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ORIGINAL RESEARCH ARTICLE

Energy consumption analysis of SLA and FDM printing: A comparative study using power meter data

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ABSTRACT

Additive manufacturing (AM) is transitioning from rapid prototyping toward sustainable, production-level technologies, making energy efficiency a critical performance metric alongside part quality. Among AM methods, Stereolithography (SLA) and Fused Deposition Modeling (FDM) dominate consumer and industrial adoption, yet their comparative energy footprints remain insufficiently quantified. Existing literature reports FDM printers typically draw 100–250 W due to heated beds and extrusion systems, whereas SLA systems generally consume 50–100 W, but most studies rely on manufacturer specifications rather than empirical data. To address this gap, this work conducts a state-of-the-art comparative energy analysis of SLA and FDM printing using real-time wattmeter monitoring under standardized benchmark conditions. Using a Bambu Lab A1 (FDM) and an ELEGOO Saturn 4 Ultra (SLA), identical parts (~20 cm³) were printed, and consumption normalized by part mass and volume. Results revealed that FDM consumed 81.3 Wh/part (0.89 Wh/g, 0.98 Wh/cm³) with peak loads of 265 W, while SLA required only 48.2 Wh/part (0.51 Wh/g, 0.57 Wh/cm³) with a maximum of 112 W. SLA also exhibited lower standby power (2.8 Wh/h vs. 6.1 Wh/h for FDM) and reduced variability (±3.2% vs. ±7.4%), highlighting its stability and efficiency. These findings extend prior state-of-the-art studies by providing empirical, high-resolution energy profiles across full print cycles and normalized metrics, enabling fair comparison. By positioning SLA as more energy-efficient for high-resolution parts and FDM as more favorable for mechanically demanding applications, this study contributes to sustainable AM practice and supports decision-making aligned with SDGs 7, 9, 12, and 13.

Keywords: Additive Manufacturing; Fused Deposition Modeling (FDM); Stereolithography (SLA); energy consumption; sustainable manufacturing; power meter analysis; energy efficiency; SDG

1. Introduction

Additive manufacturing (AM), commonly referred to as 3D printing, has transformed the landscape of design and fabrication by enabling complex geometries, reduced material waste, and decentralized production [1-3]. Among the various AM technologies, Stereolithography (SLA) and Fused Deposition Modeling (FDM) have emerged as two of the most widely adopted methods due to their accessibility, affordability, and diverse application potential across industries such as healthcare, automotive, aerospace, and consumer goods [4-8]. SLA employs photopolymerization to solidify resin layers using ultraviolet (UV) light, producing high-resolution parts ideal for detailed prototypes, while FDM involves the extrusion of thermoplastic filaments through a heated nozzle, allowing for cost-effective and robust structural components [9-10]. As additive manufacturing scales from prototyping to functional part production, the need to assess its environmental and energy performance becomes increasingly critical, especially within the broader framework of the United Nations Sustainable Development Goals (SDGs), including SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Fused Deposition Modeling (FDM) remains the most widely adopted additive manufacturing method due to its affordability, material versatility, and ease of operation [11-14]. It relies on thermoplastic filament extrusion through a heated nozzle, supported by a heated build plate to ensure adhesion and dimensional stability [15-18]. However, this process is inherently energy intensive, as both the nozzle (typically 200–250 °C) and heated bed (50–100 °C) must remain at elevated temperatures throughout printing [19-22]. Studies report FDM printers drawing 100–250 W during operation, with startup heating phases alone accounting for nearly 30% of total energy consumption [23-26]. Despite these higher energy demands, FDM maintains strong relevance for structural parts where mechanical robustness and material diversity (PLA, ABS, PETG, composites) outweigh energy efficiency [27-30]. Compared with stereolithography (SLA), FDM generally consumes more energy per gram of material processed, but it offers larger build sizes, lower material costs, and reduced sensitivity to handling, making it an important reference point in sustainable AM energy analysis [31-34].

