DISCUSSION PAPER

An analysis of Industrial Sustainability for Potential Collaborations: A study across EU, U.S., and Japan

as Phase II Discussion of

Revitalizing Human-Machine Interaction

for the Advancement of Society

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Outline

Foreword

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The COVID-19 pandemic has brought about major changes in everything from people's lifestyles to their values. The supply chain disruptions that occurred during the pandemic encouraged the rise of policies prioritizing the domestic economy and were one of the factors that accelerated the formation of economic blocs. Furthermore, remote work, which became mainstream during the pandemic, has permeated society as a new way of working and is also changing how we think about employment and education. And in Europe and Japan, where the energy crisis has become more serious due to Russia's invasion of Ukraine, we have been forced to reconsider our policy of replacing fossil fuels and nuclear power with renewable energy sources such as solar and wind power.

In Japan, the United States, and Europe, economic growth driven by demographic bonuses is a thing of the past. For the past fifteen years, these regions have been working to advocate for the digitalization of society as another growth driver. However, due to changes in people's and society's values caused by the pandemic and the energy crisis, labor productivity in each region has not improved as expected.

Eight years ago, we gathered experts from Germany and Japan to discuss the impact of digitalization on society, organized the issues, and proposed a way forward. However, now that society has undergone the major changes described above, we have once again gathered experts from Japan, the United States, and Europe to review the current status and challenges of the effectiveness of digitalization and to clarify future issues that will require international cooperation.

The frank discussion was extremely lively, and by mutually evaluating the similarities and differences between the policies of each region, a common understanding was reached, which I believe has increased momentum for future international cooperation. I hope that the readers of this book will also take the initiative to deepen their understanding as individuals involved in these issues and actively participate in future discussions and activities.

Mr. John DYCK, Project Co-leader
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The question of how industrialized societies navigate the convergence of global disruption, demographic transition, and rapid digitalization is no longer theoretical—it is urgent. Today, we are living through a time of unprecedented change; geopolitical stability is increasingly volatile, and the very fabric of work is being redefined by Artificial Intelligence (AI) and automation. In this context, the pursuit of industrial sustainability is no longer a goal—it is a prerequisite for societal and economic resilience.

This paper presents a critical examination of how three highly industrialized regions—Japan, the United States, and Germany—are confronting these challenges through different yet interconnected strategies. It highlights the role of digital transformation (DX), policy innovation, and cross-sector collaboration in driving sustainable outcomes for industry and society. I am deeply honored to have participated in this trilateral effort, which builds on years of thoughtful dialogue and cooperation among experts, institutions, and regions committed to advancing human-centric and ecologically responsible industrial ecosystems.

Each region brings a unique perspective to the table. Japan's Society 5.0 framework integrates technological advancement with societal well-being, focusing on how digital tools can enhance the quality of life. The United States, through initiatives like Manufacturing USA, emphasizes innovation and market-driven solutions that balance economic growth with environmental stewardship. Germany, meanwhile, offers a regulatory model rooted in sustainability, data sovereignty, and ethical governance—embodied in programs such as Industry 4.0 and Manufacturing-X. By understanding these diverse approaches and the values that underpin them, we uncover new opportunities for mutual learning and policy convergence.

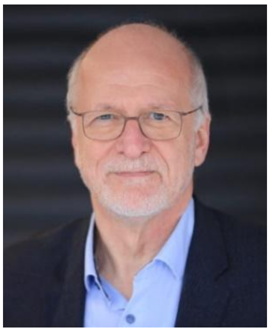
One of the most striking themes of this paper is the transformative potential of human-machine collaboration. As digital technologies—including AI, robotics, and intelligent systems—continue to evolve, so too does their capacity to reshape the nature of labor, productivity, and workforce development. However, as the paper rightly emphasizes, automation should not be about displacing human potential but augmenting it. We must reimagine our production systems in ways that empower workers, bridge skills gaps, and embed ethical considerations at every level of implementation. This includes addressing critical Ethical, Legal, and Social Issues (ELSI), which vary significantly by region, but are universally relevant to the future of industry.

Another key takeaway is the recognition that industrial sustainability is as much about social systems as it is about technology. Achieving significant productivity growth and energy resilience requires more than technological breakthroughs—it demands coordinated action among governments, industries, research institutions, and local communities. Initiatives like CESMII in the United States, the Strategic Innovation Promotion (SIP) program and Society 5.0 programs in Japan, and Germany's Plattform Industrie 4.0 and Manufacturing-X all demonstrate the importance of aligning national strategies with regional needs and global imperatives.

At the heart of this work lies the principle of cooperation. The trilateral partnership showcased in this discussion paper is not only a framework for sharing knowledge and aligning objectives—it is a testament to the power of trust, transparency, and shared vision. In an increasingly fragmented world, such collaboration is not just desirable—it is essential.

I encourage readers of this paper to engage with its findings critically and constructively. Let it inspire conversations in boardrooms, classrooms, and policy forums. Let it serve as both a reference and a catalyst—for investment, for reform, and for action.

Our industrial systems are being transformed. The path forward must be deliberate, thoughtful, and collaborative. I believe this work contributes meaningfully to that endeavor.



Mr. Thomas HAHN, Project Co-leader
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The 21st century's digital world demands a new paradigm of international cooperation. As we navigate through complex challenges in this digital world, the imperative for a resilient but also global collaboration has never been more crucial for sustainable economic growth and technological advancement.

Additionally, the convergence of aging populations and declining workforces presents a critical challenge for the global economy, particularly in developed nations. Organizations must carefully balance these elements, ensuring their operations are not only profitable but also environmentally responsible and adaptable to rapid change. This challenge is amplified by the accelerating demand for digital skills in an increasingly technology-driven business landscape. The gap between available talent and required expertise in areas such as AI, data analytics, and DX continues to widen. Organizations must adapt through strategic workforce planning to address this demographic challenge while ensuring a competitive advantage in the digital economy.

In this context, the triad of resilience, sustainability, and competitiveness has emerged as the cornerstone of successful business strategies. Organizations must balance these elements carefully, ensuring their operations are not only profitable but also environmentally responsible and adaptable to rapid change. This includes developing resilience, implementing sustainable practices and production processes, and maintaining an agile business to stay competitive in response to global challenges.

Through strategic international collaborations, supported by initiatives such as the German Plattform Industrie 4.0 and International Manufacturing-X (IM-X), we build robust global partnership networks. We create a cooperation network that can better understand regional needs, optimize resource utilization, face the aforementioned challenges together, learn from each other, and develop countermeasures for these challenges.

In this document, we analyze the key perspectives of Industry 4.0, primarily focusing on Germany's Plattform Industrie 4.0 initiative while incorporating broader European developments and insights. This comprehensive approach ensures a thorough understanding of both the German and European industrial transformation landscapes.

Executive Summary

This paper provides an overview of Japan, the United States, and Europe's efforts in industrial sustainability from the perspectives of labor productivity, changes in the labor force, and planetary boundaries such as energy and microplastics pollution. It then evaluates key cross-regional similarities and differences, and outlines opportunities for international collaboration, especially in the context of accelerating social transformation through digitalization and human-machine interaction (HMI).

Each region is working on digitalization measures to drive economic growth through collaboration between industry, academia, and government. Notable initiatives include Japan's SIP, the United States' Manufacturing USA network, and Europe's Industry 4.0-related programs under frameworks such as Horizon Europe and the Digital Europe Programme. These initiatives not only aim to boost industrial competitiveness through advanced manufacturing and digital integration but also respond to growing environmental concerns and energy transition needs. Japan's Society 5.0 aims to establish a cyber-physical space that uniquely combines technology that prioritizes societal well-being and human-centered innovation, particularly in response to its demographic challenges. The United States emphasizes digitalization and advanced manufacturing as tools to link decarbonization with energy security, economic vitality, and innovation pathways. Meanwhile, the EU, with its multinational structure and diverse economic situations, places emphasis on regulatory frameworks and policy-driven sustainability, emphasizing aligning manufacturing with environmental and social goals through comprehensive policies and regulations.

We analyzed the persistent stagnation in labor productivity across all three regions since Industry 4.0 was proposed after the 2008 global financial crisis. During the era of liberalization (1980s-2000s), productivity gains in developed countries such as Japan, the United States, and Europe were achieved by offshoring low-value manufacturing processes while retaining high-value-added activities domestically, based on the premise of open global free trade. However, in the aftermath of the 2008 financial crisis, the expansion of free trade stagnated due to rising geopolitical risks, trade frictions, and supply chain vulnerabilities. In this context, Industry 4.0, which was proposed in 2011 as a framework to boost productivity through digitalization, automation, and data-driven manufacturing has attracted global attention; however, our analysis suggests that its productivity gains have yet to materialize at scale.

Regarding decarbonization and environmental issues, all three regions are working to reduce greenhouse gas (GHG) emissions and promote renewable energy, transition to a circular economy, improve resource efficiency, and reduce waste. In terms of energy strategies, approaches vary depending on the circumstances of each region., Japan is promoting decentralization of semiconductor manufacturing and data center construction in line with its regional energy mix strategy. The U.S. is in a period of transformation, where decarbonization is no longer treated solely as emissions reduction but as an integrated strategy that balances climate goals with energy security, economic vitality, and technological leadership, pursued through a pragmatic balance that sustains industrial competitiveness while strengthening America's role as a global leader. Facing rising energy costs and geopolitical risks, the EU is working to reduce Russia's dependence on fossil fuels, integrate renewable energy, and harmonize infrastructure development among member states through its REPowerEU plan.

Regarding the labor force, Japan, the United States and Europe all share common challenges, such as poor incentives compared to other industries and an aging workforce with expert knowledge. Our findings align with recent studies that digital technologies—including generative AI, automation, and smart systems—are rapidly reshaping labor markets, accelerating job polarization, and fundamentally transforming the nature of work. We categorized human labor into three domains: simple labor requiring limited training, skilled labor that can be developed through structured education and experience, and highly creative and analytical labor. And automation and AI are rapidly transforming or replacing many mid-skill roles while creating new demand for both high-skill cognitive roles and low-skill service roles—contributing to a polarization of the labor market.

These trends underscore the urgent need to systematically reassess how tasks are distributed between humans and machines—not only to enhance efficiency but to ensure societal well-being within planetary boundaries.

In particular, we need to have a serious discussion about the fact that automation and AI are increasing, rather than decreasing, the low-skill labor market. Although much of low-skilled work is low-profit, it is essential work to support society. In the near future, it may be difficult to fully automate low-skilled work due to the lack of technological capabilities and high costs. In addition, human abilities and preferences are diverse and cannot be treated as high-skilled work alone. That is, for the sustainability and well-being of society, all humans must be accepted with psychological satisfaction by participating in social roles.

Also, the rapid deployment of advanced HMI systems—driven by generative AI, robotics, and automation—raises profound ELSI that vary across regions due to differences in cultural values, regulatory frameworks, and governance philosophies.

As a goal for solving these challenges, we have formulated a vision named Harmonized Symbiotic Society in which the environment, happiness, and economic growth are in harmony, premised on the symbiosis of humans and machines.

Emerging from the discussion is the role of HMI, as one of the important and unifying frameworks through which the complex issues of technology, labor, and sustainability can be addressed. To support this transformation, we present three strategic recommendations aimed at business executives engaged in smart manufacturing, government policymakers, and researchers focused on the future of work and industrial sustainability.

1. **Enhancing Human-Centered Work Through Digital Transformation**

   Redefine the role of work in a sustainable, equitable, and human-centric industrial economy by leveraging digital technologies to augment human capability, expand access to meaningful employment, and increase individual motivation to participate in the workforce.

2. **Essential Labor that Machines Should Support**

   Identify, empower and support roles in the category of socially essential labor. These roles include public and environmental services that contribute directly to industrial sustainability and societal resilience.

3. **ELSI for Human-Machine Collaborations**

   Identify, categorize, and align the ELSI concerns of Japan, the United States, and Europe so that inclusive and interoperable systems can be designed for sustainable and equitable industrial development.

The trilateral collaboration among Japan, the U.S., and the EU offers a unique opportunity to collectively address the economic, ethical, legal, and social complexities posed by the rise of advanced HMI. Through this partnership, the regions can establish a joint ELSI task force to align foundational principles, such as transparency, accountability, algorithmic fairness, and data governance. They can also support the development of federated governance models that allow each region to implement ethical safeguards tailored to its societal values while maintaining interoperability across borders. By co-developing certification and audit mechanisms for high-risk HMI applications, the collaboration can reinforce public trust and ensure regulatory alignment. Moreover, the creation of an international knowledge-sharing platform—potentially through a federated AI system—would enable each region to retain regulatory autonomy while operating on shared standards, fostering collective learning, proactive risk mitigation, and the responsible scaling of AI technologies globally.

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Terms and Definitions, Abbreviations and Acronyms

AI	Artificial Intelligence
AIRoA	AI Robot Association, Japan
ARPA-E	Advanced Research Projects Agency-Energy, the U.S.
bcf/d	billion cubic feet per day, a commonly used unit for expressing the volume of natural gas
BITKOM	Bundesverband Informationswirtschaft, Telekommunikation und neue Medien, Germany's Digital Association
BLS	Bureau of Labor Statistics of the U.S.
BOTTLE	Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment consortium, the U.S.
BPMN	Business Process Model and Notation
BRL	Business Readiness Level
BTU	British Thermal Unit, the amount of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit
CAD	Computer-Aided Design
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon dioxide Capture Utilization and Storage
CESMII	Collaborative Ecosystem for Smart Manufacturing Innovation Institute, U.S.
CFE	Carbon Free Energy
CHIPS	Creating Helpful Incentives to Produce Semiconductors for America
COVID-19	Coronavirus Disease
CSR	Corporate Social Responsibility
CSTI	Council for Science, Technology and Innovation of Japan
DOC	Department of Commerce, the U.S.
DOD	Department of Defense, the U.S.
DOE	Department of Energy, the U.S.
DevOps	A software development methodology that accelerates the delivery of high-performance applications and services by combining and automating the work of software development (Dev) and IT operations (Ops) teams (ref. https://www.ibm.com/think/topics/devops)
DX	Digital Transformation
EIA	Energy Information Administration, the U.S.
EISA	Energy Independence and Security Act, the U.S.
ELSI	Ethical, Legal, and Social Issues
EPA	Environmental Protection Agency, the U.S.
EPRI	Electric Power Research Institute, the U.S.
ESG	Environmental, Social, and Governance
EV	Electric Vehicle
FA	Factory Automation
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GX	Green Transformation

