



Makers Project Report

Energy Consumption Analysis and Evaluation of the Ender-3 3D Printer for Sustainable Additive Manufacturing

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Contents

1	Introduction	1
1.1	Background	1
1.2	Research Gap	2
1.3	Objectives	2
2	Experimental Setup	2
2.1	Printer Model and Printing Parameters	3
2.2	Measurement Hardware: PZEM-017	4
2.3	Calibration and Validation	4
2.4	Software and Data Logging	5
3	Methodology	5
3.1	Experiment Group 1: Layer Height Variation	5
3.2	Experiment Group 2: Component Isolation and Optimization	5
3.3	Data processing	6
4	Results and Data Analysis	6
4.1	Layer Height Experiment Analysis	6
4.2	Component Isolation and Optimization Analysis	8
4.2.1	Component-Wise Breakdown	8
4.2.2	Effect of Disabling the Heated Bed	9
4.2.3	Efficacy of Thermal Insulation	9
5	Discussion	10
5.1	The Dominance of Thermal Loads	10
5.2	The Time-Energy Dependency	11
5.3	Diagnostic Value of Ghost Printing	11
5.4	Impact of Hardware Modifications	11
6	Conclusion	11
7	Future Scope	12

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Abstract

The escalating global demand for energy, predominantly sourced from fossil fuels, requires a rigorous evaluation of emerging manufacturing technologies. Additive Manufacturing (AM), specifically Fused Filament Fabrication (FFF), has seen widespread adoption through desktop platforms like the Creality Ender-3. However, the aggregate energy footprint of these consumer-grade devices remains under-researched compared to industrial AM systems. This study quantifies the energy consumption of the Ender-3 by isolating the electrical loads of its critical subsystems, the heated bed, hotend, stepper motors, and control electronics, using a PZEM-017 DC communication module. Through a series of controlled experiments utilizing the 3DBenchy benchmark model, we investigated the impact of layer height (0.1 mm, 0.2 mm, 0.3 mm) and hardware modifications (thermal insulation, disabled heating elements) on total energy expenditure. The results reveal that thermal management subsystems dominate the energy profile, with the heated bed and hotend collectively accounting for over 80% of total power draw. Specifically, the heated bed is the single largest consumer. Increasing layer height from 0.1 mm to 0.3 mm reduced the print time significantly, resulting in a proportionate decrease in total energy consumption from 1072.29 kJ to 516.17 kJ. Furthermore, applying thermal insulation to the heated bed yielded a 27% reduction in energy usage compared to the baseline, while operating without the heated bed reduced consumption by 42%. The ghost print mode, which isolates the kinematic load, demonstrated that motors and electronics consume a negligible fraction ($\sim 16\text{W}$) of the total power. These findings underscore that simple parameter optimizations and passive thermal interventions can substantially enhance the sustainability of desktop 3D printing.

1 Introduction

1.1 Background

The global energy landscape is currently traversing a critical juncture defined by rising demand and environmental urgency. Contemporary data indicates that global energy consumption is on an upward trajectory, yet a significant majority, approximately 84.7% , is still derived from fossil fuels. This continued reliance on carbon-intensive energy sources contributes heavily to anthropogenic climate change, placing the manufacturing sector, one of the largest global energy consumers, under increasing pressure to enhance efficiency.

Within this broader context, Additive Manufacturing (AM), widely known as 3D printing, is rapidly expanding and is projected to constitute a significant share of the future manufacturing market. While initially confined to prototyping, AM is evolving into a viable production method

for end-use parts. Among the various AM modalities, Fused Filament Fabrication (FFF) has achieved ubiquitous status, largely driven by affordable, open-source desktop printers like the Creality Ender-3. These devices are now commonplace in educational institutions, research laboratories, small businesses, and private households.

While the individual energy consumption of a single desktop printer may appear trivial compared to industrial machinery, the massive install base of these devices creates a substantial cumulative energy footprint. Understanding the electrical behavior of these systems is therefore essential. It is not merely a matter of operational cost reduction; it is a prerequisite for enabling sustainable digital fabrication and mitigating the environmental impact of distributed manufacturing.

1.2 Research Gap

Despite the growing prevalence of desktop AM systems, the existing academic literature presents a notable research gap. Current energy consumption studies predominantly focus on industrial-grade AM systems, such as metal powder bed fusion, selective laser sintering (SLS), and large-scale Stereolithography (SLA). These machines operate on fundamentally different power scales and thermodynamic principles than consumer FFF printers.

