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Revitalizing Local Manufacturing through Sustainable Energy Solutions

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Abstract: Local manufacturing in developing and emerging economies faces persistent challenges due to high energy costs, unreliable electricity supply, and dependence on fossil fuel–based systems, which undermine productivity, competitiveness and industrial growth. This study investigates the role of sustainable energy solutions in revitalizing local manufacturing by integrating renewable energy technologies, hybrid and distributed generation, energy efficiency measures and digital energy management systems. A comprehensive review of smart manufacturing practices, retrofitting strategies and policy frameworks was conducted to assess their impact on operational efficiency, cost reduction and environmental performance. Evidence-based analysis indicates that sustainable energy adoption enhances industrial resilience, reduces greenhouse gas emissions, stabilizes energy supply, and improves manufacturing competitiveness, particularly for small- and medium-scale enterprises. Policy and institutional support, including regulatory incentives, public–private partnerships and innovative financing models, is critical for facilitating large-scale adoption. The study concludes that sustainable energy solutions provide a practical and strategic pathway for industrial revitalization while contributing to broader Sustainable Development Goals, including affordable and clean energy (SDG 7), industry innovation (SDG 9) and climate action (SDG 13). Future research should focus on empirical implementation studies, region-specific energy integration models and quantitative evaluation of socio-economic and environmental outcomes to guide scalable adoption in energy-constrained manufacturing ecosystems.

Key words: Industrial Revitalizing, Local Manufacturing, Sustainable Energy and Hybrid Energy Systems

INTRODUCTION

Local manufacturing is a cornerstone of economic development, providing employment opportunities, technological advancement and industrial diversification, particularly in developing and emerging economies. Despite its importance, many local manufacturing systems have experienced a marked decline over recent decades, largely due to high energy costs, unreliable electricity supply and a persistent reliance on fossil fuel–based energy infrastructures. These challenges have constrained industrial output, weakened competitiveness and limited both domestic and foreign investment in manufacturing enterprises (Aghion et al., 2016; World Bank, 2023). Energy-intensive sectors including

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metals, cement, agro-processing and textiles are especially vulnerable, as energy expenditures constitute a significant portion of operational costs. Frequent grid disruptions, dependency on diesel generators, and fluctuating fuel prices exacerbate production inefficiencies while contributing to environmental degradation (IEA, 2022; UNIDO, 2023). Consequently, current energy practices pose both economic and environmental risks to local manufacturing systems.

Even as global momentum toward clean energy grows, many manufacturing sectors continue to rely on inefficient, carbon-intensive energy sources. High electricity tariffs, inconsistent grid performance, and widespread fossil fuel self-generation elevate production costs and reduce capacity utilization, particularly for small- and medium-scale enterprises (Eberhard et al., 2018; Steinbuks & Foster, 2019). Such energy insecurity undermines the competitiveness of locally produced goods and exposes manufacturers to price shocks, regulatory pressures, and sustainability compliance risks (OECD, 2022; IEA, 2023).

Empirical research consistently identifies unreliable power supply and high energy costs as major constraints on manufacturing productivity, with energy expenditures often accounting for 30–40% of total operational costs in small- and medium-scale manufacturing (Adegboye et al., 2020; UNIDO, 2023). In response, sustainable energy solutions including solar photovoltaics, biomass systems, hybrid microgrids and energy efficiency interventions such as waste heat recovery and high-efficiency motors have emerged as critical enablers of industrial performance. These technologies enhance supply reliability, reduce dependence on fossil fuels and improve energy security, while also lowering operational costs and environmental impacts (IRENA, 2022; Backlund et al., 2012; IEA, 2024). However, most existing studies focus on large-scale industrialized economies, leaving localized manufacturing systems in developing regions underexplored.

