



THE ROADMAP TO AUTONOMOUS OPERATIONS

ENGINEERED
TO OUTFIT



INTRODUCTION

Autonomous Operations is emerging as the defining differentiator of the next industrial era.

Energy and industrial organizations are navigating a convergence of pressures: accelerating energy demand, regulatory complexity, grid and supply chain volatility, workforce scarcity, and climate-driven disruption on top of unrelenting expectations for higher uptime, quality and safety at lower operating costs. Addressing this complexity demands both advanced technology and sustained organizational change.

This is a pivotal moment for industries.

To remain globally competitive, industrial owners and operators are seeking greater visibility, control, and resiliency from their investments.

Competitiveness demands more than automation running the process; it requires integration of software and AI that help industries advance toward Autonomous Operations. Digitalization is happening at an increasingly rapid rate. This next evolution empowers facilities to self-optimize, adapt to dynamic conditions, and make data-driven decisions with minimal human intervention. The benefits are transformative: improved reliability and productivity, reduced energy consumption, emissions, and costs. Ultimately, industrial companies will maintain their competitive edge.

Building on our vision outlined in **The DCS of Tomorrow: Our Process Automation System Vision**¹, this whitepaper explores how industries can progress along the autonomous journey beginning with automation and advancing through multiple stages toward fully Autonomous Operations. This paper highlights the key milestones, benefits and strategies that enable organizations to capture value at every step.

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Drawing on more than 40 years of leadership in automation, ABB's Energy Industries division shares its perspective on how integrated technologies can advance Autonomous Operations.

¹ <https://new.abb.com/control-systems/control-systems/envisioning-the-future-of-process-automation-systems/automation-system-whitepaper>



TAXONOMY OF AUTONOMOUS OPERATIONS

For many decades, automation has played a key role in enhancing efficiency and empowering operators to manage increasingly complex energy-intensive facilities.

Industrial control has evolved from mechanical and electromechanical systems to digital architectures. Beginning in the 1970s, PLCs transformed machine level automation while DCS architectures emerged to handle the complexity and scale of continuous process industries. Rather than replacing PLCs, DCS systems expanded the automation landscape and today form the core of high availability process operations, an area where ABB is the global market leader².

Conventional automation systems have been highly effective at managing rule-based control algorithms and advanced process control under normal conditions. Yet, complex tasks and setting priorities still depend on human judgment. This is rapidly changing as AI development enables systems to move beyond rigid rules toward higher-level decision making, laying the foundation for truly Autonomous Operations.

The acceleration of AI deployment

Advances in underlying technologies have significantly accelerated deployment. Today, systems are highly intelligent and complex, applied across a wide range of industries. Latest developments in both AI techniques and automation have turbocharged progress toward being autonomous systems that can learn and understand how to independently change their behavior in response to unanticipated events without manual intervention.

According to Stanford University's Human-Centered Artificial Intelligence (HAI) analysis, **78% of global enterprises deployed AI systems in their workflows in 2024—a dramatic leap from just 55% one year earlier³**, representing a 42% increase in adoption in a single year.



² <https://new.abb.com/control-systems/the-most-popular-dcs>

³ https://hai.stanford.edu/assets/files/hai_ai_index_report_2025.pdf

UNDERSTANDING AUTOMATION VS. AUTONOMOUS

The terms “automation systems” and “autonomous systems” are often treated as distinct, when in fact both are part of the wider story of autonomy in industry. ABB’s Energy Industries division outlines definition of each below.



Automation refers to a process or system that performs tasks with minimal human intervention, but within precisely defined instructions and a limited scope of operation. Automated algorithms may act on myriad inputs and attain considerable complexity, but the input data is highly structured, and the range of possible actions is limited. Therefore, conventional automation systems enable low-level processes and advanced process control to run without human intervention under normal conditions, but human decisions are still required for more complex tasks and when anomalies outside set conditions arise.