HCPS	Human-Cyber-Physical Space
HMI	Human-Machine Interaction
HPC	High-Performance Computing
IM-X	International Manufacturing-X, EU
IRA	Inflation Reduction Act, the U.S.
IT	Information Technology
JASM	Japan Advanced Semiconductor Manufacturing, Inc.
JEITA	Japan Electronics and Information Technology Industries Association
JST	Japan Science and Technology Agency
LBNL	Lawrence Berkeley National Laboratory, the U.S.
LNG	Liquefied Natural Gas
LTRA	Long-Term Reliability Assessment
MEP	Manufacturing Extension Partnership
METI	Ministry of Economy, Trade and Industry, Japan
NAICS	North American Industry Classification System
NEDO	New Energy and industrial technology Development Organization, Japan
NERC	North American Electric Reliability Corporation, the U.S.
NIST	National Institute of Standards and Technology, the U.S.
NMPs	Nano- and Microplastics
NREL	National Renewable Energy Laboratory, the U.S.
NSF	National Science Foundation, the U.S.
O-CEI	Open CloudEdgeIoT Platform Uptake in Large-Scale Cross-Domain Pilots An Innovation Action funded by the European Commission's Horizon Europe Program starting January 1st, 2025 (ref. https://www.linkedin.com/company/o-cei-horizon/)
OECD	Organization for Economic Co-operation and Development
OJT	On-the-Job Training
PPP	Public–Private Partnerships
quad	a unit of energy equal to 10^15 BTU
REMADE	Reducing EMbodied-energy And Decreasing Emissions institute, the U.S.
RFS	Renewable Fuel Standard
RoX	A Germany's initiative with use of AI-based robotic systems (ref. https://roboception.com/wp-content/uploads/202410_RoX-PresseRelease_final_EN.pdf)
RRI	Robot Revolution & Industrial IoT Initiative, Japan
R&D	Research and Development
SAFS	Sustainable Agriculture and Food Systems, the U.S.
SDGs	Sustainable Development Goals
SEC	Securities and Exchange Commission, the U.S.
SIP	Strategic Innovation Promotion program
SMEs	Small and Medium Enterprises
SMMs	Small and Medium-sized Manufacturers
SMR	Small Modular Reactors
SysML	Systems Modeling Language
STEM	Science, Technology, Engineering, and Mathematics

TIPC	Training for Improving Plastics Circularity
TRL	Technology Readiness Level
TTF	Title Transfer Facility
UML	Unified Modeling Language
USDA	U.S. Department of Agriculture
VDMA	Verband Deutscher Maschinen- und Anlagenbau, German Engineering Federation
VET	Vocational Education and Training
WEF	World Economic Forum
WTO	World Trade Organization
ZEV	Zero-Emission Vehicle
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie, German Electrical and Electronic Manufacturers' Association
3E+S	Energy security, Economic efficiency, Environment, and Safety. It is the fundamental concept behind Japan's energy policy.
3R	Reduce, Reuse, Recycle

1 Introduction

1.1 Background

In 2017, when Industry 4.0 was beginning to be recognized as the intelligent networking of machines and processes for industry with the help of information and communication technology[1], a discussion was raised among experts in Japan and Germany on how the resulting innovations would transform the relationship between humans and machines, and how the nature of work, which has changed with technological advances and their social application, would continue to change. Based on this, from 2018 to the summer of 2019, a diverse group of experts from Germany and Japan, not only from related technical experts, but also from sociologists, psychologists, labor unions, etc., gathered to discuss the future of HMI and published a discussion paper in 2019[2].

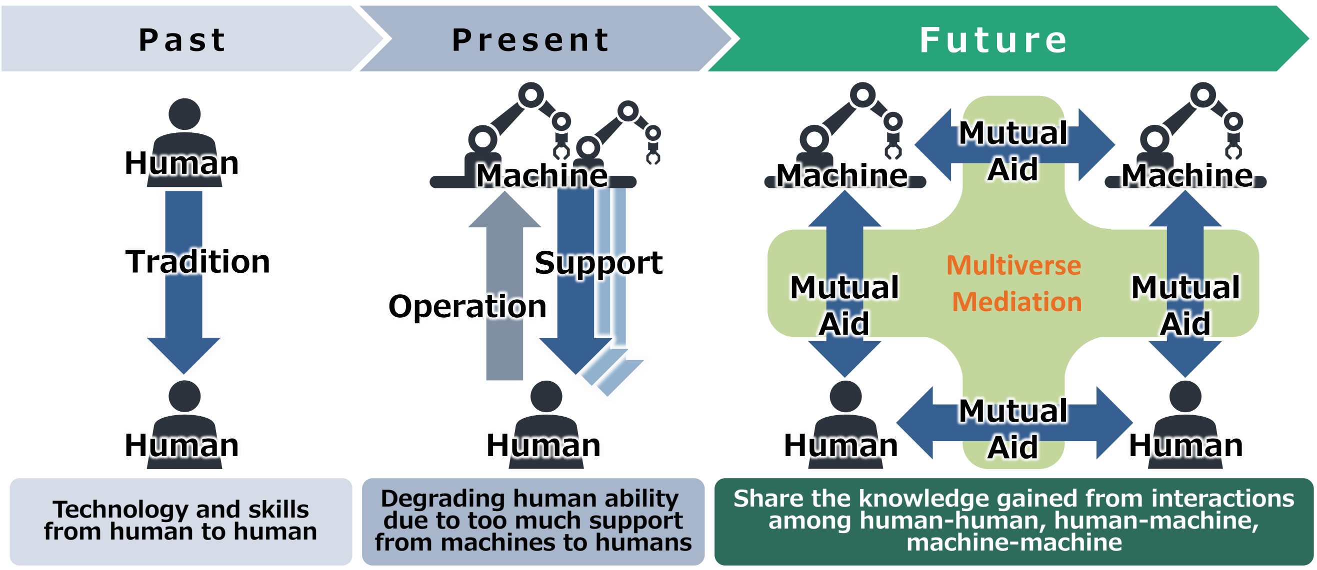


Figure 1 – "Multiverse Mediation" as the representative image of the last discussion[2]

Figure 1 shows how human society has changed and will change in the future due to technological advances, from the perspective of the transfer of technologies and skills, as the discussion result of the last project. In the past, technologies and skills were passed down from human to human, but now machines, including the Internet and computers, support humans in every aspect of their lives. However, it has been pointed out that excessive support carries the risk of impairing functions that humans should inherently possess, so there is a need to find an ideal form of HMI that will lead to the sustainable growth of individuals and human society.

In the last project, we argued that it is necessary to build a social infrastructure that allows for the transfer of technologies and skills equally between humans and other humans, humans and machines, and machines and machines, and we called this Multiverse Mediation, envisioning a sustainable society in which humans and machines help each other. That is, under coexistence with machines, we must establish the following aspects;

- A world where everyone can demonstrate their creativity and contribute to society through AI and machines
- A world where everyone can enjoy leisure and demonstrate individuality with the support of AI and machines

1.2 Motivation

Regarding industrial sustainability, Industry 4.0 and the Sustainable Development Goals (SDGs) have been proposed and are still being promoted. However, when Industry 4.0 was proposed, there was no public discussion about its relationship with the SDGs. Industry 4.0 was formulated as part of the “High-Tech Strategy 2020 Action Plan”[3], one of the strategic measures announced by the German government in November 2011, and in April 2013, three organizations, BITKOM, VDMA, and ZVEI, began operating the Industry 4.0 platform.

The SDGs are 17 international goals for sustainable development adopted by the United Nations General Assembly on September 25, 2015[4][5]. In other words, since Industry 4.0 was proposed before the SDGs, the relationship between the goals of Industry 4.0 and the goals of the SDGs has not yet been fully discussed[6]. Against this background, in the previous project, we organized the issues regarding the relationship between digitalization and a sustainable society from the perspective of HMI and proposed future directions.

After completing the last project, the COVID-19 pandemic hit the world, bringing about major changes in everything from lifestyles to values. The supply chain disruptions that emerged during the COVID-19 pandemic remain partially unresolved due to the rise of policies that prioritize domestic economies. Furthermore, remote work, which became mainstream during the COVID-19 pandemic, is permeating society as a new way of working and is also changing how we think about employment and training.

Looking around the world from this perspective, for example, the agenda for the WEF’s annual meeting in Davos in January 2024 stated the following [7]:

1. *Achieving security and cooperation in a fractured world.*
   The world is reckoning with new concentrations in global trade, complicated by rising geopolitical tensions on multiple fronts.
2. *Creating growth and jobs for a new era.*
   A new economic framework is here, borne out of increasing geopolitical instability and the climate crisis, as well as the acceleration of AI.
3. *AI as a driving force for the economy and society.*
   The year 2023 was generative AI’s breakout year.
4. *A long-term strategy for climate, nature, and energy.*

In addition, the IMF annual report 2024 published on September 2024 presents the following key messages [8]:

> *The challenge now is two-fold. The first is to safeguard macroeconomic stability from further geopolitical shocks, disruptive fiscal adjustments, and the task of bringing inflation back to target. Populations that continue to live with the legacy of successive crises will need ongoing assistance, as will those low-income countries that have experienced the most significant scarring. The second is to take advantage of global economic resilience to confront and embrace transformative developments that demand our collective action—developments such as climate change, digitalization, and an AI revolution that, for good or ill, could reshape the nature of work. These transformations will require multilateral cooperation to mitigate risks and maximize*

opportunities.

That is, in the post-COVID-19 world, we're experiencing a 'polycrisis.' Far from reaping the benefits of Industry 4.0, environmental disasters are becoming more severe, geopolitical risks are casting a shadow over the real economy, and issues with human production activities are piling up. In this context, to achieve the Multiverse Mediation set as the goal in the previous project, we must confront several practical challenges, considering the current global situation mentioned above. For example, given the uneven distribution of resources and labor on the planet, simple mutual sharing of knowledge could exacerbate income inequality. Additionally, simply sharing knowledge from others may not yield the desired results, leading to mutual distrust and exacerbating geoeconomic divisions.

1.3 Goal

As Industrial Sustainability, this paper deals with sustainability issues surrounding the manufacturing industry and solutions. Therefore, we will discuss the transition in productivity and labor force, changes in jobs and education due to digital technology. In addition, we will also discuss planetary boundary aspects such as energy issues, decarbonization issues, waste issues and so on.

As a requirement for Industrial Sustainability, the pursuit of well-being requires innovation in industrial activity for available resources while satisfying various constraints. And as for constraints, there are also absolute constraints, such as planetary boundaries, which become a mandatory requirement. On the other hand, we would like to think that **humans, technology, culture, society, geopolitical conditions, etc., which are both constraints and resources, can be changed and controlled to a certain extent. In this regard, we would like to discuss what is different and how it can be changed and controlled in Japan, the United States, and Europe.**

There are various approaches to achieving Industrial Sustainability, but the relationship between humans and machines is fundamentally important. In Japan, the United States, and Europe alike, the physical and intellectual misalignment between humans and machines causes enormous waste. To address this challenge, **it is essential to recognize the physical and intellectual diversity of humans and to establish mechanisms that enable humans and machines to coexist adaptively, reducing waste and optimizing their symbiosis**.

To this end, we would like to **discuss solutions in Japan, the United States, and Europe, recognizing differences in human, surrounding technologies, cultures, societies, geopolitical conditions, etc., as well as differences in their changes and controllability.** By generalizing the above argument, we may be able to examine the challenges of the relationship between the Global South and Japan, the United States, and Europe.

Under this policy, we will discuss the current situation and challenges of both well-being and planetary boundaries, identify the ideal form and requirements for HMI that contributes to industrial sustainability, and draw up recommendations for future international cooperation.

2 Current Activities for Industrial Sustainability in Each Region

2.1 Foreword

In Japan, the United States, and Europe, economic growth driven by demographic bonuses is a thing of the past. For the past 15 years, they have been working on social digitalization as another growth driver. However, due to changes in people's and society's values caused by the pandemic and energy crisis, labor productivity in each region has not improved as expected.

On the other hand, digitalization has also created large disparities for individuals and companies that struggle to access and effectively use data. Furthermore, negative aspects of digitalization, such as the risk of mass manipulation surrounding AI technology and geopolitical competition, are affecting the real economy.

In this chapter, we will take a detailed look at the efforts of Japan, the United States, and Europe in both digitalization measures as a driver of economic growth and measures to address the associated social challenges, and evaluate their similarities and differences. The aim is to clarify the path to sustainable development in a rapidly changing world.

2.2 Japan Activities

Major programs and projects toward industrial sustainability in Japan are briefly reviewed in terms of industry–academia–government collaboration, global warming and energy depletion, resource depletion and circular economy, and sustainable society issues. Japanese society is rather sensitive to the issues of sustainability and mentally positive about promoting the activities. The government-led programs and projects play important roles in investigating challenging issues as precursors and in convincing society and industry of the practical importance of the subjects. Industry then follows to invest in sustainability activities by considering contributions to society and business feasibility.

2.2.1 Industry–Academia–Government Collaboration

In recent years, Japan encounters critical social issues, such as severe global warming, resource depletion, increased waste disposal, environmental pollution, and other various environmental issues causing a reduction in social well-being. It becomes even worse due to the recent unstable geopolitical situation. The situation is the same across the industrially highly developed countries, including the United States and Europe. For coping with these issues, industrial sustainability is one of the most prioritized targets for the Japanese industry jointly working with government and academia.

Industrial sustainability can be considered from the viewpoint of the global environment and the planetary boundaries, and at the same time from the viewpoint of social well-being, human diversity, and inclusion. Developments of new technology and related social/human considerations are required for resolving these issues. In the past several decades, Japan has continuously worked on industrial sustainability and created many programs and projects jointly with industry, government, and academia. However, in recent years, environmental and social issues have been diversified and increased, and many issues remain unsolved or unaddressed.

2.2.2 National Level Initiatives

At the national level, the Council for Science, Technology and Innovation (CSTI), Cabinet Office, is a top-level council and determines national policies for promoting science and technology in industry and academia. CSTI decides the Science, Technology, and Innovation Basic Plan every five years. Society 5.0 is a national vision presented in the 5th Science and Technology Basic Plan. It was first proposed as “a human-centered society in which economic development and the resolution of social issues are compatible with each other through a highly integrated system of cyberspace and physical space.” In order to embody and bring into reality the concept of Society 5.0, the 6th Science, Technology, and Innovation Basic Plan[9] depicts Society 5.0 as “a society that is sustainable and resilient against threats and unpredictable and uncertain situations, that ensures the safety and security of the people, and that individual to realize diverse well-being”[10]. With the vision of Society 5.0, many programs and projects are organized to deal with the subjects of industrial sustainability.

The most important and generic national program is Cross-ministerial SIP[11][12]. SIP aims to promote interdisciplinary projects across various industry/technology domains, and industrial sustainability is one of the important topics. It supports research and development from basic research to social implementation through industry–academia–government collaborations, and intends to create a center of excellence on the targeted subjects. Some of the projects related to industrial sustainability are described in 2.2.4 and 2.2.5.

In addition to SIP, two types of complementary programs are arranged. One is the Moonshot Research and Development Program, which aims to promote ambitious goals and visions expected to yield a significant impact on social issues, and to lead to SIP activities[13]. The other is Programs for Bridging the Gap between R&D and the Ideal Society (Society 5.0) and Generating Economic and Social Value (BRIDGE) to follow up the results of SIP[14].