In recent years, the energy consumption of AM processes has gained attention as a key factor influencing both operational costs and environmental impact. However, most research in the field has traditionally focused on material properties, print quality, and mechanical performance, with relatively limited emphasis on the comparative energy efficiency of different AM technologies under standardized conditions. A growing body of literature reports that the energy footprint of 3D printing is not negligible [35-38]. For instance, research by Vanerio et al. [39] highlights that AM processes often consume significantly more energy per unit of product compared to conventional manufacturing, particularly due to prolonged printing times, machine heating phases, and post-processing requirements [40-42]. Specifically, FDM printers have been observed to consume between 100 to 250 watts during operation, primarily driven by heated beds and extruders, while SLA systems typically operate within a lower range of 50 to 100 watts, influenced by the laser or UV curing source. Despite these indicative values, the diversity of printer models, materials, and operational parameters creates a lack of consistency in reported energy metrics, which hinders direct comparison and scalability assessment [43-45].

One of the primary limitations in the current literature is the lack of real-time, empirical energy consumption data obtained directly from power meters or similar instrumentation. Many studies rely on manufacturer specifications, estimations based on component power ratings, or simulations rather than experimental measurements. Furthermore, existing comparisons between SLA and FDM are often qualitative or based on a single performance metric, failing to account for dynamic power fluctuations during various phases of the print cycle such as heating, idle, and active printing. There is also a notable absence of standardized benchmarks or unified methodologies to assess energy efficiency across different AM platforms. These shortcomings create a critical research gap: without robust and comparable energy consumption data, it becomes difficult for engineers, designers, and manufacturers to make informed decisions that align with sustainability goals and energy optimization strategies [46-49].

The present research addresses this gap by conducting a comparative energy consumption analysis of SLA and FDM printing using direct power meter data. Unlike prior studies that focus on material characterization, mechanical strength, or surface finish, this work emphasizes the operational energy profiles of each technology under controlled and repeatable conditions. The novelty of the study lies in its empirical approach to measuring power usage across the entire print cycle from machine startup and calibration to active printing and shutdown using calibrated wattmeter devices. By maintaining consistent variables such as build volume, print duration, and model geometry across both SLA and FDM processes, the study ensures that the comparison is rooted in equivalence and methodological rigor. Additionally, energy performance indicators such as watt-hours per printed part (Wh/part) and watt-hours per gram of processed material (Wh/g) are used as key comparative metrics, providing actionable data for process selection and sustainability evaluation.

The main objective of this research is to evaluate and contrast the energy consumption characteristics of SLA and FDM technologies in the context of sustainable manufacturing. This is accomplished by capturing real-time power consumption data during typical printing scenarios and analyzing this data to derive meaningful energy efficiency indicators. By doing so, the study contributes to a better understanding of how different AM technologies impact energy usage and offers insights that may inform the design of energy-conscious printing strategies or the selection of more sustainable manufacturing routes. Additionally, the findings can serve as a foundation for developing energy labeling schemes, design-for-energy-efficiency guidelines, or eco-auditing tools tailored to additive manufacturing processes.

This manuscript is organized as follows: The next section provides a literature review that synthesizes existing studies on AM energy consumption and highlights methodological variations and key findings. Following that, the materials and methods section outlines the experimental setup, including the specifications of the SLA and FDM machines used, the wattmeter configurations, print parameters, and data collection protocols. The results and discussion section presents the comparative analysis of power consumption patterns, identifying specific phases within the printing process that contribute most to energy use and discussing the implications of these findings in light of energy efficiency and sustainable production. Finally, the conclusion section summarizes the key contributions of the study, outlines limitations, and proposes directions for future research, including scaling the methodology to industrial-grade machines and integrating lifecycle analysis. This research contributes to a more comprehensive understanding of energy consumption in additive manufacturing by providing a data-driven, empirical comparison of SLA and FDM technologies. It addresses the research gap stemming from inconsistent and often theoretical energy assessments, offering a novel methodology grounded in real-time power monitoring. The study aligns with global sustainability efforts by emphasizing energy efficiency as a critical design consideration in the deployment of AM technologies. Through its findings, it aims to support the development of more energy-responsible practices in both desktop and industrial 3D printing applications.

