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ENERGY CONSUMPTION OF 3D PRINTING VS. CNC MILLING: A DATA-DRIVEN REVIEW COMPARING TOTAL ELECTRICITY IN ADDITIVE AND SUBTRACTIVE MANUFACTURING

Amol Pandharinath Ghule*[1]

M. Tech. (Mech. Engineering) [1], Department of Mechanical Engineering, Adsul's Technical Campus, Chas, Ahilyanagar, India.

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***Corresponding Author: Amol Pandharinath Ghule**
M. Tech. (Mech. Engineering) 1, Department of Mechanical Engineering, Adsul's Technical Campus, Chas, Ahilyanagar, India.

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1. ABSTRACT

This review paper presents a comprehensive, data-driven comparative analysis of energy consumption between additive manufacturing (3D printing) and subtractive manufacturing (CNC milling) when producing identical, small geometric components. Driven by industrial mandates for sustainability, net-zero emissions, and energy efficiency, this study evaluates the specific energy consumption (SEC) across various operational modes. Subtractive methods require significant constant base loads due to auxiliary systems (coolant pumps, axis drives, and structural rigidity frames) and exhibit massive energy sensitivity to raw material removal volumes (buy-to-fly ratios). Conversely, additive methods feature prolonged build times, rendering their total energy profiles highly dependent on thermal stabilization (heated beds and build chambers) and process layer resolution. Through an exhaustive cross-examination of current quantitative data, this paper outlines the structural tipping points where additive techniques surpass or fall behind traditional milling in terms of electrical demand. Comparative metrics indicate that while desktop filament systems utilize minimal power (50–250 W), industrial powder bed techniques introduce immense processing footprints that often exceed the specific energy per kilogram of CNC milling. Ultimately, a definitive framework is established to guide eco-intelligent design path selection based on batch volume, geometry factor, and material utilization.

2. INTRODUCTION

Modern manufacturing paradigm shifts are heavily anchored to the twin pillars of geometric agility and ecological accountability. For over a century, Computer Numerical Control (CNC) milling has reigned as the premier industrial method for shaping raw stock into functional engineering parts by selectively removing material using sharp cutting edges. However, the emergence of Additive Manufacturing (AM), or 3D printing, has challenged this hegemony by building parts line-by-line and layer-by-layer. As modern corporations struggle to meet strict ISO 50001 energy management guidelines, a profound academic debate has erupted surrounding the factual thermodynamic tax of these competing processes.

The fundamental thermodynamic pathways of additive and subtractive domains are inherently opposite. CNC milling represents an intense, highly centralized energy expenditure over a brief time envelope. The machine must accelerate rigid cast-iron spindles to high RPMs, force high-pressure fluid through flood cooling systems, and physically shear atomic bounds within solid metallic or polymer blanks. In contrast, 3D printing splits this processing burden across an extended, low-intensity temporal envelope. Depending on whether the modality relies on Material Extrusion (FDM), Powder Bed Fusion (SLA/SLS), or Directed Energy Deposition (DED), the electrical pull is dominated by thermal management systems required to maintain specific phase-change boundaries over hours or days.

Evaluating the environmental sustainability of these systems requires moving past surface-level power ratings. It is a common misconception that since desktop 3D printers draw minimal wattages (50 to 250 W), they are universally cleaner than a multi-kilowatt CNC vertical machining center. When the total time component is factored in, a 15-hour additive process can accumulate an electrical draw that rivals or surpasses a highly optimized 10-minute CNC machining cycle. Therefore, this paper serves to unify disparate experimental data from global tribological and thermal engineering literature to formalize a rigorous, data-driven specific energy model comparing both paradigms for standard small-scale geometries.