As a general national vision toward a sustainable society, the Ministry of the Environment has set the Sixth Basic Environment Plan in 2024[15]. It discusses the target, starting from environmental policies, to simultaneously resolve various economic and social challenges, including:

- pursuing environmental conservation and the well-being/quality of life of individuals,
- total reduction of environmental load by circulation and symbiosis based on renewable resources,
- realization of the new avenue for economic and social growth.

According to the specific subjects of industrial sustainability, respective ministries and industrial associations related to the subjects organize many industry–academia–government collaboration projects. Some of those projects are described in the following subclauses.

Generally speaking, the industry–academia–government collaboration projects perform “first-penguin” roles and validate the potential usefulness of industrial sustainability. When the results of the projects are evaluated as promising, the practical industrial and social implementation is to be promoted by the initiative of strong participation of industry.

2.2.3 Environmental Issues: Global Warming and Energy Depletion

Japan is a densely populated, highly industrialized country and lacks natural resources. Japanese industry and society have suffered from global warming and energy depletion for many years, and worked on various measures to save energy consumption, which contributes to industrial sustainability.

The Ministry of Economy, Trade and Industry (METI) announced the 7th strategic energy plan in 2025[16]. It describes the overall national energy policy from the national security viewpoint by investigating a feasible energy source mix with renewable energy, nuclear power, and conventional thermal power. Refer to Figure 2. It addresses needs to cope with the possible increase in energy usage due to the expansion of DX in industry.

Cabinet Office announced GX 2040 Vision for showcasing the long-term Green Transformation (GX) activities and investment possibilities. It includes the topics: industrial reorganization by innovative GX technologies, appropriate geological distributions of renewable energy supply and consumption, growth-oriented investment policy, and practical transition to carbon neutrality harmonized with the global environment.

Due to the recent severe global regulation for decarbonization, the Japanese government sets the target of reduction of CO_2 emissions by 60% by 2035 compared with the emissions of 2015. This is a very ambitious target to satisfy. The Japanese government has arranged many programs and projects to jointly work with industry and academia, which include not only technical developments but also various kinds of financial and legal measures.

National basic plans toward carbon neutrality include, but are not limited to, the following:

- Policy for climate changes by Cabinet Office,
- Global warming basic plan by Ministry of the Environment[17],
- Climate change adaptation information platform by Ministry of the Environment,
- GX basic plan by METI[18].

		(FY2019 ⇒ previous energy mix)	Energy mix in FY2030 (ambitious outlook)
Energy efficiency improvement		(16.55 million kl ⇒ 50.30 million kl)	**62 million kl**
Final energy consumption (without energy conservation)		(350 million kl ⇒ 377 million kl)	350 million kl
Power generation mix Electricity generated: 1,065 TWh ⇒ Approx. 934 TWh	**Renewable energy**	(18% ⇒ 22-24%) solar 6.7% ⇒ 7.0% wind 0.7% ⇒ 1.7% geothermal 0.3% ⇒ 1.0~1.1% hydropower 7.8% ⇒ 8.8~9.2% biomass 2.6% ⇒ 3.7~4.6%	**36-38%** ※If progress is made in utilization and implementation of R&D of renewable energy currently underway, 38% or higher will be aimed at. (details of renewable) solar 14~16% wind 5% geothermal 1% hydropower 11% biomass 5%
	Hydrogen/Ammonia	(0% ⇒ 0%)	**1%**
	Nuclear	(6% ⇒ 20-22%)	**20-22%**
	LNG	(37% ⇒ 27%)	**20%**
	Coal	(32% ⇒ 26%)	**19%**
	Oil, etc.	(7% ⇒ 3%)	**2%**
(+ non-energy related gases/sinks)			
GHG reduction rate		(14% ⇒ 26%)	**46%** Continuing strenuous efforts in its challenge to meet the lofty goal of cutting its emission by 50%

12

Figure 2 – Outlook of energy mix in 2024[16]

Japanese government funding agencies have set up many programs to support industry to execute practical developments of carbon emission reduction and energy saving:

- Social scenario research program toward a carbon neutral society by Japan Science and Technology Agency (JST) [19],
- Green technology of excellent program: GteX by JST[20],
  Battery, hydrogen, bio-manufacturing, etc.
- Advanced low-carbon NEXT research and development program: ALCA-NEXT by JST[21],
  Energy storage, green biotechnology, green computing, etc.
- Carbon dioxide Capture Utilization and Storage (CCUS) implementation by New Energy and industrial technology Development Organization (NEDO)[22].

Also, industrial consortia are organized to have tight discussions among industrial stakeholders under the METI initiative Green Growth Strategy Through Achieving Carbon Neutrality in 2050[23]:

- GX League by METI[24]:
  Aiming for economic and social reform to achieve 2050 carbon neutrality,
- Green x Digital Consortium by Japan Electronics and Information Technology Industries Association (JEITA) [25]:
  CO_2 visualization framework, etc.

For reducing consumption of fossil fuels and CO_2 emissions, renewable energy, including solar cells and wind power generation, is a popular way to engage the global community. However, it used to be not easy in Japan to install these renewable energies on practical scales due to the limited land areas for solar cell installation and unstable wind conditions. In recent years, by technological progress and financial and legal support by the government, the percentages of renewable energies increase in the Japanese energy source profile[26]. New technology developments are ongoing to catch up with the front edge developments in renewable energies.

Important aspects for accelerating the energy transformation to sustainability include governmental legal measures and policies to guide the industry and economic incentives, for example, carbon pricing and additional fees for fossil fuel usage.

2.2.4 Environmental Issues: Resource Depletion and Circular Economy

Japan is a poor country in terms of many important natural resources and must import them. However, due to the recent environmental and geopolitical issues, it is required to be less dependent on foreign natural resources. At the same time, due to the same reason, it becomes difficult to export used products and disposed materials to developing countries, for example, used electronic parts and disposed plastics.

Generally speaking, from an environmental viewpoint, it is mandatory to reduce the overall material flow to as minimum as possible, and to completely eliminate waste disposal and incineration. In the past twenty years, the Japanese government and industry have worked intensively to legislate for used product recycling for automobiles, household appliances, office machines, etc. A keyword “3R” has been used, meaning reduce, reuse, and recycling. Reduce and reuse are more environmentally conscious, but recycling is still a main practice in industry and society.

Recently, the circular economy is advocated for a comprehensive reorganization of the product life cycle and material flow. New business models are discussed for practical feasibility and social implementation of the circular economy. The 3R concept is embedded in the process of the circular economy, and a variety of possibilities for reducing and reusing are investigated.

In 2024, the Japanese government enacted the 5th Basic Act on Establishing a Sound Material-Cycle Society. As Figure 3 shows, the act has been upgraded since 2003, and now, as a national strategy, aims to improve economic benefits and social well-being as well as environmental burden by comprehensive implementation of the concept of circular economy[27]. Quantitative measures are specified for material circulation and social benefits.

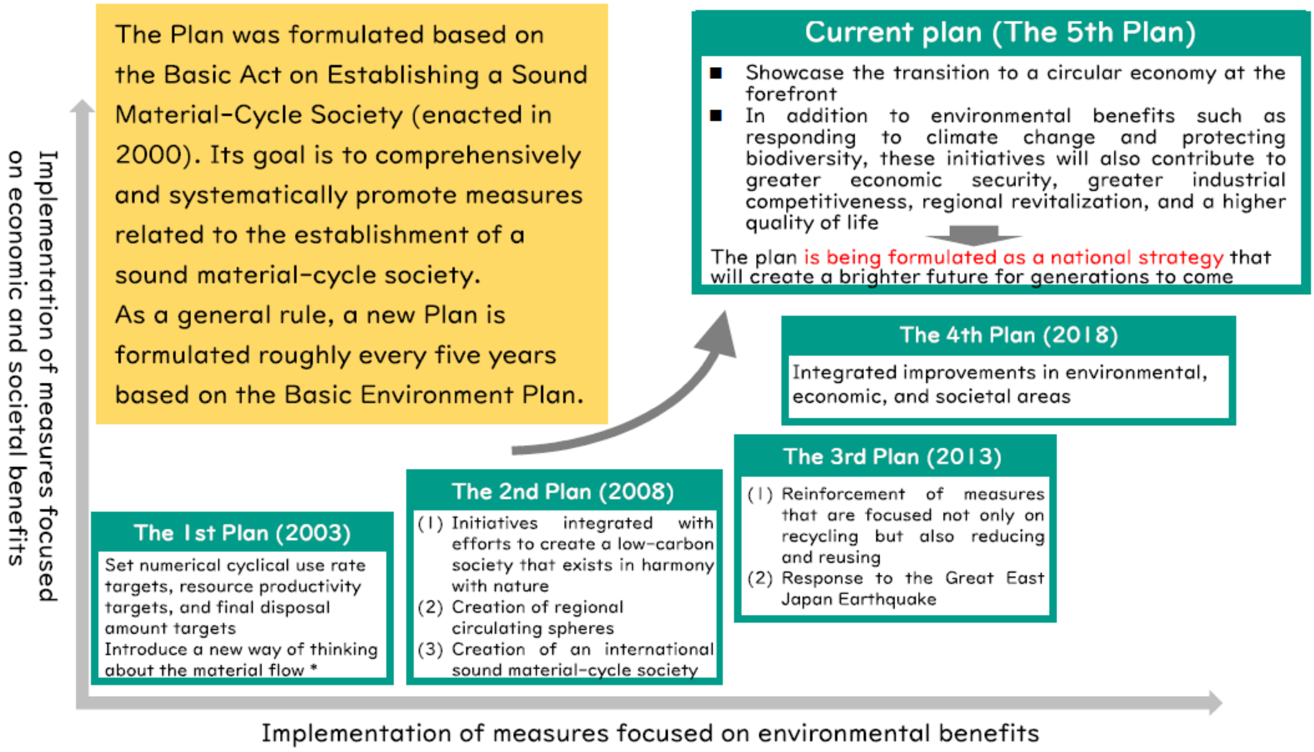


Figure 3 – Evolution of Basic Act on Establishing a Sound Material-Cycle Society[27]

For coping with the depletion of materials and the increase of disposals, METI announced the Resource-Autonomous Circular Economy Growth Strategy in 2023 to promote industrial activities toward a Circular Economy. It aims to set up activities for specifying guidelines and rules of reuse and refurbish design and quality, providing standards, toolkits, and ecosystem.

As a part of initiatives from the Circular Economy Growth Strategy, a partnership program, named Circular Partners, was established to promote cooperation among industry, government and academia to realize a circular economy together[28]. The activities include:

- defining a vision and a long-term roadmap (2030 to 2050) for realization of a circular economy,
- launching a “circular economy information distribution platform” by 2025,
- creating a “local circular model” promoting the implementation of circular economy at regional level.

Open circular economy platform is now investigated as one of the SIP projects for establishing upgradable material circular processes especially for plastics integrated with product design. The project is titled Circular Economy System based on Information Sharing Platform[29].

Materials are fundamentally important for the realization of a circular economy. Industry–academia–government joint projects are organized for basic research to develop new materials with better environmental performance. The project is titled Creating a Materials Innovation Ecosystem for Industrialization in SIP[30].

Many specific industrial projects are being run with the support of NEDO:

- Basic process technology for used electric and electronics products.
- Innovative circular process for plastics.
- Innovative circular process for aluminum.

2.2.5 Sustainable Society Issues

For a sustainable society, it is important to effectively utilize existing resources, including humans and machines. An individual human has different characteristics and capabilities. If the social environment and existing machines are somehow rigid and cannot be adapted to individual human diversity, humans cannot be well accepted in society and machines. Such mismatches of human and machine generate a lot of waste of resources and degrade the sustainability and well-being of society.

Japan has developed robot technology over many years, and a lot of industrial robots are working in factories and warehouses mostly for simple repetitive tasks. Recently, along with the development of IT and AI technologies, robots can be used for more complicated tasks in a dynamically challenging environment. Based on such progress of technology, with the vision of Society 5.0, a future society is investigated, where robots are embedded in society and can interact with humans for daily activities.

It is expected to be able to realize a sustainable society by a human-machine symbiosis, where humans and machines can communicate with each other to flexibly adapt to the environment. Much research and development work is now being performed by academia-industry-government collaboration. A comprehensive project by SIP is shown in Figure 4. The project is titled Expansion of Fundamental Technologies and Development of Rules Promoting Social Implementation to Expand HCPS Human-Collaborative Robotics[31].

In this SIP project, HCPS is studied for realizing versatile working environments for human and machine collaborations. The following use cases are considered.

- Support for people with disabilities and their supporters for activities of daily living and well-being.
- Daily household activities with childcare.
- Routine physical support activities in working environments.
- Building maintenance services.
- Evacuation support in case of disasters for people with disabilities and children.

These use cases can be adapted to various HMI requirements discussed in Chapter 6. There are many industry-led activities which aim to explore new practical businesses for accepting people with diversified abilities toward a sustainable society.

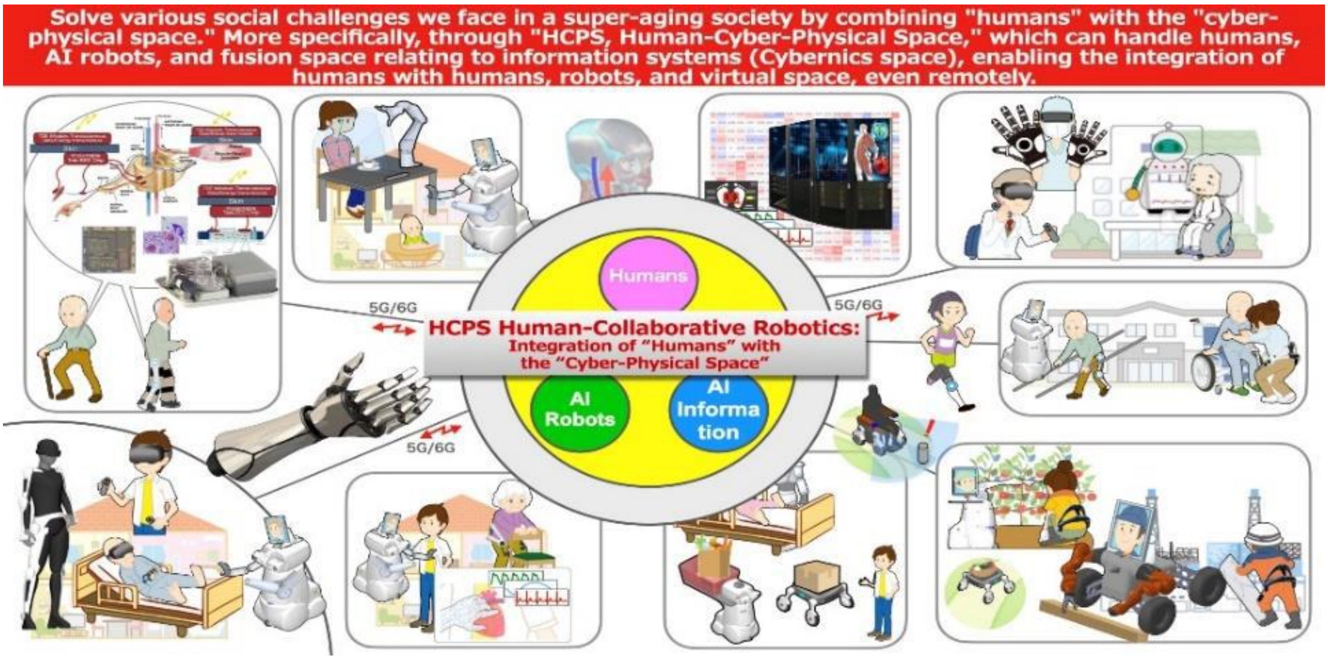


Figure 4 – Human-Machine Symbiosis for Sustainable Society[31]

For innovating machine adaptability to human diversity and achieving comprehensive human-machine symbiosis, it is becoming very popular to integrate recent AI and advanced robotics technologies. By multi-modal foundation models and deep learning, it may be possible to realize natural interactions of complex activities among humans and machines. In 2025, with the support of METI, the AI Robot Association (AIRoA) is established by the participation of industry and academia. The expected activities include the collection of large amounts of open data across various industries, the development of foundation models with an open-source approach, and scalable ecosystems for AI robots. The development is just starting but is expected to contribute to industrial and social sustainability by effective inclusion of human resources into industry and society.

