Global Journal of Energy Technology Research Updates, 2025, 94-105

Published by Avanti Publishers

Global Journal of Energy Technology Research Updates

ISSN (online): 2409-5818

Sustainable Industry 6.0 Manufacturing: Integrating Nanotechnology, Quantum Intelligence, and Autonomous Production Systems

Dinesh K. Madheswaran[1,*], Ram Krishna[2] and Suresh Gopi[3]

[1]*School of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur Campus - 603203, India*

[2]*Department of Metallurgical and Materials Engineering, National Institute of Technology, Jamshedpur, Jharkhand, India*

[3]*Department of Mechanical Engineering, Rajalakshmi Engineering College, Thandalam, Chennai - 602105, India*

ARTICLE INFO

Article Type: Review Article

Academic Editor: Obie Farobie

Keywords:
Industry 6.0 manufacturing,
Autonomous and smart factories,
Quantum intelligent manufacturing,
Sustainable manufacturing systems,
Nanotechnology-enabled production.

Timeline:
Received: October 30, 2025
Accepted: December 05, 2025
Published: December 15, 2025

Citation: Madheswaran DK, Krishna R, Gopi S. Sustainable industry 6.0 manufacturing: integrating nanotechnology, quantum intelligence, and autonomous production systems. Glob J Energ Technol Res Updat. 2025; 12: 94-105.

DOI: https://doi.org/10.15377/2409-5818.2025.12.7

ABSTRACT

The shift from Industry 5.0 to Industry 6.0 marks a significant change in manufacturing, with control transitioning from workflows to the materials themselves involved, while autonomous systems manage production at nanometer and quantum levels. Sustainable nanotechnology is at the heart of this evolution, combining environmental performance, process efficiency, and material precision as key governance factors. This chapter outlines a detailed framework for integrating sustainability into manufacturing choices, showing that environmental performance can shift from being an afterthought to a key factor in operational control. The discussion outlines mechanisms ranging from atomic-scale materials to fleet-level autonomy, positioning Industry 6.0 as a robust, energy-efficient, and scalable framework for future production systems.

*Corresponding Author
Email: mdineshautomobile@gmail.com
Tel: +(91) 99650 74145

1. Introduction

The manufacturing industry is experiencing a significant shift as it transitions from the current paradigm of Industry 5.0 to the future vision of Industry 6.0. While Industry 5.0 focused on working together with machines and getting things done, Industry 6.0 changes the very nature of production by moving control from workflows to matter itself [1, 2]. In this new way of performing operations, human intelligence makes decisions, and autonomous robotic systems carry out tasks on global networks that are all connected. The shift to Industry 6.0 is marked by a focus on the nano-to-quantum range, where the basic connections between the structure, properties, and functions of materials can be accurately designed, monitored, and customized in real time [3]. Industry 6.0 aims to design and configure environmental and material variables directly, which is different from earlier industrial models that mostly arrived at these factors. This is a big step toward making manufacturing fit with both performance goals and environmental goals. Nanotechnology is a key part of this change [4]. Nanotechnology makes it achievable to connect design, fabrication, use, and regeneration at the molecular level by allowing atomically calibrated manufacturing and modular design. This approach changes sustainability from a limit on what can be done to a design goal for industrial systems when used with advances in quantum computing, AI-driven control systems, and circularity-by-design principles [5].

In this context, Industry 6.0 is more than just a technology change; it is a change in the way manufacturing works as a whole. The goal is not just to make workflows better, but also to design production systems that work well with the physics of materials and processes [6]. This point of view needs new tools, measurements, and rules to make sure that high-stakes business operations can grow, stay reliable, and bounce back. Fig. (**1**) situates this paper's scope within quantum nanoscience [7], where nanoscale materials and fabrication methods are explicitly engineered to preserve quantum coherence and enable device-to-factory control in Industry 6.0.

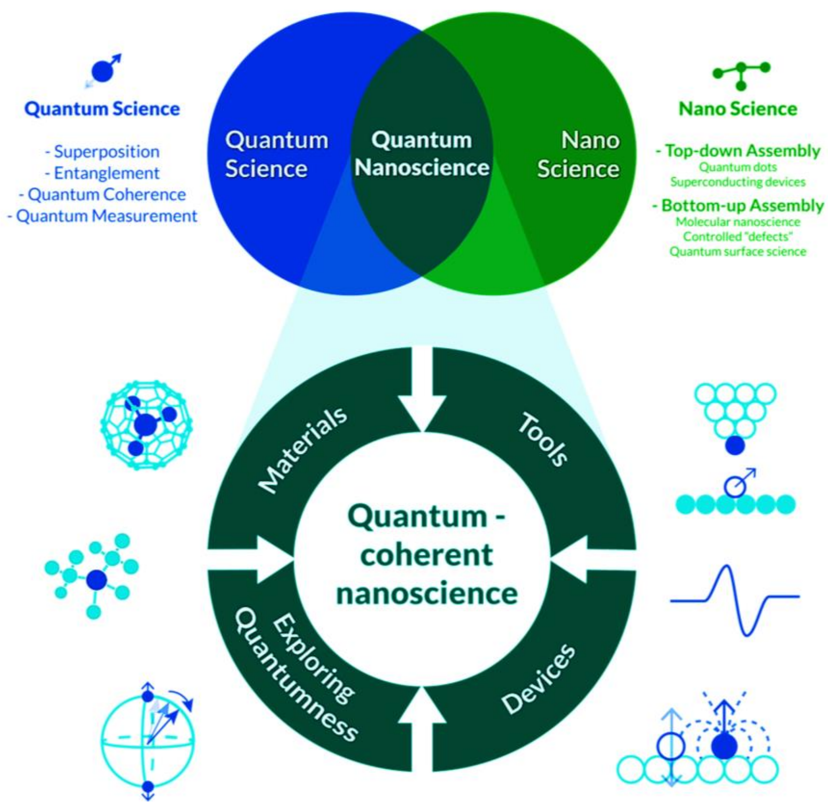

Figure 1: Conceptual map of the overlap between quantum science and nanoscience [7], showing how coherence-preserving materials, tools, devices, and methods form "quantum-coherent nanoscience," the nano-to-quantum core of Industry 6.0.

