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Energy Efficiency Analysis of 3D Printing Machines (Additive Manufacturing) in Supporting Local MSMEs: Poverty Alleviation Opportunities in the Digital Era

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ABSTRACT

Background. The rapid development of additive manufacturing, particularly 3D printing technology, has created new opportunities for small and medium enterprises (SMEs) to engage in flexible and low-volume production within the digital economy. Energy efficiency has become a critical factor influencing the operational feasibility of this technology, especially for SMEs that operate with limited financial resources and infrastructure. Understanding the energy performance of 3D printing machines is therefore essential for evaluating their potential role in supporting sustainable entrepreneurship and poverty alleviation.
Purpose. This study aims to analyze the energy efficiency of 3D printing machines in additive manufacturing processes and examine their potential contribution to strengthening local SMEs and expanding economic opportunities in the digital era.
Method. The research employs a quantitative experimental design combined with descriptive analysis. Energy consumption data were collected using digital power meters during standardized printing experiments involving several desktop 3D printers commonly used by SMEs. Statistical analysis was conducted to compare machine efficiency and evaluate the relationship between printing parameters and electricity consumption.
Results. The findings indicate significant differences in energy consumption across machine types and printing configurations. Optimized parameter settings and efficient machine architecture reduce electricity usage and operational costs. Evidence from SME production contexts demonstrates that energy-efficient additive manufacturing supports faster prototyping and flexible small-scale production.
Conclusion. Energy-efficient 3D printing technology represents a promising tool for strengthening SME productivity and fostering inclusive economic development in the digital era.

KEYWORDS

Additive Manufacturing, Digital Economy, Energy Efficiency, Small and Medium Enterprises, 3D Printing.

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INTRODUCTION

The rapid advancement of digital manufacturing technologies has transformed contemporary production systems and opened new opportunities for small-scale economic actors. Additive manufacturing, commonly known as 3D printing, represents one of the most disruptive innovations within Industry 4.0 because it enables the fabrication of complex objects directly from digital models with minimal material waste and flexible design capabilities. The diffusion of this technology is no longer limited to large industrial corporations; it has increasingly entered the sphere of small and medium enterprises (SMEs), including community-based microenterprises that seek affordable production alternatives (Liu dkk., 2025). Such technological accessibility has generated interest among policymakers and researchers who view additive manufacturing as a potential catalyst for inclusive economic growth.

Energy efficiency has emerged as a critical dimension in evaluating the sustainability and feasibility of digital manufacturing technologies (L. Zhang dkk., 2025). The operational cost of 3D printers is not determined solely by material consumption but also by electricity usage during printing processes such as heating, extrusion, and layer deposition (Jian dkk., 2025). Energy consumption becomes particularly relevant in developing economies where electricity costs represent a significant portion of production expenses for small enterprises (Zhao dkk., 2025). Understanding the efficiency profile of additive manufacturing machines is therefore essential for assessing whether these technologies can truly support the economic resilience of local entrepreneurs (Shang dkk., 2025). Efficient energy utilization can reduce operational costs and increase profitability, making technological adoption more attractive for small-scale producers.

Local micro, small, and medium enterprises play a strategic role in poverty alleviation and economic empowerment within many developing regions (Lee & Park, 2025). These enterprises often operate with limited capital, restricted access to advanced technology, and constrained production capacity (Geng dkk., 2025). The integration of affordable digital fabrication tools such as 3D printing has the potential to expand product diversification, accelerate prototyping, and reduce dependency on conventional manufacturing infrastructure (Soori dkk., 2025). The intersection between technological innovation, energy efficiency, and community-based entrepreneurship highlights the importance of investigating how additive manufacturing systems can support sustainable local economic development in the digital era.

Despite the growing enthusiasm surrounding additive manufacturing, several practical challenges remain regarding its implementation among local SMEs (Chi dkk., 2025). Many entrepreneurs perceive 3D printing technology as expensive or technically complex, which discourages widespread adoption (Zolfagharian dkk., 2025). Limited empirical evidence regarding operational efficiency further contributes to uncertainty among potential users (Li dkk., 2025). Questions arise concerning whether the technology can genuinely deliver economic advantages when applied in small-scale production environments (J. Yang dkk., 2025). Energy consumption during printing processes often becomes a hidden cost that is not fully considered during technology adoption decisions.

Energy efficiency represents a central issue that influences the long-term sustainability of additive manufacturing for small businesses (Han dkk., 2025). Variations in machine specifications, printing materials, and operating parameters can significantly affect the amount of electricity consumed during production (Kelly dkk., 2025). In many cases, users lack clear guidelines regarding which machines or operational settings provide optimal efficiency for microenterprise applications (Dai dkk., 2025). Inadequate knowledge about energy performance may lead to inefficient usage patterns, increased production costs, and reduced competitiveness for small manufacturers attempting to integrate digital fabrication tools into their operations.