Autonomous, unlike automation, enables a system to independently change its behavior in response to unanticipated events during operation. There are no clear parameters and rule-based responses that it must abide by. Inputs are considerably less structured and call for a greater range of reactions that the system must itself determine. It has the capability to learn and autonomously adapt to changing conditions. Making automation systems more autonomous is about progressively handing over more and more tasks to the system and enabling it to continually learn so it can calibrate a response in real-time.

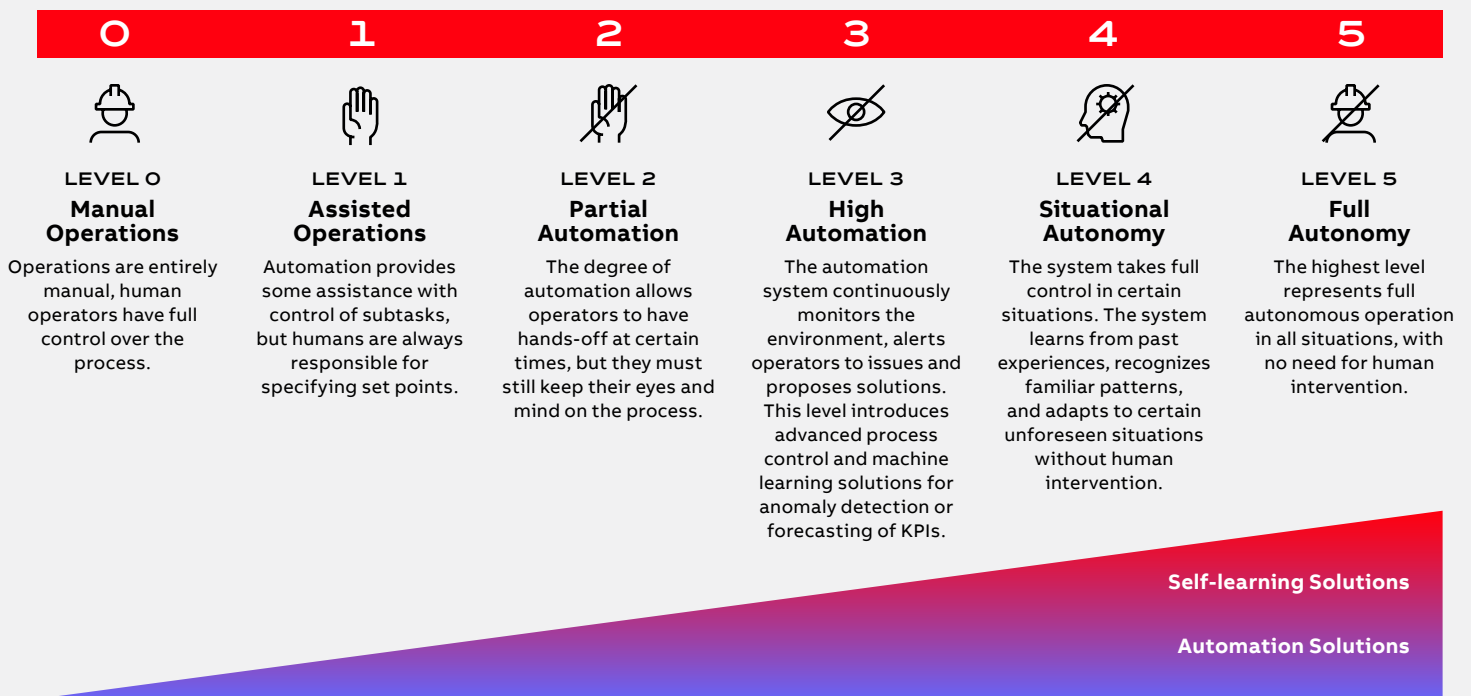
THE SIX LEVELS OF INDUSTRIAL AUTONOMY

A journey across levels

ABB has established a structured, use-case-driven framework for industrial autonomy, supported by references across multiple domains [1–5]. At its core is a multi-level autonomy taxonomy (Figure 01), closely aligned with ARC’s industry taxonomy [6] and similar to the principles used in the SAE levels for autonomous driving.

