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INTEGRATING RENEWABLE ENERGY SOURCES INTO INDUSTRIAL MANUFACTURING: TECHNOLOGIES, CHALLENGES, AND BEST PRACTICES

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Abstract: The industrial sector is one of the largest consumers of energy and contributors to global greenhouse gas emissions. As pressure mounts to reduce environmental impact and comply with increasingly strict regulations, the integration of renewable energy sources (RES) into manufacturing systems is gaining momentum as a pathway toward sustainable production. This paper presents a concise review of available RES technologies applicable to industrial environments, with a particular focus on photovoltaic systems, heat pumps, waste heat recovery, and bioenergy. The technical feasibility, integration strategies, and primary challenges associated with each solution are discussed, along with relevant economic and regulatory considerations. Additionally, examples of successful implementation in manufacturing are highlighted to illustrate current trends and practical benefits. The review reveals that successful RES deployment requires a holistic approach that combines technological adaptation, financial planning, and supportive policy frameworks. The findings emphasize that while technical and financial barriers remain, RES integration represents a key opportunity for decarbonizing the industrial sector and advancing toward the objectives of circular economy and net-zero emissions.

Keywords: Industrial decarbonization, Waste heat recovery, Solar PV systems, Industrial heat pumps, Renewable energy sources

1. INTRODUCTION

The manufacturing industry plays a central role in global economic development but also represents a significant source of energy consumption and greenhouse gas (GHG) emissions. According to the International Energy Agency, the industrial sector accounts for approximately 38% of final energy use worldwide, with fossil fuels still dominating the energy mix in many regions. The urgent need to reduce carbon emissions, coupled with

increasing energy costs and regulatory pressures, is compelling manufacturers to explore cleaner and more sustainable energy solutions.

In this context, the integration of renewable energy sources (RES) into industrial production systems has emerged as a viable strategy to support the transition toward low-carbon manufacturing [1]. Renewable technologies such as solar photovoltaic (PV) systems, industrial heat pumps, waste heat recovery units, and biomass-based cogeneration offer

opportunities not only for reducing emissions but also for enhancing energy security and operational resilience.

Beyond the environmental imperative, the alignment with international policy frameworks, such as the European Union's *Fit for 55* package and the introduction of mechanisms like the Carbon Border Adjustment Mechanism (CBAM), is further accelerating the decarbonization of industrial sectors. These policies emphasize the need for systemic energy transitions, especially within energy-intensive industries such as metal processing, cement, and chemicals. For example, CBAM specifically targets imports from sectors like cement, aluminium, iron and steel, fertilisers, and hydrogen while reducing free allowances through the EU Emissions Trading System as part of a broader strategy to cut greenhouse gas emissions by at least 55% by 2030 and reach climate neutrality by 2050.

However, while the potential of RES integration in industry is widely acknowledged, its practical implementation is constrained by a range of technical, financial, and infrastructural barriers [2]. Intermittency of energy supply, limited space for on-site installations, high upfront investment costs, and the complexity of retrofitting legacy systems are among the key challenges facing manufacturers.

The purpose of this paper is to give a succinct summary of renewable energy technologies that can be incorporated into manufacturing systems. It examines implementation's technical and financial facets, pinpoints typical roadblocks, and offers a few chosen instances of industry best practices. The study adds to the larger conversation on sustainable production and industrial decarbonization by charting the present state of RES applications in manufacturing.

2. TYPES OF RENEWABLE ENERGY SOURCES FOR INDUSTRIAL APPLICATIONS

The transition toward sustainable manufacturing involves the strategic integration of RES that are technically feasible, economically viable, and environmentally

beneficial. The choice of technology depends on multiple factors, including energy demand patterns, site-specific conditions, available infrastructure, and regulatory incentives. This section provides an overview of the key RES technologies applicable to industrial environments [3].

Solar PV systems are among the most accessible renewable technologies for manufacturing facilities, particularly due to the availability of large roof areas on industrial buildings. These systems convert sunlight directly into electricity and can be used either to supplement grid power or to operate in partially off-grid configurations. Industrial users benefit from predictable daytime energy loads, which align well with solar generation patterns, making self-consumption strategies highly effective. Additionally, falling PV module prices and favorable policies, such as net metering and tax incentives, have improved the return on investment for solar integration in industry [4].