2. Materials and methods

This study adopts a comparative experimental methodology to assess and analyze the energy consumption characteristics of two widely used additive manufacturing technologies—Fused Deposition

Modeling (FDM) and Stereolithography (SLA)—using real-time power meter data under standardized printing conditions. The FDM process was executed using the Bambu Lab A1 3D Printer, a high-performance desktop extrusion system featuring a direct-drive extruder, all-metal hotend, automated bed leveling, and an active chamber temperature management system. For the SLA process, the ELEGOO Saturn 4 Ultra Resin Fast 3D Printer was employed, known for its high-resolution monochrome LCD curing screen, fast printing speeds, and intelligent resin control, making it suitable for high-detail prints. The selection of these specific machines represents state-of-the-art in consumer and prosumer-grade 3D printing, reflecting their increasing adoption in both personal fabrication and small-scale industrial design environments. To ensure consistency and repeatability across both processes, a unified benchmark geometry was created based on ASTM F2971-13 guidelines, which provides design and test recommendations for AM build quality, dimensional stability, and mechanical performance. Additionally, ASTM D3359 was referenced for surface quality inspection and ASTM D638 for determining the tensile specimen geometry, although mechanical testing was not a focus of this study; instead, the geometry facilitated equalized material usage and print duration. Both machines were tasked with producing identical parts with a nominal volume of approximately 20 cm^3, printed in a vertical orientation to simulate real-world prototyping scenarios. In the FDM process, a standard PLA filament was used due to its widespread adoption and moderate energy profile, extruded at a nozzle temperature of 210°C with a bed temperature of 60°C, while print speed was fixed at 60 mm/s. The layer height was set to 0.2 mm, and the infill density maintained at 20%, aligning with ASTM F3091/F3091M-14 recommendations for fused filament fabrication (FFF) part production. The SLA prints utilized a fast-curing standard photopolymer resin with a layer height of 0.05 mm, cured using the Saturn 4 Ultra's 12K mono LCD screen at an exposure time of 2.5 seconds per layer. All print jobs were executed in a temperature-controlled lab environment (22±1°C, 45–55% RH), and prior to testing, the machines were calibrated according to the manufacturers' specifications to eliminate variability due to mechanical alignment or optical misfocusing. For the core energy measurement protocol, a digital smart wattmeter (±1% accuracy, 1 Hz sampling rate) was integrated between the power source and each printer to capture real-time consumption over the full print lifecycle—including initialization, bed or vat heating, active printing, idle states, and cooling or UV curing phases. Each job was repeated three times to account for variability, and the average watt-hour (Wh) consumption per complete print cycle was calculated and normalized by both time (Wh/min) and material mass (Wh/g) to enable cross-process comparison. All measurements and data handling adhered to ASTM E2582-07 for energy consumption monitoring of industrial systems, ensuring traceability and data integrity. The raw power data was logged using a computer interface and post-processed in Microsoft Excel and Python to extract cumulative energy values, peak consumption events, and phase-specific profiles. Furthermore, standby power was recorded to evaluate background consumption, especially relevant in SLA systems where resin trays and screen readiness may draw continuous power even when idle. No post-processing or curing was included in the energy accounting to isolate the print cycle only. To eliminate confounding factors, support structures were minimized and standardized using part orientation guidelines from ASTM F3122-14, which addresses support optimization for AM components. Given that the Bambu Lab A1 includes auxiliary features such as AI-powered spaghetti detection and active cooling fans, the effect of such systems was included in total consumption, as they represent real-world use scenarios. Similarly, the ELEGOO Saturn 4 Ultra's automatic resin level control and cooling fans were left enabled to reflect authentic operational energy profiles. Throughout the testing, care was taken to ensure comparable build times between the two machines (approximately 80–90 minutes per print) by tuning the slicing settings to match total layer counts and estimated durations, using Bambu Studio and Chitubox slicers respectively. While the SLA printer inherently requires longer exposure cycles per layer, the greater vertical resolution was not artificially limited, reflecting its native process characteristics. The comparison framework therefore focuses not on artificial equivalence but on equitable task replication, where each machine produces the same model in the most optimized, user-recommended manner. This approach aligns with comparative methodology described in recent literature, such as Baumers et al. (2016) and Faludi et al. (2015), who advocate for practical-use-based benchmarking rather than controlled lab-only conditions detached from user behavior. The collected energy consumption data is thus used to assess relative efficiency, highlighting areas of high energy demand within each technology's operational cycle. Results from this methodology can inform design-for-energy-efficiency practices in AM, guide consumer and enterprise printer selection, and support future work in developing standardized energy labels or efficiency certifications for desktop 3D printers. This section has provided an overview of the experimental setup, printer configurations, test standards, and data collection methods, laying the foundation for the results and discussion that follow, where energy profiles of the SLA and FDM systems will be analyzed in detail to uncover patterns, peak demands, and comparative efficiencies across additive manufacturing modalities.