The relationship between additive manufacturing technology and poverty reduction remains insufficiently explored in empirical research (Lu dkk., 2025). Discussions about 3D printing frequently emphasize technological sophistication, rapid prototyping, and industrial innovation rather than its socioeconomic implications for marginalized communities (Weeks dkk., 2025). Limited research has examined whether energy-efficient additive manufacturing systems can realistically support income generation among local entrepreneurs (Jin dkk., 2025). This gap creates uncertainty regarding the actual contribution of digital fabrication technologies to poverty alleviation strategies within emerging digital economies.

This study aims to analyze the energy efficiency of 3D printing machines within the context of additive manufacturing applications for local micro, small, and medium enterprises (W. Yang dkk., 2025). The research seeks to evaluate the extent to which different printing configurations influence electricity consumption and operational costs during production processes (Branco dkk., 2025). Accurate measurement of energy usage provides valuable insights into the economic feasibility of additive manufacturing technology when implemented by resource-constrained entrepreneurs (Azher dkk., 2025). Understanding the efficiency characteristics of these machines can help determine whether digital fabrication tools are suitable for supporting sustainable small-scale production.

The research also aims to explore the potential role of energy-efficient additive manufacturing systems in strengthening the productivity of local SMEs (An dkk., 2025). Investigating how efficient technology adoption affects production capacity, cost structures, and product innovation contributes to a broader understanding of digital transformation at the grassroots economic level (Scheideler & Im, 2025). Empirical findings from this analysis may assist entrepreneurs, policymakers, and development institutions in designing strategies that encourage the adoption of efficient manufacturing technologies (Shin dkk., 2025). Such insights can contribute to improving the competitiveness of local enterprises within rapidly evolving digital markets.

Another objective of this research is to examine the broader socioeconomic implications of additive manufacturing adoption among community-based enterprises (Ejeromedoghene dkk., 2025). The analysis seeks to identify whether energy-efficient 3D printing technologies can create new opportunities for entrepreneurship, product development, and localized manufacturing ecosystems (S. dkk., 2025). Increased technological accessibility may enable microenterprises to participate in digital value chains and develop innovative products tailored to local market needs (Schossler dkk., 2025). Investigating these dynamics provides important evidence regarding the potential of digital manufacturing technologies to contribute to inclusive economic development and poverty alleviation initiatives.

Existing literature on additive manufacturing has predominantly focused on technological capabilities, material science innovations, and industrial-scale production applications (Subramani dkk., 2025). Numerous studies analyze mechanical performance, printing precision, and material optimization in order to enhance the functionality of 3D printing systems (Rojek dkk., 2025). Energy consumption has also been examined in certain technical contexts, particularly in relation to industrial manufacturing environments (Mikołajewska dkk., 2025). However, these studies rarely address the operational realities of small-scale enterprises that operate with limited financial and technical resources.

Research exploring the socioeconomic dimensions of additive manufacturing remains relatively limited (Aktepe & Ergün, 2025). Most investigations concentrate on technological efficiency rather than evaluating the potential impact of digital fabrication technologies on grassroots economic development (Pancholi dkk., 2025). Small and medium enterprises in developing regions face unique challenges, including restricted access to infrastructure, fluctuating electricity availability, and limited technical expertise (Wittek dkk., 2024). Empirical studies examining the interaction between energy efficiency and SME productivity within additive manufacturing contexts are still scarce, leaving significant knowledge gaps regarding the practical benefits of technology adoption for marginalized communities.

The intersection between additive manufacturing, energy efficiency, and poverty reduction has received minimal scholarly attention (Mao dkk., 2025). Few studies attempt to integrate engineering perspectives with socioeconomic analysis when assessing the implications of digital fabrication technologies (Z. Zhang dkk., 2025). A comprehensive evaluation that simultaneously examines machine energy performance, operational feasibility, and entrepreneurial outcomes is largely absent from current academic discourse (Nida dkk., 2025). Addressing this gap is essential for developing a more holistic understanding of how digital manufacturing technologies can contribute to inclusive economic transformation.

The present study introduces a multidisciplinary perspective that integrates technological analysis with socioeconomic evaluation in the context of additive manufacturing adoption among local SMEs (Kantaros dkk., 2025). Energy efficiency is examined not only as a technical parameter but also as an economic factor that influences the viability of digital manufacturing for small-scale entrepreneurs (Omigbodun & Oladapo, 2025). This approach expands the analytical framework commonly used in additive manufacturing research by incorporating considerations of local economic empowerment and poverty alleviation (Grira dkk., 2025). The study therefore bridges the gap between engineering research and development-oriented economic studies.

