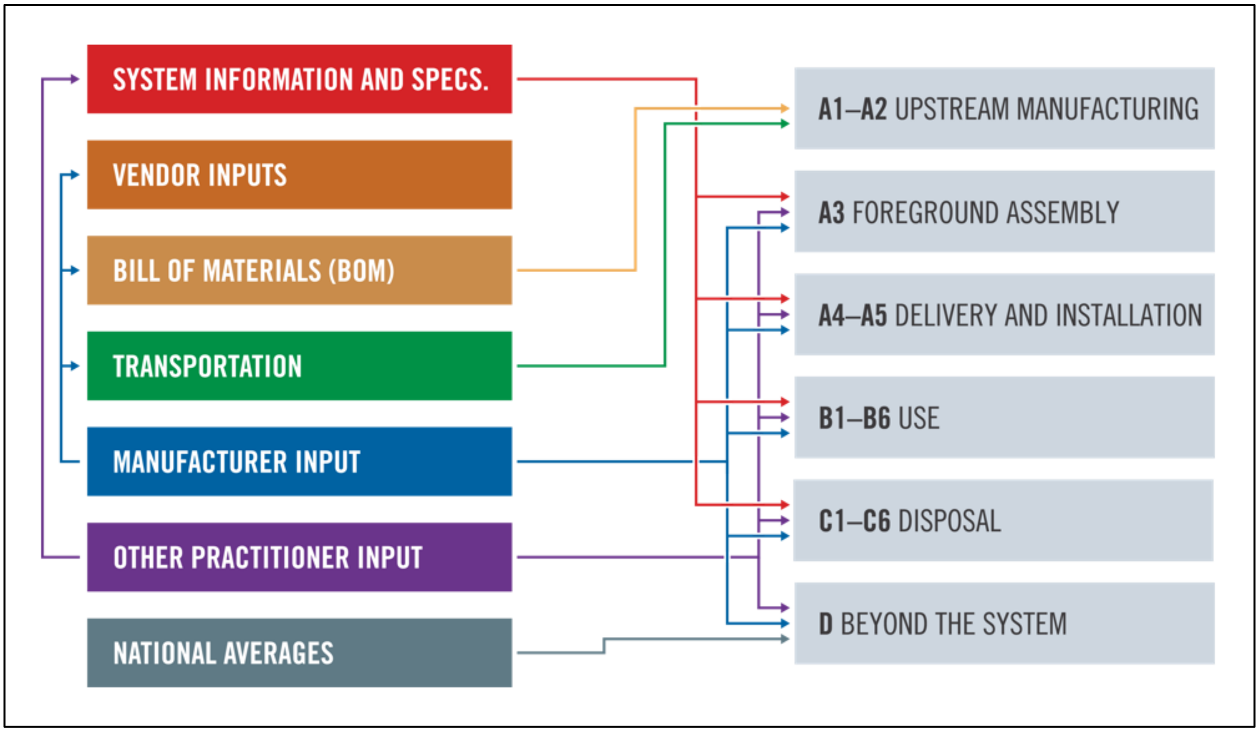

Figure 3. Template workflow. Consistent field Keys, value domains, and lifecycle tags (A1–A5, B, C, D) enable reliable cross-tool data exchange.

Pilot Testing and Analytical Findings

Pilot testing was conducted on the templates using anonymized RTU data provided by the industry partners. This testing demonstrated the analytical value of the structure data approach, especially highlighting the benefit of aggregating materials data at the subsystem level. This was best represented through items like aluminum coils, copper coil, and steel cabinet assemblies, which consistently represented the largest contribution to the RTUs overall mass and production impacts (see Figure 4).

Figure 4 represents an aggregation of those data into the materials' respective fossil resource use impacts and minerals and metals resource use impacts for the five highest-mass materials identified across the RTU dataset. Material selection was based on average mass contribution across all evaluated RTUs, resulting in the inclusion of steel, copper, aluminum, tube Insulation, and refrigerant R134A. Steel dominates the material inventory, with an average mass exceeding 2,500 kg per unit, while copper and aluminum represent the next-largest material categories at approximately 140 kg and 118 kg, respectively. Despite steel's overwhelming contribution to total product mass, the fossil resource impacts are not distributed proportionally across materials. Copper exhibits fossil resource use impacts of a similar order of magnitude to steel despite comprising less than six percent of steel's average mass, illustrating the disproportionate influence of energy-intensive material production processes on upstream resource consumption. These relationships would be difficult to identify through a BOM review alone and instead emerge through the integration of material quantities with inventory data.