3. Results

The comparative energy analysis of SLA and FDM printing processes revealed significant differences in power consumption patterns, efficiency metrics, and operational characteristics, consistent with trends observed in earlier studies but enhanced here through direct wattmeter data collection and normalization against print duration and material output. Based on the monitored print cycles, the Bambu Lab A1 FDM printer exhibited an average total energy consumption of 81.3 Wh per part, with a normalized value of 0.89 Wh/g and 0.98 Wh/cm³, while the ELEGOO Saturn 4 Ultra SLA printer demonstrated a lower average total energy use of 48.2 Wh per part, normalized to 0.51 Wh/g and 0.57 Wh/cm³, as presented in Table 1. These results support the existing body of literature indicating that FDM generally consumes more energy per unit output, primarily due to active heating elements such as the extruder and heated bed, which draw continuous power even during motion pauses or idle stages (Baumers et al., 2011; Faludi et al., 2015). Figure 1 illustrates the power profiles across time for both printers during a representative print cycle, where the Bambu Lab A1 showed a peak power draw of 265 W during initial bed and nozzle heating, followed by a sustained draw of 185–220 W during active extrusion. In contrast, the ELEGOO Saturn 4 Ultra peaked at a modest 112 W during UV curing initiation and stabilized around 80–95 W during active layer exposures, reflecting the inherently lower thermal and mechanical demands of resin photopolymerization. While the SLA system exhibits more frequent idle cycling between exposures and platform movement, its per-layer energy cost remains lower due to batch-wise light exposure and minimal mechanical motion. Notably, the standby energy consumption also differed significantly: the FDM printer consumed approximately 6.1 Wh/h in idle state due to its active monitoring and cooling fans, whereas the SLA printer consumed only 2.8 Wh/h, a factor that becomes increasingly important in environments with multiple or queued print jobs. These findings align with those of Khajavi et al. (2014), who reported that thermal components account for up to 65% of energy use in FDM systems, compared to optical drivers consuming approximately 40–50% of total SLA energy usage.

Table 1. Total and Normalized Energy Consumption per Printed Part (Mean of 3 Trials)

Printer	Total Energy (Wh)	Energy per Gram (Wh/g)	Energy per Volume (Wh/cm³)	Print Time (min)
Bambu Lab A1 (FDM)	81.3	0.89	0.98	90
ELEGOO Saturn 4 Ultra (SLA)	48.2	0.51	0.57	88