Another novel contribution lies in the empirical assessment of 3D printer energy consumption within microenterprise production environments (Wang dkk., 2025). Previous research often evaluates machine performance in controlled laboratory or industrial settings, which may not accurately reflect the operational conditions experienced by small entrepreneurs (C. Yang dkk., 2025). This study emphasizes real-world usage scenarios in which entrepreneurs must balance production efficiency with limited financial resources (Najeeb & Islam, 2025). Investigating energy consumption patterns under such conditions provides practical insights that can guide technology adoption strategies for grassroots enterprises.

The justification for conducting this research is grounded in the urgent need to identify sustainable technological solutions that support inclusive economic development (Elsayed dkk., 2025). Digital transformation continues to reshape global production systems, creating both opportunities and challenges for small-scale enterprises in developing economies. Efficient additive manufacturing technologies may enable local entrepreneurs to participate in emerging digital manufacturing ecosystems while minimizing operational costs. Evidence-based understanding of energy efficiency in 3D printing systems therefore becomes essential for designing policies, training programs, and technological interventions that empower SMEs and contribute to poverty reduction in the digital era.

RESEARCH METHODOLOGY

This study employs a quantitative research design supported by an experimental–analytical approach to evaluate the energy efficiency of 3D printing machines within additive manufacturing processes used by local micro, small, and medium enterprises (SMEs) (Y. Zhang dkk., 2025). The design focuses on measuring and comparing electrical energy consumption during the operation of selected 3D printers under controlled production conditions (Docherty dkk., 2025). Quantitative measurements enable the identification of efficiency patterns associated with different printing parameters such as printing duration, layer height, material type, and machine specifications (Zhu dkk., 2025). Empirical analysis provides an objective basis for determining whether additive manufacturing technology can operate efficiently enough to support sustainable small-scale production environments.

The research also integrates a descriptive analytical framework to interpret the relationship between energy consumption, production costs, and potential economic benefits for SMEs. Energy efficiency is treated as a measurable variable that directly influences operational expenses and technological feasibility for small enterprises. Analytical comparisons between printing conditions allow the study to identify operational configurations that produce optimal efficiency outcomes. Data obtained from energy consumption measurements are analyzed statistically in order to generate reliable indicators of machine performance.

The methodological design further incorporates an applied research orientation that seeks to generate practical recommendations for technology adoption among local entrepreneurs. Findings from the efficiency analysis are interpreted within the context of SME production environments and digital economic transformation. The research framework therefore bridges engineering-based efficiency evaluation with socioeconomic considerations relevant to local enterprise development. Such an integrated design enables the study to contribute both technical insights and policy-relevant implications regarding the role of additive manufacturing in supporting poverty alleviation strategies.

The population of this research consists of additive manufacturing systems and local SMEs that utilize or have the potential to utilize 3D printing technologies in small-scale production activities. The focus on SMEs reflects the strategic role these enterprises play in local economic development and poverty reduction initiatives. SMEs operating in creative industries, product prototyping, handicrafts, and customized manufacturing represent the most relevant sectors for the application of 3D printing technology. These enterprises typically rely on flexible production methods that can benefit from the design adaptability offered by additive manufacturing.

The sample of this study includes a selection of commercially available desktop 3D printers commonly used by small enterprises due to their affordability and accessibility. Sampling is conducted using a purposive sampling technique to ensure that selected machines represent the types of additive manufacturing technologies most frequently adopted by local entrepreneurs. Several printing units are chosen based on criteria such as printer type, printing material compatibility, power rating, and operational cost. The selected machines allow for comparative analysis of energy efficiency under different operational settings.

Sampling also involves the selection of representative production tasks that simulate typical manufacturing activities carried out by SMEs. These tasks include the printing of standardized test objects and simple commercial products that reflect realistic production scenarios. The use of standardized models ensures consistency across printing experiments while enabling reliable comparisons of energy consumption between machines and configurations. This sampling strategy ensures that research findings remain relevant to real-world SME production environments and provide meaningful insights for local technological adoption.

Data collection in this research utilizes several instruments designed to measure energy consumption and operational efficiency during the 3D printing process. A digital power meter functions as the primary instrument for recording electricity usage in real time during machine operation. The device measures voltage, current, and power consumption throughout the printing cycle, enabling precise calculation of total energy consumption for each production task. Continuous monitoring ensures accurate recording of fluctuations in electricity usage during different phases of the printing process.

Additional instruments include a computer-based monitoring system used to control printing parameters and document machine performance during experiments. The system records printing time, layer configuration, nozzle temperature, and printing speed, all of which may influence energy consumption. Recording these parameters allows researchers to examine how different operational settings affect the efficiency of additive manufacturing processes. Documentation software is also used to store experimental data and maintain consistent records of each printing session.