The conceptual foundation of this study combines Sustainable Development Theory, which emphasizes balancing economic growth, environmental protection, and social equity (Sachs, 2015), with the Industrial Energy Transition Framework, which describes how manufacturing systems shift from fossil fuel dependence to cleaner, more efficient energy configurations through technological innovation, policy support and market adaptation (Geels et al., 2017; Köhler et al., 2019). These frameworks provide a robust basis for understanding how sustainable energy adoption can drive local manufacturing revitalization and long-term industrial resilience.

Despite the growing body of research on industrial sustainability, notable gaps remain. Few studies establish a direct, systematic link between sustainable energy adoption and local manufacturing revitalization. Small- and medium-scale enterprises, which face distinct financial, technical, and infrastructural challenges, are underrepresented. Existing research also often examines energy, economic, and environmental dimensions in isolation, rather than through an integrated framework capable of informing practical industrial transformation. Context-specific policy and implementation models suitable for developing economies are particularly scarce (IRENA, 2022; UNIDO, 2023).

This study addresses these gaps by proposing an integrated, context-sensitive approach that positions sustainable energy as a central driver of manufacturing recovery. By synthesizing economic, environmental, and energy perspectives within a unified framework, the study provides actionable insights for decentralized and hybrid energy systems, and aligns clean energy deployment with industrial development strategies. Its practical relevance is particularly significant for small- and medium-scale manufacturers operating under persistent energy constraints, offering pathways to enhance competitiveness, resilience, and environmental performance.

In conclusion, the decline of local manufacturing due to high energy costs, unreliable power supply, and fossil fuel dependence represents a critical economic and environmental challenge. This study demonstrates that sustainable energy solutions provide a strategic pathway for revitalizing local manufacturing by stabilizing energy supply, reducing operational costs, and mitigating environmental impacts. Coordinated energy-industrial policies that facilitate clean energy adoption are therefore essential. Revitalizing local manufacturing through sustainable energy solutions is not only an environmental necessity but also a strategic economic opportunity for fostering resilient, competitive and sustainable industrial development in the context of global energy and climate transitions.

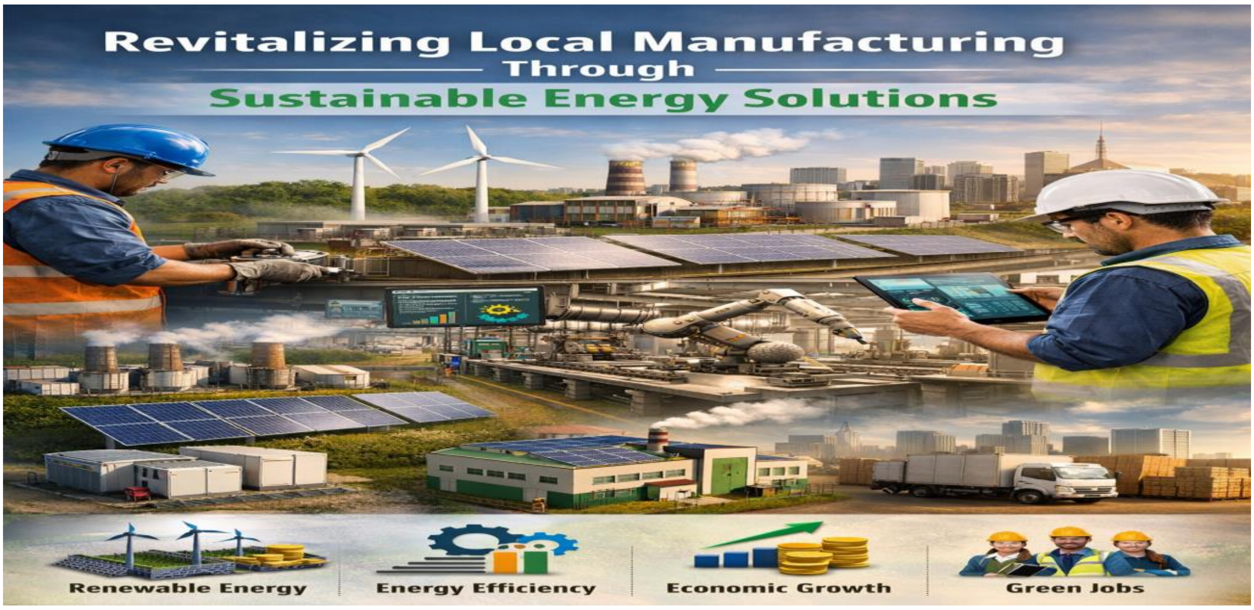

Figure 1: Visual abstract showing the revitalizing local manufacturing- through sustainable energy solutions