Each level is defined by degree of autonomy, ranging from Level 0 (manual operations) to Level 5 (full autonomy). Autonomy in industry should not be seen as a single state, but rather as a journey along these levels. There is no such thing as “the one autonomous plant” but plants can be characterized by the level of autonomy they have reached.

Autonomy levels in industrial applications | Taxonomy⁴



01 Taxonomy of autonomy levels in industry

Transitioning from completely manual to full autonomy is not a one-step process but an incremental journey. Lower levels of autonomy are achieved through automation solutions, while higher levels require the integration of advanced, self-learning, AI-enabled solutions.

⁴ https://library.e.abb.com/public/17e186f5547b476386be9f9376dd09ed/08-11%20m8099_EN_72dpi.pdf

THE DRIVERS FOR AUTONOMOUS OPERATIONS

Autonomy in industrial operations is never implemented in isolation, it is driven by a strong business case, a clear value proposition, and the need to maintain safe and reliable operations.

The path toward a higher level of autonomy



Improved safety

Autonomy removes people from hazardous environments; process safety incidents occur five times more frequently during start-up than normal operations



Efficiency and productivity gains

Autonomy enables continuous optimization without manual intervention, delivering increase energy and process efficiency with overall productivity gains



Flexibility, scalability, agility

Autonomous systems implement operational adjustments faster than manual operations, offering real-time responses



Reducing life cycle costs

Digital and Autonomous Operations can reduce life cycle costs



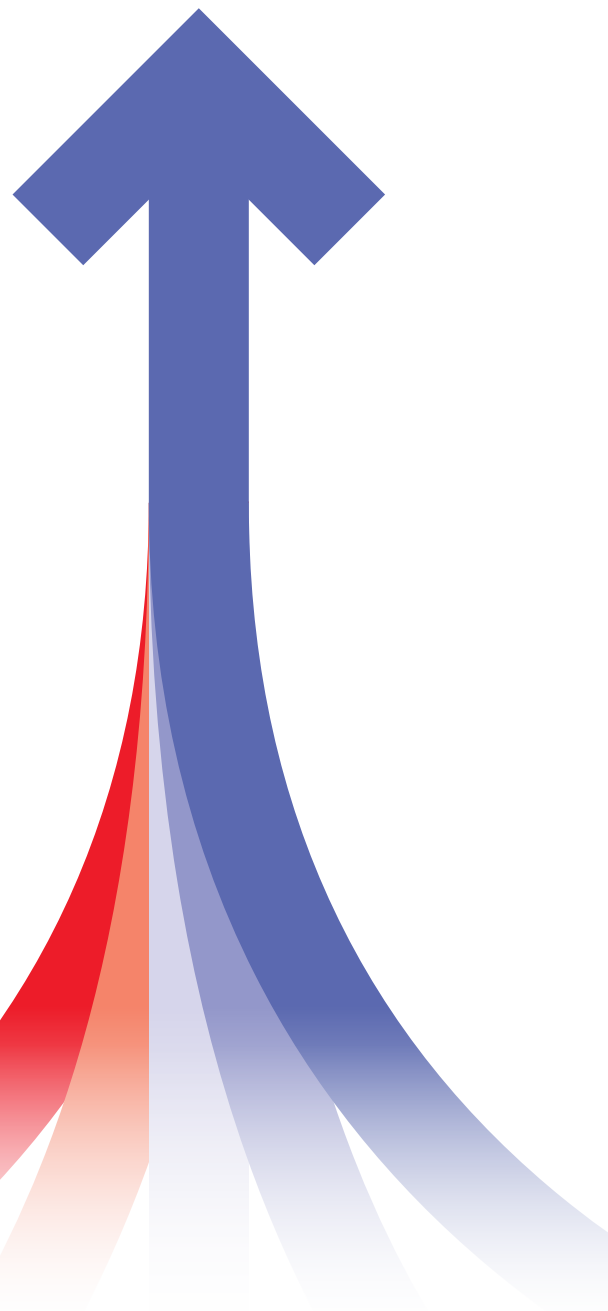
Mitigating skills shortages

2.5 million job openings for machine and plant operators need to be filled in Europe alone between 2022 and 2035⁵