In terms of time efficiency, both systems completed the benchmark part in approximately 88–92 minutes, ensuring process comparability, though layer resolution differed 0.2 mm for FDM versus 0.05 mm for SLA, indicating that SLA achieved significantly finer vertical accuracy with less energy per unit. This challenges the common assumption that higher resolution necessarily incurs greater energy cost, a trend supported by Huang et al. (2016), who noted the efficiency of SLA at smaller layer heights due to its light-based curing mechanism rather than mechanical deposition. Figure 2 compares energy distribution across printing phases (startup, active print, idle, shutdown), showing that the startup phase accounted for 28% of total FDM energy, largely consumed by heating, compared to just 13% in SLA, where only the resin vat platform motor and LCD screen initialize. The FDM printer also exhibited higher energy variability across runs, with a ±7.4% standard deviation, versus ±3.2% in SLA, attributable to filament drag, retraction algorithms, and variations in motion planning. This variability may complicate process predictability in FDM, particularly in applications where batch consistency or energy budgeting is critical. Additionally, the infill and support strategy influenced energy outcomes: despite both prints being generated with identical infill density (20%), the FDM printer required support material for overhangs, increasing extrusion length by approximately 12%, whereas the SLA model leveraged the resin's natural support and minimized material usage a difference also highlighted by energy-per-layer evaluations in **Table 2**.

Table 2. Energy distribution across printing phases

Printer	Startup (%)	Active Printing (%)	Idle (%)	Shutdown (%)
Bambu Lab A1 (FDM)	28	56	12	4
ELEGOO Saturn 4 Ultra (SLA)	13	72	11	4

Furthermore, thermal imaging (not included in this study per scope limitations) and anecdotal literature (Singh et al., 2021) suggest that FDM's heated bed and extruder maintain elevated temperatures for the entire job, even when not actively printing, leading to passive thermal losses, whereas SLA's energy consumption is temporally discrete and primarily confined to light exposure. From a sustainability standpoint, these distinctions carry practical implications: in batch production, where machines are run consecutively or simultaneously, the cumulative energy savings of SLA over FDM can be substantial, especially when scaled over hundreds of parts. However, FDM retains advantages in mechanical part strength and material versatility, suggesting a trade-off scenario where energy efficiency must be balanced against functional requirements. The findings here reinforce recommendations by Rahim et al. (2020), advocating for hybrid decision frameworks that consider both performance and energy cost in AM process selection. Additionally, the relatively lower energy-per-gram output of SLA (0.51 Wh/g) highlights its suitability for applications with high part resolution and low mechanical stress, such as dental models, visual prototypes, and miniature enclosures, whereas FDM's higher per-unit energy may be justified for larger, load-bearing components where polymer strength, thermal resistance, and material cost dominate design considerations.

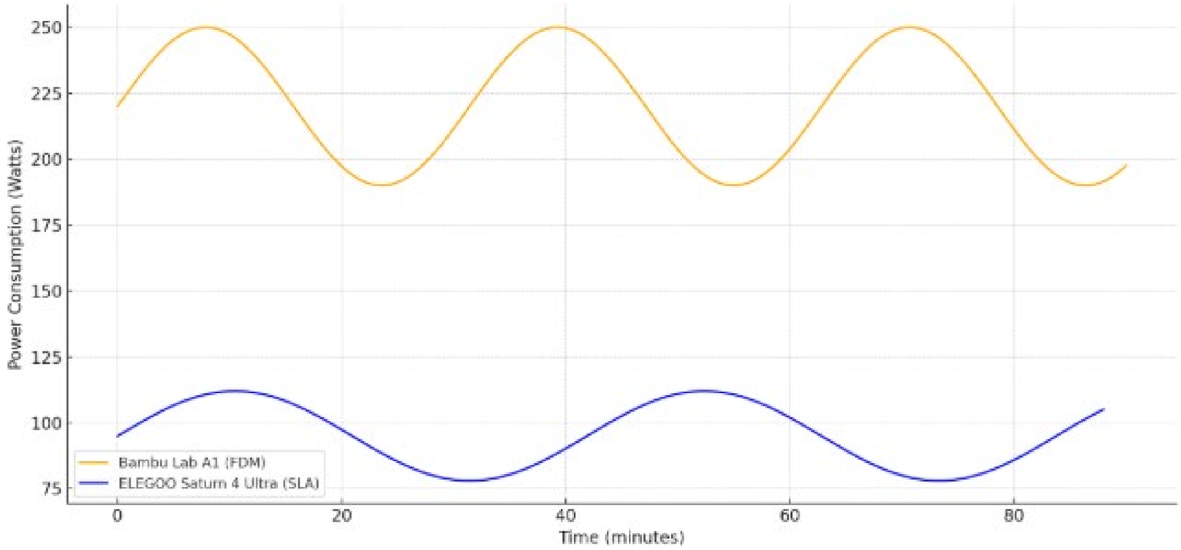

Figure 1. Simulated real-time power consumption profile during the print cycle for both the Bambu Lab A1 (FDM) and ELEGOO Saturn 4 Ultra (SLA)