2.2.6 Outlook

Criticality of sustainability is recognized in Japanese society and industry, and many activities are being executed by national projects and industrial practices. However, society and industry are not yet convinced of the current solutions to a sustainable society and industry. There are many demanding issues requiring more effort in long-term perspectives.

Sustainable energy supply is still a problem in Japan. According to the government target of carbon neutrality in 2050, the intermediate target of a 73% reduction of CO_2 emissions in 2040 compared to 2013 is announced. This target is based on the energy mix plan, which constitutes 50% renewable energy, 20% nuclear energy, and 30% fossil fuel energy. There remain various technological, economic, and social issues for practical implementation.

Comprehensive social implementation of the circular economy takes time, including the changes in the social and economic systems. There are many depleting resources that require recycling/reuse by the circular economy. Copper is the most urgent mass material needing complete recycling. In worldwide, production of copper ore is predicted not to increase, but the demand for copper usage will increase almost double by 2050.

Due to the decrease in the total population, human resource shortage is a very critical issue in Japan. It is estimated that the number of people of working age (15-64 years old) will be about half of that in 2070 compared to today. Along with the change of the working environment, this is a severe problem for a sustainable society and industry.

As discussed in this document, various solutions are being pursued toward industrial sustainability. It is essential to continue the efforts in a long-term perspective. In Japan, it is considered important to seek the solution not only technologically, but also with social and economic incentives. There will be interesting subjects for collaboration among Japan, the United States, and Europe.

Column: Empowering Regional Revitalization Through Digital Transformation

To achieve productivity improvement and regional revitalization through DX, it is crucial not only to develop and apply new technologies but also to cultivate the ability of users to understand and utilize these technologies. This includes initiatives such as education and investment support for technology utilization. Such efforts are operated as an ecosystem involving not only technology vendors but also local governments and banks.

For example, in the Omika area of Hitachi City, Ibaraki Prefecture, Japan, initiatives are being promoted to decarbonize regional industries, including small and medium-sized enterprises, through technological innovation, with the aim of building a green industrial city[32][33]. Here, not only do they support the introduction and demonstration of DX-related technologies, but many stakeholders are also participating in regional revitalization through DX, such as by collaborating with local financial institutions to enable SMEs that support local industries to operate, and by evaluating convenience from the perspective of residents.

There is a need for a form of international collaboration that will enable the sharing and utilization of such initiatives to spread from the region to the country, and from the country to the world, overcoming differences in cultural backgrounds, economic situations, regulations and standards.

2.3 U.S. Activities

The United States stands at a pivotal juncture in advancing industrial sustainability. While Japan and the EU have leaned heavily on government-led visions and regulatory frameworks, the U.S. trajectory has been shaped by a combination of federal legislation, market-driven innovation, and strong public–private partnerships. Over the past two decades, industrial sustainability in the U.S. has been framed primarily around climate action, energy transition, and the modernization of critical infrastructure.

However, as global disruptions—including the COVID-19 pandemic, geopolitical tensions, and supply chain vulnerabilities—reshaped priorities, the U.S. approach broadened to emphasize resilience, economic competitiveness, and technological leadership.

This section examines how the U.S. has navigated this evolution. It begins with an overview of the pre-2025 period, characterized by a legislation-driven, climate-centric model anchored in landmark policies such as the Energy Policy Act, the Bipartisan Infrastructure Law, the CHIPS and Science Act, and the Inflation Reduction Act. It then explores the post-2025 redefinition of industrial sustainability, which integrates climate goals with energy abundance, supply chain resilience, and innovation pathways. Finally, the section provides a synthesis of these efforts, highlighting how the U.S. model—built on legislation, innovation, and cross-sector collaboration—has positioned the country to both decarbonize and strengthen its industrial base in a globally competitive environment.

2.3.1 Pre-2025: A Legislation-Driven, Climate-Centric Model

The U.S. perspective on industrial sustainability has been undergoing a transformation. Prior to 2025, the dominant narrative placed decarbonization at the center of industrial sustainability. Legislative agendas and federal policy frameworks reflected this emphasis, with successive laws expanding clean energy deployment, research funding, and infrastructure investment.

The Industrial Sustainability Context (Pre-2025)

During the pre-2025 period, industrial sustainability emerged as a critical national priority as the United States sought to reconcile economic growth with long-term environmental responsibility and social equity. The industrial sector—including manufacturing, energy production, and resource extraction—was a cornerstone of the U.S. economy, contributing significantly to both employment and GDP. Yet it was also a major source of environmental challenges.

According to the U.S. Environmental Protection Agency (EPA), the sector accounted for approximately 30 percent of total GHG emissions, including both direct emissions and those associated with electricity consumption[34]. It consumed about 35 percent of total end-use energy and nearly one-third of the nation's overall energy use as of 2022[35]. Waste generation compounded these challenges: in 2018, the EPA reported 35.7 million tons of plastic waste[36], while the National Renewable Energy Laboratory (NREL) estimated closer to 44 million metric tons, much of which was landfilled or leaked into ecosystems due to inadequate recycling infrastructure[37]. This high energy intensity, dependence on fossil fuels, and growing waste burden underscored the urgent need to transition toward cleaner, more efficient, and circular industrial practices.

In response, both federal and state governments began adopting comprehensive frameworks to decarbonize industry, modernize infrastructure, and promote clean technologies. Industry actors themselves embraced circular economy models, invested in sustainable practices, and formed public–private partnerships to accelerate innovation and workforce readiness.

By the early 2020s, the green technology and sustainability market was expanding rapidly. Valued at approximately $6.6 billion in 2023, it was projected to quadruple by 2030, reflecting a compound annual growth rate of more than 22 percent [38]. This growth was driven not only by federal incentives but also by global market and policy pressures, such as the European Union's Carbon Border Adjustment Mechanism, as well as shifting consumer preferences, with nearly 70 percent of Americans favoring environmentally responsible brands.

Against this backdrop, federal policy frameworks were developed to provide the strategic foundation for industrial sustainability, setting the stage for coordinated national action in the pre-2025 period.

Industrial Sustainability Federal Policy Frameworks (pre-2025)

In the pre-2025 period, federal policy frameworks played a central role in shaping the nation's approach to industrial sustainability. These frameworks were designed to balance economic competitiveness with the urgent need to reduce greenhouse gas emissions, modernize infrastructure, and foster innovation in clean technologies. Building on earlier energy and environmental legislation, federal agencies worked in tandem with state governments to establish roadmaps for decarbonizing heavy industry, advancing circular economy models, and securing domestic supply chains. The emphasis was not only on meeting international climate commitments, but also on positioning the United States as a leader in the rapidly expanding global sustainability and green technology market.

The **Energy Policy Act of 2005** represented a landmark shift, establishing loan guarantees and tax credits for renewable projects (solar, wind, biofuels), efficiency programs for appliances and industrial systems, and incentives for carbon reduction through nuclear energy and early carbon capture demonstrations. It also created the Renewable Fuel Standard (RFS), requiring increasing volumes of biofuels in the U.S. fuel mix. Updates such as the Energy Independence and Security Act (EISA, 2007) reinforced these goals, setting vehicle efficiency standards, strengthening the RFS, and supporting smart grid development. These laws laid the early foundation for emissions-conscious industrial policy and advanced the idea that energy security and sustainability could be pursued together.

The **America COMPETES Act (2007, reauthorized 2010)** advanced industrial sustainability through R&D and innovation ecosystems. It authorized the doubling of funding for the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST), and the Department of Energy (DOE)'s Office of Science, and established the Advanced Research Projects Agency–Energy (ARPA-E) to accelerate high-risk, high-reward energy innovations. It also strengthened STEM education pipelines, preparing a workforce for clean energy and advanced manufacturing. Together, these provisions aligned federal science and industrial policy with the competitive challenges posed by emerging clean technologies.

The **Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act, 2021)** marked a new phase of large-scale investment in clean industrial infrastructure. Of its $1.2 trillion allocation, more than $60 billion targeted energy and sustainability priorities: $7.5 billion for a national EV charging network, $65 billion for grid modernization and resilience, $8 billion for regional clean hydrogen hubs to decarbonize heavy industry, and $12 billion for carbon capture and direct air capture projects. It also included funding for industrial energy efficiency and weatherization programs, reinforcing the connection between industrial competitiveness and energy modernization.

Closely linked to this was the **Federal Sustainability Plan** (2021) show in Figure 5, which set ambitious goals for the federal government—the largest energy consumer in the United States—to lead by example in decarbonization and industrial sustainability. The plan committed federal agencies to achieve 100% carbon pollution-free electricity by 2030, transition the federal vehicle fleet to 100% zero-emission acquisitions by 2035, and reach net-zero emissions operations by 2050. It also mandated improvements in federal supply chains, building efficiency, and procurement standards to favor low-carbon materials such as clean steel and cement. By aligning federal purchasing power with sustainability goals, the plan aimed to catalyze innovation and market demand in clean technologies, while sending long-term investment signals to industry.

Figure 5 – Federal Sustainability Plan (2021)[39]

The **CHIPS and Science Act** (2022), while primarily designed to strengthen semiconductor manufacturing, embedded sustainability in its provisions. It allocated $52.7 billion in incentives for domestic semiconductor production, incorporating requirements for clean energy use, water efficiency, and resilient supply chains. Nearly $170 billion in authorizations for R&D supported DOE laboratory modernization and emerging technology development, including AI, quantum computing, advanced materials, and clean energy. By linking sustainability with industrial independence and national security, the CHIPS Act positioned resilience as part of the sustainability equation even before the 2025 shift.

Figure 6 **– The CHIPS and Science Act (2022)[41]**

The most consequential of these was the **Inflation Reduction Act (IRA, 2022)**, the largest climate and industrial policy package in U.S. history, with ~$370 billion in clean energy investments. It extended and expanded tax credits for wind, solar, geothermal, nuclear, and storage; provided consumer EV credits tied to domestic critical mineral supply chains; enhanced Section 45Q incentives for carbon capture, utilization, and storage; and created production credits for low-carbon hydrogen. It also included direct investments to decarbonize energy-intensive industries (steel, cement, chemicals) and to strengthen environmental justice and workforce training. The IRA created a stable, long-term investment horizon that anchored U.S. decarbonization strategies.

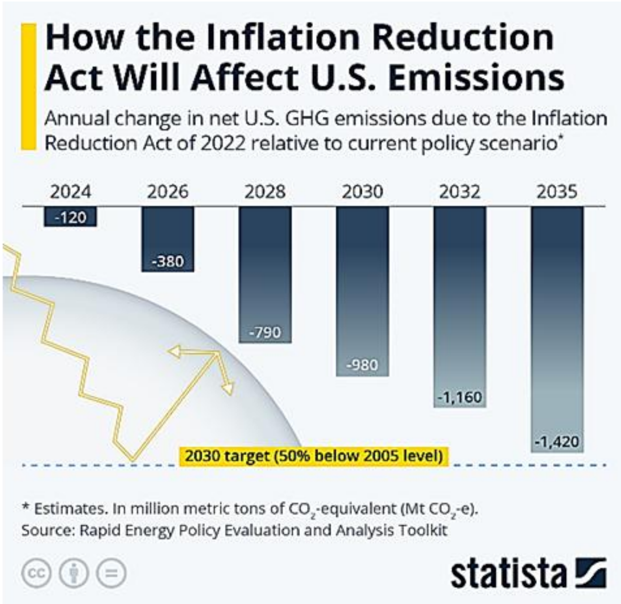


Figure 7 – Inflation Reduction Act (2022)[40]

Summary (pre-2025 U.S. Model)

In summary, the pre-2025 U.S. Industrial Sustainability model can be characterized as a legislation-driven, climate-centric model of industrial sustainability. It was underpinned by major federal investments, regulatory frameworks, and incentives aimed at reducing emissions and accelerating energy transition, while simultaneously building capacity in innovation and workforce development. However, structural challenges—high industrial emissions, energy intensity, waste generation, and global competitiveness pressures—set the stage for the post-2025 shift toward a redefined model based on resilience, abundance, and innovation.

2.3.2 The Post-2025 Strategy for Industrial Sustainability

Since 2025, the U.S. has deliberately broadened its framing of industrial sustainability. Rather than equating sustainability solely with emissions reduction and net-zero objectives, the current approach encompasses energy security, economic vitality, technological leadership, and resilience against global shocks. This reframing stems from the conviction that sustainability is not possible without abundance: a manufacturing sector that is energy-starved, over-regulated, or uncompetitive cannot realistically sustain jobs, innovation, or environmental progress. The philosophy of “energy addition, not subtraction” underpins this strategy, driving expanded investment across oil, gas, nuclear, geothermal, hydropower, and renewables to secure reliable supply at home while strengthening U.S. export leadership. Policies emphasize affordability, domestic job creation, and shielding strategic industries from offshoring pressures, while pursuing a technology-neutral approach to support carbon capture, hydrogen, small modular nuclear reactors (SMRs), and digitalization. Climate change is acknowledged as real, but innovation—rather than mandates—is emphasized as the pathway to sustained emissions reduction and long-term industrial competitiveness.

Details of the current U.S. administration policy are organized around three interlocking pillars:

Energy Security and Abundance − This pillar emphasizes that abundant, reliable, and diverse energy supply is the foundation of sustainability. In 2023, U.S. energy production reached 102.83 quadrillion BTU (British Thermal Unit), exceeding consumption by nearly 9 quadrillion BTU, making the nation a net energy exporter. Fossil fuels continue to provide about 84% of production, but renewables and nuclear are steadily growing. The administration's "energy addition, not subtraction" philosophy underscores that energy security comes not from restricting supply but from expanding it across all sources — natural gas, petroleum, nuclear, geothermal, hydropower, and renewables. Energy abundance secures domestic industry, strengthens grid reliability, and positions the U.S. to export LNG and nuclear power technologies that displace higher-emission fuels abroad.

