



Green Technology with Automation in Industry 4.0: Applications for Sustainable Industrial Development in India

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Abstract: The integration of green technology and Industry 4.0 automation offers opportunities to improve industrial energy efficiency, resource utilization, and environmental performance. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), cyber-physical systems, cloud computing, data analytics, programmable logic controllers (PLCs), and supervisory control and data acquisition (SCADA) can support real-time monitoring, predictive maintenance, renewable-energy coordination, and emissions management. This paper examines applications relevant to Indian industry, including smart manufacturing, digital power infrastructure, electric mobility, and green hydrogen. A conceptual, literature-based approach is used to organize these applications into a layered green-automation architecture and to identify expected benefits, implementation barriers, and research priorities. The analysis suggests that outcomes depend on site-specific baselines, system integration, workforce skills, cybersecurity, and the carbon intensity of electricity. The paper proposes an implementation framework for Indian industries and highlights the need for measured, transparent evaluation rather than assuming uniform savings across sectors.

Keywords—Green technology, Industry 4.0, smart manufacturing, industrial automation, IoT, renewable energy, smart grid, sustainability

I. INTRODUCTION

Industrial development supports employment, infrastructure, and economic growth, but it can also increase energy demand, material consumption, and greenhouse-gas emissions. Industry 4.0 refers to the integration of digital and automation technologies into industrial systems, enabling connected equipment, data-driven decisions, and more flexible production [1], [2]. When these capabilities are designed around environmental objectives, they can support energy efficiency, waste reduction, and improved use of renewable energy.

India's industrial and electricity systems are changing in response to growing demand, renewable-energy deployment, electrification, and national climate commitments. India announced a target of achieving 500 GW of non-fossil electricity capacity by 2030 and a net-zero emissions goal by 2070 [3], [4]. These targets make industrial energy management and efficient infrastructure important areas for technology deployment. The National Green Hydrogen Mission, approved in January 2023, also creates a policy context for developing green hydrogen production and use [5]. Digitalization does not automatically make a process sustainable. Sensors, data centres, communication networks, and automated equipment consume resources, and a poorly designed control strategy can shift rather than eliminate environmental impacts. Sustainable implementation therefore requires baseline measurement, life-cycle awareness, secure system design, and evaluation of energy and emissions outcomes.

The objectives of this paper are: (1) to examine the integration of green technology with Industry 4.0; (2) to discuss applications relevant to Indian renewable energy, smart grids, electric mobility, and green hydrogen; (3) to identify potential benefits and implementation challenges; and (4) to propose a practical green-automation framework for industrial adoption.

II. LITERATURE REVIEW

Research on sustainable manufacturing links environmental performance with process efficiency, resource productivity, and improved production planning. Stock and Seliger [6] discuss opportunities for sustainable manufacturing associated with emerging production technologies. Industry 4.0 systems can collect operational data from machines and production lines, making energy and material flows more visible and enabling better control of industrial processes.



Lee, Bagheri, and Kao [7] describe a cyber-physical systems architecture for Industry 4.0 manufacturing. In such systems, physical equipment is linked with computation and communication, allowing monitoring and control to be coordinated with production requirements. Internet-connected sensors and industrial control systems can provide operational data, while analytics may support fault detection and maintenance planning.

Digital twins and data-driven models can be used to represent assets or processes, test operating scenarios, and support optimization. Their value depends on model quality, data availability, and whether model recommendations are incorporated safely into plant operations. Renewable-energy literature also emphasizes that digitalization can improve forecasting, system flexibility, and integration of variable renewable resources [8].

The literature supports the potential of digital technology for sustainable manufacturing, but reported benefits should not be treated as universal. Energy savings, downtime reduction, and waste reduction vary with the industrial sector, baseline equipment, system boundaries, operating practices, and the quality of implementation. This paper therefore presents the technologies as enabling options and does not treat generalized percentages as measured results for Indian industry.

III. RESEARCH METHOD AND SCOPE

This paper adopts a conceptual review and technology-mapping approach. It synthesizes selected foundational literature on Industry 4.0, sustainable manufacturing, cyber-physical systems, digitalization of energy, and Indian policy documents available by the end of 2023. The material is organized by application area and mapped to the functions of a layered green-automation architecture.

The paper does not report primary experiments, a field survey, or an independently audited industrial case study. The automotive-sector example is used as an illustrative application scenario based on commonly deployed automation technologies, not as evidence of measured performance at a named plant. Numerical performance claims are included only where supported by a traceable source; otherwise, expected benefits are described qualitatively.