Despite these advantages, challenges include intermittency of solar radiation, space limitations in high-density industrial zones, and the need for inverters and storage systems to manage peak loads and variability.

Heat pumps have gained traction as a low-carbon solution for providing thermal energy in the form of hot water, process heat, or space heating. Unlike conventional boilers, heat pumps operate on the principle of transferring heat from a low-temperature source (e.g., air, water, or waste heat) to a higher-temperature sink, typically using electricity. Their coefficient of performance (COP) often exceeds 3.0, meaning that for every unit of electricity consumed, they can deliver three or more units of heat energy. Industrial heat pumps are particularly useful in processes with moderate temperature requirements (<150°C), such as washing, drying, or pre-heating [5].

The main limitation lies in their inability to provide very high process temperatures, as required in metallurgical or chemical applications. Nevertheless, ongoing technological developments are extending their application range.

While not a renewable source per se, waste heat recovery is a critical component of industrial energy efficiency and can complement RES strategies [6]. Many manufacturing processes emit substantial quantities of low- to medium-grade waste heat, which often goes unused. Technologies such as recuperators, economizers, and heat exchangers can be employed to capture this heat and redirect it into useful applications, such as space heating, water pre-heating, or even electricity generation via Organic Rankine Cycles (ORC). This improves overall system efficiency and reduces fuel consumption.

Implementation requires careful process integration and feasibility analysis, especially when retrofitting existing plants. However, waste heat recovery can often achieve short payback periods due to direct energy savings.

Industries that generate organic waste—such as food, wood processing, and agricultural sectors—can harness biomass and biogas as internal energy resources. Biomass can be combusted directly or converted into syngas and bio-oil, while biogas is typically produced via anaerobic digestion and used in combined heat and power (CHP) systems.

These technologies support circular economy principles by converting waste streams into usable energy, thereby reducing both environmental impact and energy costs [7].

Barriers include high capital costs, logistical complexities of biomass supply, and emissions control. Nonetheless, in sectors where biomass is abundant and regulations favor bioenergy, these systems can offer competitive advantages.

3. TECHNICAL INTEGRATION OF RENEWABLE ENERGY SOURCES IN INDUSTRIAL SYSTEMS

The integration of RES into industrial systems requires more than the mere installation of green technologies—it involves the adaptation of existing infrastructure, operational strategies, and energy management practices. This section outlines key technical

considerations and integration strategies for deploying RES within manufacturing environments.

Table 1. Overview of RES Technologies for Industrial Applications

Technology	Primary Use in Industry	Main Advantages	Key Challenges
Solar PV	Electricity generation for machinery, lighting	- Reduces electricity bills - Low maintenance - Scalable	- Intermittent production - Roof space limitations - Need for storage/inverters
Heat Pumps	Process heat, space heating, hot water	- High efficiency (COP > 3) - Electrification of heat - Reduced emissions	- Limited to moderate temperatures - High initial cost
Waste Heat Recovery	Reuse of thermal energy from processes	- Improves energy efficiency - Quick payback in many cases	- Requires careful integration - Often process-specific
Biomass/Biogas	Heat and electricity (via CHP), waste valorization	- Utilizes internal waste - Supports circular economy - On-site generation	- Logistics and fuel preparation - Emission control - High CAPEX

Most industrial facilities adopt grid-connected RES systems, where renewable energy complements the grid supply. This approach allows flexibility: excess energy can be exported to the grid under net metering or feed-in tariff schemes, while deficits can be covered from the grid. Grid-connected systems are especially common in solar PV applications, as they reduce the need for costly storage systems. Standalone systems, on the other

hand, are relevant in remote industrial operations or in facilities aiming for energy independence. These often require a combination of RES (e.g., PV + biomass) and battery storage or backup generators to ensure reliability.