When materials and surfaces at the nanoscale are designed and fabricated with explicit coherence limitations in mind, this is known as quantum-coherent nanoscience. The operation-dependent control of T1, T2, dephasing rates, and two-level system (TLS) defect concentrations is achieved within this framework through the selection of thin-film thickness, junction geometry, barrier uniformity, and surface chemistry [8]. Kinetic inductance, defect involvement, and coherence time can be directly influenced by altering the thickness of the aluminum sheet, which can range from 3 to 100 nm. In a similar vein, keeping the variance in junction areas to a range of 5-7% relative standard deviation (RSD) limits the dispersion of frequencies and decreases the burden of mistake correction [9]. As a result, coherence is more of a fabrication variable than a diagnostic after fabrication.

This paper examines the role of nanotechnology in the transition to Industry 6.0 and how molecular-level control, enhanced by digital and intelligent technologies, can transform sustainability in manufacturing. By looking at these mechanisms, the discussion shows how Industry 6.0 can set up a reliable and useful framework for the future of global production.

2. Sustainability Imperative of Industry 6.0 with Nanotechnology

Sustainability within Industry 6.0 is not a theoretical target; it is a demand that can be measured and is based on evidence. Green nanotechnology exemplifies this truth, where reductions are not just aesthetic but transformative. Devade *et al*. [10] show that compared to traditional industrial methods, there is a 32% decrease in greenhouse gas (GHG) emissions, a 33% decrease in energy use, and a 37% decrease in eutrophication on land. If these kinds of technologies were used in only half of the world's most resource-intensive manufacturing sectors by 2035, they would save 2.2 to 2.6 $GtCO_2e$/year of emissions, 28 to 35 EJ/year of energy, and a lot less nutrients that contribute to eutrophication. The savings are still significant, ranging from 0.65 to 1.8 $GtCO_2e$ and 8 to 24 EJ/year, even at low adoption rates (15 to 35%). If we used nanotechnology to make one-fourth of the world's steel production more efficient, we could save 10 to 12 EJ/year and 0.6 to 0.9 $GtCO_2e$ [11]. These numbers set the standard: nanotechnology is the least amount of leverage needed for Industry 6.0 to make a real difference in lowering emissions. In addition to environmental metrics, sustainability also comes from quantum-enabled process efficiency. The coherence properties of qubits show this connection: longer T1 (161 μs) and T2 (245 μs) times cut down on energy losses by cutting down on error correction cycles, refrigeration loads, and unnecessary computations [12]. In real life, this means that there are fewer joules per logical operation and fewer watt-hours per validated routine [13]. So, coherence is not just a quantum performance benchmark; it is also an energy-saving tool for Industry 6.0's control systems.

The same idea of efficiency applies to making quantum devices. Processes made possible by nanotechnology, like precision etching, deposition, lithography, and surface modification, have shown a 33% energy drop per wafer in mature fabs [14]. This means big savings for fabs that make 75 dies per 300 mm wafer. It lowers the energy footprints at both the unit and system levels. These reductions add up over time as wafer improvements are made, connecting coherence-first design directly to energy-efficient manufacturing. Industry 6.0 sees atomic-scale patterning as a way to make things more sustainable [15]. For instance, adjusting the thickness of aluminum sheets to roughly 3 to 200 nm depending on film quality and microstructure, with ultraclean epitaxial Al remaining superconducting down to ~3 to 4 nm and polycrystalline/granular Al commonly used in the 10 to 100+ nm range to balance Tc, kinetic inductance, and thermal/mechanical robustness for circuits and interconnects, while using less energy and causing less thermal stress [16]. Nanometer-precision metrology lets you use thinner targets and fewer rework cycles, which lowers joules per device and stabilizes qubit performance [17]. This method links minimizing materials with coherence-first layouts, which lets you save energy without losing reliability. Fig. (**2**) visualizes the sector-by-adoption heatmap that places cross-sector deployments (15%, 35%, 50%) and a steel-sector subset (25%) against environmental outcomes.

Sustainability also includes the entire lifecycle of quantum assets. Devices need fewer recalibrations and replacements because they have low defect densities (34.4 defects/GHz) and age slowly. This lowers the intensity of the life cycle by spreading the embodied energy of making and packaging over more operational cycles [18]. AI-supervised maintenance routines make things even better by lengthening calibration intervals and cutting down on high-energy tool recertifications [19]. This is in line with Industry 6.0's antifragile design philosophy.

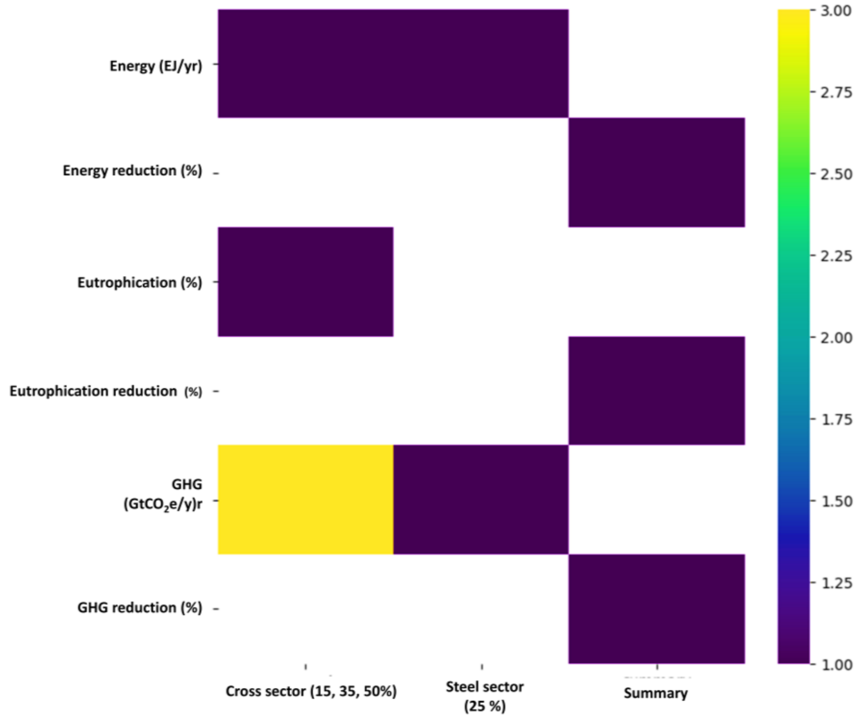

Figure 2: Adoption-by-sector heatmap showing cross-sector deployments (15%, 35%, 50%) and a steel-sector subset (25%) mapped to environmental outcomes.