The results further demonstrate that the materials driving fossil resource use are not necessarily the same materials driving minerals and metals resource use. Steel exhibits the highest median fossil resource use impact, reflecting its substantial mass contribution and energy-intensive production pathway. However, copper displays the highest median minerals and metals resource use impact among the five materials evaluated, despite its lower mass contribution. This finding shows the importance of evaluating performance across multiple indicators rather than relying solely on mass-based screening approaches. Such insights can support targeted design improvements, material substitution evaluations, procurement strategies, and broader efforts to reduce resource and/or critical material consumption across RTU product portfolios.

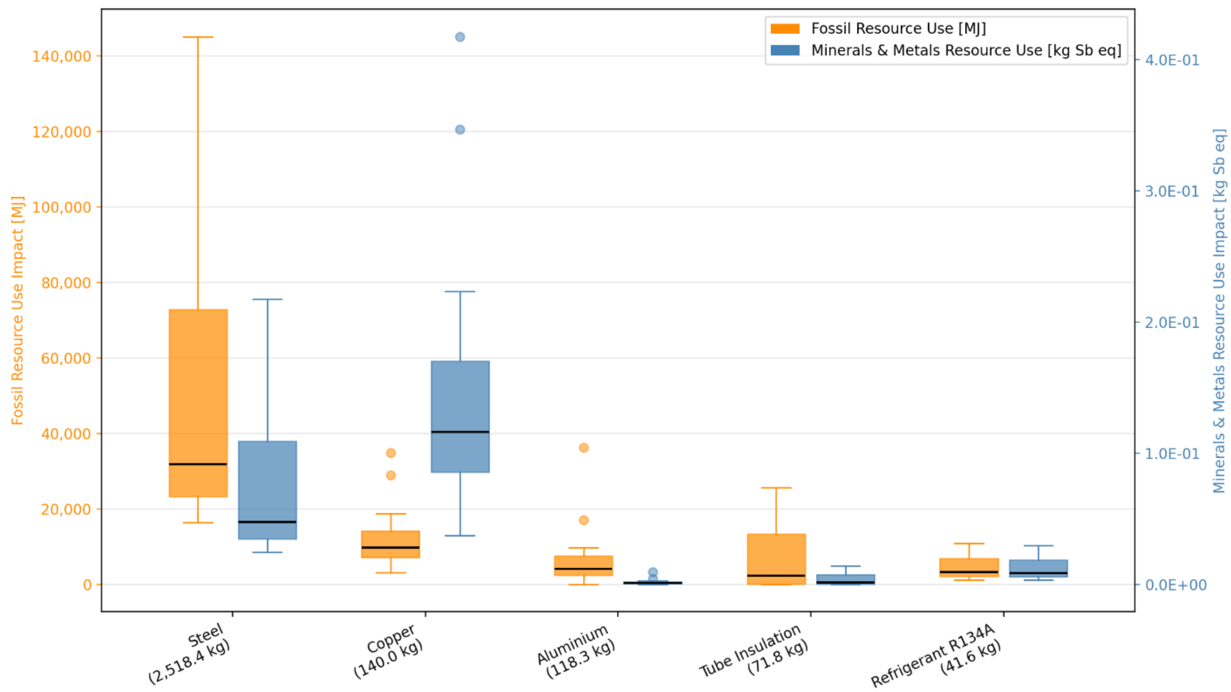

Figure 4. Distribution of fossil resource use and minerals and metals resource use impacts for the five highest-mass RTU materials. Average weight of each material across the RTU dataset is shown in parenthesis on the x-axis.

Furthermore, operational data analysis showed that a uniform data structure enabled consistent comparison of operating profiles across systems and manufacturers. These comparisons indicated that fan and economizer control strategies can provide measurable energy savings in specific areas (e.g. marine, cold, hot-dry, hot-humid, etc.) (see Figure 5).

Rooftop unit (RTU) operational electricity consumption was estimated over a 15-year service life. Total site electricity consumption was disaggregated into Thermal Systems (HVAC) electricity use and non-Thermal Systems electricity use. The Thermal Systems electricity attributable to RTU operation was further allocated among heating, cooling, fan, and economizer functions. The template was configured with a constant average HVAC operating demand and climate-dependent baseline annual operating hours for four representative U.S. climate categories (i.e., marine, cold, hot-dry, hot-humid). Operational management strategies were represented as package-specific fractional reductions in HVAC runtime (Types A–D), enabling consistent comparison of alternative control approaches under a common baseline equipment power assumption. Total lifetime HVAC electricity was calculated as the product of HVAC power and managed lifetime operating hours. These HVAC-only results are presented in Figure 5.