Structured observation sheets are employed to document operational conditions, machine stability, and production outcomes during the experiments. These sheets provide supplementary qualitative information that helps interpret variations in energy efficiency results. Instruments used in this research are calibrated and tested prior to data collection to ensure accuracy and reliability. Such instrumentation ensures that energy consumption measurements accurately reflect the operational characteristics of the tested machines.

The research procedure begins with the preparation phase, during which the selected 3D printing machines are installed and calibrated according to manufacturer specifications. Standardized digital models are prepared using computer-aided design (CAD) software to ensure uniformity in the objects printed during the experiment. Printing parameters such as layer height, infill density, and printing speed are predetermined to create consistent testing conditions across machines. Preliminary testing is conducted to verify the functionality of the power monitoring equipment and ensure that the data recording system operates correctly.

The experimental phase involves conducting a series of controlled printing sessions using the selected machines and standardized models. Each printing session is monitored using the digital power meter to record electricity consumption from the beginning to the completion of the printing process. Data regarding printing duration, energy consumption, and operational parameters are recorded systematically for each trial. Multiple repetitions of printing tasks are performed to increase the reliability and validity of the collected data.

The final phase involves data processing and analysis to determine the efficiency characteristics of each machine. Energy consumption values are calculated in relation to production output, enabling the identification of energy efficiency ratios for different printing configurations. Statistical analysis is conducted to compare the performance of the selected machines and determine which configurations provide the most efficient energy usage. Interpretation of results is carried out within the broader context of SME production environments in order to evaluate the feasibility of additive manufacturing technology as a tool for supporting local economic empowerment and poverty reduction in the digital era.

RESULT AND DISCUSSION

The quantitative data collected in this study describe the energy consumption of three desktop 3D printing machines commonly used by local SMEs. Measurements were conducted during standardized printing tasks using PLA material under controlled settings. Energy consumption, printing time, and electricity cost were recorded during each printing cycle. The observed data indicate variations in electricity usage among the tested machines despite operating under identical production parameters. These variations suggest that machine design, heating mechanisms, and operational efficiency significantly influence the energy demand of additive manufacturing processes.

Table 1 presents the descriptive statistics of energy consumption and printing time across the selected machines. The data illustrate the mean energy usage, standard deviation, and estimated electricity cost for each machine during the production of standardized objects. Variability in energy consumption becomes visible across machines, demonstrating that not all additive manufacturing systems operate with the same efficiency level in SME-scale production environments.

Table 1. Descriptive Statistics of Energy Consumption in 3D Printing Experiments

Machine Type	Average Energy Consumption (kWh)	Printing Time (minutes)
Printer A	0.62	85
Printer B	0.54	80
Printer C	0.71	92

Energy consumption differences across the machines demonstrate that additive manufacturing efficiency varies according to machine configuration and operational design. Printer B shows the lowest average electricity consumption among the tested machines, indicating a higher level of energy efficiency during the printing process. Printer C displays the highest energy usage due to longer printing duration and higher heating requirements, suggesting that machine architecture significantly influences overall efficiency.

The cost implications of these energy differences are particularly relevant for SMEs operating with limited production budgets. Even small variations in electricity consumption may accumulate over multiple production cycles, increasing operational expenses. Efficient machines can therefore reduce production costs and improve the economic feasibility of adopting additive manufacturing technologies in small-scale enterprises.

Additional descriptive analysis examines the relationship between printing parameters and energy consumption. Printing speed, nozzle temperature, and infill density were monitored to determine their influence on electricity usage during production. Observed data indicate that higher nozzle temperatures and increased infill density tend to raise the overall energy demand of the printing process. Machines operating under higher thermal loads require more electrical power to maintain consistent extrusion performance.

Table 2 illustrates the influence of printing parameters on energy consumption during experimental production. Differences in energy usage across parameter configurations demonstrate that operational settings can significantly affect machine efficiency. Adjusting these parameters may therefore serve as an effective strategy for reducing electricity consumption in SME production contexts.

Table 2. Influence of Printing Parameters on Energy Consumption

Parameter Configuration	Average Energy Consumption (kWh)	Printing Time (minutes)
Low Infill (20%)	0.50	70
Medium Infill (40%)	0.63	85
High Infill (60%)	0.78	102

Inferential statistical analysis was conducted using analysis of variance (ANOVA) to determine whether differences in energy consumption among the tested machines were statistically significant. Results indicate a statistically significant difference in energy usage across the three machine types ($p < 0.05$). These findings suggest that machine design plays a measurable role in determining the efficiency of additive manufacturing systems used in SME production environments.