There is a scarcity of high-resolution, component-level energy data for consumer-grade printers like the highly adopted Ender-3 platform. Existing studies often aggregate power consumption, failing to distinguish between the energy required for thermal maintenance versus mechanical motion. Specifically, there is a need to:

- **Measure energy usage of individual components:** Distinctly quantifying the load of the heated bed, the hotend cartridge, and the stepper motors.
- **Evaluate print parameters:** Systematically analyzing how standard slicer settings, particularly layer height, influence the specific energy consumption (SEC) of a print.
- **Assess optimization strategies:** Testing the empirical validity of low-cost hardware modifications, such as bed insulation, which are often discussed in the community but rarely quantified in rigorous academic settings.

1.3 Objectives

This research aims to address these gaps through a structured experimental approach. The primary objectives are:

1. To analyze and quantify the energy consumption of the Ender-3 3D printer by measuring individual subsystem loads. This involves a granular breakdown of the power contributions from the heated bed, hotend, motors, and control electronics.
2. To identify and evaluate effective strategies for reducing overall energy usage by testing specific modifications. These strategies include the application of thermal insulation to the build plate, the optimization of printing parameters (specifically layer height).

2 Experimental Setup

The experimental framework was designed to ensure precise, replicable measurement of the printer’s DC energy consumption, eliminating the variables introduced by AC-DC power supply inefficiencies.



Figure 1: Creality Ender 3 Printer

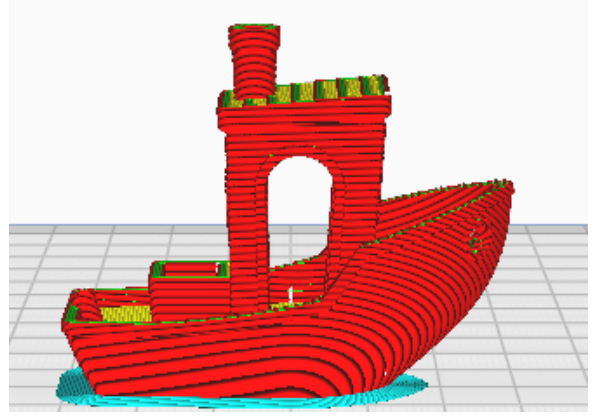


Figure 2: Benchmark printing model

2.1 Printer Model and Printing Parameters

The subject of this study is the Creality Ender-3 Figure 1 a standard Cartesian FFF 3D printer. The machine features a single extruder and a heated build plate, powered by a 24V DC supply.

Benchmark Model: The 3DBenchy Figure 2 was selected as the standardized test artifact. This model is the industry standard for benchmarking FFF printers due to its comprehensive inclusion of geometric features such as overhangs, bridges, and fine details, ensuring that the printer undergoes a representative range of kinematic movements during the test.

Baseline Print Settings: Unless essentially varied for specific experimental conditions (layer height tests), the following Baseline parameters were strictly maintained to ensure consistency:

Material: PLA	Nominal Print Speed: 50 mm/s
Nozzle Diameter: 0.4 mm	Retraction: 5 mm
Extrusion Width: 0.4 mm	Brim Width: 5 mm
Layer Height: 0.3 mm	Nozzle Temperature: 200°C
Infill Density: 20%	Heated Bed Temp.: 50°C
Perimeters (Shells): 3	Top/Bottom Layers: 6

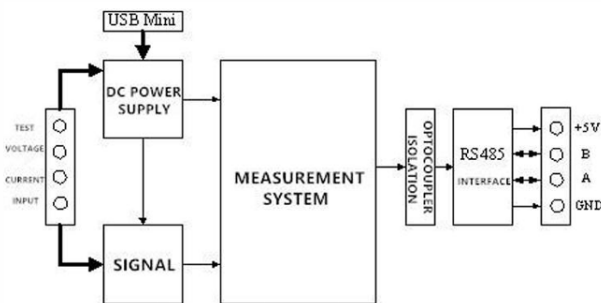


Figure 3: Block diagram of PZEM-017

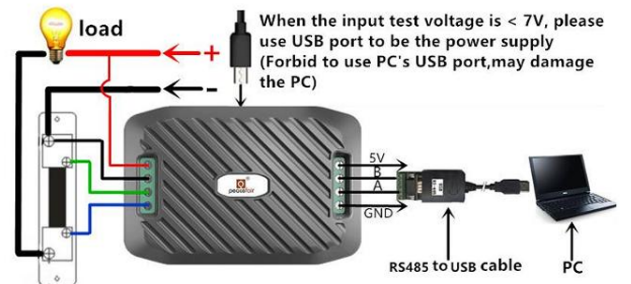


Figure 4: PZEM-017 Wiring diagram

2.2 Measurement Hardware: PZEM-017

To capture the electrical metrics, a PZEM-017 DC Communication Module was utilized. This is designed to measure voltage, current, power, and energy consumption in DC circuits.