Enabling energy transition

Process automation and autonomy-driven efficiency gains reduce carbon emissions while supporting compliance reporting



⁵ <https://www.cedefop.europa.eu/en/data-insights/machine-and-plant-operators-skills-opportunities-and-challenges-2023-update>

IMPLEMENTATION STRATEGY

Developing toward a higher level of autonomy will transform processes and the day-to-day running of a facility, meaning there are considerable organizational and adoption issues to address. Success requires careful planning across multiple dimensions. This progression requires not just technological maturity but also organizational readiness, regulatory frameworks and demonstrated reliability.



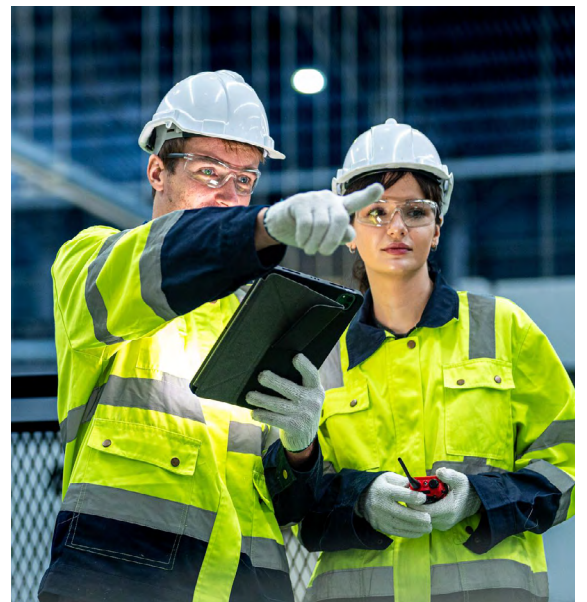
Workforce

For autonomy to be successful, it needs the buy-in of the workforce. Employees must be brought along on the journey in a collaborative approach, including training through the stages. For more advanced stages such as augmented and remote operations, companies will need to devise training strategies to upskill personnel in how to work with remote systems and advanced technologies. As sites scale up the levels of autonomy, the cognitive load of industrial workers declines in tandem which presents a critical challenge. While they are required to intervene less, they still must maintain a high skill level. Similar to an airline pilot leveraging autopilot technology, the pilot must be ready to take over when issues arise. Operating personnel need to go through regular simulation-based training to maintain and grow their skill levels, even when they are not required to use those core skills as often. Many operators are keen to adopt Autonomous Operations to address skills shortages and attract upcoming generations that are digital natives and expect different working conditions.



Regulatory

Industry standards that were written for traditional concepts are not always appropriate or relevant in supporting unattended or highly automated operations. Operators must consider regional and national regulations and how increasing levels of autonomy affect compliance. They will need to conduct a thorough risk assessment for all these factors to ensure trust and confidence within autonomous systems across the organization from control room floor to the executive suite.