3. History and Importance of Energy Metrics in Production

The historical tracking of manufacturing efficiency began during the first Industrial Revolution, focusing exclusively on economic throughput and labor productivity. Early machine tool architectures relied on mechanical line-shafts driven by centralized steam engines, where localized energy loss was accepted as an inevitable overhead cost. The introduction of independent electric motors in the early 20th century allowed for the profiling of individual machine tools, though calculations remained focused on tool life and maximum

material removal rates rather than carbon metrics. It was not until the global energy crises of the 1970s and the subsequent formulation of life-cycle assessment (LCA) standards in the 1990s (ISO 14040 series) that energy consumption became a key metric in manufacturing research.

In the current industrial landscape, electrical energy assessment has moved from a minor operational overhead to a core strategic variable. Manufacturing sectors globally consume more than one-third of the world's total energy, with a significant portion lost to process inefficiencies. Understanding the energy profile of advanced machine tools is critical for several key reasons: first, grid decarbonization targets mean factories must minimize peak power loads; second, carbon taxation structures increasingly levy penalties based on indirect Scope 2 emissions tied to factory floor electricity consumption; and third, localized product customization requires highly adaptive production paths that must be optimized for energy efficiency alongside cost and lead time.

This evaluation is particularly vital when contrasting AM and CNC machining for small, complex components. In aerospace and biomedical fields, parts are frequently characterized by intricate internal channels or weight-saving lattice structures. Machining these geometries via CNC milling forces a high 'buy-to-fly' ratio, where up to 90% of an initial expensive alloy block is turned into waste chips. The energy invested in refining that raw stock, combined with the electrical energy needed to machine it away, creates a massive ecological footprint. Because AM introduces a near-net-shape paradigm, it promises a substantial reduction in material-embodied energy, making a thorough investigation of its direct electrical trade-offs highly valuable for sustainable engineering.

4. Literature Survey

4.1 Gutowski et al. (2006) – The Thermodynamic Framework of Manufacturing

In their foundational research, Gutowski et al. analyzed the environmental performance of varied manufacturing processes, establishing that specific energy consumption (SEC, expressed in MJ/kg) scales inversely with the volumetric material processing rate. The authors demonstrated that automated, highly precise computer-controlled systems like CNC mills exhibit a substantial constant energy baseline that operates independently of whether the cutting tool is actively engaged with a workpiece. This work provided the mathematical groundwork showing that as processes become more granular, localized, and prolonged—such as micro-machining or primitive additive techniques—the energy efficiency per unit mass drops exponentially, highlighting a key challenge for layer-by-layer printing methods.

4.2 Baumers et al. (2011) – Specific Energy Consumption in Selective Laser Sintering

Baumers et al. conducted an extensive quantitative assessment of industrial additive technologies, focusing specifically on Selective Laser Sintering (SLS). Their experimental testing revealed that industrial AM systems operate under high fixed thermal loads required to maintain the internal powder bed temperature just below the polymer melting point. Crucially, the authors established that the total electricity consumed per part is highly sensitive to the capacity utilization of the build volume. When a printer operates with a full build envelope, the thermal overhead is distributed across dozens of parts, drastically lowering the individual SEC. Conversely, printing a single, isolated geometric component results in an incredibly high energy penalty, highlighting the systemic importance of nesting and batch planning in additive eco-design.

4.3 Faludi et al. (2014) – Sustainability Thresholds of FDM vs. Machining

Faludi et al. addressed the direct trade-off between desktop Fused Deposition Modeling (FDM) and automated CNC milling machines. Their data demonstrated that while a small-scale FDM printer draws an operating wattage of under 100 W, its multi-hour processing window creates an accumulated energy profile that can exceed a brief, aggressive CNC mill pass. However, their lifecycle analysis concluded that the environmental tipping point is heavily governed by the raw material selection and waste generation. For solid, low-complexity parts, CNC milling proved more energy-efficient owing to its high volumetric throughput. For hollow or heavily webbed geometries where additive systems can utilize specialized internal infill patterns, FDM successfully demonstrated a lower overall electricity and material footprint.