The fluctuating nature of RES, particularly solar and wind, necessitates real-time Energy Management Systems (EMS) that can balance generation, storage, and demand. EMS can dynamically adjust load profiles, prioritize self-consumption, and reduce peak demand charges. Smart EMS platforms are typically integrated with Industrial Internet of Things (IIoT) technologies, enabling remote monitoring and predictive maintenance [8]. This not only improves system performance but also extends equipment lifespan and helps with demand-side management.

In many cases, RES must be integrated into existing production processes without disrupting productivity. This can be particularly challenging when retrofitting older facilities. For example, heat pumps may require modifications in process temperature levels and distribution systems, waste heat recovery systems demand a thorough thermal audit to identify viable heat sources and match them to nearby sinks, and biomass boilers require dedicated fuel handling and emissions control infrastructures. Process integration also involves matching energy supply profiles with demand, e.g., aligning solar PV output with peak machine operation hours.

Because RES such as solar and wind are intermittent, energy storage systems are often required to ensure continuity and reliability in industrial settings. Options include electrical storage (e.g., lithium-ion batteries) for PV integration, thermal storage (e.g., hot water tanks, phase-change materials) for processes with heating demands, hydrogen production via electrolysis is emerging as a long-term storage solution and can be used in high-temperature industrial applications.

In addition to physical storage, flexibility measures such as load shifting, demand response, or hybrid RES systems contribute to more efficient integration [9].

Continuous monitoring is critical for maximizing the benefits of RES. The use of digital twins, virtual models of energy systems, allows for real-time simulation, performance prediction, and optimization under variable operating conditions.

Digitalization thus plays a key enabling role, especially in complex manufacturing environments where interactions between energy and production processes are dynamic and multidimensional.

4. ECONOMIC AND REGULATORY ASPECTS OF RES INTEGRATION IN MANUFACTURING

While the technical feasibility of renewable energy integration in manufacturing continues to improve, the decision to invest in such systems is often governed by economic considerations and regulatory frameworks. This chapter outlines key financial drivers, cost-related barriers, and policy instruments that shape industrial adoption of RES technologies [1, 3, 4].

The initial capital expenditure (CAPEX) for renewable energy installations, especially for solar PV systems, industrial heat pumps, and biomass boilers, can be substantial. However, decreasing equipment costs and improved efficiency have made many technologies economically attractive over time. For example, the global average cost of installed utility-scale solar PV dropped by over 80% between 2010 and 2020.

The return on investment (ROI) varies depending on energy prices, self-consumption rates, system sizing, and available incentives. In some regions, ROI for industrial PV systems can be achieved within 5–7 years, particularly when electricity tariffs are high and peak shaving is enabled. However, uncertainty about long-term policy stability, fluctuating energy markets, and lack of awareness about lifecycle savings still act as deterrents for some manufacturers.

Compared to conventional systems, RES technologies typically offer lower operating costs (OPEX) due to reduced fuel dependency and fewer moving parts (e.g., in PV systems). Maintenance requirements are also lower,

though periodic cleaning, performance monitoring, and inverter replacement are necessary [3, 4].

In contrast, biomass systems may have higher OPEX, driven by fuel logistics, combustion system upkeep, and emission control requirements.

Many governments and international institutions offer financial incentives to support RES deployment in industry. These include investment subsidies and grants, feed-in tariffs or premium tariffs, accelerated depreciation schemes, carbon credits and tax breaks, and net metering and virtual net metering for grid-connected PV. These mechanisms significantly improve the financial viability of RES projects and encourage early adoption. For example, the European Union's Recovery and Resilience Facility (RRF) earmarks billions of euros for green industrial upgrades, including RES integration.

However, access to funding may be limited for small and medium-sized enterprises (SMEs) due to administrative complexity, lack of technical capacity, or insufficient upfront capital.

RES deployment in manufacturing must comply with a variety of local, national, and supranational regulations. These include grid connection standards, environmental permits (especially for bioenergy systems, energy performance reporting, building codes for rooftop PV, and emissions monitoring and reporting.

In the European Union, the *Fit for 55* legislative package mandates stricter emissions reductions across industrial sectors, alongside the introduction of the Carbon Border Adjustment Mechanism (CBAM). This mechanism imposes a carbon cost on imported goods from countries with less stringent climate policies, thereby incentivizing domestic industries to decarbonize.