IV. INDUSTRY 4.0 ARCHITECTURE FOR GREEN SYSTEMS

A. Layered architecture

A green Industry 4.0 system can be organized into five connected layers. The physical layer includes machines, motors, drives, meters, sensors, and actuators. The control layer includes PLCs, SCADA, distributed control systems (DCS), and local controllers. The communication layer transfers data through industrial Ethernet, fieldbus systems, wireless networks, or other suitable protocols. The data layer stores and processes time-series and production information using edge or cloud computing. The application layer presents dashboards, energy analytics, carbon accounting, fault prediction, and optimization recommendations.

Data should flow from physical equipment toward analytics and operator interfaces, while approved control commands return through secure control pathways. Safety-critical functions should remain within appropriately engineered control and protection systems; cloud analytics should not bypass established safety interlocks. The architecture should also include access control, network segmentation, logging, backup, and recovery procedures.

B. Integrated green-automation workflow

A typical workflow begins with renewable generation and utility meters supplying energy data to the monitoring system. Sensors record equipment status, electrical parameters, temperature, production rate, and selected environmental variables. PLCs and SCADA provide local control and supervisory visibility. Edge or cloud analytics then compare actual performance with operating targets and identify opportunities such as peak-load reduction, abnormal energy use, or maintenance needs. Recommendations are reviewed by operators and implemented under defined control and safety procedures.

C. Key enabling technologies

IoT sensors and smart meters provide visibility into equipment and energy use. AI and machine-learning methods may assist forecasting, anomaly detection, and quality inspection when sufficient representative data are available. Digital twins can support simulation and scenario comparison. Robotics and automated handling can improve repeatability and reduce some forms of process waste. Cloud and edge computing support data processing, although their energy use and cybersecurity implications should be considered. No single technology guarantees sustainability; the benefit comes from matching a suitable technology to a measured operational problem.



V. APPLICATIONS IN THE INDIAN CONTEXT

A. Renewable energy and industrial energy management

Solar and wind generation vary with weather and time. Digital monitoring, forecasting, automated inverter controls, and condition monitoring can help operators improve asset visibility and coordinate generation with demand. In factories, sub-metering and production data can identify high-consumption processes, idle loads, compressed-air losses, and inefficient motor operation. Variable-speed drives, power-factor correction, efficient motors, and automated scheduling may complement digital monitoring.

India's 2030 non-fossil capacity target provides a policy context for expanding renewable generation and improving system flexibility [3]. Installed-capacity figures should be stated with a clear reporting date and category definition because renewable energy, large hydro, and total non-fossil capacity are not identical measures. For a 2023 submission, the manuscript should use data published by the relevant cutoff date rather than later 2024 totals.

B. Smart grid and digital power infrastructure

Smart-grid functions include automated substations, digital relays, supervisory monitoring, smart metering, distribution automation, and data analytics. These technologies can help utilities observe voltage, loading, faults, and consumption patterns more quickly. Smart meters may support improved billing and demand information, while automated distribution equipment can assist fault isolation and restoration. Their effectiveness depends on communication reliability, interoperability, data governance, and the capability to act on the information generated.

An illustrative information flow is: generating station or distributed energy resource → automated substation and distribution network → smart meter and consumer interface → utility analytics platform. The diagram represents a functional concept; actual networks include protection, communications, operational technology, and regulatory requirements not shown in this simplified flow.

C. Electric vehicles and automated energy systems

Electric vehicles (EVs) connect transport electrification with electricity distribution. Charging management can schedule charging according to grid capacity, tariffs, renewable generation, and user requirements. IoT-enabled chargers and energy-management systems can monitor charger availability, charging demand, and equipment status. Battery-management systems monitor parameters such as voltage, current, temperature, state of charge, and state of health; advanced analytics may support diagnostics, subject to validation and safety constraints.

Vehicle-to-grid (V2G) systems can enable bidirectional power flow when the vehicle, charger, communication system, and grid rules support it. V2G should be described as an emerging capability rather than a universal feature of EV infrastructure. Coordinated charging can reduce unmanaged peaks, but the outcome depends on charging behaviour, local transformer capacity, tariff design, battery requirements, and the availability of suitable equipment.

D. Green hydrogen automation

The National Green Hydrogen Mission was approved by the Government of India in January 2023, with an objective of developing India as a hub for green hydrogen production, use, and export [5]. In a green hydrogen facility, automation can monitor renewable-electricity input, electrolyzer operating conditions, water treatment, gas purity, pressure, temperature, and storage systems. Hydrogen detection, ventilation, emergency shutdown, and process interlocks are important safety functions.

AI-based optimization may help coordinate variable renewable generation with electrolyzer operation, but safety-related control must be engineered and validated for the specific facility. Remote monitoring can improve visibility, while cybersecurity and safe operating procedures remain essential. Green hydrogen claims should also state the production pathway and electricity source because environmental performance depends on the energy supply and process boundary.