Eventually, sustainability and yield optimization go hand in hand. In Industry 6.0 fabs, high yield is not only a measure of quality, but also a limit on energy. With an efficiency of 98.25% over 400 superconducting transmon qubits fabricated on a 300 mm wafer using industrial Complementary Metal-Oxide-Semiconductor (CMOS)-compatible processes, 393 were functional, and almost all lithography, vacuum, and cryogenic cycles turned into usable capacity instead of scrap [20]. The high yield maintains a consistent takt time throughout multi-hundred-step flows by reducing delays caused by excursions and minimizing variability in work-in-progress as complexity rises. Avoiding rework eliminates unnecessary high-energy furnace batches and probe-station retests, thereby reducing the cumulative time-in-tool for diffusion, lithography, and testing. Large fabs consume approximately 100 MWh per hour, with electricity costs accounting for about 5 to 30% of OPEX [21]. Consequently, reducing the number of reruns decreases both total and peak loads on utilities and subfab systems. As the energy consumption per chip increases at advanced nodes, the need to avoid repeats driven by yield considerations becomes a primary factor in reducing energy per good die. Therefore, increased yield directly influences energy feasibility by providing a more consistent takt, reducing peak demands, and minimizing unnecessary process and test cycles [22]. These examples show how nanotechnology supports the sustainability goal of Industry 6.0 on many levels, from reducing global emissions to quantum coherence, from wafer-level fabrication to material optimization, and from extending the life of products to maximizing yield. By bringing these parts together, Industry 6.0 changes the definition of sustainability from a limit to a changeable part of advanced manufacturing.

3. Digital Twin and Nanotechnology

In Industry 6.0, a digital twin serves as more than just a simulation tool; it acts as an independent control layer that manages energy-constrained manufacturing. The purpose is to consistently combine wafer-scale measurements and time-resolved device information to reduce energy consumption per logical operation while enhancing predictable throughput [23]. The basis of this control is rooted in coherence telemetry, spatial gradients across 300 mm wafers on a die-by-die basis, frequency variance at the junction level, aging drift kernels, TLS density priors, and yield distributions [24], all integrated into one cohesive decision-making framework.

At the device scale, nanotechnology provides the detailed information required for such a twin. A single wafer with 12,840 Josephson-junction test structures can provide enough statistical depth to create device-physics-informed surrogates. These surrogates correlate junction area and barrier uniformity to frequency, allowing the twin to adjust etching, oxidation, and deposition setpoints in real time [25]. By preventing out-of-family dies instead of reworking them, the twin directly avoids extra vacuum pump-downs, furnace cycles, and probe hours, processes that significantly contribute to fab energy overhead.

At the process level, spatial modeling allows for enhanced efficiency. Coherence gradients typically vary from 113 μs close to the centers of wafers to 42 μs at the edges [20]. As illustrated in Fig. (**3**), wafer-scale coherence mapping shows a center-to-edge gradient that the digital twin uses to drive spatially adaptive control. By adjusting the dose, temperature, or local plasma exposure, the twin can enhance the performance of weaker areas while maintaining energy efficiency. Coherence telemetry with σ approximately 20 μs and caps close to $T2_{e,}$ approximately 245 μs further specifies the simulation timestep and control horizon [26]. This precision enables the twin to arrange gate sequences, adjust biases, and manage cryogenic load balancing in sync with the actual progression of decoherence. Each avoided retry or additional activation leads to a decrease in the electronics duty cycle and refrigeration load, resulting in evident energy savings during consistent operation.

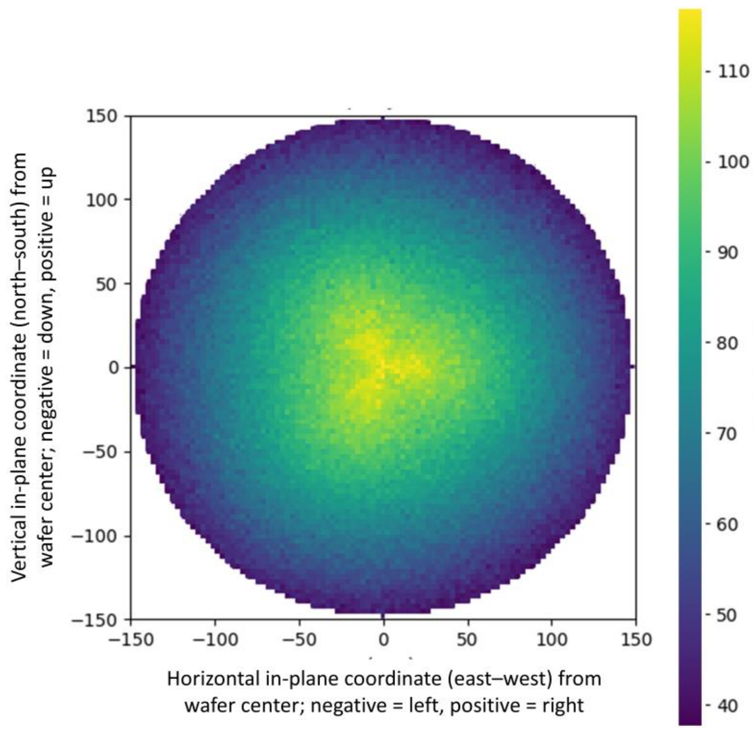

Figure 3: Wafer-scale coherence map (synthetic) showing center ≈113 μs and edge ≈42 μs, used by the digital twin for spatial compensation.