Post-hoc comparisons further reveal that Printer B performs significantly more efficiently than Printer C in terms of electricity consumption during standardized production tasks. The difference between Printer A and Printer B appears smaller but remains observable in operational performance. Statistical results therefore confirm that energy efficiency differences among machines are not random but reflect underlying variations in machine design and operational characteristics.

Correlation analysis was conducted to examine the relationship between printing time and energy consumption. Statistical results indicate a strong positive correlation ($r = 0.82$) between printing duration and electricity usage. Longer printing processes tend to require greater electrical energy due to prolonged operation of heating elements, motors, and control systems. Energy efficiency therefore depends not only on machine design but also on the duration of production activities.

Another important relationship emerges between parameter configuration and production efficiency. Lower infill density significantly reduces printing time and electricity consumption without drastically affecting structural quality for certain product types. SMEs producing decorative objects, prototypes, or lightweight components may therefore benefit from optimizing printing parameters to minimize operational costs while maintaining acceptable product functionality.

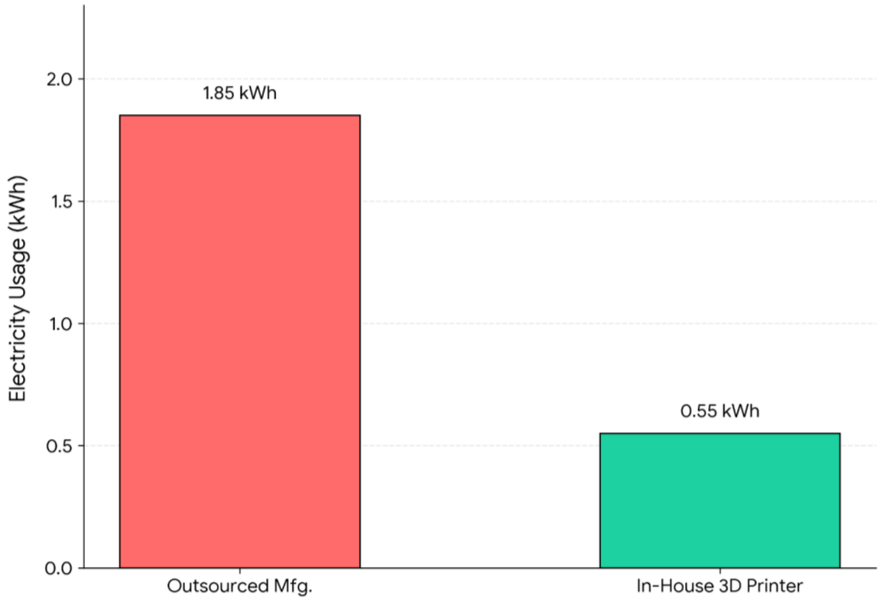

Figure 1. Energy Consumption Comparison: SME Case Study

A case study was conducted with a local SME that adopted 3D printing technology to produce customized accessories and small consumer products. The enterprise previously relied on outsourced manufacturing processes, which resulted in higher production costs and longer lead times. Adoption of a desktop 3D printer allowed the business to conduct in-house prototyping and small-batch manufacturing. Energy consumption data collected during daily production operations indicate an average electricity usage of approximately 0.55 kWh per printing cycle.

Production output within the enterprise increased significantly after the adoption of additive manufacturing technology. The SME reported the ability to produce small customized products within shorter development cycles compared to traditional manufacturing methods. Reduced reliance on external suppliers enabled greater flexibility in responding to market demand and developing new product designs tailored to local consumers.

Operational efficiency observed in the case study demonstrates the practical advantages of energy-efficient additive manufacturing systems for small enterprises. Lower electricity consumption combined with flexible production capabilities enables SMEs to maintain cost-effective operations while expanding product offerings. Efficient machines reduce operational expenses and allow businesses to allocate financial resources toward innovation and product development.

The SME also reported improved production autonomy after integrating additive manufacturing technology into its workflow. Shorter product development cycles enabled rapid prototyping and design experimentation, which improved the enterprise's competitiveness within local markets. Energy-efficient machines therefore contribute not only to cost reduction but also to the broader capacity of SMEs to innovate and diversify their products.

Findings from the statistical and case study analyses indicate that energy efficiency plays a critical role in determining the feasibility of additive manufacturing technologies for SME adoption. Machines with lower electricity consumption provide measurable advantages in operational cost reduction and production sustainability. Efficient printing parameters further enhance machine performance and allow entrepreneurs to optimize production processes according to their specific economic conditions.