Problem Statement

Local manufacturing in developing economies faces critical structural challenges driven by unreliable, high-cost, and carbon-intensive energy systems, which undermine productivity, competitiveness and growth potential. In Nigeria, frequent grid outages have forced over 60% of manufacturers to rely on costly self-generated power, raising production costs, reducing profit margins and discouraging reinvestment in domestic manufacturing capacity (AllAfrica, 2024; MAN Economic Review, 2024). In 2024 alone, industrial energy expenditures exceeded N1.1 trillion, reflecting escalating financial pressures from grid instability and rising diesel and petrol prices (Tribune Online, 2024; Guardian Nigeria, 2024). These energy constraints coincide with declining investment, lower employment, and reduced industrial output, signaling broader sectoral stagnation.

Beyond financial impacts, energy insecurity lowers capacity utilization, causes production delays, elevates unit costs and weakens export competitiveness, particularly for small- and medium-scale enterprises (Independent Nigeria, 2024). Persistent reliance on fossil fuel–based self-generation also contributes to greenhouse gas emissions, air pollution, and resource depletion, while exposing firms to regulatory pressures and sustainability-linked financial risks.

The central challenge, therefore, is the systemic lack of integrated, sustainable energy pathways capable of stabilizing supply, reducing costs, mitigating environmental impacts, and enhancing industrial resilience. Despite global progress in renewable energy, many manufacturers remain locked into high-carbon energy regimes due to policy gaps, infrastructure deficits, and limited access to affordable clean technologies (International Energy Agency [IEA], 2023; United Nations Industrial Development Organization [UNIDO], 2022). This study investigates how sustainable energy solutions can strategically revitalize local manufacturing, strengthen resilience, and support long-term socio-economic transformation.

Industrial Revitalization

Industrial revitalization can be described as a purposeful set of policy, technological, and institutional interventions designed to rejuvenate weak or declining industrial sectors and reposition them for sustained economic performance. This process commonly focuses on modernizing production systems through advanced technologies, improving energy utilization, encouraging digital transformation and automation, reinforcing industrial linkages, and providing an enabling regulatory and policy environment (UNIDO, 2020). In developing and transitional economies, efforts toward industrial revitalization are strongly associated with expanded access to reliable energy, improved infrastructure, targeted workforce skill development and the strengthening of national and regional innovation ecosystems, particularly in response to the challenges of premature deindustrialization and shrinking manufacturing capacity (Rodrik, 2016). More recently, the concept has evolved to incorporate sustainability objectives, with greater emphasis on low-carbon production methods, the deployment of renewable and clean energy solutions and environmentally responsible manufacturing practices to align industrial growth with climate action and sustainable development targets (UNIDO, 2020). Ultimately, industrial revitalization seeks to raise productivity and operational efficiency, lower production and energy costs, improve competitiveness in domestic and international markets and create employment opportunities that support inclusive and resilient economic growth (Rodrik, 2016)

Local Manufacturing

Local manufacturing can be understood as the localized production of goods within a specific region or national boundary, largely intended to satisfy nearby market demand rather than distant export markets. This approach prioritizes the use of indigenous raw materials, local labor, technical expertise and complementary industries, thereby minimizing reliance on imported products and strengthening economic independence. By anchoring production closer to consumption, local manufacturing enhances domestic value chains, reduces transportation and logistics burdens, improves supply reliability, and creates favorable conditions for the expansion of small and medium-sized enterprises. The integration of advanced manufacturing technologies and sustainable energy solutions further improves the adaptability, efficiency and environmental performance of local production systems. Overall, local manufacturing supports employment generation, workforce capacity building, reduced import exposure, and more robust regional supply networks, contributing to balanced, inclusive and sustainable industrial development (Kaldor, 1967; OECD, 2019).