At the lifecycle scale, longitudinal drift data, like a 3.7% decrease in resistance over 146 days, are integrated into compact aging kernels within the twin. This allows for maintenance based on actual conditions instead of scheduled interventions, which helps to minimize energy-intensive reconditioning processes and cryostat warm-ups that usually lead to peak-load spikes [27]. TLS defect densities, approximately 34.4 defects per GHz, act as reliability priors, enabling the twin to direct workloads away from decoherence hotspots and consequently minimize the necessity for excessive cooling or redundant qubits [28]. At the production-planning scale, the twin leverages yield priors to enhance sustainability optimization. A proven yield of 393 out of 400 functional qubits enables forward-yield inference before engaging in energy-intensive processing. Only wafer lots that meet a sustainability threshold enforced by autonomy are approved, ensuring that resources are directed towards high-probability successes [29]. Using around 75 dies for each 300 mm wafer, the hierarchical roll-up from die-level predictions to lot dispatch allows for consistent facility load profiles while maintaining throughput. The outcome is not a retrospective dashboard; rather, it is a closed-loop governor: a digital twin that connects microsecond timing with nanometer-scale physics to inform decisions at both the wafer and fleet levels [30]. By compressing embodied energy, reducing operational watt-hours, and enhancing device longevity, the twin creates the resilient, energy-focused operating stance that Industry 6.0 demands to ensure that quantum manufacturing is both economically and environmentally sustainable at scale.

4. Nanotechnology as a Governance Layer in Industry 6.0

In Industry 6.0, green nanotechnology has evolved from being an elementary bonus tool for sustainability to serving as a governance layer that converts measurable environmental reductions into executable control thresholds. Metrics for emission, energy, and eutrophication are integrated directly into scheduling rules, process recipes, and qualification standards, ensuring that environmental performance is monitored per unit throughput and consistently upheld throughout design, fabrication, and field operation [31]. Fig. (**4**) depicts the Industry 6.0 governance layer in which quantified environmental thresholds drive scheduling, recipes, and qualifications as closed-loop controls.

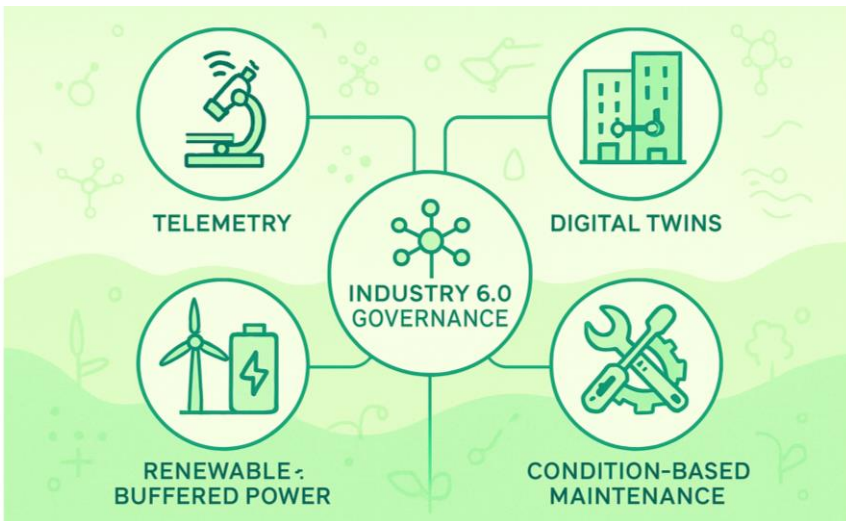

Figure 4: Industry 6.0 with green nanotech governance driving control.

Telemetry feeds a digital twin that tracks drift, defect-density, and per-unit energy/emissions; deviations trigger condition-based interventions rather than fixed schedules. A renewable-buffered power layer aligns tool starts, pump-downs, and cryo cycles with low-carbon availability, reducing peak draws and warm-up interruptions [32]. Material minimalism at atomic-scale thickness, yield-driven stability, condition-based maintenance (CBM), renewable buffering, and wafer-level statistical learning form the antifragile loop that lowers joules per logical operation [33]. The digital twin enforces thresholds as executable rules, enabling center-to-edge compensation and rule-based adjustments without additional energy overhead. The initial lever in this governance framework is a focus on minimalism in both materials and processes [34]. Controlling thickness at the atomic scale, whether in aluminum films for superconducting circuits or interconnect layers, guarantees that only the necessary material volume for optimal performance is applied [35]. Eliminating each nanometer decreases the energy required for upstream smelting and sputtering, while also lessening the cryogenic demands downstream. When combined with nearly flawless yields, such accuracy reduces the concealed energy expenses associated with scrap and rework, leading to stabilized takt times and more even facility load profiles [36].

Industry 6.0 utilizes telemetry informed by nanotechnology to establish durability as a key aspect of sustainability, focusing on both time and reliability. Drift and defect-density statistics are consistently analyzed, transitioning maintenance from predetermined schedules to condition-based triggers [37]. This eliminates unnecessary requalification cycles and avoids redundant cooling or ancilla provisioning, integrating energy efficiency into reliability itself. The connection with clean, buffered power systems completes the cycle. Improvements in solar efficiency and energy storage enhance the buffer capacity of fabs, enabling tools to manage renewable variability without causing disruptive peak draws [38]. There are fewer instances of furnace starts occurring during carbon-heavy hours, pump-downs experience less frequent interruptions, and cryogenic systems successfully bypass warm-ups triggered by the grid. Consequently, process energy is in harmony with a decarbonized supply instead of competing with it [39]. At the infrastructure level, Industry 6.0 eliminates the need to wait for new facilities by integrating nanotechnology-enabled control within existing production nodes. Standard lithography and CMOS-compatible stacks offer a well-established foundation for gathering high-density characterization data, allowing for the collection of tens of thousands of test structures per wafer [40].