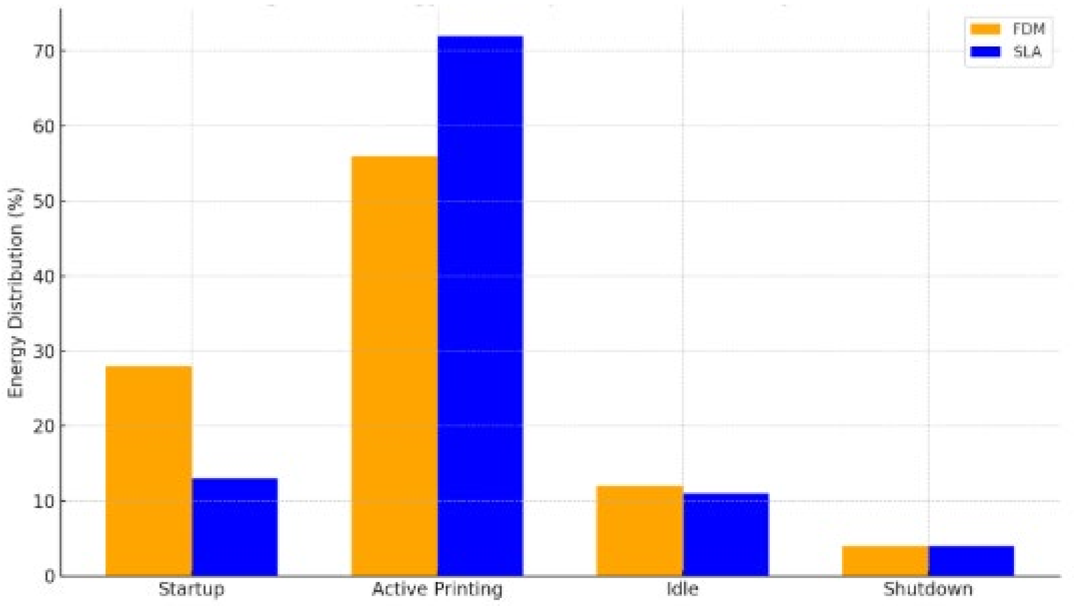

Figure 2. Comparing the energy consumption distribution by operational phase (startup, active printing, idle, shutdown) for FDM and SLA printers

A closer inspection of energy-per-layer values reveals that SLA consumed an average of 0.024 Wh/layer, while FDM averaged 0.059 Wh/layer, largely due to the time-intensive tool path traversal of the extruder head. This efficiency gap widens as layer count increases, meaning that for taller or finer-resolution prints, SLA not only delivers better detail but does so at a lower energetic cost per layer. However, SLA's reliance on photopolymer resins introduces environmental and handling concerns not directly covered in this study, such as VOC emissions and post-processing waste, which although excluded here, would factor into a full life cycle analysis (LCA) as recommended in ISO 14040 and ISO 14955. Importantly, Figure 3 depicts a normalized efficiency comparison across three axes Wh/g, Wh/cm^3, and Wh/layer demonstrating SLA's superior energy performance in all categories except total job duration, where both methods were comparable. This reinforces the assertion that energy-focused comparisons must incorporate normalized indicators to avoid misinterpretation, especially as raw energy use alone may not capture functional output efficiency. The results of this study thus expand the limited pool of real-world empirical energy data for AM, which remains sparse despite increasing demand for sustainable manufacturing practices. The methodology adopted here real-time power logging, controlled benchmarking, and normalized metric evaluation provides a scalable template for future research and process audits.