Sustainable Energy

Sustainable energy describes an approach to energy production and uses that satisfies current societal and economic demands while safeguarding the capacity of future generations to access reliable energy resources, a concept grounded in the broader framework of sustainable development (United Nations, 1987). It encompasses energy systems with minimal environmental impact, dependable long-term availability, and sound economic performance, drawing largely from renewable sources such as solar, wind, hydropower, biomass and geothermal energy, as well as from enhanced energy efficiency and conservation practices (IEA, 2021). Within industrial and manufacturing settings, the transition to sustainable energy is increasingly important for lowering greenhouse gas emissions, reducing long-term operating and energy expenditures and strengthening energy security and system reliability. In addition, the use of sustainable energy enables industries to meet environmental regulations and global climate obligations while improving operational efficiency, minimizing waste, protecting ecosystems, and delivering lasting economic and social benefits that reinforce industrial competitiveness (IEA, 2021).

Hybrid Energy Systems

Hybrid energy systems are energy supply configurations that integrate two or more energy sources typically combining renewable energy technologies with conventional generation units or energy storage systems to provide reliable, efficient and continuous power supply, with common configurations including solar–diesel, solar–wind, solar–battery and wind–battery systems (Chauhan & Saini, 2014). In industrial and manufacturing applications, hybrid energy systems address the inherent intermittency of renewable energy by balancing supply and demand, improving power reliability and quality, and reducing dependence on fossil fuels, making them particularly valuable in regions with unstable or unreliable grid infrastructure such as rural or developing industrial zones (Lund et al., 2015). Through enhanced integration of renewable energy, reduced fuel consumption and greenhouse gas emissions, and lower long-term energy costs, hybrid energy systems support sustainable industrial operations while strengthening energy security and operational resilience (Chauhan & Saini, 2014; Lund et al., 2015).

SUSTAINABLE ENERGY PATHWAYS FOR MANUFACTURING

Adopting sustainable energy is crucial for enhancing the competitiveness, resilience, and environmental performance of manufacturing systems. Rising energy costs, unreliable supply and stricter climate regulations make the transition to cleaner, efficient energy essential. Integrating renewable technologies, hybrid and distributed systems, and energy efficiency measures reduces fossil fuel dependence while maintaining productivity (IEA, 2023; UNIDO, 2023).

Renewable Energy Integration

However, according to the IRENA, (2022); IEA, (2023)., stated that the manufacturers are increasingly adopting solar PV, wind, biomass, and bioenergy to decarbonize operations and improve energy security. Solar PV offers modular, cost-effective on-site generation, reducing grid reliance and stabilizing energy expenses. Wind energy benefits energy-intensive clusters and biomass systems convert agricultural residues and process waste into thermal and electrical energy, particularly in agro-processing and pulp-and-paper industries (UNIDO, 2023; OECD, 2022). Together, these solutions lower emissions, hedge against fuel price volatility, and align operations with global sustainability standards

Figure 1: Solar integration in building

The diagram illustrates in figure 1 on**-site renewable energy systems** by placing *On-Site Renewable Energy* at the center, showing it as the core of decentralized and sustainable power generation for buildings or industrial facilities. Surrounding the central hub are eight renewable energy options, each connected to emphasize direct integration at the point of use rather than reliance on centralized grids

Energy Efficiency and Demand-Side Management

Energy efficiency measures such as high-performance motors, variable-speed drives, waste heat recovery, and process optimization offer substantial cost savings and rapid payback (IEA, 2022; Backlund et al., 2012). Demand-side management, supported by IoT sensors, smart meters and AI analytics, enables real-time monitoring, load shifting, predictive maintenance and adaptive scheduling, further lowering costs and complementing renewable integration (Zhang et al., 2023; UNIDO, 2023).