These statistics drive autonomous digital twins that consistently map geometry, barrier formation, and frequency distributions, performing center-to-edge compensations that enhance coherence levels without requiring extra energy use. When considered as a whole, these mechanisms represent an ongoing decrease in joules used per logical operation rather than just isolated improvements in efficiency. Material minimalism, yield-driven stability, condition-based maintenance, renewable-buffered power, and wafer-level statistical learning come together to form a cohesive, antifragile manufacturing approach. Here, "antifragile design" is a manufacturing system that is more stable and energy efficient even when subjected to variations. Recipes, lot dispatch, and maintenance intervals can be dynamically adjusted in real-time using yield distributions, TLS defect statistics, and spatial coherence gradients. It does away with resistance to variability in favor of more stringent control limits and reduced joules per validated logical operation as a result of statistical deviations [41]. There are a few operational instances of this behavior, such as rejected lots and adaptive CBM. Through the lens of Industry 6.0, environmental performance has transformed from a constraint or afterthought into the primary control objective that directs production across all scales.

5. Risks, Challenges, and the Realistic Horizon

In Industry 6.0, the measurements that facilitate optimization also establish the control limits for the operation of autonomous systems. Spatial coherence gradients across 300 mm wafers, TLS-driven reliability tails, frequency variability across junction areas, cryogenic energy loads, and yield-cost dependencies together define the essential boundaries for achieving sustainability, scale, and reliability in harmony [42]. The differences seen in wafers and their changes over time require flexible management strategies. Achieving center-to-edge echo coherence in the range of approximately 42 to 113 μs necessitates localized adjustments to the processes of oxidation, etching, and annealing on the wafer [43]. In the absence of this spatially adaptive control, minor inconsistencies can escalate as the scale increases, leading to greater error-correction demands and higher energy consumption for each logical operation. Even a slight temporal drift, around 3.7% over a period of five months, influences TLS defect densities (approximately 34.4 defects/GHz) to initiate infrequent decoherence events [44]. Industry 6.0 tackles this issue by integrating distribution-aware statistical learning and condition-based recalibration directly into control loops, ensuring that maintenance is initiated based on real risk instead of predetermined schedules [45].

Precision is a vital limitation when it comes to scaling. Frequency spreads of 5 to 7% RSD in junction areas can be handled in pilot lots, but they become delicate at industrial volumes. Closed-loop metrology needs to operate in almost real time to adjust recipes and control tool drift; if not, yield losses directly result in increased energy used for rework [46]. In this context, precision serves as a regulator for both quality and energy. The integration of energy systems further influences operational risk. Despite significant advancements in renewable energy generation and storage, millikelvin refrigeration still presents a fundamental energy demand. Scheduling should optimize cryogenic duty cycles alongside renewable availability to avoid increases in carbon intensity due to off-peak grid draws or cryo warm-ups [47]. Industry 6.0 views energy as a coordinated control factor, closely linked to the pace of production. The limits of feasibility are shaped by economic and standardization constraints. Reaching yields close to perfection, like 393 functional qubits out of a 400-device lot on specialized CMOS, represents a significant technical achievement, yet it does not guarantee scalability [48]. Autonomous digital twins predict minimal functionality before executing process steps, discarding runs that do not meet energy-constrained limits, while the ability to transfer recipes across established 193 nm CMOS nodes guarantees that environmental benefits throughout the lifecycle are maintained without the need for expensive new developments [49].

Ultimately, scale brings about statistical fragility that requires careful management. Demonstration-level yields alone do not ensure reliability across the entire fleet. It is essential to implement procurement, scheduling, and maintenance strategies that take into account confidence intervals and tail protection. Each adjustment in the recipe, every job assignment, and all maintenance activities must concurrently decrease wafer-scale variance, lower energy consumption for validated routines, and lessen lifetime risk amidst uncertainty informed by TLS. An action enters the production system only when all three conditions are satisfied.

5.1. Sociotechnical and Ethical Constraints

Sociotechnical limitations brought about by the same measurement density that allows autonomous control in Industry 6.0 cannot be considered liabilities. The first limiting factor is the workforce transformation. Instrument certification, maintenance scheduling, and coherence telemetry are replacing operator judgment in process choices, which means that routine inspections will play a lesser role. Accounting at the system level, control interpretation, and statistical reasoning are required for the remaining positions [21]. This shift increases the danger of silent failure propagation rather than removing it because there are no organized reskilling channels; instead, operational authority is concentrated while human control is shrunk.

As a second limitation, data security becomes apparent. Industry 6.0 digital twins integrate energy telemetry, yield distributions, priors on defect density, and maps of wafer-scale coherence across different facilities. These databases store signatures of processes that are essentially the same as secret family recipes [41]. Dispatch rules, maintenance triggers, and energy thresholds can be changed without physically modifying hardware if unauthorized access or model manipulation occurs. With more and more control moving to software, cybersecurity is becoming a risk to production rather than data [34], necessitating governance measures as stringent as those for tool certification and recipe control.

A tertiary stipulation is ecological fairness. Supply chains for aluminum, high-purity silicon, rare-earth elements, specialty chemicals, and nanomaterials used in cryogenic infrastructure, sophisticated interconnects, and superconducting circuits are highly concentrated in certain geographic areas. Ignoring the effects of extraction, purification, and transportation can cause energy savings at the fab level to be counterbalanced upstream [50]. Thus, lifetime traceability is essential for Industry 6.0 sustainability claims, as in-fab efficiency measurements alone are insufficient. Reducing joules per logical process without holding sources explicitly accountable increases the likelihood of displacement over actual decarbonization.

These limitations do not stand in the way of Industry 6.0 implementation, but rather serve to outline its potential. Coherence control and yield optimization must progress in tandem with workforce adaptability, digital twin security, and material sourcing responsibility. They resurface as scalable failure modes if ignored. When they are incorporated into governance thresholds, they stabilize the system and maintain social legitimacy and technical performance simultaneously.