VI. ILLUSTRATIVE INDUSTRIAL APPLICATION

An automotive manufacturing facility in an Indian industrial cluster may combine robotic assembly, programmable logic controllers, SCADA monitoring, machine-vision inspection, and energy metering. A proposed green-automation deployment would first establish baseline values for electricity per unit produced, compressed-air consumption, scrap rate, equipment downtime, and peak demand. Sensors and production systems would then collect synchronized operating data, and an energy dashboard would highlight abnormal loads and idle equipment.



Predictive maintenance could be piloted on selected high-impact assets, such as motors, pumps, compressors, or critical production equipment. Machine-vision inspection could be evaluated for a defined quality task. Renewable electricity could be integrated through appropriate metering and energy-management controls. After implementation, the plant would compare the baseline and post-deployment periods while controlling, as far as possible, for production volume, product mix, operating hours, and weather-related effects.

No measured results are claimed for this illustrative scenario. A valid case study would report the site, study period, baseline, measurement method, production normalization, system boundaries, uncertainty, and data source. Percentages such as energy savings or productivity improvement should not be attributed to an industry or region without that evidence.

VII. COMPARATIVE ANALYSIS

Table I compares conventional practices with a green Industry 4.0 approach at a conceptual level. The comparison describes intended capabilities, not guaranteed outcomes.

VIII. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

Potential environmental benefits include lower energy use per unit of output, reduced material scrap, improved equipment utilization, and better coordination of renewable electricity. Economic benefits may include lower energy bills, fewer unplanned stoppages, improved quality, and better production planning. These benefits must be assessed against capital expenditure, integration costs, training, software and communications expenses, maintenance, and cybersecurity requirements.

Investment evaluation should use a defined baseline and include capital cost, operating cost, asset lifetime, expected utilization, and relevant energy or emissions factors. A simple payback period can be useful for initial screening, but it does not capture all risks or long-term benefits. Claims such as a fixed three-to-five-year return on investment should not be generalized without project-specific financial analysis.

IX. IMPLEMENTATION CHALLENGES

Initial investment can be a barrier, particularly for small and medium-sized enterprises. Legacy equipment may use incompatible protocols or lack instrumentation. Poor-quality or incomplete data can undermine analytics, and a shortage of personnel with both automation and energy-management skills can limit implementation. Operational technology also introduces cybersecurity risks because connected control systems can affect physical processes. Other challenges include vendor lock-in, unclear data ownership, uncertain standards, production disruption during installation, and difficulty attributing changes in energy use to a single intervention. These challenges can be reduced through phased pilots, open and documented interfaces where feasible, staff training, network segmentation, secure remote access, backup and recovery planning, and independent measurement of performance.

X. FUTURE RESEARCH DIRECTIONS

Future work should develop and validate AI-assisted carbon and energy monitoring methods using transparent system boundaries. Digital twins could be evaluated for specific industrial processes with reported model accuracy and operational outcomes. Research is also needed on secure industrial IoT architectures, interoperable energy data, renewable-aware production scheduling, and the use of EVs and storage to support flexible demand.

Studies should include small and medium-sized Indian industries and report costs, implementation barriers, energy and material baselines, and post-deployment outcomes. Life-cycle assessment can help establish whether digital interventions reduce total environmental impact rather than shifting impacts to data processing, equipment manufacture, or other parts of the system. Research on green hydrogen automation should address operational optimization alongside process safety and emissions accounting.

XI. CONCLUSION

Green technology integrated with Industry 4.0 can provide Indian industry with better visibility and control over energy use, equipment condition, production quality, and renewable-energy interaction. IoT, PLC/SCADA systems, data analytics, AI, digital twins, smart-grid technologies, EV charging management, and green hydrogen controls each offer



application-specific opportunities. Their value depends on the quality of implementation, appropriate system boundaries, trained personnel, cybersecurity, and measured results.

This paper proposes a layered architecture and a practical implementation approach that begins with a baseline, pilots a defined use case, evaluates performance, and scales only when benefits are demonstrated. As this is a conceptual review rather than an empirical study, further site-level research is required to quantify energy, emissions, productivity, and economic effects. Sustainable industrial digitalization should be judged by transparent evidence, not by technology adoption alone.

TABLE I. CONCEPTUAL COMPARISON OF INDUSTRIAL PRACTICES

Parameter	Conventional practice	Green Industry 4.0 approach / consideration
Monitoring	Periodic/manual readings	Continuous metering and dashboards
Maintenance	Reactive or time-based	Condition monitoring and predictive analytics
Energy supply	Grid supply with limited coordination	Renewable-integrated energy management
Quality control	Manual or sampled inspection	Automated inspection where suitable
Emissions	Estimated from aggregate data	Process-level energy and emissions tracking
Cybersecurity	Limited connectivity in some systems	Connected OT/IT with formal security controls

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