Economic Vitality − This second pillar links industrial sustainability directly to economic competitiveness and job creation. U.S. electricity generation exceeded 4.18 trillion kWh in 2023, demonstrating the scale of industrial capacity needed to power manufacturing, digital infrastructure, and national security priorities. Policies aim to ensure that industries such as steel, chemicals, and semiconductors remain globally competitive and resistant to offshoring pressures. Sustaining affordability and reliability in energy supply is central to avoiding **carbon leakage** and preserving domestic jobs. Economic vitality is further reinforced by strategic energy exports, which strengthen trade balances while supporting global decarbonization. The underlying principle is clear: decarbonization must not undermine industrial strength but instead provide a platform for long-term prosperity.

Innovation Pathways − The third pillar reflects a shift from regulation-first to innovation-first. Rather than mandating specific technologies, the U.S. supports a technology-neutral environment where carbon capture, hydrogen, small modular reactors (SMRs), geothermal, and renewables can all compete. The Department of Energy is modernizing National Labs to accelerate the cycle from research to commercialization. Permitting reforms reduce bottlenecks, enabling private-sector capital to flow into large-scale infrastructure projects. This "all-of-the-above" R&D strategy allows renewables to scale through market signals (solar and wind together supplied 17% of U.S. electricity in 2024, surpassing coal for the first time), while also advancing next-generation nuclear and storage solutions. Innovation is not treated as an ideological choice but as the engine of sustainable growth, ensuring that technological breakthroughs strengthen both competitiveness and decarbonization.

Climate change continues to be acknowledged as a real and pressing issue but is now framed as one challenge among many within a broader sustainability agenda. U.S. electricity-sector CO_2 emissions have already declined by about 30% since 2013, driven by the coal-to-gas transition and renewable growth. The administration maintains that further reductions will come most effectively from innovation and diversification, rather than mandates or narrow prescriptive policies.

Post-2025 Strategy & The Long-Term Outlook – Building a Sustainable Industrial Base

In the years since 2025, the United States has sought to redefine industrial sustainability in terms of abundance, competitiveness, and resilience, moving beyond a narrow focus on carbon accounting to a broader strategy that secures the nation's industrial base while advancing global climate goals. This long-term outlook rests on the belief that sustainability cannot emerge from scarcity or restrictive mandates, but from the expansion of energy supply, modernization of technology, and strengthening of economic foundations. Under this framework, decarbonization is achieved not as a constraint on growth, but as a natural outcome of technological innovation, efficiency, and global leadership in energy exports.

The administration's approach organizes sustainability into four strategic dimensions. Autonomous innovation, enabled by deregulation, ensures that industries can adapt and deploy solutions at the speed of markets rather than the pace of regulation. Global leadership in energy exports allows the U.S. to shape decarbonization beyond its borders by providing allies with lower-emission alternatives and advanced nuclear technologies. Integration of advanced technologies, from AI to digital twins and smart grids, transforms industrial and energy systems into intelligent, adaptive networks that optimize efficiency while reducing emissions. Finally, resilient supply chains anchor sustainability in stability, ensuring that U.S. industries can withstand global disruptions and remain competitive in an uncertain geopolitical environment.

Together, these elements chart a pragmatic pathway where sustainability is not a trade-off against industrial growth but a foundation for it. The following subsections outline how each dimension contributes to building a sustainable industrial base for now and beyond.

Autonomous Innovation Enabled by Deregulation

A defining feature of the U.S. model is its conviction that innovation flourishes most effectively in flexible, competitive environments. Rather than mandating specific technologies, the government has positioned deregulation as a catalyst for private-sector creativity and investment. Streamlined permitting reforms accelerate the siting and approval of energy and industrial infrastructure, enabling faster deployment of hydrogen hubs, nuclear small modular reactors (SMRs), geothermal facilities, and carbon capture projects. The modernization of DOE's National Laboratories — described as the "envy of the world" — further strengthens this innovation ecosystem by equipping labs with high-performance computing, testbeds for advanced manufacturing, and pilot lines for clean technologies. Incentives are designed to favor firms that can bring scalable solutions to market, from energy storage breakthroughs to carbon utilization processes and advanced materials. This "innovation-first" pragmatism seeks to reduce reliance on heavy-handed mandates, instead unleashing competition to identify the most cost-effective and impactful pathways to decarbonization.

Global Leadership Through Energy Exports

Energy exports are framed not only as a cornerstone of U.S. economic vitality but also as a powerful instrument of global decarbonization. By supplying cleaner alternatives to higher-emission fuels, the U.S. indirectly supports emissions reductions abroad without imposing additional domestic costs. Liquefied natural gas (LNG) exports exemplify this role: shipments are projected to rise from 11.9 billion cubic feet per day (bcf/d) in 2024 to 21.5 bcf/d by 2030, nearly a ten percent annual growth rate (Reuters, 2024). DOE approvals already cover up to 48 bcf/d of export capacity, underscoring the scale of U.S. influence in global markets. Alongside LNG, nuclear energy exports are expanding as the U.S. pursues a plan to triple its domestic nuclear capacity by 2050 (DOE, 2024). This creates opportunities to export nuclear technology, including advanced SMRs, and to supply nuclear fuels to allied nations seeking low-carbon, baseload power. By combining fossil fuel abundance with advanced nuclear capabilities, the U.S. positions itself as a unique energy superpower, able to simultaneously bolster global energy security and contribute to worldwide emissions reductions.

Advanced Technology Integration

At the heart of the long-term sustainability strategy is the integration of advanced digital technologies into every layer of the industrial system. Artificial intelligence (AI) is increasingly used for predictive maintenance in manufacturing plants and for real-time optimization of grid operations, improving efficiency and reducing downtime. Digital twins — high-fidelity simulations of industrial facilities — allow for continuous modeling of processes, enabling proactive quality control, predictive maintenance, and detailed emissions monitoring. These innovations reduce waste, improve productivity, and enhance resilience during supply chain disruptions. At the system level, smart grids are being deployed to integrate distributed energy resources, storage, and demand-side management, ensuring reliable electricity even as renewable penetration grows. By balancing intermittent wind and solar with stable baseload power, smart grids guarantee the reliability needed to sustain industrial competitiveness. Together, AI, digital twins, and smart grids form an interconnected digital ecosystem where industrial production, energy supply, and logistics operate seamlessly, driving down carbon intensity while strengthening resilience.

Resilient Supply Chains as Sustainability

The U.S. model treats resilience itself as a core dimension of sustainability, recognizing that an industrial system vulnerable to global shocks cannot secure long-term progress. To this end, expanded domestic production of oil, gas, and critical minerals reduces dependence on foreign imports, insulating U.S. industries from geopolitical price swings. Strategic sectors such as steel, chemicals, and semiconductors are protected from offshoring pressures to prevent the “carbon leakage” that occurs when production shifts to regions with weaker environmental standards. Investments in infrastructure diversification, including ports, pipelines, and transportation networks, create redundancy that lowers vulnerability to chokepoints in global trade. At the same time, strengthened partnerships with allies in LNG, nuclear, and advanced technologies create cooperative networks that distribute risks and enhance resilience across supply chains. By treating supply chain stability as inseparable from sustainability, the U.S. embeds resilience into its broader model of industrial strength and competitiveness.

Collectively, these strategies embody the pragmatic redefinition of sustainability as abundance, competitiveness, and resilience — positioning the United States to lead not just in climate mitigation, but in shaping the industrial and energy systems of the future.

Collaborative Public–Private Partnerships in the Post-2025 Model

The long-term outlook for U.S. industrial sustainability emphasizes that resilience, abundance, and innovation cannot be achieved by government policy alone. These outcomes depend on collaborative frameworks that connect federal agencies, industry leaders, and academic institutions in ways that scale both innovation and implementation. In the post-2025 model, public–private partnerships (PPPs) serve as the operational backbone of industrial transformation: they mobilize federal funding to de-risk advanced technologies, channel industry investment into commercialization, and leverage academic expertise to train the workforce of the future. Through this model, PPPs accelerate the deployment of clean energy and digital technologies, ensure that resilient supply chains extend beyond large corporations to include SMEs, and foster inclusive participation in sustainability transitions. Two flagship platforms — **Manufacturing USA** and the **Manufacturing Extension Partnership (MEP)** exemplify this approach: the former advances cutting-edge technologies such as smart manufacturing, hydrogen, and circular economy solutions, while the latter ensures these innovations are diffused across the broader industrial base. Together, they illustrate how collaborative partnerships in the post-2025 era operationalize national strategy, linking innovation with industrial resilience and widespread sustainability impact.

Manufacturing USA: Driving Innovation and Competitiveness

The Manufacturing USA network, encompassing 17 technology-specific institutes, operates as a national testbed for applied research, commercialization, and workforce training. In the post-2025 paradigm, it plays four key roles. First, it builds resilience by addressing vulnerabilities in supply chains. Institutes such as CESMII (smart manufacturing) and REMADE (recycling and remanufacturing) enable digitalization, circular material flows, and predictive capabilities that reduce reliance on imports and mitigate exposure to global shocks. Second, it enables abundance by advancing frontier technologies — from additive manufacturing and photonics to biofabrication — thereby expanding the diversity of production pathways. This aligns directly with the philosophy of "energy addition, not subtraction," broadening industrial options instead of narrowing them. Third, it fosters innovation at the intersection of research and commercialization. By de-risking advanced technologies, the institutes make it easier for private capital to scale solutions; CESMII's digital integration efforts are a prime example, mirroring the administration's emphasis on digital transformation as a core driver of sustainability. Finally, it builds workforce capacity by preparing a pipeline of next-generation talent in robotics, AI, renewable energy, and advanced manufacturing, ensuring that U.S. competitiveness is underpinned by a future-ready workforce.

The Manufacturing Extension Partnership: Scaling Innovation Across SMEs

While Manufacturing USA advances the frontier, the NIST MEP program ensures that innovation reaches the vast network of small and medium-sized enterprises (SMEs) that make up more than 90% of U.S. manufacturers. In the post-2025 model, MEP plays a complementary role by embedding resilience, abundance, and innovation across the broader industrial ecosystem. It expands resilience by equipping SMEs with digital tools and sustainable practices, preventing systemic vulnerabilities that would emerge if smaller firms were left behind. It scales abundance by providing SMEs with access to technology integration, lean production methods, and supply chain optimization, ensuring that sustainability is not confined to flagship corporations but distributed across the entire economy. MEP also accelerates innovation diffusion, helping SMEs adopt technologies pioneered in Manufacturing USA institutes — such as smart manufacturing platforms, additive processes, and circular economy practices — thereby bridging the gap between federally funded R&D and everyday manufacturing practice. Equally important, MEP invests in workforce development and inclusion, expanding participation in STEM and manufacturing careers among underrepresented groups. This aligns with the broader definition of sustainability in the post-2025 model, which places economic vitality and social equity alongside energy security.

Synergies That Define the U.S. Model

Together, Manufacturing USA and MEP create a two-tiered system that operationalizes the nation's sustainability strategy. Manufacturing USA drives front-end innovation, pushing the boundaries of technology and resilience, while MEP ensures back-end diffusion, embedding those innovations across SMEs and strengthening the industrial ecosystem from the ground up. In this sense, collaborative public–private partnerships are not peripheral but central to the U.S. approach. They transform resilience, abundance, and innovation from abstract policy principles into tangible outcomes delivered on factory floors, supply chains, and energy systems nationwide.

This dual framework reflects a distinctively American model of industrial transformation: one in which government sets the enabling conditions, but deep collaboration across sectors delivers the results. By coupling technological breakthroughs with broad-based adoption, the U.S. ensures that its pursuit of industrial sustainability strengthens competitiveness, builds resilience against global shocks, and secures long-term leadership in the global energy and industrial economy.

2.3.3 Summary: U.S. Strategy for Industrial Sustainability

In summary, the pre-2025 model of U.S. industrial sustainability was driven by legislation, federal incentives, and a decarbonization agenda, exemplified by the IRA, CHIPS, and Federal Sustainability Plan. The post-2025 model represents a pragmatic redefinition: sustainability as resilience, abundance, and innovation.

In the post-2025 model, the U.S. has redefined industrial sustainability through a pragmatic model centered on resilience, abundance, and innovation. Moving beyond a climate-only focus, the strategy integrates energy security, economic vitality, and technological leadership as core priorities. In this model the U.S. emphasizes "energy addition, not subtraction," expanding oil, gas, nuclear, geothermal, and renewables to ensure affordability and grid reliability while reinforcing global energy leadership. Industrial resilience is treated as sustainability in itself, with policies to streamline regulation, modernize standards, and protect strategic industries from offshoring. This redefinition positions the U.S. not just to reduce emissions, but to secure its industrial base, expand global competitiveness, and shape sustainability transitions globally.

2.4 EU Activities

Industry 4.0 describes a fundamental process of innovation and transformation in industrial production. This transformation is driven by new forms of economic activity and work in global digital ecosystems. Today's rigid and strictly defined value chains are being replaced by flexible, highly dynamic, and globally connected value networks that emphasize new forms of cooperation. Data-driven business models prioritize customer benefits and solutions, replacing the product-centric focus that has been the prevailing paradigm of industrial value creation. Availability, transparency, and access to data are key factors for success in the connected economy and largely determine competitiveness.

In this 2030 Vision as shown in Figure 8, the stakeholders of Plattform Industrie 4.0 present a holistic approach to the shaping of digital ecosystems. Working from the specific situation and established strengths of Germany's and the European industrial base, their aim is to create a framework for a future data economy in line with the requirements of a social market economy: emphasizing open ecosystems, diversity and plurality, and supporting competition between all the stakeholders in the market. The Vision is primarily addressed to industry and commerce in Germany and Europe, but explicitly highlights the importance of openness and a willingness to work together with partners around the world. The strength of German and European industry is rooted in a system of innovation and commerce driven by heterogeneity, diversity, and specialization. In combination with commercial freedom, data and information security, and the protection of individual personal rights, these are the central pillars of the European industrial society. A decentralized system of open and flexible ecosystems is built on this structure and offers the best preconditions for shaping the digital economy within the set of values of a free and social market economy. Three closely interlinked strategic fields of action are crucial for the successful implementation of Industry 4.0: autonomy, interoperability, and sustainability. In its role as sensor and source of inspiration for future research topics, the German Research Council Industrie 4.0 (Forschungsbeirat Industrie 4.0) has identified and designed specific research and development needs that should make a significant contribution to successfully realizing the 2030 target vision[43]. In the process, key topics were defined that include the changing landscape of industrial value creation, the prospects of technological developments, the engineering of Industry 4.0 solutions, and the interactions between work, enterprises, and society.