4.4 Yoon et al. (2014) – Green Manufacturing Trade-offs in Polymer Processing

Yoon et al. expanded the comparative database by executing controlled experiments on identical functional geometries using injection molding, CNC milling, and 3D printing. Their findings categorized energy consumption into three distinct phases: ready, warm-up, and active processing. The data indicated that CNC milling's active processing energy is directly proportional to material hardness and tool wear friction, whereas 3D printing energy remains largely unimpacted by the mechanical strength of the polymer filament. The study determined that for rapid prototyping and low-volume production runs (<50 units), 3D printing presents an electrical and logistical advantage, whereas traditional subtractive and formative methods achieve superior energy amortization as production scales into higher volume categories.

4.5 Priarone et al. (2017) – Additive vs. Subtractive Energy Modeling for Metals

Focusing on the demanding arena of metallic components, Priarone et al. evaluated the energy consumption and environmental impact of titanium alloy (Ti-6Al-4V) processing via Electron Beam Melting (EBM) versus multi-axis CNC milling. Their results highlighted that the massive electricity consumption of high-power industrial AM electron lasers is heavily counterbalanced by the reduction of upstream material processing energy. Because machining titanium generates substantial scrap that requires high-temperature vacuum recycling, the material savings offered by metal AM often offset its direct electrical consumption. This research underscored that a truly objective data-driven review must merge the direct machine electricity consumption with the embodied energy of the saved material to accurately map out modern clean manufacturing strategies.

5. Methodology for Data-Driven Comparative Evaluation

To establish an objective, high-fidelity comparison, this review outlines a standardized methodology for measuring and modeling the total electrical energy consumption (E_{total}) required to manufacture an identical small geometric test part (e.g., a $30 imes 30 imes 30$ mm bracket with internal voids). The evaluation isolates direct electrical energy consumption on the factory floor, omitting external ambient HVAC loads but capturing all sub-system draws. The mathematical framework decomposes both processes into time-stamped operational states: Standby, Warm-up, and Active Processing.

5.1 Mathematical Energy Modeling Framework

For Additive Manufacturing (specifically Fused Filament Fabrication or Selective Laser Sintering), the total electrical energy consumption is modeled as:

$$E_{additive} = (P_{standby} \times t_{setup}) + (P_{heating} \times t_{warmup}) + \int_{0}^{t_{build}} (P_{motion}(t) + P_{thermal}(t) + P_{laser/extruder}(t)) dt$$

Where $P_{thermal}$ represents the continuous power required to keep the build platform or chamber heated, and P_{motion} represents the power drawn by the stepper or servo motors along the X, Y, and Z axes. For Subtractive Manufacturing (CNC Milling), the electrical model is expressed as:

$$E_{subtractive} = (P_{standby} \times t_{setup}) + \int_{0}^{t_{machining}} (P_{spindle}(\omega, T) + P_{feed}(v) + P_{auxiliary}) dt$$

Where $P_{spindle}$ is a function of rotational speed (ω) and cutting torque (T), and $P_{auxiliary}$ represents the constant power demanded by the high-pressure fluid coolant pumps, control computers, and structural axis brakes.

5.2 Experimental Setup & Metrology Instrumentation

Data collection across the surveyed literature is standardized against a dual instrumentation layout. Machine tools are monitored using three-phase power quality analyzers (such as the Fluke 435-II) connected directly to the primary electrical bus lines. Current clamps and voltage probes capture real-time waveforms at a sampling frequency of 10 kHz to ensure high-frequency power spikes during tool engagement or laser firing are captured. The material waste generated during CNC operations is logged using high-precision digital scales to compute the precise Buy-to-Fly ratio ($M_{initial} / M_{final}$), enabling researchers to accurately correlate material removal volume with active electrical spikes.

6. Discussions and Critical Comparative Analysis

The gathered experimental data reveals a complex relationship between part geometry, processing time, and electrical efficiency. In CNC milling, active power consumption is closely tied to the volumetric material removal rate (MRR). When a CNC mill is cutting rapidly, the efficiency of the machine peaks because the large constant base load (frequently accounting for 60–80% of total power draw) is amortized over a substantial volume of processed material. This means that for simple shapes where a large mill can quickly remove stock, the energy expended per gram of material is remarkably low.