SMART MANUFACTURING, DIGITAL INTEGRATION, AND RETROFITTING

Smart manufacturing transforms traditional production into interconnected, adaptive and energy-aware systems. Using automation, advanced sensors, cyber-physical systems and real-time analytics, manufacturers can optimize energy use and production processes. Technologies such as high-performance electric drives, automated process optimization, additive manufacturing and advanced material processing reduce energy intensity by 10–30% across industries, while dynamic adjustments to energy availability improve cost-efficiency and grid stability (Kusiak, 2018; IEA, 2022; UNIDO, 2023). According to Xu et al., (2021); Zhang et al., (2023), stated that the digital tools, including IoT, AI and advanced energy management systems, provide real-time monitoring and analytics, enabling predictive maintenance, process optimization and energy scheduling. These technologies enhance reliability, reduce energy waste, and strengthen economic and environmental performance

Given that most industrial infrastructure consists of legacy plants, retrofitting with renewable energy, storage systems, high-efficiency equipment and intelligent controls is vital. Targeted retrofits such as motor upgrades, waste heat recovery and rooftop solar installations can lower energy intensity and emissions cost-effectively without disrupting operations. This approach is particularly suited for small- and medium-scale manufacturers, enabling incremental adoption of sustainable energy while maintaining competitiveness (OECD, 2022; IEA, 2023; UNIDO, 2023).

Economic and Socio-Industrial Impacts

Integrating sustainable energy in manufacturing delivers significant economic and socio-industrial benefits, particularly in developing economies constrained by unreliable energy. By lowering costs, improving efficiency and enhancing resilience, clean energy adoption revitalizes local industries and strengthens economic systems (IEA, 2023; UNIDO, 2023).

Energy-intensive manufacturers can reduce operating costs by 20–40% through on-site renewable energy, efficiency upgrades and digital energy management, boosting profitability and enabling reinvestment (IRENA, 2022; IEA, 2024). Beyond savings, reliable energy supply minimizes downtime, increases capacity utilization, ensures consistent product quality and supports compliance with international energy and environmental standards, collectively enhancing industrial competitiveness (OECD, 2022; UNIDO, 2023).

Employment, Energy Security, and Policy Impacts

Deploying sustainable energy in manufacturing creates jobs across renewable energy, engineering, digital systems, and supply chains, while promoting workforce upskilling in energy management, automation, and data analytics (IRENA, 2023; UNIDO, 2023). Accordingly, World Bank, (2024), stated that using local energy resources also strengthens domestic value chains, reduces import reliance, and enhances industrial–agricultural–energy linkages

Clean energy integration improves energy security by diversifying sources and reducing dependence on imported fuels. Hybrid and decentralized systems enhance resilience to grid failures and price volatility, supporting stable operations, long-term investment and industrial growth (IEA, 2023). Environmentally, it lowers emissions, pollution, and resource intensity, aligning with climate targets, net-zero commitments, and circular economy strategies (OECD, 2022; IEA, 2024).

Effective adoption relies on supportive policies, strong institutions, and accessible financing. Government incentives, clear regulations, renewable targets, and fiscal measures combined with PPPs, green bonds, and performance-based financing facilitate technology deployment, particularly for small- and medium-scale manufacturers (IEA, 2023; UNIDO, 2023; World Bank, 2022; IRENA, 2023).

Barriers include weak infrastructure, regulatory gaps, limited technical capacity, and high upfront costs. Addressing these requires integrated approaches: capacity building, financial support, institutional strengthening, knowledge transfer and adaptive, context-specific policies to ensure scalable, resilient, and equitable industrial energy transitions (UNIDO, 2023; OECD, 2022; IEA, 2024; World Bank, 2023).