Non-HVAC electricity was calculated separately and added to HVAC electricity to obtain total lifetime consumption, consistent with the template's component-level structure. These non-HVAC contributions are reported separately in Figure 6 to highlight their magnitude relative to HVAC electricity and to clarify how added management hardware can offset a portion of runtime-based HVAC electricity reductions over multi-year lifetimes.

Table 1 and Table 2 summarize the scenario inputs used to generate the operational electricity results in Figure 5 and Figure 6. Table 1 defines the regional climate assumptions through baseline annual RTU operating hours scaled over a 15-year lifetime. Table 2 defines the operational management packages (A–D) through runtime reduction factors and associated non-HVAC loads, such as controls and, where applicable, variable frequency drive (d) standby and conversion losses.

Table 1. Assumptions for operational management profiles.

Management type	Intended profile	HVAC runtime reduction (fraction of baseline)	Added controls standby power (W)	VFD included?	VFD standby power	VFD efficiency	Avg. fan motor output during operation (kW)
A	Baseline (no added management)	0	0	No	0	—	—
B	Scheduling / time-of-day control	0.08	4	No	0	—	—
C	Smart controls + VFD	0.15	6	Yes	10	0.97	1
D	Advanced + VFD + demand response capability	0.2	8	Yes	10	0.97	1

Table 2. Assumptions for regional climates and operational profiles.

Item	Marine (mild/coastal)	Cold (heating-dominant)	Hot-Dry (cooling-dominant)	Hot-Humid (cooling + latent)
Climate description (qualitative)	Mild temperatures; lower HVAC demand	Long heating season; moderate cooling	High dry-bulb temps; low humidity	High temp and humidity; significant latent load
Baseline HVAC runtime (hrs/year)	1,600	1,800	2,200	2,600
Lifetime (years)	15	15	15	15
Baseline lifetime HVAC runtime (h)	24,000	27,000	33,000	39,000
HVAC average operating demand (kW)	3.2	3.2	3.2	3.2
Baseline lifetime HVAC electricity (kWh)	76,800	86,400	105,600	124,800

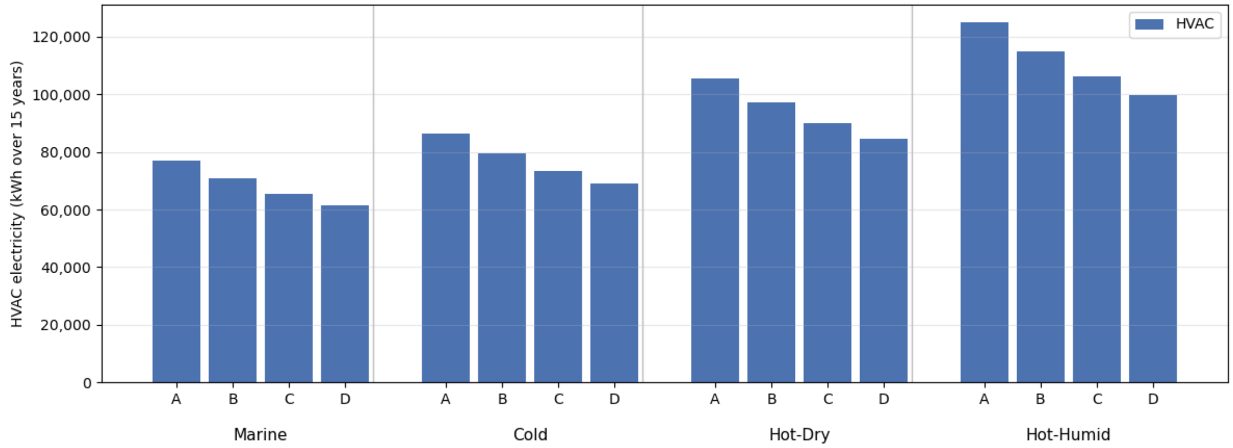

Figure 5. Fifteen-year RTU HVAC electricity consumption by climate and operational management package (HVAC-only component).