Wiring and Integration: As shown in Figure 5, the PZEM-017 was installed in-line between the printer's 24V Power Supply Unit (PSU) and the mainboard. This configuration measures the total power delivered to the printer's subsystems while excluding the conversion loss of the PSU itself.

- **Connection Diagram:** As shown in Figure 3 4 , the RS-485 to USB cable connects the data interface of the PZEM-017 to the logging computer (PC).
- **Power Circuit:** The DC power supply connects to the input terminals of the PZEM-017, and the printer load connects to the output terminals.
- **RS485 Interface:** The module utilizes the RS485 industrial protocol for data transmission. Terminal A and Terminal B on the module are connected to the corresponding terminals on a USB-RS485 adapter.
- **Power Source:** As the test voltage (24V) is within the operating range ($>7V$), the module draws its operating power directly from the measurement circuit, removing the need for an external 5V USB power source.

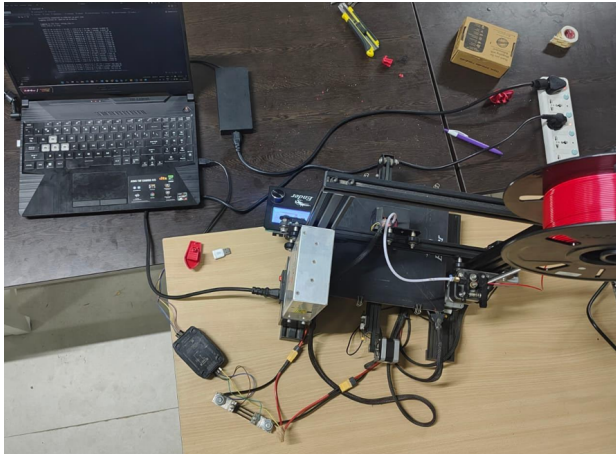


Figure 5: Experimental Setup

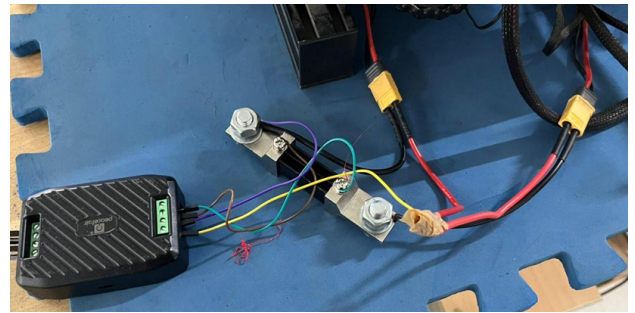


Figure 6: PZEM-017 Connection Setup

2.3 Calibration and Validation

Prior to data collection, the measurement setup underwent a rigorous calibration process in Figure 6 to ensure the fidelity of the readings.

- **Setup:** A known resistive load was connected to the PZEM-017 output terminals in place of the printer.
- **Measurement:** Voltage, current, and power readings were logged via the RS485 interface.
- **Validation:** These readings were compared against theoretical values derived from Ohm's Law ($V = IR$, $P = VI$) and reference measurements taken with a calibrated digital multimeter.

- **Result:** The comparison confirmed that the PZEM-017 module was reporting accurate values, validating the integrity of the subsequent experimental data.

2.4 Software and Data Logging

Data logging was performed using a Python script executing in a Jupyter Notebook environment. The script utilized the `minimalmodbus` library to interface with the PZEM-017 via a virtual COM port.

- **Sampling Rate:** The script was configured to query the sensor approximately every 2 seconds.
- **Logged Metrics:** Timestamp, Voltage (V), Current (A), Power (W), Delta Time (s), and Cumulative Energy (Wh).
- **Preprocessing:** A Gaussian moving average (window size 101) was applied to the raw power data during post-processing to smooth out the high-frequency fluctuations caused by the PID (Proportional-Integral-Derivative) controllers of the heating elements, allowing for clearer visualization of power trends.

3 Methodology

The research was divided into two distinct experimental groups to isolate variables effectively.

3.1 Experiment Group 1: Layer Height Variation

This experiment investigated the relationship between vertical print resolution (layer height) and total energy consumption. The hypothesis was that lower layer heights, which require more passes to build the same Z-height, would significantly increase print time and therefore total energy usage.

Three trials were conducted using the standard 3DBenchy model:

1. **0.1 mm Layer Height:** (Data Source: `baseline_l1.csv`)
2. **0.2 mm Layer Height:** (Data Source: `baseline_l2.csv`)
3. **0.3 mm Layer Height:** (Data Source: `baseline_l3.csv`)

All other parameters remained same.

3.2 Experiment Group 2: Component Isolation and Optimization

This group focused on dissecting the energy load of the printer's components. The 0.3 mm layer height profile (from `baseline_l3.csv`) was established as the Baseline for all comparisons in this group.