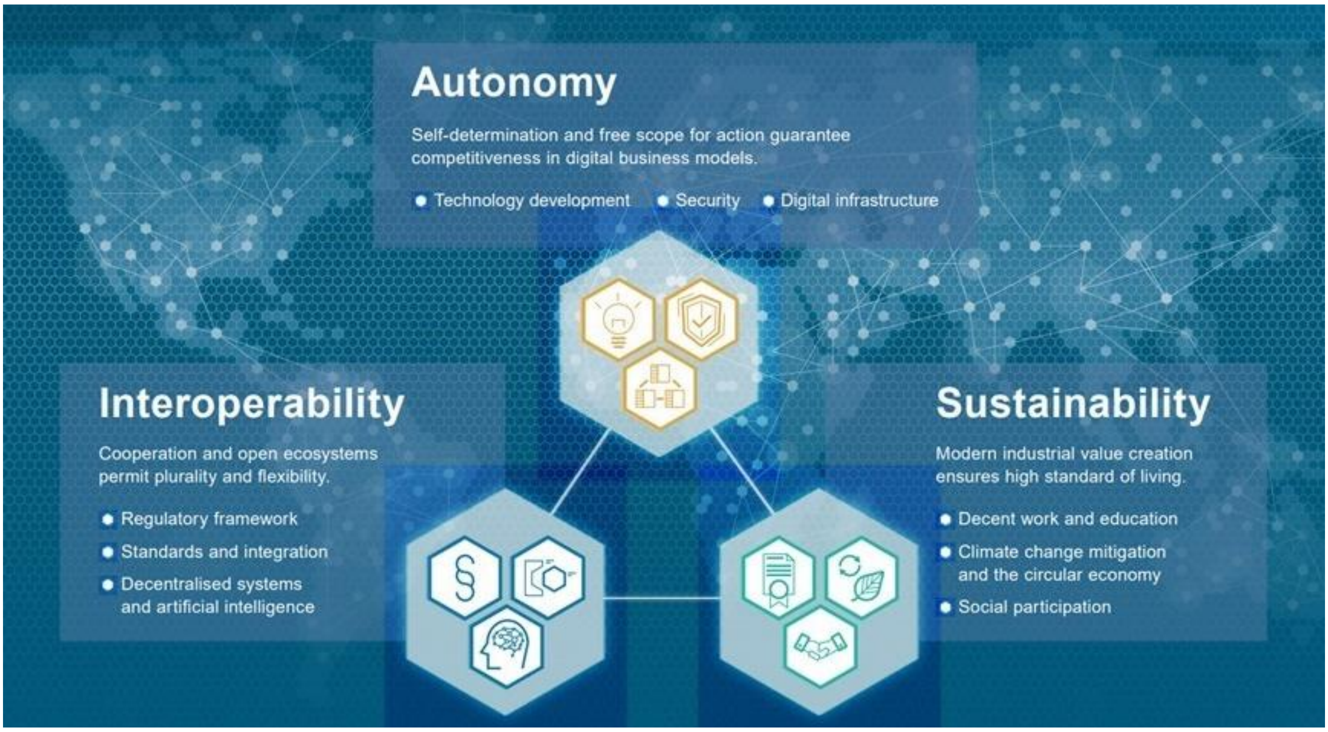


Figure 8 – 2030 Vision for Industry 4.0[42]

The stakeholders on Plattform Industrie 4.0 commit jointly to these fields of action as guiding principles for the coming decade of the incipient scaling-up of Industry 4.0 in Germany, Europe and globally. In a dialogue with all the stakeholders in the industrial society, the aim is to establish a framework for action so that—building on the current outstanding position of industry in global terms, the DX of industry can take place in a sustainable manner, and Industry 4.0 can be successfully established throughout a flourishing European Mittelstand. To keep this engine efficient and competitive, it is crucial not only to keep up with new technologies, but also to become an international leader in strategically relevant, differentiating areas. This requires concrete measures to make the innovation system in Germany more agile, interdisciplinary and adaptive, while always maintaining a long-term focus[44][45][46]. In particular, it is important to create new spaces in which innovative and flexible ecosystems can emerge and to establish new forms of collaboration that meet the dynamic requirements of modern technology and knowledge development.

2.4.1 Autonomy

The principle of autonomy underpins the freedom of all stakeholders in the market (companies, employees, scientists, individuals) to take self-determined, independent decisions and to interact in fair competition—from the defining and shaping of the individual business model to the individual's decision to make a purchase within the I40 ecosystems. In this context, approaches such as systems engineering are becoming increasingly important, particularly due to the interdisciplinary nature that is required for the engineering of autonomously changeable Industry 4.0 systems. One concrete example of this is cyber-physical matrix production systems, which open up new possibilities for the implementation of such systems thanks to their flexibility and networking[47][48].

2.4.2 Interoperability

The flexible networking of different stakeholders to form agile value networks is one of the core building blocks of digital business processes in Industry 4.0. The interoperability of all stakeholders is a key strategic element in the shaping of such complex, decentralized organized structures. A high level of interoperability—to which all the partners commit and contribute equally—is required to ensure the direct networking of operations and processes across companies and sectors. In the other direction, interoperable structures and interfaces give both manufacturers and customers an unrestricted possibility to participate in digital value networks and thus to shape new business models. In this way, interoperability also boosts autonomy. An important cornerstone for interoperability is the creation and implementation of data spaces that enable open, sovereign and (legally) secure access to data[49]. These data spaces form the basis for the efficient networking of systems and players and are crucial for promoting the exchange of information across company and sector boundaries. In addition, they must be designed in such a way that they guarantee both data security and data protection to ensure the trust of those involved and create the basis for the sustainable use of data in the context of Industry 4.0.

2.4.3 Sustainability

Economic, environmental, and social sustainability is a fundamental pillar of the values of our society. This works in two directions: firstly, this sustainability is being embedded in Industry 4.0, and secondly, Industry 4.0 permits substantial progress in sustainability. For example, the prosperity and quality of life of each individual largely depend on a forward-looking and competitive industrial sector. The ecosystem of innovation and the implementation of Industry 4.0 thus create a fertile environment in which sustainability can result from Industry 4.0 and Industry 4.0 itself can be sustainable—and thus make a key contribution toward maintaining the standard of living of our society[50].

2.4.4 Focus on the Human Being

New forms of HMI are becoming increasingly important in an industrial context. These interactions are changing the way in which people work together with machines and automated systems[51][52][53][54]. Instead of the traditional, purely functional interfaces, where the human controls the machine, a cooperative approach is being pursued in which machines and humans act in a symbiotic relationship. The machines take on repetitive, precise tasks, while humans make more complex, creative and strategic decisions.

The acceptance of new forms of HMI can be increased through transparent communication and the early involvement of employees in the change process. Training and continuous education strengthen competence in the use of new technologies, while ergonomic, user-friendly interfaces and the preservation of human control promote trust. It is also important that technology improves working conditions by taking over monotonous or dangerous tasks and improving the quality of life for employees. An iterative process that relies on feedback from the workforce also ensures that adjustments are made that promote both efficiency and employee well-being.

For implementation of this vision a dedicated initiative “IM-X” was started.

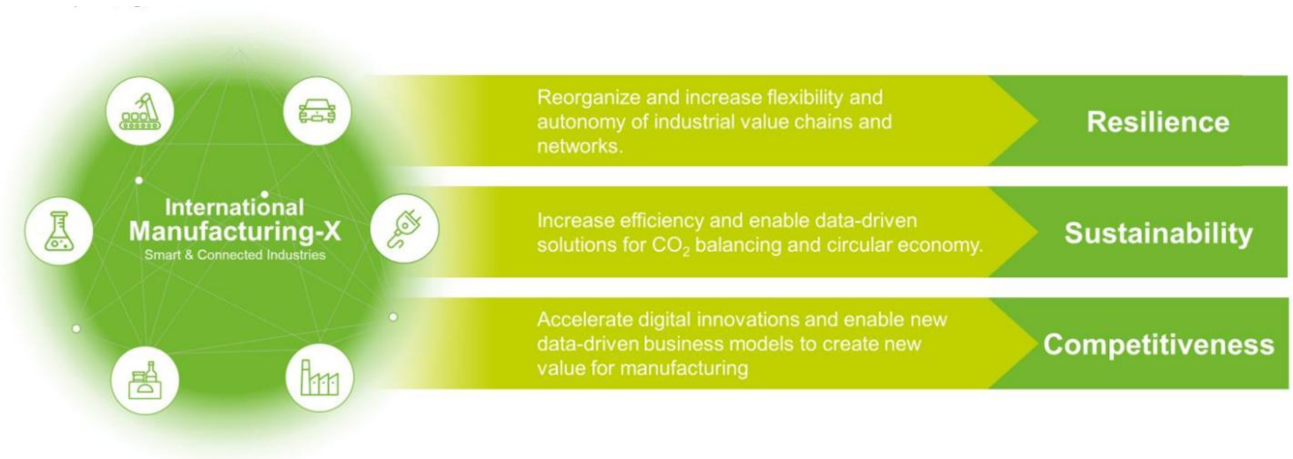


Figure 9 – IM-X Council[55]

The number of initiatives with a “-X” has grown over the last few years. Factory-X is the lighthouse project of the Manufacturing-X initiative. Manufacturing-X initiative, Catena-X, Factory-X and other projects are the key concepts to enable a networked, flexible and sustainable production world and stand for the DX of the manufacturing industry.

On that basis, the focus has now shifted toward Data Spaces that support multilateral data sharing across the industrial value chain, like Catena-X or Factory-X projects (Manufacturing-X initiative). On a European level, 14 Common European Data Spaces are being built right now, focusing on industrially relevant areas like energy, manufacturing, or healthcare.

The Manufacturing-X initiatives include various projects for different industries such as machine tool manufacturing (Factory-X), the semiconductor industry, automotive (Catena-X), aerospace, the process industry and others. The aim is to network production processes across different companies and thus create a fully integrated value chain. By using technologies such as IoT, AI and edge/cloud computing, data is to be collected, analyzed and used in real time to optimize production and reduce costs. Manufacturing-X enables closer collaboration between suppliers, manufacturers and customers, thereby increasing innovation capabilities and competitiveness. This not only enables more efficient production, but also greater adaptability to changing market conditions. As shown in Figure 10, the vision of Factory-

X is an autonomous, self-optimizing factory, in which human workers and machines work together seamlessly.

From this perspective, research and development into robots that use AI is also progressing in the EU. See Annex A.

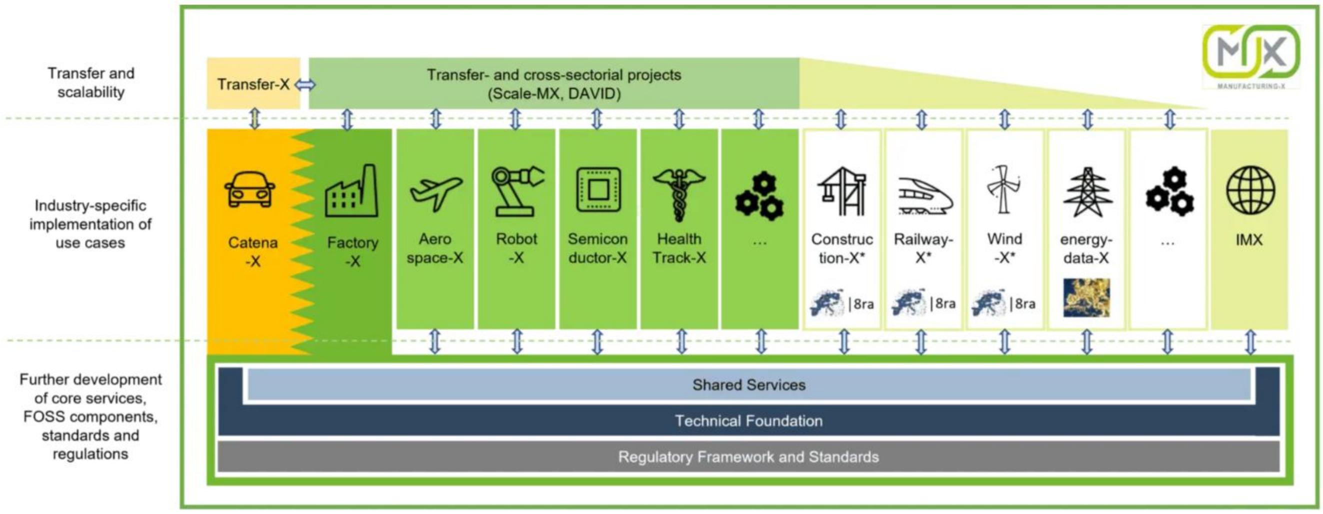


Figure 10 – Manufacturing-X: Cooperation between the projects[56]

2.4.5 Use Cases

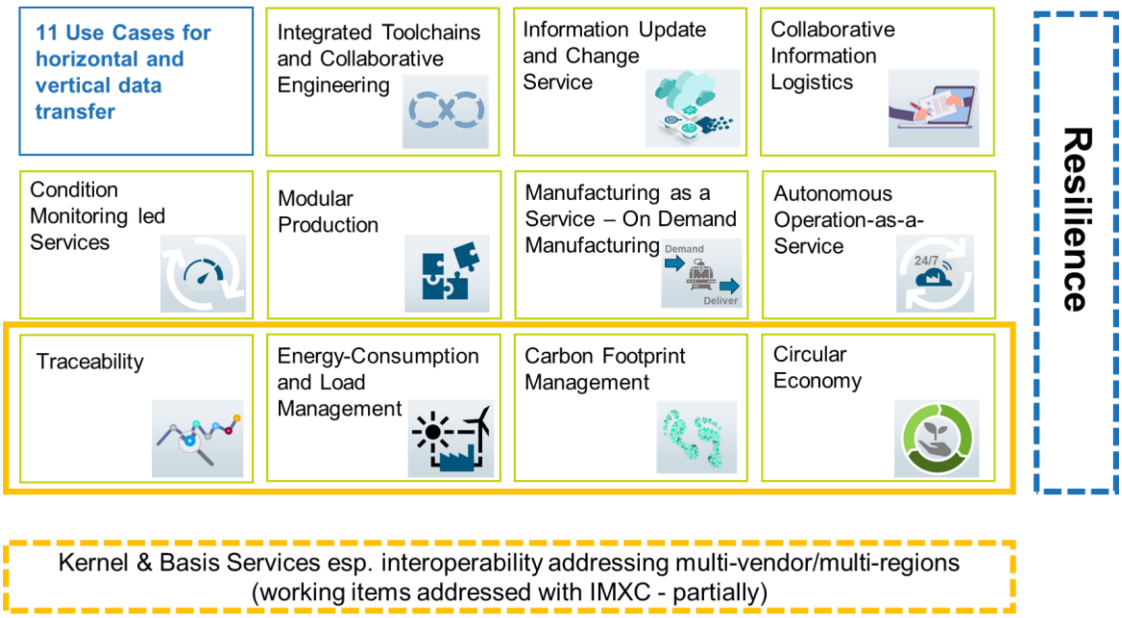


Figure 11 – The eleven use cases of Factory-X, based on a common kernel and basic services[56]