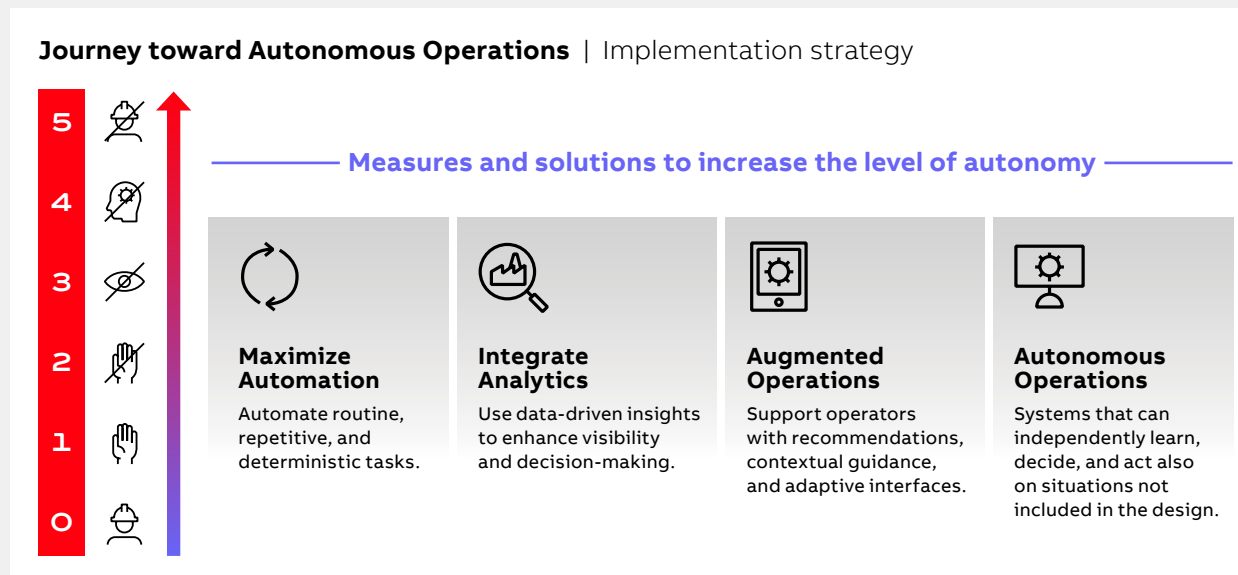
THE TOOLBOX APPROACH TO IMPLEMENTATION

Advancing toward autonomy is best understood as a toolbox approach. Rather than following a fixed sequence, operators can select from a range of solutions depending on the industry use case, value proposition, and the legal, regulatory context in which they operate. This flexibility enables autonomy to be adopted incrementally and scaled across operations.

As autonomy levels increase, more data will be captured within the facility. This data supports integrated analytics and self-learning capabilities, which further shift the balance of tasks from the human operator to the Process Control System. The specific allocation of tasks will depend on the business model of the process plant and the measures implemented.

Toolboxes for the transition

ABB supports this journey by offering solutions categorized into four toolboxes. These categories contain different ABB technologies that can be deployed independently or in combination, without a prescribed order. Each solution contributes to increasing autonomy levels while serving distinct operational outcomes.



02 Measures and solutions to increase the level of autonomy in industry.

HOW AI ENABLES HIGHER AUTONOMY LEVELS

Artificial intelligence is the critical enabler to move toward higher autonomy levels. While conventional automation relies on predefined rules and structured inputs, AI-enabled systems can handle unstructured data, learn from experience and adapt to unforeseen situations. To achieve a higher level of autonomy, both technologies are essential and must work together in close coordination.

AI in anomaly detection

Machine learning algorithms continuously analyze operational data to identify patterns that precede equipment failures or disruptions in processes. Unlike rule-based systems that only detect known fault signatures when they occur, AI models can recognize the earlier warnings in subtle deviations from normal operation. These systems learn what 'normal' looks like for each piece of equipment and process condition, then flag anomalies early enough for proactive intervention.

AI in predictive maintenance

AI systems process data from multiple sources such as vibration sensors, temperature readings, process parameters and historical maintenance records, to predict when equipment will require maintenance. This moves operations from reactive or time-based maintenance to condition-based maintenance, reducing unplanned downtime and extending asset life. AI continuously refines its predictions as it learns from actual failure and maintenance outcomes.

AI in process optimization

Advanced process control has traditionally relied on model-based approaches that require significant engineering effort to develop and maintain. AI-enabled systems can learn optimal operating strategies directly from data, adapting to changing feedstocks, product specifications and equipment conditions. These systems can balance multiple objectives, such as maximizing throughput, minimizing energy consumption and ensuring product quality, in real time.