Four distinct operational modes were tested:

1. **Baseline:** Standard print at 0.3 mm layer height, Bed at 50°C, Nozzle at 200°C.
2. **Insulated Setup:** Identical to the baseline, but with thermal insulation applied to the whole system to reduce heat loss. (Data Source: `Insulation_result.csv`)

3. **No Heated Bed:** The printer operated with the nozzle at 200°C, but the heated bed was turned OFF (ambient temperature). This isolates the energy consumption of the bed heater from the rest of the system. (Data Source: `Without_heat_bed.csv`)
4. **Ghost Print (No Heat, No Extrusion):** The printer executed the G-code movements with no filament and no heating (Bed=0°C, Nozzle=0°C). This mode isolates the base load of the motion system (stepper motors), cooling fans, and mainboard electronics. (Data Source: `without_heatbed_heat_end.csv`)

By subtracting the energy values of these modes from the baseline and each other, the specific contribution of each component could be derived.

3.3 Data processing

- Each CSV was parsed to extract timestamp, power (W), and cumulative energy (Wh) where available.
- Mean power was computed as arithmetic mean of instantaneous power samples: $\bar{P} = \frac{1}{N} \sum_{i=1}^N P_i$.
- Total energy per print was taken from the cumulative energy column (final value) if present (Wh), converted to kJ by multiplying by 3.6: $E_{\text{kJ}} = E_{\text{Wh}} \times 3.6$.
- For component energy attribution, direct subtraction was used:

$$E_{\text{bed}} = E_{\text{baseline}} - E_{\text{no-bed}}, \quad E_{\text{hotend}} = E_{\text{no-bed}} - E_{\text{no-bed-no-hotend}}$$

The remaining energy corresponds to motors, control board and fans.

4 Results and Data Analysis

The data collected from the PZEM-017 logs provides a high-resolution view of the Ender-3's power characteristics. The analysis is presented in two sections corresponding to the experimental methodology.

4.1 Layer Height Experiment Analysis

The variation of layer height had a profound impact on the total energy consumption, primarily driven by the linear relationship between layer count and print duration.

Table 1: Layer Height vs. Energy Consumption

Layer Height (mm)	Print Time (min)	Mean Power (W)	Energy per Print (kJ)
0.1	224.0	79.611	1070.695
0.2	122.0	80.279	591.461
0.3	102.0	83.86	513.279

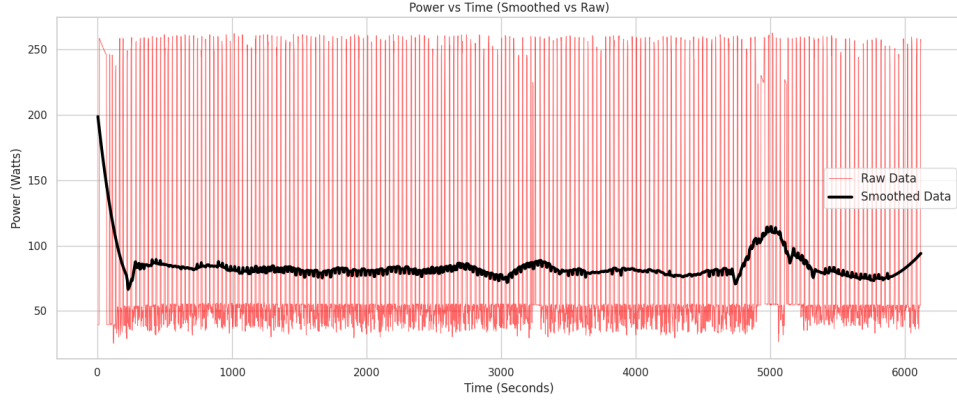


Figure 8: Power v/s Time Graph

Analysis of Trends: The data in Table 1 and Figure 7 reveals that although the Mean Power draw remains relatively consistent (between 79–84 W), the total **energy per print** decreases significantly with increasing layer height.

Specifically, the 0.1 mm layer height configuration consumed 1070.69 kJ, more than double the energy required for the same part printed at 0.3 mm layer height (513.27 kJ). This sharp reduction is driven by shorter print durations at larger layer heights, which reduce the cumulative time heaters and motors must remain active.

Power Fluctuation Behaviour: Analysis of raw CSV data (baseline_13.csv) in Figure 8 and Figure 9 reveals the typical sawtooth waveform of energy consumption characteristic of PID-regulated heaters:

- **Heating Phase:** At the beginning of the print, the system draws peak power (up to 250–260 W) to quickly reach bed and nozzle temperatures.
- **Printing Phase:** During the print, power toggles cyclically from ~ 34 W (idle) to ~ 250 W (active heating). Despite this fluctuation, the total energy consumed integrates over time to values shown in the table.