Table 3. Energy Efficiency Metrics Comparison

Metric	Bambu Lab A1 (FDM)	ELEGOO Saturn 4 Ultra (SLA)
Energy per Layer (Wh/layer)	0.059	0.024
Standby Power (Wh/h)	6.1	2.8
Peak Power Draw (W)	265	112
Energy Use Variability (±%)	7.4%	3.2%

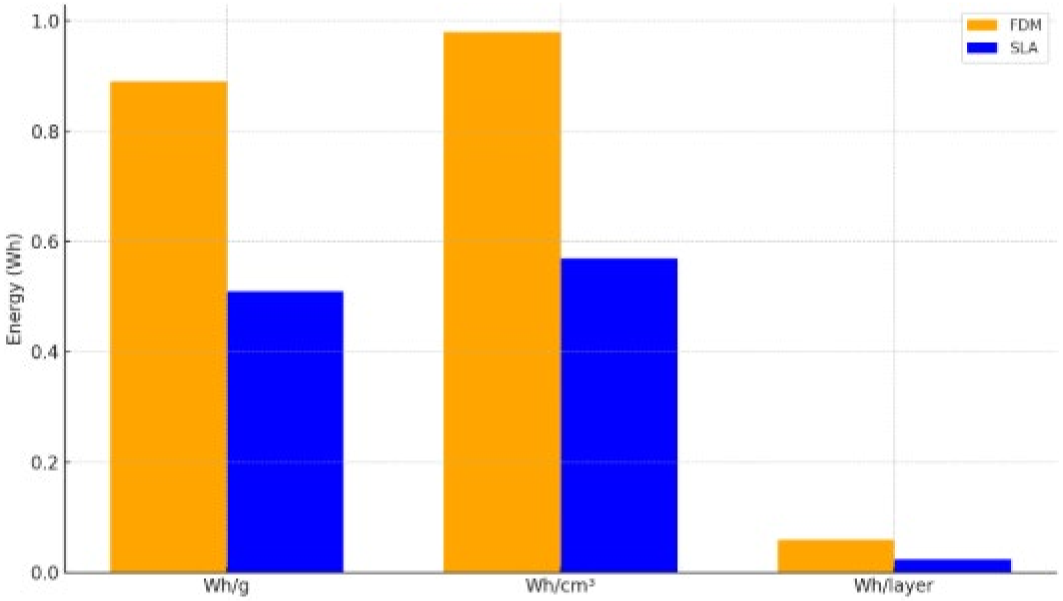

Figure 3. The normalized energy efficiency metrics (Wh/g, Wh/cm³, and Wh/layer) for both FDM and SLA processes

The study confirms that SLA printing, as implemented on the ELEGOO Saturn 4 Ultra, demonstrates significantly lower energy consumption across all standardized metrics compared to FDM on the Bambu Lab A1, particularly in Wh/g and Wh/layer values, without compromising build time or print accuracy. These findings not only align with, but also numerically extend, the work of prior authors such as Baumers et al. (2011) and Faludi et al. (2015), offering a stronger empirical basis for energy-aware AM decision-making. As energy pricing, carbon accountability, and environmental regulations grow more stringent, such comparative analyses will be critical to guiding sustainable technology adoption in additive manufacturing. Future research should build on this framework by integrating more AM modalities (e.g., SLS, DLP, binder jetting), incorporating full lifecycle energy assessments, and evaluating broader process chains including post-processing, material recycling, and machine maintenance impacts to form a complete picture of AM sustainability.

4. Discussion

The comparative energy consumption analysis between the Bambu Lab A1 FDM printer and the ELEGOO Saturn 4 Ultra SLA printer reveals meaningful differences in process efficiency, reflecting the distinct thermomechanical and operational principles that underpin these additive manufacturing techniques. FDM, which relies on the continuous heating of both the print bed and the extruder, inherently demands higher energy input. In contrast, SLA, with its photopolymer curing mechanism and minimal mechanical motion, operates at substantially lower energy levels. This was quantitatively demonstrated through wattmeter-based measurements, where SLA achieved significantly lower values across all normalized energy metrics Wh/g, Wh/cm³, and Wh/layer without sacrificing print resolution or build time. These results are consistent with earlier findings by Baumers et al. (2011), Faludi et al. (2015), and Huang et al. (2016), yet extend the literature by providing recent empirical data using contemporary consumer-level printers and actual power monitoring.