AI in decision support

AI systems provide operators with concrete recommendations when abnormal situations arise, based on analysis of similar past events and their outcomes. Advanced AI can simulate different response strategies, allowing operators to evaluate options before taking action. This augmented decision-making accelerates response times and improves outcomes.

Self-learning capabilities in AI

An AI system's ability to handle situations not explicitly anticipated during design requires self-learning capabilities where the AI continuously updates its understanding based on new data and experiences. Neural networks and deep learning architectures enable this adaptive behavior, allowing the system to recognize familiar patterns in unfamiliar contexts and generalize from past experiences to new situations.

IMPLEMENTATION ACROSS PLANT OPERATION PHASES

Autonomy will look different depending on the complexity of the operation, the use case, goal of adoption and the operational phase. The ease of deployment will be determined by plant complexity, cultural aspects, regional regulations and the business case.



Engineering phase: Autonomy can dramatically accelerate engineering. Common applications include AI systems automatically digesting piping and instrumentation diagrams (P&IDs) and writing code. This can range from reusing simple artifacts, such as libraries for process control, to full model-based engineering with no manual automation engineering required.

Ramp down and ramp up: Autonomy can support faster industrial process start-up and shutdown sequences that requires fewer personnel and less safety risk. Levels of automation can range from stage-by-stage guidance by the system with tasks triggered manually, to fully automated operations that only alert the operator if an unusual situation arises. In the future, the system could take full responsibility handling all unforeseen abnormal situations, optimizing start-up itself.

Field operations: A higher level of autonomy in field operations can save significant time and money while minimizing safety risks. At a basic level, the system can notify personnel about the need for field activities rather than requiring scheduled physical checks, and drones can be deployed for inspection. At the more advanced end, full autonomy would require no manual actions except during planned maintenance.

Steady state: The most important stage of any operation is steady state, where the facility operates under normal conditions and delivers the desired output. Adoption of automation in this phase is the most common and most consequential to safe and profitable operation. It's also the operational state where autonomy is typically most advanced. At this stage, autonomy can maximize efficiency and reliability through automation, integration, and optimization of the entire facility.

Abnormal situations: Autonomy is crucial in handling abnormal situations, such as equipment failures or process upsets. Here, rapid and effective response can prevent safety risks and costly downtime. In many sites, these situations are still handled in manual operation. However, more autonomous systems including advanced AI technologies can predictively detect anomalies, analyze data, and either recommend or in special cases also take corrective actions without hesitation. This speed and consistency ensure issues are managed efficiently, reducing risk and maintaining smooth operations as plant complexity increases.

IMPLEMENTATION EXAMPLES

Augmented Operation: Climbing autonomy levels with operator assistance systems

Before: Level 2-3

The plant is equipped with a DCS system using advanced process control. It's well-connected with secure data access and historical data from plant automation is available, but the operator is responsible for corrective actions.

After: Level 3-4

Advanced operator assistance is incorporated to react to unanticipated events: the system continuously analyzes the process and gives very early warning on abnormal situations. It offers concrete solutions based on past success strategies. AI-based simulation of plant behavior enables an operator to try out different solutions and make robust decisions. The plant is highly automated in steady state operation. Operators are assisted with decision support when abnormalities arise. Plant behavior can be quickly simulated to decide on the best course of action.

Maximizing Automation – DCS with State Based Control (SBC)

Before: Level 2

Manual control design adaptation for different plant stages (e.g., during different production phases) is required. Highly skilled operators are needed for adaptation of set-points, alarm levels, etc., for different stages.

After: Level 3

State Based Control, which manages a system's operation by identifying and responding to different states or phases of the process, automatically monitors plant behavior and switches between different states. Manual intervention of plant operations is reduced to a minimum. Fast adaptation to different plant states leads to more efficient and time-reduced intervals in non-productive steady state phases.