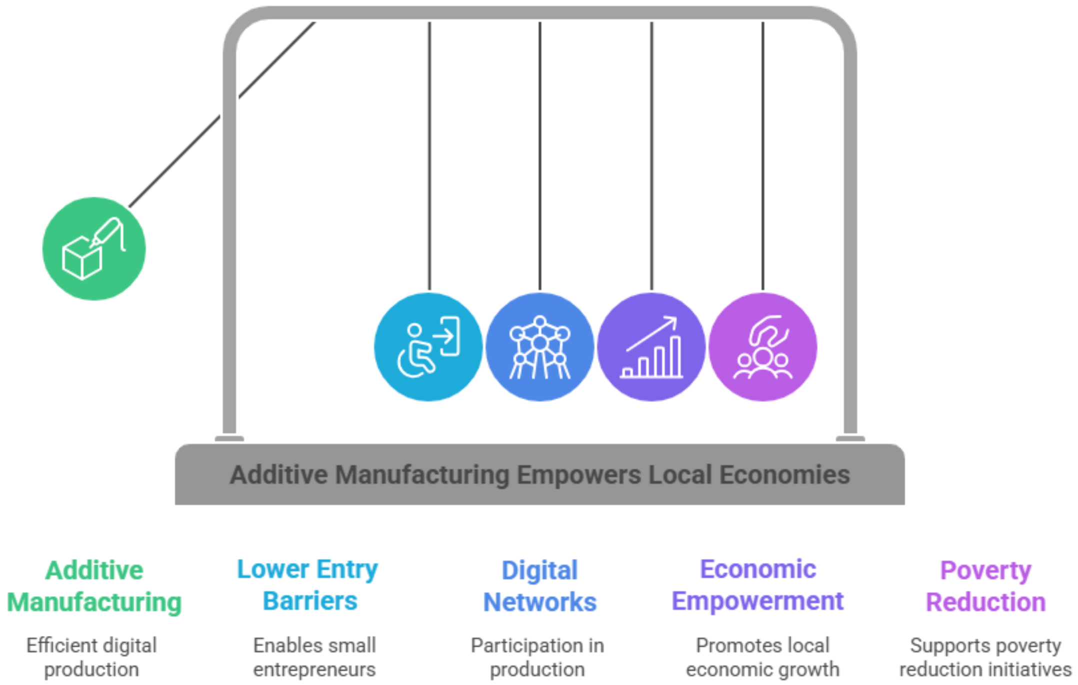

Figure 2. Additive Manufacturing Empowers Local Economies

The results also highlight the broader socioeconomic implications of additive manufacturing adoption in local enterprise ecosystems. Energy-efficient digital manufacturing technologies can lower entry barriers for small entrepreneurs and enable participation in emerging digital production networks. The integration of efficient 3D printing systems within SME production environments therefore represents a promising pathway for promoting local economic empowerment and supporting poverty reduction initiatives in the digital era.

The findings of this study demonstrate that the energy efficiency of desktop 3D printing machines varies significantly depending on machine configuration, operational parameters, and printing duration. Empirical measurements show that certain machines consume less electricity during standardized printing tasks, indicating that machine design plays a critical role in determining operational efficiency. Energy-efficient printers require lower electrical input to maintain heating stability, extrusion consistency, and motion control during the additive manufacturing process. Such efficiency becomes particularly relevant in the context of small and medium enterprises (SMEs) where operational cost reduction is essential for sustainable production.

Quantitative analysis further reveals that printing parameters such as infill density, printing speed, and nozzle temperature strongly influence electricity consumption. Lower infill densities and optimized temperature settings reduce printing time and energy demand without significantly compromising structural integrity for certain product categories. Efficient parameter configurations therefore represent a practical strategy for SMEs seeking to reduce electricity costs during additive manufacturing operations. Energy optimization becomes an operational variable that can be adjusted by entrepreneurs without requiring substantial additional investment.

Statistical results also indicate a strong correlation between printing duration and total energy consumption. Machines operating for longer production cycles require sustained heating and motor activity, leading to higher electricity usage. Shorter printing cycles reduce energy demand and enhance overall efficiency. These findings suggest that production planning and design optimization are essential components of energy-efficient additive manufacturing practices in SME environments.

Case study observations from a local SME adopting 3D printing technology reinforce these quantitative results. The enterprise experienced reduced production costs and increased product development flexibility after integrating an energy-efficient printer into its workflow. Shorter prototyping cycles and lower electricity expenses allowed the business to experiment with new product designs and respond more quickly to customer demand. Such practical outcomes demonstrate how technological efficiency can translate into tangible economic benefits for small-scale entrepreneurs.

Previous research on additive manufacturing has primarily focused on industrial-scale production environments and technical performance improvements. Studies conducted by researchers in manufacturing engineering often emphasize mechanical precision, material performance, and structural optimization in 3D printing systems. Energy consumption is sometimes addressed in relation to industrial production lines where machines operate continuously under controlled factory conditions. Comparisons with the present study highlight an important distinction because this research focuses specifically on SME-scale production environments where operational constraints differ significantly from industrial settings.