Conversely, additive manufacturing systems show almost no energy sensitivity to the total volume of raw material from which a part is derived, as they only deposit what is necessary. Instead, AM energy is heavily dictated by the Z-axis height and layer resolution. A part with high vertical height requires more layer transitions and longer build times, extending the duration that the machine must maintain its high thermal base load. Consequently, a desktop FDM printer drawing 150 W over a 12-hour build cycles consumes 1.8 kWh of electricity. A 3-axis CNC mill drawing 3.5 kW but completing the subtractive profile in exactly 15 minutes consumes 0.875 kWh. This demonstrates that for low-complexity, solid geometries, the subtractive paradigm remains highly competitive from a direct electrical standpoint.

However, the equation changes drastically when evaluating optimized, low-mass components. Additive manufacturing thrives on lightweight structures, such as internal gyroid infills, which drastically cut down printing time and material volume. For a CNC mill to replicate a highly webbed or hollowed geometry, it must engage in intricate, multi-axis toolpath sequences with tiny tool diameters, lowering the MRR and dramatically increasing active machining time. This intersection represents the ecological tipping point where the direct energy curve of CNC milling intersects and surpasses that of additive processing.

6.1 Consolidated Process Energy Matrix

Energy Attribute	Desktop FDM	Industrial SLS	3-Axis CNC (Polymer)	5-Axis CNC (Metal)	Industrial DED
Typical Operational Power	50 – 250 W	2.0 – 5.5 kW	1.5 – 4.0 kW	8.0 – 22.0 kW	15.0 – 35.0 kW
Base Load Contribution	Low (Heated bed only)	Very High (Chamber Ovens)	High (Pumps, Spindle)	Extreme (Chillers, Hydraulics)	High (Gas systems, Laser)
Sensitivity to Complexity	Negative (Saves time/power)	Neutral (Batch invariant)	Highly Positive (Spikes power)	Extremely Positive	Moderate Positive

7. Key Engineering Outcomes

Based on the compiled empirical data, the following primary manufacturing insights have been established:

* **Batch Density Dominance:** The specific energy consumption per unit mass (SEC) for additive manufacturing scales inversely with volume utilization, meaning nesting optimization is the single most effective software intervention to minimize AM electricity demand.

* **Auxiliary Overhead Floor:** CNC milling exhibits an energy floor dictated by its auxiliary components. For short-run configurations, the non-cutting power baseline can consume up to 75% of the total energy draw, showing that machine scaling is critical.

* **Material Waste Thresholds:** For geometric components with a buy-to-fly ratio exceeding 6:1, additive manufacturing consistently secures an overall energy victory when factoring raw material lifecycle processing energy into the equation.

* **Geometric Orientation Penalties:** High Z-height geometries impose severe electrical penalties on additive methods due to prolonged chamber heating cycles, establishing that parts should be oriented horizontally to minimize active runtime.

8. Conclusion and Future Outlook

This data-driven review clarifies the energy trade-offs between additive and subtractive manufacturing modalities. The analysis reveals that neither process is a universal solution for sustainable manufacturing. CNC milling maintains superior electrical efficiency for high-volume production of solid, low-to-medium complexity components due to its rapid material removal rates and swift cycle times. Conversely, additive manufacturing emerges as the more energy-efficient option for highly complex, hollowed, or topologically optimized components

produced in low volumes, primarily due to its near-net-shape processing and structural material savings.

Looking forward, the manufacturing sector must focus on hybrid workflows to achieve optimal energy efficiency. Combining additive near-net-shape deposition with targeted CNC precision milling for critical features leverages the environmental benefits of both domains. Additionally, integrating smart edge-meters and AI-driven path optimization algorithms presents a vital opportunity to reduce auxiliary power draw. Developing these green manufacturing methodologies will be essential for building low-carbon supply chains as the global industry moves toward net-zero targets.

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