Integrated Analytics – Predictive Maintenance with Condition Monitoring

Before: Level 1

Labor-intensive manual inspection rounds in the plant are undertaken to look after analyzers and measurement devices. Unforeseen plant disturbances due to unexpected malfunctioning devices are frequent and costly.

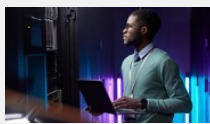
After: Level 3

On-premises analytics-based condition monitoring with automated reporting and fast resolution support is implemented. The operator has Cloud-based plant and fleet view for overall predictive maintenance planning. This means manual maintenance tasks are supported by advanced analytics providing a drastic reduction of labor and time investments. Predictive maintenance processes also allow for a fleet-wide service strategy with centralized operations and minimum labor involvement.

THE FUTURE OF AUTONOMOUS OPERATIONS

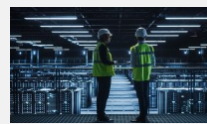
Enabling technologies that drive the future

Underpinning the shift to greater autonomy is a trusted control system integrated with new technologies. Several key technologies that were once emerging but have now substantially matured and continue to do so. They include:



Artificial intelligence and machine learning

Self-learning algorithms that enable systems to handle unanticipated events and continuously improve performance



Cyber security

Robust security frameworks that protect increasingly connected industrial systems from threats



Cloud and edge computing

Distributed processing power that enables real-time analytics and decision-making at the edge while leveraging cloud-based fleet analytics



Digital twins

Digital replicas of physical assets that enable simulation, optimization and predictive capabilities



Smart sensing

Advanced sensors and soft sensors that provide richer operational data and support AI-driven insights



Drones

Automated field inspection and maintenance capabilities that reduce human exposure to hazards

These technologies are not solutions by themselves but enablers that help a facility progress toward greater autonomy levels. Control systems are evolving toward open, standards-based architectures, enabling interoperability between assets, vendors and platforms for a scalable, more flexible approach.

Stepwise evolution toward Autonomous Operations

The vision for industries is to achieve a higher level of autonomy where systems not only manage steady-state conditions but can also independently navigate process upsets, start-ups and shutdown scenarios. This ambition is no longer a distant goal. Advances in automation and digital technologies, growing trust in remote operations, and the drive toward decarbonization are accelerating this industry transformation.

As industries move toward more Autonomous Operations, they can expect to unlock operational agility, lower costs, safer and more sustainable production. Although the foundational technologies already exist, deployment today at upper autonomy levels remains limited. The challenge now lies in bridging the gap between potential and implementation.

Seventy-three percent of executives believe that companies failing to embrace industrial realignment, which includes Autonomous Operations, will be irrelevant within a decade, according to a PwC survey of over 500 C-suite leaders in the industrials and energy sectors⁶.

⁶ <https://www.pwc.com/us/en/industries/industrial-products/library/future-of-industrial-products.html>

OUR ROLE IN THE AUTONOMOUS FUTURE

ABB's Energy Industries division enables this journey with future-proof, upgradeable systems that support both greenfield deployments and legacy modernization. Our portfolio is built to protect past investments while seamlessly integrating new capabilities.



With more than 40 years of hands-on experience guiding customers toward higher autonomy, ABB brings the credibility, deep expertise, and industry leadership needed to advance this evolution with confidence.

In this evolving landscape, autonomy becomes more than just a technological milestone. It becomes a strategic enabler. By leveraging ABB's integrated electrification, automation and digital solutions, industries can move confidently toward an autonomous future that enhances efficiency, safety and sustainability.

The path to autonomy is not about racing to Level 5 but rather identifying the right level of autonomy for each use case, implementing it thoughtfully and building organizational capability alongside technological capability.

— Success requires a holistic approach that addresses technology, people, processes and governance. With the right strategy and partners, industries can navigate this transformation and emerge more competitive, resilient and sustainable.

Ready to explore what the next level of autonomy could look like for your operations?

SPEAK WITH AN ABB EXPERT



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