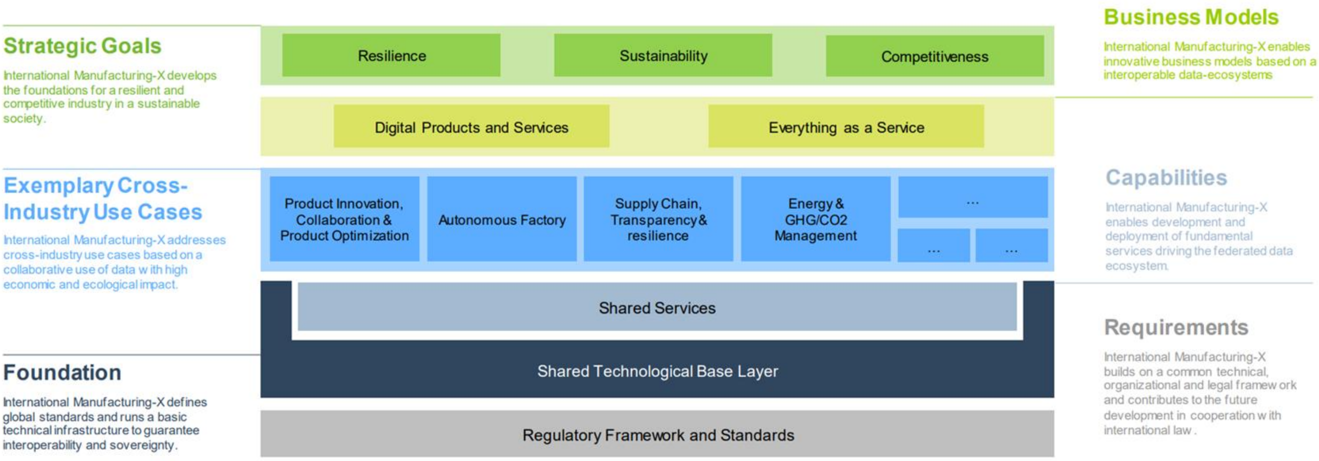


Figure 12 – Foundational framework for activities and international stakeholders[57]

2.4.6 IM-X – Close Cooperation Worldwide

Through the IM-X Council, in which cooperation with leading manufacturing countries and companies is being established, Manufacturing-X attains global reach. Major initiatives worldwide are in regular exchange to establish a worldwide network of compatible industrial data ecosystems. More initiatives and countries will join soon.

Figure 13 – IM-X[58]

2.5 Cross-regional Similarities and Differences

In this chapter, we have looked at the efforts being made in Japan, the United States, and Europe regarding industrial sustainability.

We learned that each country is working on digitalization measures to drive economic growth with the combined efforts of industry, academia, and government, such as the SIP program in Japan, Manufacturing USA in the United States, and Industry 4.0-related programs in Europe.

Furthermore, in terms of the environmental burden associated with economic growth, each region is taking measures to achieve a circular economy, such as the construction of an information sharing platform based on the concept of 3R (Reduce, Reuse, Recycle) in Japan, scientific efforts through programs such as the REMADE Institute that promotes recycling and remanufacturing technologies in the United States, and the construction of a regulatory framework in Europe that integrates the practice of a circular economy into sustainability strategies to minimize waste and resource consumption.

And in terms of energy supply, which is the foundation for sustainable industrial growth, each region is working to reduce carbon dioxide emissions and strengthen energy security.

Thus, while awareness of the issues and the willingness to work together with industry, academia, and government are common to all regions, each region has its own priorities and approaches based on its own economic situation.

Japan's Society 5.0 vision advocates for a cyber-physical space that uniquely combines technology and social welfare, seeking to harmonize economic development with the resolution of social issues. The United States is in a period of transformation, moving toward an "innovation first" pragmatism, reducing reliance on heavy-handed mandates, instead unleashing competition to balance climate goals with energy security, economic vitality, and technological leadership. In Europe, which includes many countries with a variety of economic situations, the focus is often on regulatory frameworks and policy-driven sustainability, emphasizing the alignment of manufacturing with environmental and social goals through comprehensive policies and regulations.

Regional differences were also observed in terms of resource constraints. In Japan, due to limited natural resources and a heavy reliance on imports, the focus is on energy efficiency and material innovation to enhance sustainability. In the United States, the focus is on optimizing resource use and improving efficiency through innovation and advanced technology to achieve sustainability goals. In Europe, each country faces different resource constraints, and the strategies for resource efficiency and sustainability are also diverse.

As mentioned above, it was found that each region has a shared awareness of the issues and a willingness to collaborate with industry, academia, and government to address industrial sustainability. However, each region has its own unique priorities and approaches to specific measures, taking into account the economic situation and other factors relevant to the region. It is important to mutually understand these similarities and differences and to promote international cooperation in order to achieve industrial sustainability on a global scale. In the following chapters, we will delve deeper into related topics and explore the possibilities of international collaboration.

Column: Empowering SMEs Through Tailored Digital Transformation

SMEs play a crucial role in society and the economy, and their DX has the potential to enhance the overall competitiveness of a nation.

However, there are still challenges to be addressed in order to improve productivity through digital means for SMEs.

One specific challenge faced by SMEs is the effort required to accommodate different conditions and document formats for each business partner[59]. Traditionally, initiatives involving industry, government, and academia have encouraged the use of DX solutions designed for large corporations to address this issue. However, solutions tailored to the perspectives and digital utilization capabilities of SMEs are necessary. In other words, SMEs are looking for customized solutions that fit their needs and budgets, rather than developing digital solutions from scratch in-house. To achieve this, there is a demand for environments that allow SMEs to customize digital solutions with no-code to make customization easier as an example.

In this way, it is important to realistically assess the mindset, financial capacity, and response capabilities of small and medium-sized enterprises and citizens, who are at the core of society's DX, and to proceed with the transformation from their perspective.

3 Labor Productivity, Trade Openness, Incentives, Labor Mobility

3.1 Foreword

3.1.1 Long-term Trends in Global Productivity

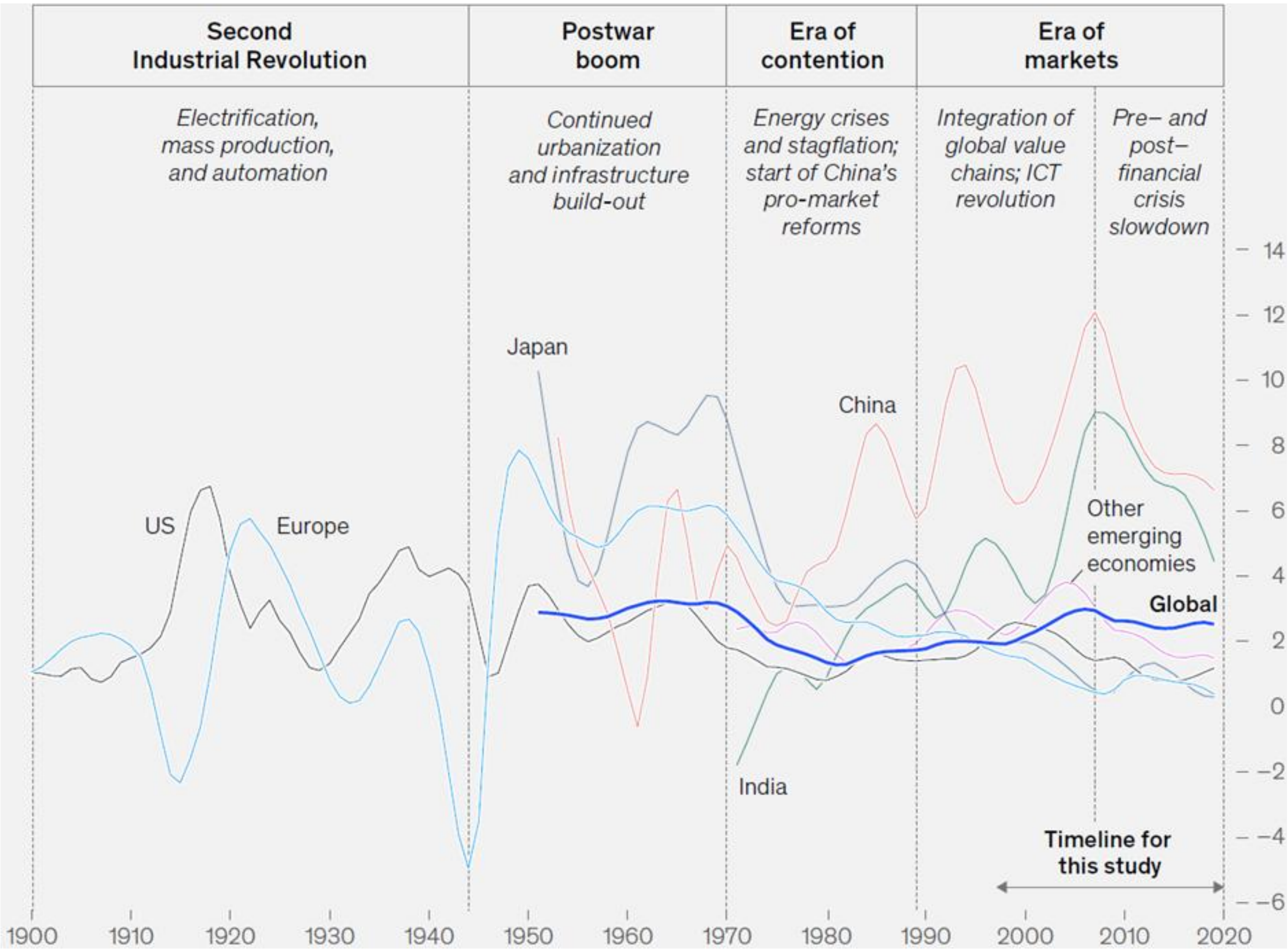
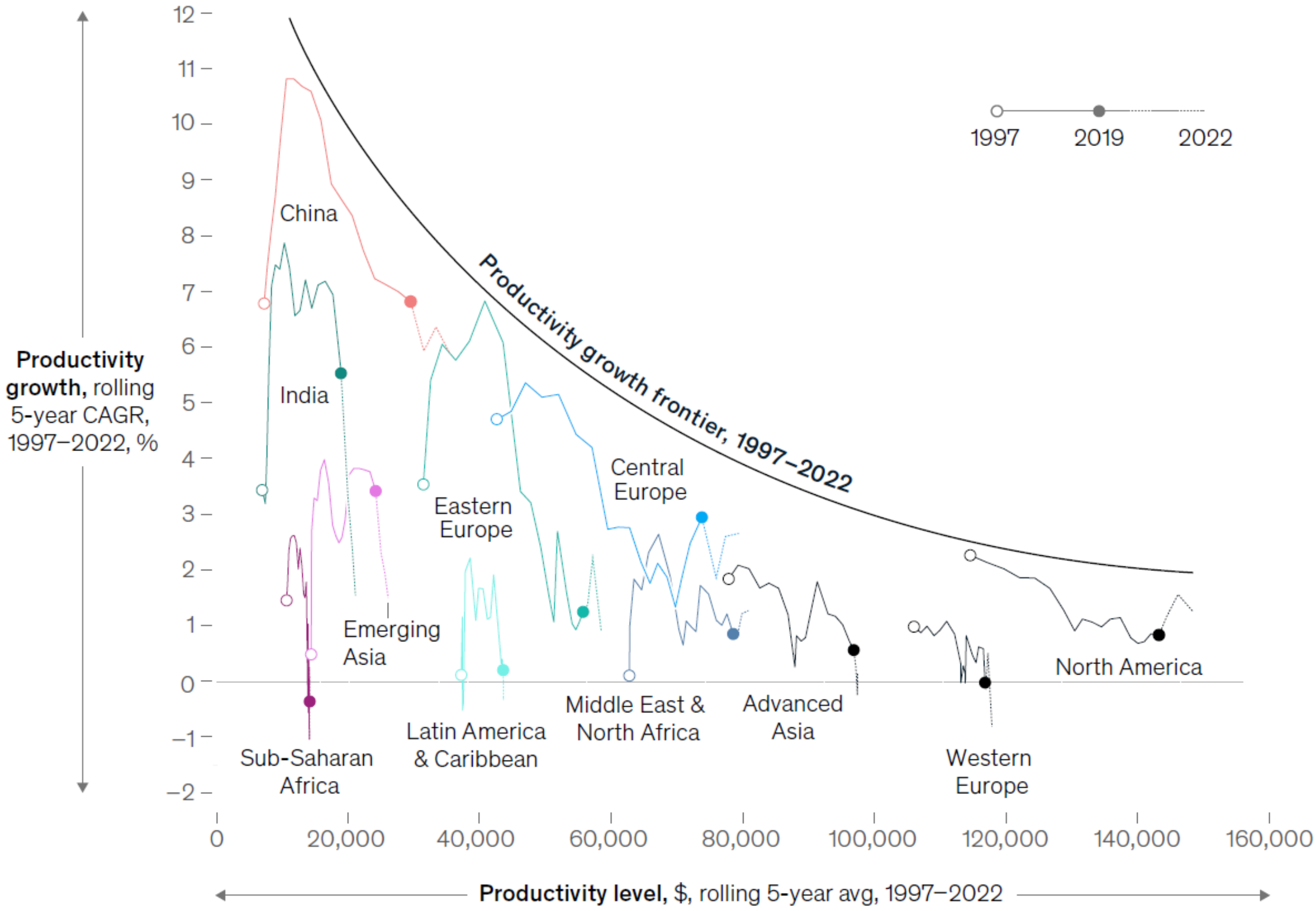


Figure 14 – Trendline of labor productivity growth, total economy, % year on year [6]

In the face of evolving global economic challenges, understanding the intricacies of labor productivity and the factors influencing it is paramount for sustaining growth and competitiveness. This chapter provides a comprehensive examination of labor productivity trends across Japan, the United States, and Europe, offering valuable insights into the unique dynamics shaping each region. There is an argument that there are two key drivers of labor productivity[6]. The first is the amount of capital per worker, and its increase is also called capital deepening. Capital can be tangible, such as machines, electricity, gas, water, and roads, or intangible, such as software and intellectual property. It is generally said that office workers are more productive if they have a laptop computer, construction workers are more productive if they have a crane, and transportation workers are more productive if roads are in good condition. The second is human capital, such as the ability, education, and accumulated experience of workers. For example, it is said that office workers who use laptop computers are more productive if they have the ability, education, and accumulated experience. In other words, the key points in the discussion of labor productivity are capital depending on and how to promote the growth of human capital.