Figure 3: Presents a systems-level view of how sustainable energy deployment in manufacturing influences employment, energy security, and policy outcomes

The diagram figure 2 presents a systems-level view of how sustainable energy deployment in manufacturing influences employment, energy security, and policy outcomes, while also highlighting adoption barriers. At the center, Energy Security & Sustainability represents the primary outcome of integrating clean and decentralized energy into industrial systems. It connects cyclically to three reinforcing pillars, showing mutual dependence and feedback.

FUNDAMENTAL CONTRIBUTIONS AND NOVELTY

This study advances sustainable industrial development by positioning sustainable energy as a key driver for revitalizing local manufacturing. Its novelty lies in moving beyond descriptive analyses to provide actionable, evidence-based insights linking energy transitions with productivity, industrial resilience and sustainable development. By integrating technological, economic and policy dimensions, it addresses literature gaps and offers practical guidance for implementation.

Practical Roadmap for Sustainable Energy Integration

A major contribution is a context-specific roadmap for local manufacturing, detailing steps such as energy demand assessment, selection of renewable technologies, deployment of hybrid and distributed systems, adoption of energy efficiency and digital energy management tools and alignment with supportive policies and financing. Emphasizing gradual adoption, affordability and scalability, the roadmap provides a practical pathway for manufacturers, policymakers and planners, particularly benefiting small- and medium-scale enterprises.

Evidence-Based Evaluation of Energy Manufacturing Synergies

This study provides an evidence-driven analysis showing that reliable, affordable, and clean energy directly improves productivity, capacity utilization, operational costs, and competitiveness in local manufacturing (IEA, 2023; UNIDO, 2023). By linking energy, economic, and environmental metrics, it highlights feedback loops where sustainable energy enhances efficiency, reduces emissions and mitigates operational risks, offering a holistic understanding of energy–manufacturing interactions.

Relevance to Industrial Revitalization and SDGs

The framework supports industrial revitalization and the SDGs by promoting inclusive and sustainable industrialization (SDG 9), affordable and clean energy access (SDG 7), climate action (SDG 13), and responsible consumption and production (SDG 12). Sustainable energy thus functions as a strategic enabler of economic transformation, employment growth, and long-term industrial resilience (IEA, 2023; UNIDO, 2023).

Advantages of Revitalizing Local Manufacturing through Sustainable Energy Solutions

A compelling argument for integrating sustainable energy into local manufacturing lies in its ability to reduce long-term operational costs. Although initial investments may be high, renewable energy systems such as solar, biomass, and wind significantly lower recurring energy expenses, particularly in regions with unstable grid supply. This cost stability enhances the competitiveness of local industries.

Another critical benefit is energy security and reliability. In many developing economies, inconsistent power supply constrains manufacturing productivity. Decentralized renewable energy systems (e.g., solar mini-grids and hybrid energy systems) provide uninterrupted power, thereby improving production efficiency and reducing downtime.

Sustainable energy adoption also strengthens environmental compliance and global market access. With increasing international emphasis on carbon neutrality, manufacturers using clean energy are better positioned to meet export standards and participate in global value chains. This aligns with sustainability frameworks such as circular economy models and low-carbon industrialization.

Furthermore, the transition promotes technological innovation and job creation. The deployment and maintenance of renewable energy infrastructure stimulate local skill development, foster innovation ecosystems, and generate employment opportunities in green technology sectors.

Disadvantages of **Revitalizing Local Manufacturing through Sustainable Energy Solutions**

Despite these benefits, several challenges hinder widespread adoption. A major limitation is the high initial capital investment required for renewable energy technologies. Small and medium-scale enterprises (SMEs), which dominate local manufacturing, often lack access to affordable financing mechanisms.

Another significant concern is technical and infrastructural limitations. Renewable energy systems, particularly solar and wind, are inherently intermittent and require energy storage solutions, which further increase costs and complexity. Additionally, inadequate technical expertise for installation and maintenance can limit system efficiency.