Research conducted in the field of sustainable manufacturing has identified energy consumption as an important factor in evaluating the environmental impact of additive manufacturing technologies. Several studies have suggested that 3D printing can reduce material waste compared to subtractive manufacturing processes. However, these studies rarely examine the electricity consumption of machines when used by small enterprises operating under limited infrastructure conditions. The present findings contribute additional empirical evidence by examining how machine efficiency affects operational feasibility for grassroots entrepreneurs.

Other studies examining digital manufacturing in emerging economies emphasize the role of technological accessibility and knowledge transfer in supporting local innovation ecosystems. Such research often discusses the potential of digital fabrication laboratories and maker spaces to stimulate entrepreneurship and community innovation. Differences emerge when comparing these perspectives with the current study because energy efficiency is introduced as an additional dimension influencing technological adoption. Efficient machines not only enable technological experimentation but also reduce operational barriers for small enterprises.

Comparative analysis with prior research also reveals that discussions about additive manufacturing frequently overlook socioeconomic implications related to poverty alleviation. Existing literature tends to frame 3D printing primarily as an industrial innovation rather than a tool for inclusive economic development. Findings from the present study suggest that energy-efficient additive manufacturing technologies may support local economic empowerment by lowering production costs and enabling micro-scale manufacturing activities. Such insights extend the scope of additive manufacturing research beyond purely technological considerations.

The findings indicate that technological efficiency represents a critical determinant in the successful adoption of digital manufacturing technologies among local SMEs. Energy consumption is not merely a technical characteristic of a machine but also an economic variable that influences production sustainability. Efficient machines enable entrepreneurs to maintain lower operational expenses, thereby increasing the financial feasibility of adopting additive manufacturing technologies in small-scale production environments.

Results also indicate that digital manufacturing technologies can function as tools for economic empowerment when integrated into local enterprise ecosystems. SMEs often face structural barriers such as limited capital, restricted access to advanced manufacturing infrastructure, and dependence on external suppliers. Energy-efficient 3D printing systems provide an alternative production model that enables small entrepreneurs to create customized products and prototypes without relying on large-scale manufacturing facilities.

Observations from the case study indicate that additive manufacturing technology can enhance entrepreneurial creativity and product diversification. Entrepreneurs using energy-efficient machines are able to experiment with design variations and respond quickly to consumer preferences. Rapid prototyping capabilities allow SMEs to reduce product development cycles and explore niche market opportunities. Such flexibility can strengthen the competitive position of local enterprises within increasingly digitalized markets.

The findings also signal broader shifts in the relationship between digital technology and local economic development. Digital fabrication tools such as 3D printers reduce the scale of infrastructure required for manufacturing activities. Small enterprises can therefore participate in production networks that were previously accessible only to larger firms. Efficient technological adoption may gradually reshape the structure of local economies by enabling decentralized and flexible manufacturing systems.

The implications of these findings extend to several domains, including technological policy, SME development strategies, and sustainable manufacturing practices. Policymakers interested in promoting digital economic transformation should consider energy efficiency as a key criterion when supporting technology adoption programs for SMEs. Government initiatives that encourage the use of efficient additive manufacturing technologies may help reduce operational barriers for small enterprises and stimulate local innovation ecosystems.

Implications also arise for entrepreneurship development programs aimed at strengthening the capacity of local SMEs. Training initiatives that focus on energy-efficient machine operation, parameter optimization, and digital product design can improve the technological literacy of entrepreneurs. Such programs may increase the ability of SMEs to adopt additive manufacturing technologies effectively and integrate them into sustainable business models.

Environmental sustainability also emerges as an important implication of the findings. Efficient additive manufacturing processes reduce electricity consumption and contribute to more sustainable production systems. SMEs adopting energy-efficient technologies can reduce their environmental footprint while maintaining productive economic activities. Sustainable production practices align with broader global efforts to promote environmentally responsible technological innovation.

Implications for poverty alleviation strategies are particularly significant in developing economies. Energy-efficient digital manufacturing technologies can create new economic opportunities for communities with limited access to traditional industrial infrastructure. Small entrepreneurs can produce customized goods, develop local brands, and participate in digital marketplaces. Such technological empowerment may contribute to reducing economic inequality and expanding local income-generating opportunities.

Energy consumption differences observed among the tested machines can be explained by variations in machine architecture and heating mechanisms. Certain printers utilize more efficient thermal systems that maintain stable temperatures with lower electrical input. Improved motion control and optimized hardware components reduce unnecessary energy expenditure during printing operations. Machine engineering therefore directly influences the efficiency characteristics observed in the experimental results.