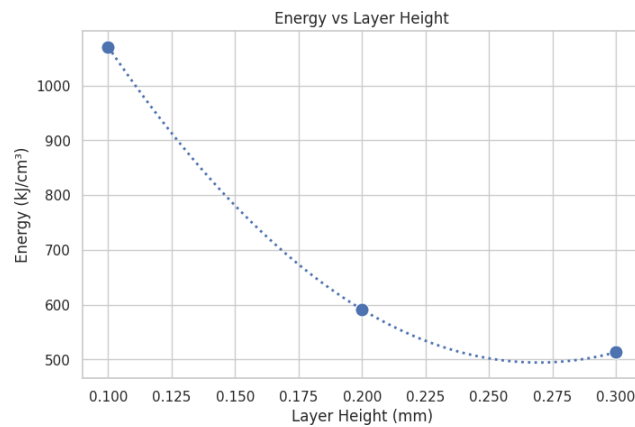


Figure 7: Layer Height v/s Energy Graph

The relationship between layer height and energy density (kJ/cm^3) is visually represented in Figure 7 of the presentation, which shows a clear logarithmic decay in specific energy consumption as layer height increases.

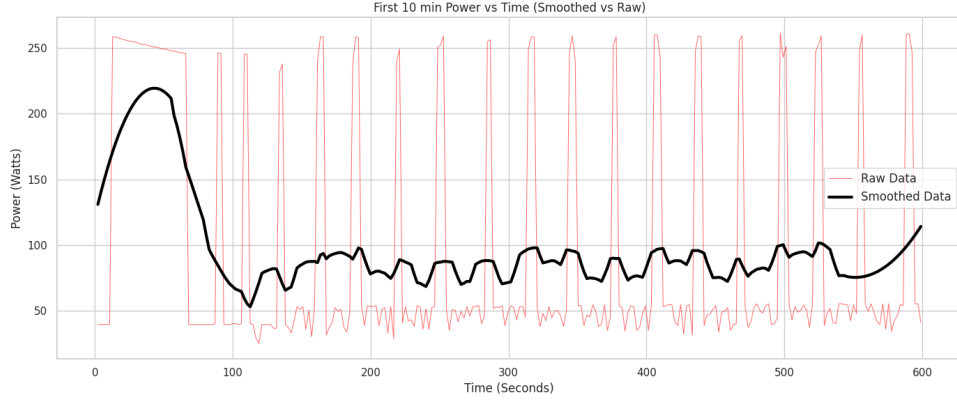


Figure 9: Power v/s Time Graph for initial 10 min

4.2 Component Isolation and Optimization Analysis

This section deconstructs the total energy load to identify the primary consumers and evaluate the effectiveness of the insulation modification. The 0.3 mm Baseline is used as the reference point (0% reduction).

Table 2: Energy Usage Comparison with Baseline

Print Mode	Time (min)	Mean Power (W)	Energy (kJ)	Reduction
Baseline (0.3 mm)	102.0	83.86	513.279	0%
Insulated Bed	97.0	64.757	377.052	27%
No Heated Bed	101.0	47.186	288.120	43%
Ghost Print	87.0	16.406	86.333	83%

4.2.1 Component-Wise Breakdown

Using the total energy values from Table 2, we can estimate the energy consumption of individual printer subsystems as follows:

1. **Base Load (Motors + Electronics):** Isolated from the Ghost Print mode.
 - **Value:** ~ 86.333 kJ
 - **Observation:** The CSV data for this mode shows a steady current draw of approximately 0.6A–0.7A with minimal fluctuation, indicating that the motion and control systems consume consistent, low energy.
2. **Hotend Heater:** Derived by subtracting the Ghost Print energy from the No Heated Bed energy.
 - **Calculation:** $288.120 \text{ kJ} - 86.333 \text{ kJ} = \mathbf{201.78 \text{ kJ}}$
 - **Observation:** Maintaining the hotend at 200°C required over 212 kJ of energy during the print duration.
3. **Heated Bed:** Derived by subtracting the No Heated Bed energy from the Baseline energy.
 - **Calculation:** $513.279 \text{ kJ} - 288.120 \text{ kJ} = \mathbf{225.159 \text{ kJ}}$
 - **Observation:** The heated bed is the largest individual energy consumer, consuming over 217 kJ to maintain 50°C throughout the print.

Percentage Breakdown: Based on these total energy values from the baseline (516.168 kJ), the energy usage distribution is as shown in Figure:

- **Heated Bed:** $\frac{225.159}{513.278} \times 100 \approx 43.86\%$
- **Hotend:** $\frac{201.78}{513.278} \times 100 \approx 39.3\%$
- **Motors & Electronics:** $\frac{86.333}{513.278} \times 100 \approx 16.8\%$

This confirms that the heating elements (bed and hotend) contribute approximately 83.3% of the total energy consumption, making them the primary targets for energy optimization strategies.