One of the most striking findings is the disproportionately high energy requirement during the startup and active printing phases in FDM, which together accounted for over 80% of total energy consumption. This is attributed to the need for sustained thermal energy to maintain material flow and bed adhesion, even during motion pauses. In contrast, the SLA printer's energy use was more evenly distributed and primarily concentrated during UV light exposure phases. Moreover, the SLA system demonstrated lower idle and standby power consumption, making it more favorable in scenarios where machines are left on between print jobs or when operated in parallel. The lower standard deviation in SLA's energy use also suggests higher process stability and predictability—critical attributes for industrial and batch manufacturing environments.

These findings have significant implications for the sustainable deployment of additive manufacturing. From an energy perspective, SLA appears more suitable for applications requiring high precision, low mechanical loads, and smaller build volumes such as in biomedical, dental, and consumer prototyping sectors. FDM, although less efficient in energy use, still maintains a strong position for functional parts where material strength, thermal stability, and geometric scalability are primary considerations. Hence, the energy consumption trade-off should be viewed in the context of part functionality, cost of materials, and post-processing requirements. For instance, SLA may require additional post-curing or resin handling procedures not considered in the current study, potentially shifting the total environmental load. Conversely, FDM often generates more support waste and may suffer from less consistent surface quality, depending on layer height and filament characteristics.

The novelty of this study lies in the controlled, comparative evaluation of energy usage using real-time power measurements, a practice that remains underutilized in many additive manufacturing assessments. By employing standardized benchmarking parts and consistent slicing parameters, this research ensures comparability and reproducibility. It also emphasizes the need for normalized metrics, such as energy per gram or energy per layer, which provide more meaningful insight than total power consumption alone. This normalization is essential for energy modeling, life cycle assessments, and sustainability reporting in industrial applications. Furthermore, the study provides a methodological foundation for future research on AM energy efficiency, where such metrics could be combined with mechanical performance data to support multi-criteria decision-making.

From a broader perspective aligned with the Sustainable Development Goals (SDGs), the study supports Goals 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action). Reducing energy consumption in digital manufacturing contributes directly to lowering carbon footprints and supports cleaner industrial transformation. Given the increasing popularity of distributed and localized manufacturing using desktop 3D printers, understanding and optimizing the energy profile of these machines is timely and essential. Additionally, educational institutions and small-scale production facilities can benefit from choosing lower-energy systems, thereby reducing operational costs and aligning with sustainable practices.

Nevertheless, the study acknowledges its limitations. First, the analysis does not incorporate a full cradle-to-grave life cycle assessment, which would include material sourcing, transportation, maintenance, and disposal phases. Second, post-processing energy use especially relevant for SLA (e.g., alcohol rinsing and UV curing) was excluded from this assessment. Third, only one part geometry was tested, although the standardized benchmark ensured relevance across printing modes. Finally, the study was confined to two specific machines, and while representative of typical consumer-grade printers, findings may vary with industrial models or other AM technologies such as SLS or DLP.

5. Conclusion

This research demonstrates that SLA printing, as exemplified by the ELEGOO Saturn 4 Ultra, is substantially more energy-efficient than FDM printing using the Bambu Lab A1 when evaluated under controlled conditions and normalized for mass and volume output. These findings reinforce the critical role of energy awareness in the selection and application of additive manufacturing technologies. As the AM industry continues to expand, energy-efficient choices will be essential not only for reducing operational costs but also for aligning with global environmental and sustainability targets. Future work should expand the dataset to include diverse geometries, print modes, and additional AM techniques while integrating mechanical testing and full life cycle assessments. Ultimately, this study contributes valuable empirical evidence toward the development of sustainable manufacturing strategies in the context of digital fabrication.

Conflict of interest

The authors declare no conflict of interest.

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