6. Outlook

A reliable Industry 6.0 roadmap is based on measurable elements: high-yield CMOS-based quantum fabrication, microsecond-scale coherence appropriate for utility-scale circuits, solid integration with clean energy and storage, and established green nanoprocess benchmarks. Scaling up occurs only when variance, energy, and lifetime risk reach specific thresholds, guaranteeing that growth is justified rather than taken for granted. In the short term (0 to 24 months), it is essential to industrialize pilot-line capabilities within multi-lot, multi-fab environments. The functional yield on 300 mm wafers is expected to be around 98.25% and should be consistently achievable under specific criteria. This includes reducing junction-frequency variance from 5 to 7% RSD to 3 to 4%, ensuring wafer-edge coherence remains above 100 μs, and demonstrating a quarter-on-quarter decrease in energy per validated routine while maintaining a constant takt [51]. The effective implementation of any recipe change relies on quantifiable decreases in both per-die embodied energy and in-field watt-hours for each successful routine. At the same time, integrating clean power needs to guarantee that cryogenic baseloads steer clear of carbon-heavy peaks, with storage capacity adequate to manage at least one complete cryostat warm-up or restart without any disruptions to the grid [52]. In this context, solar efficiency and battery capacity are viewed as service levels representing hours of independent fabrication operation rather than mere abstract percentages.

The mid-term horizon (24 to 60 months) focuses on growth while maintaining stability. Production shifts from hundreds to tens of thousands of devices each quarter only when spatially adaptive process control reliably sustains center-to-edge coherence within target bands, TLS-informed scheduling minimizes ancilla duty cycles, and condition-based maintenance prolongs recalibration intervals by specified multiples [53]. The standardization of portable process kits, 193 nm optical lithography, and CMOS-compatible stacks guarantees that new capacity is compatible with existing facilities, maintaining consistent performance across different locations instead of depending on isolated lab results [54].

Long-term growth over the next 5 to 10 years is determined by actual performance rather than mere excitement. The environmental performance across the entire line needs to match the standards set by green nanotechnology once network effects are considered [55]. Additionally, funding must be linked to clear reductions in energy consumption per logical operation, from fabrication to deployment, validated through precise measurement that differentiates end-use efficiency from the carbon intensity of the supply side [56]. Quality systems progress from inspection to prediction: high-density test-structure analytics complete the loop within control-cycle times, rejecting lots pre-commit when marginal functionality does not meet energy-constrained thresholds.

The realistic outlook for Industry 6.0 is thus determined not by a specific date but by certain conditions. Expansion achieves true scalability, financial sustainability, and ecological legitimacy only when yield, coherence, energy integration, and environmental intensity all meet strict, verifiable thresholds at the same time [57]. Up to that moment, the roadmap emphasizes reducing variance, solidifying energy baselines, and transforming each new capability into fewer joules per validated outcome, making certain that every growth step is dictated by physics rather than mere ambition.

7. Conclusion

Industry 6.0 transforms manufacturing by integrating sustainability, yield, and energy efficiency into all operational levels, from atomic-scale material deposition to the lifecycle management of quantum devices. High-yield CMOS fabrication, microsecond-class coherence, and TLS-informed predictive maintenance showcase how nanotechnology and digital twins convert precision control into energy and material efficiency. By setting strict limits on variance, energy, and lifetime risk, autonomous systems guarantee that growth remains scalable and environmentally sustainable. Integrating clean energy with adequate storage allows fabs to function without relying on carbon-heavy grid cycles. Additionally, condition-based recalibration and adaptive spatial control minimize waste and prolong asset lifespans.

The Industry 6.0 roadmap is shaped by measurable performance indicators rather than specific dates: functional yield (~98.25%), wafer-edge coherence (>100 μs), per-die energy efficiency, and fleet-level environmental metrics. Expansion happens only when these metrics are met together, guaranteeing financial sustainability, ecological legitimacy, and operational resilience. Industry 6.0 creates a new model for resilient, energy-efficient manufacturing by turning environmental goals into active control objectives and combining them with precise materials and processes, aligning industrial growth with global sustainability needs.

Conflict of 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.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

References

[1] Duggal AS, Malik PK, Gehlot A, Singh R, Gaba GS, Masud M, *et al*. A sequential roadmap to Industry 6.0: exploring future manufacturing trends. IET Commun. 2022; 16: 521-31. https://doi.org/10.1049/cmu2.12284

[2] Reddy CKK, Doss S, Pamulaparty L, Lippert K, Doshi R. Industry 6.0: technology, practices, challenges, and applications. 1st ed. Boca Raton: CRC Press; 2024.https://doi.org/10.1201/9781003517993

[3] Schrödinger E. Quantum mechanics 100 years on: an unfinished revolution. Nature 2025; 637: 251-2. https://doi.org/10.1038/d41586-025-00014-5

[4] Elzein B. Nano revolution: tiny tech, big impact: how nanotechnology is driving SDGs progress. Heliyon. 2024; 10: e31393. https://doi.org/10.1016/j.heliyon.2024.e31393

[5] Sharma S. Quantum-nano synergies: business potential and disruptions. Nanoscale Rep. 2019; 2: 41-4. https://doi.org/10.26524/nr1942

[6] Kumar U, Kumar R, Singh M, Singh M, Singh H, Singh R, *et al*. A critical review on history of industrial revolutions. AIP Conf Proc. 2025; 3185: 020097. https://doi.org/10.1063/5.0240534

[7] Center for Quantum Nanoscience. What is Quantum Nanoscience? Available from: https://qns.science/what-is-quantum-nanoscience/ (accessed 4 Sep 2025).

[8] Matityahu S, Shnirman A, Schön G, Schechter M. Decoherence of a quantum two-level system by spectral diffusion. Phys Rev B. 2016; 93: 134208. https://doi.org/10.1103/PhysRevB.93.134208

[9] López-Núñez D, Torras-Coloma A, Portell-Montserrat Q, Bertoldo E, Cozzolino L, Ummarino GA, *et al*. Superconducting penetration depth of aluminum thin films. Supercond Sci Technol. 2025; 38: 095004. https://doi.org/10.1088/1361-6668/adf360

[10] Devade K, Singh PK, Kumar S, Kumar H, Prasad B, Rao ALN, *et al*. Green nanotechnology based sustainable energy solutions and environmental impacts. In: E3S Web Conf. Vol 511. Gurugram, India: EDP Sciences; 2024. p. 01031. https://doi.org/10.1051/e3sconf/202451101031

[11] Malik S, Muhammad K, Waheed Y. Nanotechnology: a revolution in modern industry. Molecules. 2023; 28: 661. https://doi.org/10.3390/molecules28020661