4.2.2 Effect of Disabling the Heated Bed

The No Heated Bed experiment (`Without_heat_bed.csv`) resulted in a total energy consumption of 288.120 kJ compared to the baseline of 513.278 kJ. This reflects a substantial **43% reduction** in total energy. While PLA can sometimes be printed on unheated beds using adhesives like glue stick or blue tape, this result clearly illustrates the energetic cost of maintaining bed temperature. Disabling the heated bed offers a significant opportunity for energy savings without necessarily compromising printability.

4.2.3 Efficacy of Thermal Insulation

The Insulated Bed experiment (`Insulation_result.csv`) demonstrates the potential of passive thermal management. By simply insulating the bottom of the heated bed, the total energy consumption reduced to 377.032 kJ from the baseline value of 513.279 kJ.

- **Energy Savings:** This modification yielded a **27% reduction** in total energy consumption.
- **Mechanism:** As Figure Analysis of the CSV data suggests, the insulation effectively reduces heat loss to the environment. As a result, the bed heater operates with a lower duty cycle, remaining in the off state for longer durations during PID control, thereby consuming less energy over the print duration.

Figures 10 11 show Power vs. Time with insulation, and Figures 12 show component energy breakdown, both of which visually support these findings.

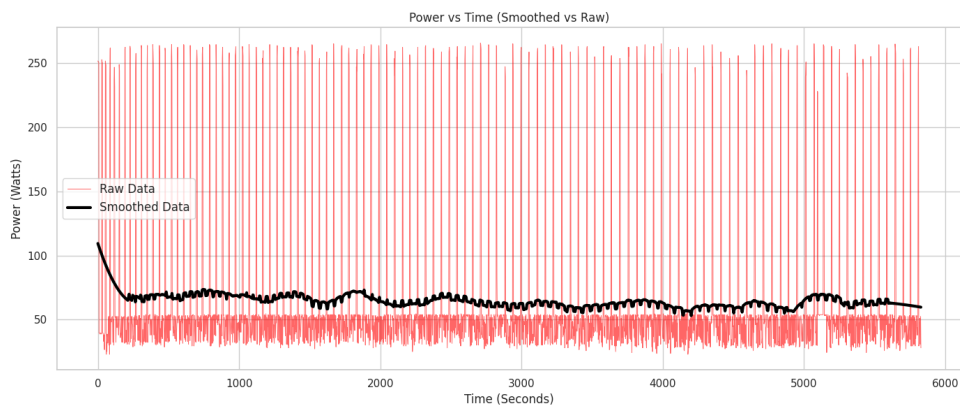


Figure 10: Power v/s Time Graph with Insulation

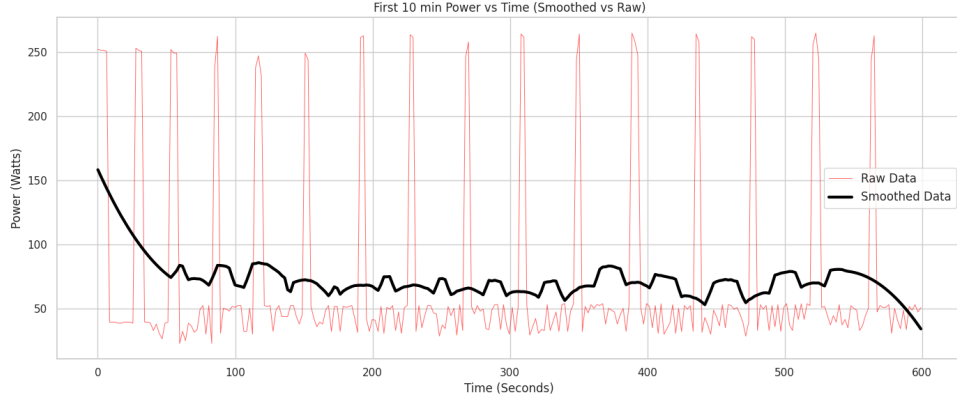


Figure 11: Power v/s Time Graph with Insulation (Zoomed)

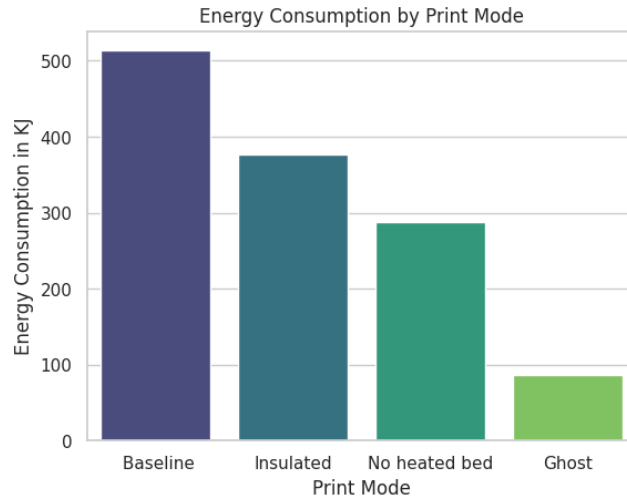


Figure 12: Energy Consumption v/s Print Mode

5 Discussion

The comprehensive analysis of the Ender-3's energy profile offers several critical insights into the nature of consumer-grade additive manufacturing.