Policy and regulatory barriers also pose challenges. In many regions, there is lack of coherent energy policies, incentives, and institutional support, which discourages private sector investment. Bureaucratic bottlenecks and unclear regulatory frameworks further delay project implementation.

Finally, there is the issue of limited awareness and resistance to change among local manufacturers. Many industry stakeholders are accustomed to conventional energy systems and may be reluctant to adopt new technologies due to perceived risks and uncertainty.

Way Forward Strategy to revitalize local manufacturing through sustainable energy solutions

To effectively revitalize local manufacturing through sustainable energy solutions, a multi-dimensional approach is required:

1. Financial Incentives and Investment Support: Governments and financial institutions should introduce subsidies, tax incentives, and low-interest green financing schemes targeted at SMEs. Public-private partnerships (PPPs) can also play a vital role in mobilizing capital for renewable energy projects.
2. Policy and Regulatory Framework Strengthening: There is a need for clear, stable, and supportive energy policies that encourage renewable energy adoption. This includes streamlined licensing processes, feed-in tariffs, and regulatory incentives for decentralized energy systems.
3. Capacity Building and Technical Training: Investment in technical education and workforce development is essential. Training programs should focus on renewable energy system design, installation, and maintenance to ensure sustainability and efficiency.
4. Integration of Hybrid Energy Systems: To address intermittency issues, manufacturers should adopt hybrid energy systems (e.g., solar-diesel, solar-battery combinations) that ensure continuous power supply while gradually reducing dependence on fossil fuels.
5. Research, Innovation, and Localization: Encouraging local research and development (R&D) can drive innovation tailored to regional conditions. Localization of renewable energy technologies can reduce costs and improve adaptability.
6. Awareness and Stakeholder Engagement: Awareness campaigns and demonstration projects can help change perceptions and build confidence among manufacturers. Showcasing successful case studies will accelerate adoption.

CONCLUSION

The decline of local manufacturing in developing economies, driven by high energy costs and unreliable electricity, underscores the need for sustainable energy–driven revitalization. This study shows that integrating renewable energy, energy efficiency measures, and digital energy management can restore competitiveness, improve productivity and enhance resilience. Coupled with smart manufacturing, IoT/AI-driven optimization, supportive policies, and public–private partnerships, these solutions reduce costs, mitigate environmental impacts, and generate socio-economic benefits such as job creation and local value-chain strengthening. By linking energy adoption to industrial performance and sustainability, this approach aligns with SDGs 7, 9, 12, and 13, offering a practical, replicable roadmap for resilient, competitive, and environmentally responsible industrial growth.

RECOMMENDATIONS

This study provides actionable insights for policymakers, manufacturers, investors, and government institutions to strengthen energy-constrained manufacturing through sustainable energy adoption. Government support is essential in creating an enabling environment through stable policy frameworks, fiscal incentives, subsidies, and strategic investments in energy infrastructure. Policymakers should implement long-term regulatory frameworks that incentivize renewable energy adoption and energy efficiency, supported by capacity-building initiatives, research and development funding, and knowledge transfer programs. Manufacturers are encouraged to integrate hybrid energy systems, on-site renewable energy solutions, digital energy management systems, and IoT/AI-driven process optimization to enhance competitiveness, reduce operational costs, and improve resilience.
However, for industries and businesses that cannot fully adopt these measures due to technical, financial, or operational constraints, a phased and flexible transition strategy is necessary. Such industries should prioritize incremental efficiency improvements, partial electrification, fuel switching (e.g., to lower-carbon alternatives), and participation in shared or off-site renewable energy systems. Government and policymakers should provide targeted support mechanisms such as transitional subsidies, tax relief, carbon credit schemes, and access to shared infrastructure to ensure inclusivity and prevent economic displacement. Investors and financial institutions can capitalize on emerging opportunities by financing energy retrofits and digital transformation initiatives through green financing instruments, concessional loans, and blended finance mechanisms, with government-backed guarantees and risk-sharing schemes to further lower investment risks and attract private sector participation

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