[12] Kjaergaard M, Schwartz ME, Braumüller J, Krantz P, Wang JI-J, Gustavsson S, *et al*. Superconducting qubits: current state of play. Annu Rev Condens Matter Phys. 2020; 11: 369-95. https://doi.org/10.1146/annurev-conmatphys-031119-050605

[13] Putterman H, Noh K, Hann CT, MacCabe GS, Aghaeimeibodi S, Patel RN, *et al*. Hardware-efficient quantum error correction via concatenated bosonic qubits. Nature. 2025; 638: 927-34. https://doi.org/10.1038/s41586-025-08642-7

[14] Mullen E, Morris MA. Green nanofabrication opportunities in the semiconductor industry: a life cycle perspective. Nanomaterials. 2021; 11: 1085. https://doi.org/10.3390/nano11051085

[15] Gao J, Luo X, Fang F, Sun J. Fundamentals of atomic and close-to-atomic scale manufacturing: a review. Int J Extrem Manuf. 2021; 4: 012001. https://doi.org/10.1088/2631-7990/ac3bb2

[16] Tarasov MA, Chekushkin AM, Fominsky MYu, Zaharov DM, Lomov AA, Devitsky OV, *et al*. Superconducting thin films and tunnel junctions based on aluminum. Phys Solid State. 2022; 64: 1352. https://doi.org/10.21883/PSS.2022.10.54217.35HH

[17] Yang Z, Liu S, Li L, Chen Q, Shi C, Dong L, *et al*. From nano robotic manipulation to nano manipulation robot. SmartBot. 2025; : 1(3): e12021. https://doi.org/10.1002/smb2.12021

[18] Chen S, Yu VW, Jin Y, Govoni M, Galli G. Advances in quantum defect embedding theory. J Chem Theory Comput. 2025; 21: 7797-812. https://doi.org/10.1021/acs.jctc.5c00559

[19] Shadi MR, Mirshekali H, Shaker HR. Explainable artificial intelligence for energy systems maintenance: a review on concepts, current techniques, challenges, and prospects. Renew Sustain Energy Rev. 2025; 216: 115668. https://doi.org/10.1016/j.rser.2025.115668

[20] Van Damme J, Massar S, Acharya R, Ivanov T, Perez Lozano D, Canvel Y, *et al*. Advanced CMOS manufacturing of superconducting qubits on 300 mm wafers. Nature. 2024; 634: 74-9. https://doi.org/10.1038/s41586-024-07941-9

[21] Thulasi M, Faieza AA, Azfanizam AS, Leman Z. State of the art of dynamic value stream mapping in the manufacturing industry. JMMST. 2022; 6: 41-52. https://doi.org/10.15282/jmmst.v6i1.7376

[22] Liu I-Y, Winckel LV, Boakes L, Bardon MG, Rolin C, Ragnarsson L-Å. Modeling the energy consumption of integrated circuit fab infrastructure. IEEE Trans Semicond Manuf. 2024; 37: 422-7. https://doi.org/10.1109/TSM.2024.3408926

[23] Burkard G, Ladd TD, Pan A, Nichol JM, Petta JR. Semiconductor spin qubits. Rev Mod Phys. 2023; 95: 025003. https://doi.org/10.1103/RevModPhys.95.025003

[24] Ohba T, Sakui K, Sugatani S, Ryoson H, Chujo N. Review of bumpless build cube (BBCube) using wafer-on-wafer and chip-on-wafer for tera-scale three-dimensional integration. Electronics. 2022; 11: 236. https://doi.org/10.3390/electronics11020236

[25] Schmelz M, Mutsenik E, Bravin S, Sultanov A, Ziegler M, Hübner U, *et al*. Wafer-scale Al junction technology for superconducting quantum circuits. IEEE Trans Appl Supercond. 2024; 34: 1-5. https://doi.org/10.1109/TASC.2024.3350580

[26] Bar-Gill N, Pham LM, Jarmola A, Budker D, Walsworth RL. Solid-state electronic spin coherence time approaching one second. Nat Commun. 2013; 4: 1743. https://doi.org/10.1038/ncomms2771

[27] You Y, Chen C, Hu F, Liu Y, Ji Z. Advances of digital twins for predictive maintenance. Procedia Comput Sci. 2022; 200: 1471–80. https://doi.org/10.1016/j.procs.2022.01.348

[28] Abdurakhimov LV, Mahboob I, Toida H, Kakuyanagi K, Matsuzaki Y, Saito S. Identification of different types of high-frequency defects in superconducting qubits. PRX Quantum. 2022; 3: 040332. https://doi.org/10.1103/PRXQuantum.3.040332

[29] Arnold G, Werner T, Sahu R, Kapoor LN, Qiu L, Fink JM. All-optical superconducting qubit readout. Nat Phys. 2025; 21: 393-400. https://doi.org/10.1038/s41567-024-02741-4

[30] Dong Z, Lin Y. Ultra-thin wafer technology and applications: a review. Mater Sci Semicond Process. 2020; 105: 104681. https://doi.org/10.1016/j.mssp.2019.104681

[31] Vijay AJ, William BNJ, Haruna AA, Prasad DD. Exploring the synergy of IIoT, AI, and data analytics in Industry 6.0. In: Reddy CKK, Doss S, Pamulaparty L, Lippert K, Doshi R, Eds. Industry 6.0: technology, practices, challenges, and applications. 1st ed. Boca Raton: CRC Press; 2024, p. 36.