5.1 The Dominance of Thermal Loads

The most significant finding is the overwhelming dominance of thermal loads in the total energy consumption profile of the Ender-3 printer. Contrary to the intuitive perception that 3D printing is primarily a mechanical process (involving stepper motors and motion systems), it is in fact energetically a thermodynamic process. Over **80% of the total energy input** is consumed in generating and maintaining heat first to melt the filament (hotend), and more significantly, to sustain the build environment temperature (heated bed).

The heated bed alone accounts for approximately **43% of the total energy consumption** (as derived from a 225.159 kJ difference between the baseline and no-heated-bed trials). This component operates as a large resistive heater, continuously radiating energy into the surrounding ambient environment. Since most consumer-grade printers like the Ender-3 lack enclosures, this leads to substantial heat loss.

The efficacy of the insulation experiment, which demonstrated a **27% reduction** in total energy usage (from 5163.279 kJ to 377.032 kJ), confirms that reducing this radiant heat loss

is among the most effective and low-cost strategies for improving energy efficiency in fused filament fabrication (FFF) systems.

5.2 The Time-Energy Dependency

The Layer Height experiment highlights a linear dependency between print time and energy consumption. Since the fixed costs of printing (keeping heaters active) are high ($\sim 83\text{W}$), any parameter that extends print time incurs a heavy energy penalty.

- Printing at 0.1 mm delivers high resolution but is energetically inefficient (1070 kJ).
- Printing at 0.3 mm is highly efficient (513 kJ) but sacrifices surface finish.

This suggests that for sustainable operation, users should prioritize the largest layer height that satisfies the functional requirements of the part. Using high-resolution settings for draft parts or internal structural components is a significant waste of energy.

5.3 Diagnostic Value of Ghost Printing

The Ghost Print mode, which consumed the least energy among all trials—**only 86.333 kJ**, representing an **83% reduction** compared to the baseline (513.279 kJ)—offers utility beyond just energy analysis. This mode, involving motion without heating or extrusion, reflects the baseline mechanical and electronic energy usage of the printer. Its consistent and low total energy consumption serves as a valuable diagnostic benchmark. Future deviations from this expected energy signature could signal underlying mechanical or electronic issues, such as increased friction in the V-slot wheels, misaligned belts, binding lead screws, or degraded stepper motor drivers. Thus, ghost printing can function as a lightweight, non-invasive method for assessing printer health and mechanical efficiency.

5.4 Impact of Hardware Modifications

The study conclusively demonstrates that simple, low-cost modifications can have measurable impacts. The insulation material, likely a simple foam or cotton sheet with reflective backing, provided a 27% energy reduction. This is a passive, one-time modification that requires no change to workflow or software, making it a highly recommended upgrade for all Ender-3 users concerned with efficiency.

6 Conclusion

This research successfully analyzed and quantified the energy consumption of the Creality Ender-3 3D printer, fulfilling the objectives of component-level breakdown and optimization assessment.

1. **Thermal systems are the primary energy consumers:** The heated bed and hotend together account for approximately 80% of the total energy consumption, with the heated bed alone responsible for nearly half ($\sim 43\%$, based on a 225.158 kJ difference between baseline and no-heated-bed trials).
2. **Kinematics are secondary:** The stepper motors and control electronics contribute only a small share of energy use ($\sim 17\%$, derived from the Ghost Print mode's total energy of 86.333 kJ), countering the common belief that motor movement dominates energy demand.