Operational parameters also play a critical role in determining electricity consumption during additive manufacturing processes. Higher nozzle temperatures and denser infill structures require longer printing times and sustained heating activity. These operational conditions increase the energy demand of the printing process. Parameter optimization therefore becomes an essential strategy for balancing product quality with energy efficiency in SME production environments.

Economic conditions faced by SMEs also help explain the importance of energy efficiency in this context. Small enterprises typically operate with limited financial resources and must carefully manage production costs. Electricity expenses represent a recurring operational cost that directly affects profit margins. Energy-efficient machines provide an economic advantage because they reduce ongoing production expenditures without requiring major structural changes in the enterprise.

Technological accessibility further explains why additive manufacturing can influence SME development outcomes. Desktop 3D printers have become increasingly affordable and user-friendly, enabling small entrepreneurs to adopt digital manufacturing technologies without extensive technical training. Energy-efficient models lower operational barriers and make the technology more practical for small-scale production activities. Such accessibility supports the integration of digital manufacturing into local entrepreneurial ecosystems.

Future research should explore broader dimensions of additive manufacturing adoption in SME environments by integrating technical, economic, and social perspectives. Investigations involving larger samples of 3D printing machines and diverse SME sectors would provide more comprehensive insights into energy efficiency patterns (Yuan dkk., 2025). Comparative studies across different regions could also reveal how local infrastructure conditions influence the feasibility of digital manufacturing technologies.

Technological development initiatives should focus on designing additive manufacturing machines specifically optimized for small enterprise applications (Tang dkk., 2025). Energy-efficient hardware components, intelligent power management systems, and simplified operational interfaces may enhance the usability of 3D printing technologies for entrepreneurs (Yuan dkk., 2025). Collaboration between engineers, policymakers, and SME development organizations could accelerate the creation of such technologies.

Entrepreneurship support programs should incorporate digital manufacturing training as part of broader capacity-building initiatives. Educational workshops focusing on digital design, additive manufacturing techniques, and energy-efficient production practices may empower local entrepreneurs to adopt advanced technologies confidently. Skills development programs could also encourage innovation and product diversification within SME communities.

Long-term strategies should examine the integration of additive manufacturing within local digital economies. SMEs equipped with efficient 3D printing technologies may participate in decentralized production networks and online marketplaces. Future development policies should therefore consider digital manufacturing as a component of inclusive economic transformation strategies aimed at strengthening local entrepreneurship and reducing poverty in the digital era.

CONCLUSION

The findings of this study reveal that the energy efficiency of 3D printing machines significantly influences the feasibility of additive manufacturing adoption among local small and medium enterprises (SMEs). Empirical measurements demonstrate that variations in machine configuration, printing parameters, and production duration lead to substantial differences in electricity consumption during the printing process. Machines with optimized energy performance enable SMEs to reduce operational costs while maintaining flexible and responsive production systems. Evidence from the case study further indicates that energy-efficient additive manufacturing technologies support faster prototyping, product customization, and reduced dependence on external manufacturing services. These results highlight that energy efficiency is not merely a technical parameter but a strategic factor that determines whether digital manufacturing technologies can realistically contribute to economic empowerment and poverty reduction within local entrepreneurial ecosystems.

The primary contribution of this research lies in the integration of technological efficiency analysis with socioeconomic perspectives on SME development and poverty alleviation. The study introduces an analytical framework that evaluates additive manufacturing not only through engineering performance metrics but also through its potential economic implications for grassroots enterprises. Empirical assessment of electricity consumption within SME-scale production environments provides practical insights that extend beyond laboratory-based technical evaluations commonly found in additive manufacturing research. The conceptual contribution emphasizes energy efficiency as a bridge between technological innovation and inclusive economic development. Methodologically, the research combines experimental energy measurement with contextual SME analysis, offering a multidimensional approach for evaluating the real-world feasibility of digital manufacturing technologies in emerging digital economies.

Several limitations should be acknowledged when interpreting the results of this study. The experimental analysis focuses on a limited number of desktop 3D printing machines and standardized production tasks, which may not fully represent the diversity of additive manufacturing technologies or SME production scenarios. Variations in materials, machine models, and operational environments may produce different efficiency outcomes. The case study component is also limited to a single SME context, which restricts the generalizability of socioeconomic interpretations. Future research should expand the scope of investigation by including a larger range of additive manufacturing technologies, broader SME sectors, and diverse geographic contexts. Longitudinal studies examining the long-term economic impact of additive manufacturing adoption among SMEs would provide deeper insights into how energy-efficient digital manufacturing technologies can contribute to sustainable entrepreneurship and poverty reduction in the digital era.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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