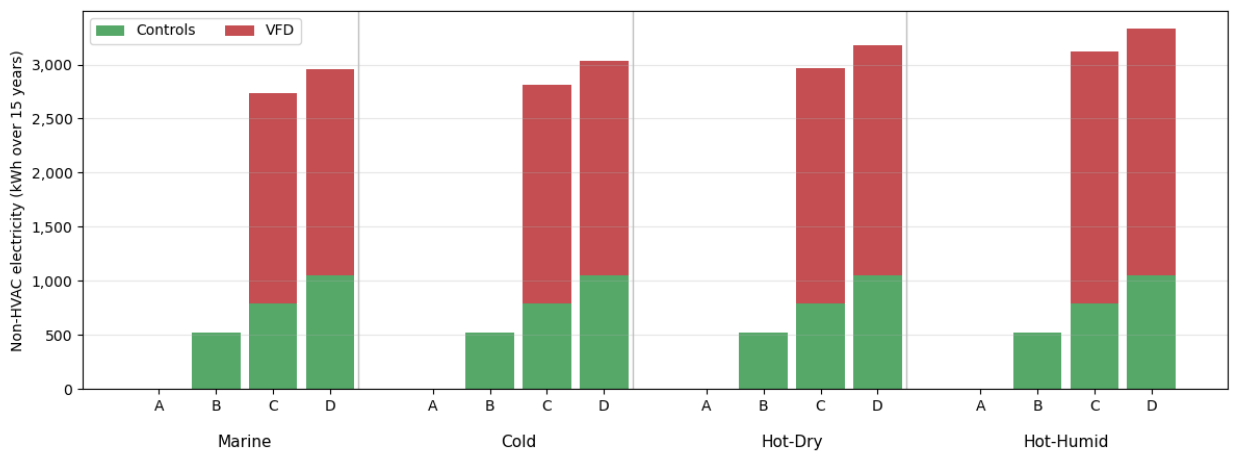

Figure 6. Fifteen-year RTU non-HVAC electricity consumption by climate and operational management package (controls and VFD components).

Pilot studies with anonymized BOM data also revealed several opportunities for material reduction within cabinet assemblies. Several high impact structures were identified within the assembly which could be reinforced through varying geometries rather than increased thickness. Similarly, design discussions around heat exchange assemblies indicated that alternative tube layouts could reduce copper usage while maintaining thermal performance. These innovation, design, and development opportunities could not be properly targeted without a uniform template for holistic evaluations.

From a supply chain perspective, the BOM level documentation surfaced sourcing risks that were not visible in the product's summary documentation. In several cases, the template revealed single-source components with long lead times, prompting discussions around alternative suppliers and domestic sourcing opportunities. Integrating domestic content workflows further supported analysis by highlighting supplier locations and manufacturing origins in a structured format. This approach improved traceability while simultaneously providing insight into supply chain dependencies and sourcing risks.

Implications for Consistency of Thermal System Data

The structured data template developed in this study provides a foundation for improving transparency and comparability across thermal system equipment. By harmonizing materials data, operational inputs, and supply chain documentation, the template enables analysts and decision makers with the ability to evaluate equipment using consistent datasets and assumptions.

For manufacturers, this template also highlights how design decisions influence material mass, operational performance, recovery potential and sourcing patterns. This transparency can support iterative design improvements by making technical tradeoffs more visible earlier in the product development process. Additionally, the template also strengthens benchmarking capacities by enabling cross manufacturer comparisons based on inputs. The template provides procurement teams with the ability to evaluate equipment using comparable datasets and allows researchers to perform consistent analysis across product categories.

Beyond RTUs, the modular structure of the template also makes it adaptable to other thermal technologies. Components such as coils, compressors, fans, enclosures, controls, and electronics appear across many thermal systems, which gives the template an advantage in being able to structure this data across multiple designs.

Conclusion

This work presents a practical pathway for improving how materials, operational characteristics, EoL information, and sourcing details are documented for thermal systems equipment. Through collaboration with manufacturers, industry organizations, and research partners, this study built on a template approach featuring a structured input-output data framework that addresses longstanding challenges associated with fragmented product documentation and inconsistent data formats.

Pilot testing demonstrated that a harmonized data structure enables clearer identification of material amounts, operational hotspots, and recovery constraints within thermal systems. Furthermore, organizing performance inputs in consistent formatting can improve the comparability of energy modeling results, which can reveal opportunities for operational efficiency improvements.

This template also revealed that the inclusion of domestic content documentation can further enhance the traceability of sourcing information for compliance with emerging procurement requirements such as BABA. By using structured fields (i.e. supplier location, origin, and component information) the users are given a consistent method for documenting supply chain information while maintaining reporting requirements.

Overall, the template advances a transparent and consistent approach to product level data organization that supports design improvements, supply chain visibility, and more reliable performance evaluations across thermal system applications. These benefits are only expected to increase as additional industry partners use this template and provide feedback.

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