Beyond regulatory compliance, manufacturers are increasingly subject to market-driven decarbonization pressures. Many large buyers, investors, and financial institutions now require Environmental, Social, and Governance (ESG) disclosures. A company's

energy mix and emissions profile are key ESG metrics that influence supply chain decisions and investment attractiveness. As a result, integrating RES can enhance not only environmental performance but also brand value, access to green financing, and competitive positioning in global markets [10].

5. CASE STUDIES AND BEST PRACTICES

To illustrate the practical implementation of renewable energy technologies in manufacturing, this chapter presents selected case studies and examples from leading industrial companies. These cases highlight both the potential benefits and real-world challenges associated with the integration of RES into production systems.

Siemens has implemented solar photovoltaic (PV) systems in several of its manufacturing plants worldwide. In its Kalwa plant in India, Siemens installed a 1 MW rooftop solar system that supplies up to 25% of the facility's daytime electricity demand, reducing annual CO₂ emissions by approximately 1,200 tons. The company reports a payback period of fewer than six years, supported by national feed-in tariffs and tax incentives. This case demonstrates the compatibility of PV with facilities that have large roof surfaces and stable energy loads during daylight hours [10].

Bosch has implemented a comprehensive energy efficiency strategy that includes waste heat recovery systems across its European plants. In its Homburg factory (Germany), Bosch uses heat exchangers and thermal storage to capture and reuse process heat for space heating and hot water, reducing fossil fuel use by over 20% [6]. The success of this approach relies on thorough thermal audits and integration planning. Bosch's experience illustrates that even legacy facilities can achieve significant improvements through targeted retrofitting.

A major pharmaceutical manufacturer in France implemented a waste-heat recovery heat pump in one of its production facilities. This industrial heat pump captures low-grade waste heat and upgrades it to useful process

heat, reducing reliance on fossil fuels and improving the site's carbon footprint. This case demonstrates that industrial heat pumps can be effectively deployed even in energy-intensive manufacturing settings, provided that temperature requirements are suitable and the process integration is carefully engineered.

Interface Inc., a global flooring manufacturer, integrates biogas-fueled CHP systems at its manufacturing facilities in Europe. By using directed biogas for thermal energy and combined heat & power, the company captures renewable thermal energy and implements circular economy practices—recycling production waste—and aligns its operations with ambitious carbon neutrality goals [7].

Despite differences in technology and scale, several common factors emerge across these best practices: top management commitment and alignment with long-term sustainability goals, thorough energy audits and feasibility studies, use of public incentives and regulatory frameworks to reduce investment risk, digital monitoring systems for performance tracking and optimization, and integration with broader decarbonization strategies (e.g., circular economy, waste valorization).

These cases underscore that RES integration is not limited to specific sectors or company sizes; rather, it is a viable strategy for any manufacturer with the vision and capacity to invest in long-term energy and environmental performance.

6. CONCLUSION

The integration of RES into manufacturing systems represents a critical step toward achieving industrial decarbonization, improving energy security, and aligning with broader sustainability goals. As the industrial sector faces increasing pressure from regulatory frameworks, market expectations, and environmental imperatives, renewable energy technologies offer a viable path forward.

This paper has presented an overview of key RES technologies applicable to industrial

environments, including solar PV, heat pumps, waste heat recovery, and biomass-based systems. Technical integration requires careful planning, process compatibility assessments, and energy management strategies—particularly when retrofitting existing facilities. While economic challenges persist—such as high upfront costs and administrative complexity—available financial incentives and policy support can significantly improve project viability.

Real-world case studies demonstrate that manufacturers across various sectors and geographies have successfully adopted RES technologies, resulting in reduced emissions, operational savings, and enhanced ESG performance. These examples highlight the importance of strategic planning, strong leadership commitment, and the use of digital tools for performance monitoring and optimization.

Looking ahead, further progress will depend on the continued evolution of enabling technologies (e.g., energy storage, smart grids), regulatory clarity, and increased awareness within the industrial community. Integrating RES is not merely an environmental measure—it is an opportunity to future-proof industrial operations and create resilient, sustainable production systems.

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