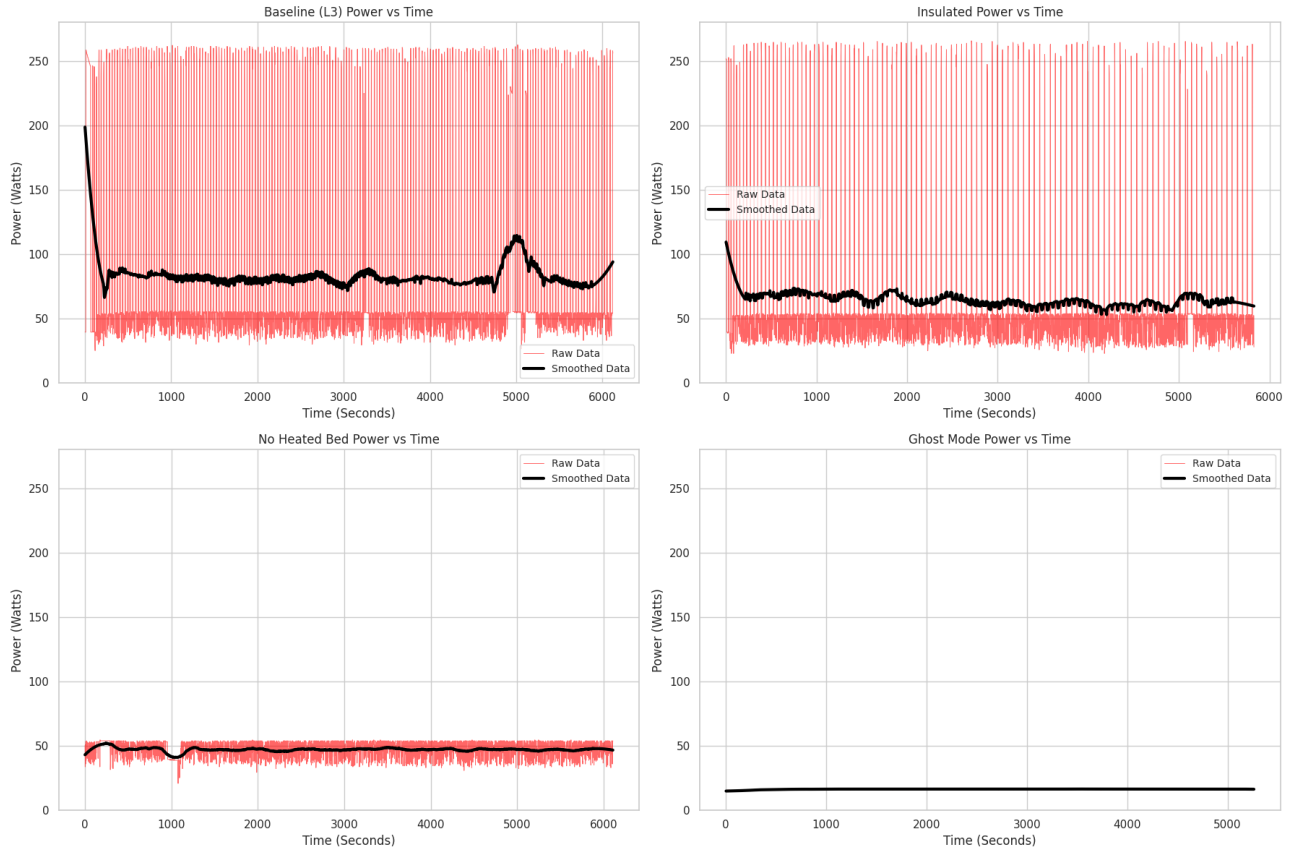


Figure 13: Power v/s Time Graph

3. **Insulation is highly effective:** Applying thermal insulation to the heated bed led to a reduction in total energy consumption from 513.279 kJ (baseline) to 377.032 kJ, achieving a **27% improvement in energy efficiency** making it a cost-effective upgrade for sustainability.
4. **Layer height dictates efficiency:** Increasing the layer height from 0.1 mm to 0.3 mm resulted in a drop in total energy consumption from 81070.695 kJ to 513.279 kJ yielding an impressive **39% reduction**. This is attributed to the reduced number of layers and shorter print time, which minimizes the operation time of heat-intensive components.
5. **Methodology Validation:** The integration of the PZEM-017 sensor via RS485 communication enabled accurate, real-time tracking of voltage, current, power, and energy metrics. This confirmed its reliability for monitoring the energy profile of DC-powered 3D printing systems with high resolution.

In summary, sustainable desktop 3D printing is best achieved by minimizing thermal losses through insulation and reducing print duration through optimized slicing parameters such as coarser layer heights.

7 Future Scope

The findings of this study pave the way for further research into sustainable additive manufacturing:

- **Material-Specific Energy Analysis:** Extending this methodology to high-temperature materials like ABS, PETG, and Nylon. These materials require significantly higher bed

temperatures (100°C for ABS), which would likely exacerbate the thermal dominance and make insulation even more critical.

- **Real-Time Adaptive Energy Models:** Developing machine learning models or firmware plugins that utilize real-time power data to optimize PID tuning dynamically. This could reduce heater overshoot and energy waste during the print.
- **IoT Integration for Carbon Monitoring:** Integrating the PZEM-017 data stream with IoT platforms (Home Assistant, OctoPrint) to provide users with a real-time ”Carbon Cost” dashboard. This would raise user awareness of the environmental impact of their fabrication choices.

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