[32] Iliuţă M-E, Moisescu M-A, Pop E, Ionita A-D, Caramihai S-I, Mitulescu T-C. Digital twin: a review of the evolution from concept to technology and its analytical perspectives on applications in various fields. Appl Sci. 2024; 14: 5454. https://doi.org/10.3390/app14135454

[33] Hess P. Thickness of elemental and binary single atomic monolayers. Nanoscale Horiz. 2020; 5: 385-99. https://doi.org/10.1039/C9NH00658C

[34] Kantaros A, Ganetsos T, Pallis E, Papoutsidakis M. From mathematical modeling and simulation to digital twins: bridging theory and digital realities in industry and emerging technologies. Appl Sci. 2025; 15: 9213. https://doi.org/10.3390/app15169213

[35] Mathew PT, Rodriguez BJ, Fang F. Atomic and close-to-atomic scale manufacturing: a review on atomic layer removal methods using atomic force microscopy. Nanomanuf Metrol. 2020; 3: 167-86. https://doi.org/10.1007/s41871-020-00067-2

[36] Garg R, Gonuguntla S, Sk S, Iqbal MS, Dada AO, Pal U, *et al*. Sputtering thin films: materials, applications, challenges and future directions. Adv Colloid Interface Sci. 2024; 330: 103203. https://doi.org/10.1016/j.cis.2024.103203

[37] Ingemarsdotter E, Kambanou ML, Jamsin E, Sakao T, Balkenende R. Challenges and solutions in condition-based maintenance implementation: a multiple case study. J Clean Prod. 2021; 296: 126420. https://doi.org/10.1016/j.jclepro.2021.126420

[38] Caro-Ruiz C, Lombardi P, Richter M, Pelzer A, Komarnicki P, Pavas A, *et al*. Coordination of optimal sizing of energy storage systems and production buffer stocks in a net zero energy factory. Appl Energy. 2019; 238: 851-62. https://doi.org/10.1016/j.apenergy.2019.01.125

[39] Sovacool BK, Geels FW, Iskandarova M. Industrial clusters for deep decarbonization. Science. 2022; 378: 601-4. https://doi.org/10.1126/science.add0402

[40] Liu F, Christou A, Dahiya AS, Dahiya R. From printed devices to vertically stacked, 3D flexible hybrid systems. Adv Mater. 2025; 37: 2411151. https://doi.org/10.1002/adma.202411151

[41] Koenig F, Carwehl M, Imrie C. ResMetric: analyzing resilience to enable research on antifragility. In: 2025 IEEE/ACM 20th Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS). 2025. p. 32-8. https://doi.org/10.1109/SEAMS66627.2025.00012

[42] Trujillo-Sevilla JM, Roqué-Velasco A, Sicilia MJ, Casanova-González Ó, Ramos-Rodríguez JM, Gaudestad J. Wafer geometry technique for blank 300 mm silicon wafers. In: 2022 33rd Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC). 2022. p. 1-7. https://doi.org/10.1109/ASMC54647.2022.9792490

[43] Kim T, Lee J. Fabrication and characterization of silicon-on-insulator wafers. Micro Nano Syst Lett. 2023; 11: 15. https://doi.org/10.1186/s40486-023-00181-y

[44] Naeij HR. Open quantum system approaches to superconducting qubits. Quantum Inf Process. 2025; 24: 220. https://doi.org/10.1007/s11128-025-04838-y

[45] Hu Q, Guo Y, Cordy M, Xie X, Ma L, Papadakis M, *et al*. An empirical study on data distribution-aware test selection for deep learning enhancement. ACM Trans Softw Eng Methodol. 2022; 31: 78:1-30. https://doi.org/10.1145/3511598

[46] Osman A, Fernández-Pendás J, Warren C, Kosen S, Scigliuzzo M, Frisk Kockum A, *et al*. Mitigation of frequency collisions in superconducting quantum processors. Phys Rev Res. 2023; 5: 043001. https://doi.org/10.1103/PhysRevResearch.5.043001

[47] Cao H. Refrigeration below 1 kelvin. J Low Temp Phys. 2021; 204: 175-205. https://doi.org/10.1007/s10909-021-02606-7

[48] Bartee SK, Gilbert W, Zuo K, Das K, Tanttu T, Yang CH, *et al*. Spin-qubit control with a milli-kelvin CMOS chip. Nature. 2025; 643: 382-7. https://doi.org/10.1038/s41586-025-09157-x

[49] Zhang Q, Zhang Y, Luo Y, Yin H. New structure transistors for advanced technology node CMOS ICs. Natl Sci Rev. 2024; 11: nwae008. https://doi.org/10.1093/nsr/nwae008

[50] Fan YY. Demand prediction of production materials and simulation of production management. Int J Simul Model. 2022; 21: 720-31. https://doi.org/10.2507/IJSIMM21-4-CO20

[51] Neyens S, Zietz OK, Watson TF, Luthi F, Nethwewala A, George HC, *et al*. Probing single electrons across 300-mm spin qubit wafers. Nature. 2024; 629: 80-5. https://doi.org/10.1038/s41586-024-07275-6

[52] Nagapurkar P, Das S. Economic and embodied energy analysis of integrated circuit manufacturing processes. Sustain Comput Inform Syst. 2022; 35: 100771. https://doi.org/10.1016/j.suscom.2022.100771

[53] Meshalkin VP, Stoyanova OV, Dli MI. Project management in the nanotechnology industry: specifics and possibilities of taking them into account. Theor Found Chem Eng. 2012; 46: 50-4. https://doi.org/10.1134/S0040579512010101

[54] Zhu J, Liu X, Wang Q, Li Y, Wu Q, Li Y. A study of the via pattern lithography process window under the 7 nm logic design rules with 193 nm immersion lithography. In: China Semiconductor Technology International Conference (CSTIC). Shanghai: IEEE; 2024. p. 1–3. https://doi.org/10.1109/CSTIC61820.2024.10531838

[55] Huang X, Auffan M, Eckelman MJ, Elimelech M, Kim J-H, Rose J, *et al*. Trends, risks and opportunities in environmental nanotechnology. Nat Rev Earth Environ. 2024; 5: 572-87. https://doi.org/10.1038/s43017-024-00567-5

[56] Dhingra R, Naidu S, Upreti G, Sawhney R. Sustainable nanotechnology: through green methods and life-cycle thinking. Sustainability. 2010; 2: 3323-38. https://doi.org/10.3390/su2103323

[57] Shim W, Natelson D, Arbiol J, Besley E, Dionne JA, Herrmann C, *et al*. The next 25 years of nanoscience and nanotechnology: a Nano Letters roadmap. Nano Lett. 2025; 25: 12789-98. https://doi.org/10.1021/acs.nanolett.5c04115