Productivity growth has spread throughout the world through the social application of new technologies and the development of infrastructure in human society[6]. In Japan, the critical role of labor productivity in the manufacturing sector highlights the need for strategic incentives to attract and retain talent. In the U.S., technological innovation and workforce dynamics shape productivity, while the EU faces diverse productivity trends that require targeted support and investment. As shown in Figure 14 and Figure 15, historically, around the time of World War I, leadership in innovation and productivity shifted from Europe to the United States, driving electrification, mass production, and automation. Then, despite the Great Depression and the recessions at the end of World War I and World War II, the United States was able to maintain an average productivity growth rate of 3% from 1910 to the 1970s[6]. After World War II, Europe and Japan experienced a significant increase in productivity. Investments rebuilt cities, and investments in technology tried to catch up with the United States. China accelerated its productivity growth after opening up its economy in 1978, but it peaked in the late 2000s. Other major Asian economies, such as India, have also seen productivity growth over the past 25 years as they have integrated into global value chains[6].



Note: N=242, weighted averages for 11 regions in 21 rolling 5-year periods.

Figure 15 – Productivity level and productivity growth per employee [6]

3.1.2 Trade Openness

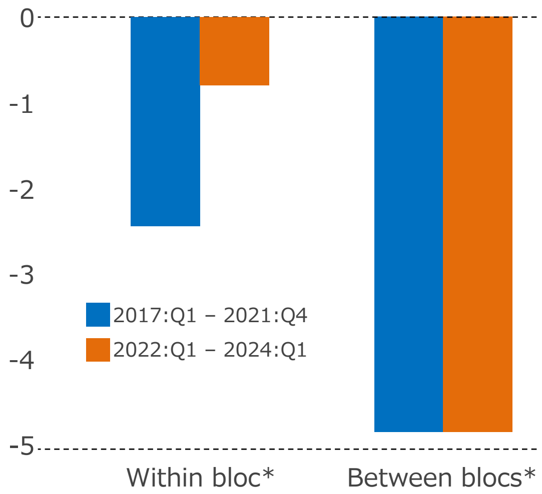


Figure 16 – Percentage point differences in trade growth before and after the start of war in Ukraine [8]

The bloc definition is based on a hypothetical bloc comprising Australia, Canada, Europe, New Zealand, and the U.S. and a hypothetical bloc including China, Russia, and countries siding with Russia during the March 2, 2022, UN General Assembly vote on the war in Ukraine. Other countries are considered non-aligned [8].

Figure 16 shows the percentage point differences in trade growth before and after the start of the war in Ukraine, analyzed by IMF[8]. According to the IMF, the figure shows that increasing geopolitical fragmentation is one of the reasons the world is moving toward a lower growth economy. Also, around 3,000 trade restrictive measures were introduced in 2023, almost three times as many as in 2019. The IMF reported that, as global markets become more integrated and value chains become more complex, the costs of geopolitical fragmentation become greater, as trade restrictive measures stifle efficiency gains from regional specialization.

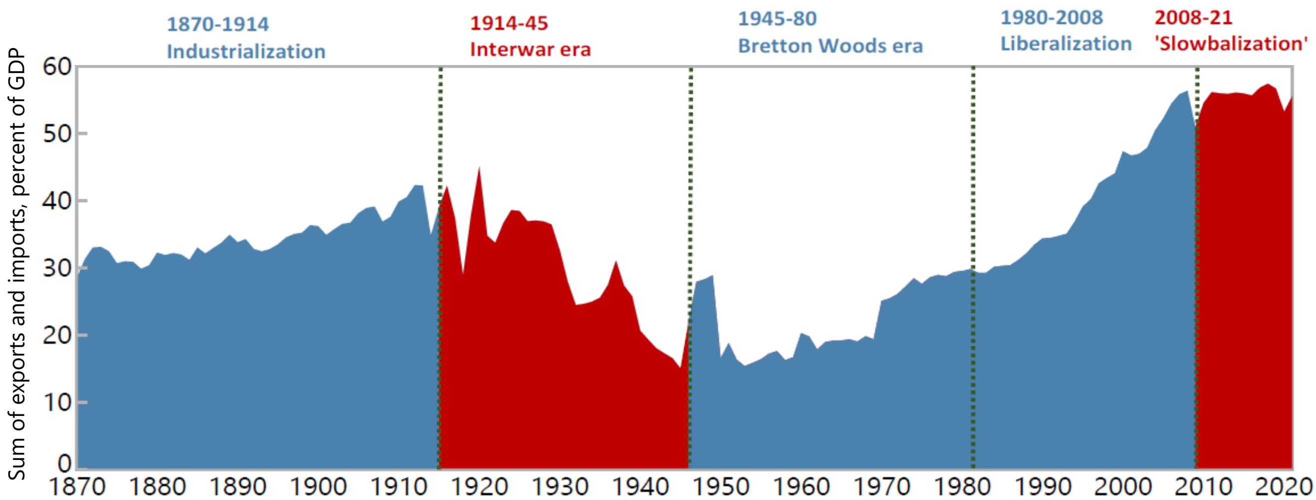


Figure 17 – Trade Openness[60]

Figure 17 shows the trade openness metric—the sum of exports and imports of all countries relative to global GDP[60]. The horizontal axis shows a timeline from 1870 to 2020. Also, if you look at the red column on the right, you can see that it has stagnated since the global financial crisis of 2008. The question is whether there is a correlation between labor productivity and trade openness.

In other words, **during the era of liberalization from the 1980s to the financial crisis of 2008, there is a hypothesis that the manufacturing industries of developed countries such as Japan, the United States, and Europe increased their labor productivity by keeping only high-value-added processes in their own countries and offshoring other processes to third countries, based on the premise of free trade.** However, since the 2008 financial crisis, the expansion of free trade, which is the premise, has stagnated, so it can be said that it has become **necessary to take different measures to improve labor productivity in the manufacturing industry in developed countries.**

In this context, Industry 4.0, which was one of the pillars of the "High-Tech Strategy 2020" approved by the German government in November 2011, attracted the attention of the world. **Industry 4.0 was proposed as one of its goals to dramatically improve labor productivity in the manufacturing industry by utilizing digital technology.**

Now that 15 years have passed since the proposal of Industry 4.0, **has labor productivity in the manufacturing industries of Japan, the United States, and Europe really improved through digitalization?** And has it been strengthened more than the labor productivity of the manufacturing industries of other countries that have emerged over the past 15 years, such as China and India? In the following chapters, we will analyze the actual situation and issues based on reports from each country, highlight common global issues, and explore the possibility of future international collaboration.

3.2 Japan Activities

3.2.1 Labor Productivity

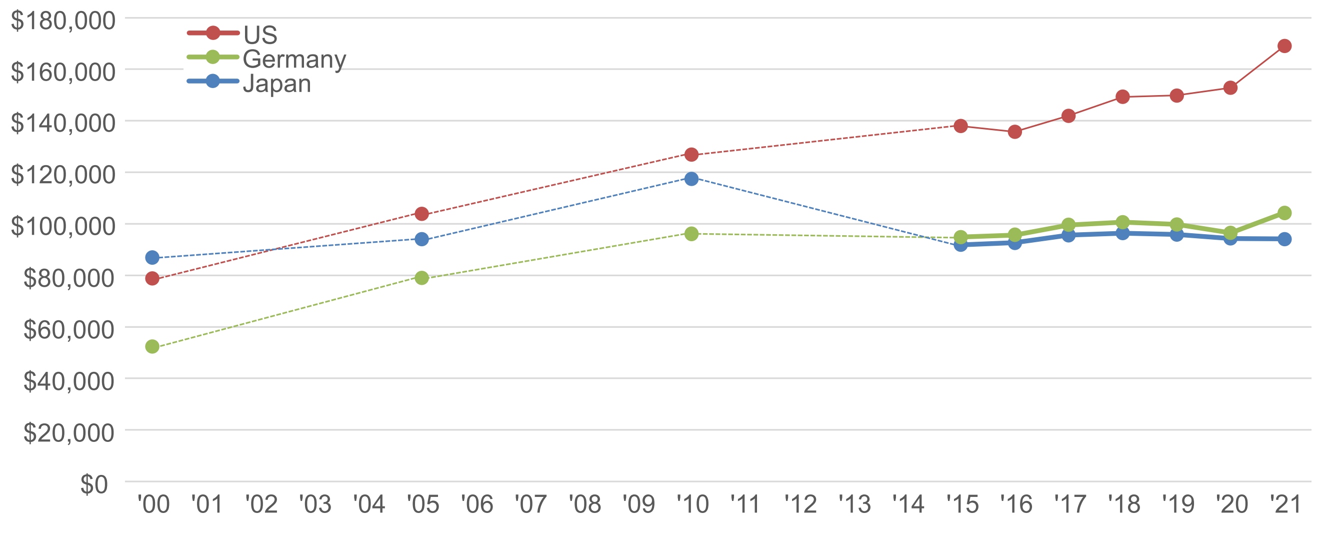


Figure 18 – Labor productivity in manufacturing sector[5]

Figure 18 shows labor productivity in the manufacturing sector by the Japan Productivity Center published on Dec 22, 2023[5]. The Japan Productivity Center has been recording labor productivity statistics for many years as value added per employed person. To convert the labor productivity of the manufacturing industry into dollars, the exchange rate is used as a moving average in the calculations.

3.2.2 Incentives

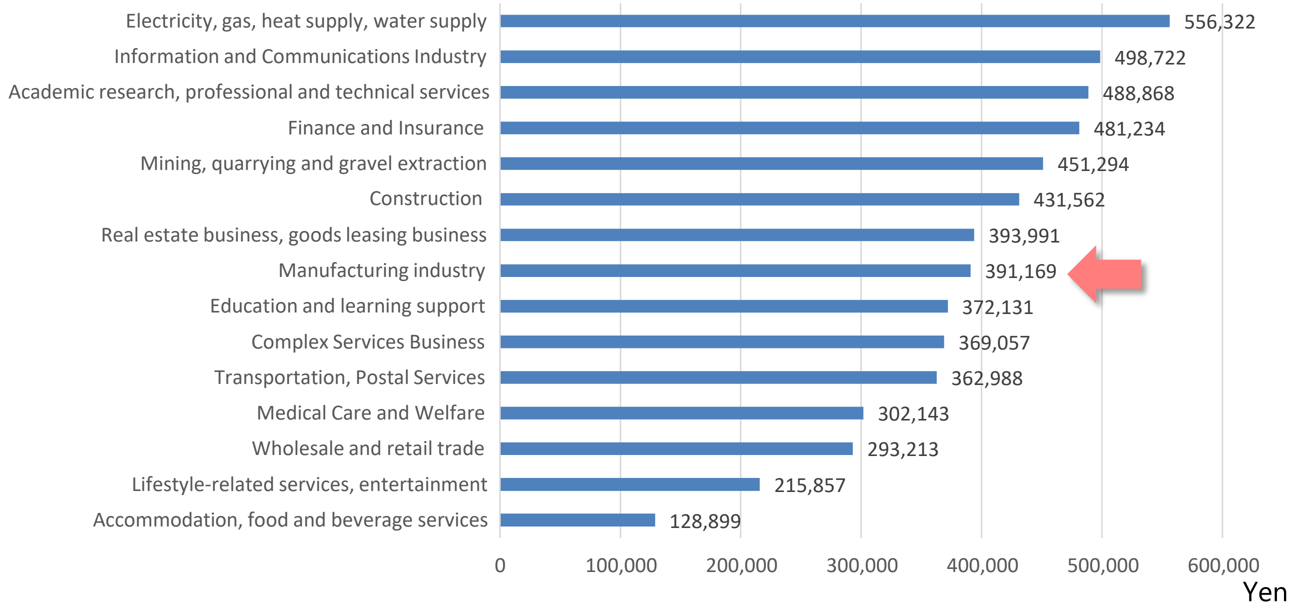


Figure 19 – Average monthly cash salary per regular worker by industry[61]

Figure 19 shows an average monthly cash salary per regular worker by industry, published by the Statistics Bureau, Ministry of Internal Affairs and Communications, Japan, 2022[61]. We can see that wages are lower in the manufacturing industry compared to industries such as electricity, gas, and water, and information and communications. From an incentive perspective, it can be hypothesized that one of the causes of the labor shortage is that talented people prefer industries with higher wages rather than manufacturing.

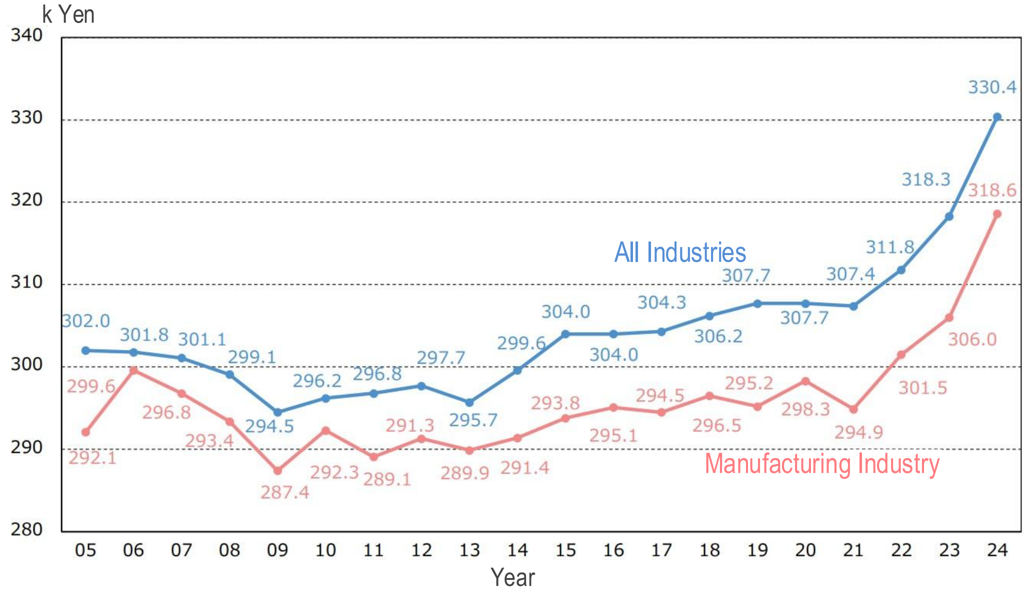


Figure 20 – Changes in wages (regular salary) [62]

Looking at the trends in wages (regular salary) for general workers in all industries and manufacturing as shown in Figure 20, both have been on the rise since 2014, with wages in all industries expected to be 330,400 yen in 2024, while wages in manufacturing will be 318,600 yen [62]. Looking at the difference in wages between all industries and manufacturing, wages in manufacturing have consistently been lower than wages in all industries. In addition, the wage gap between the two was about 2,000 yen in 2006, but will exceed 10,000 yen in 2024.

3.2.3 Capital Investment and Human Resource Development Status

As mentioned in the Foreword, a key point in any discussion of labor productivity is how to promote capital dependence and the growth of human capital, so below we will evaluate trends in capital investment and human resource development in Japan's manufacturing industry.

As shown in Figure 21, capital investment in the manufacturing industry has exceeded depreciation expenses since the fiscal year ended July 2012[62]. The upward trend has continued since the fiscal year ending April 2021, due in part to the easing of the impact of the spread of COVID-19.

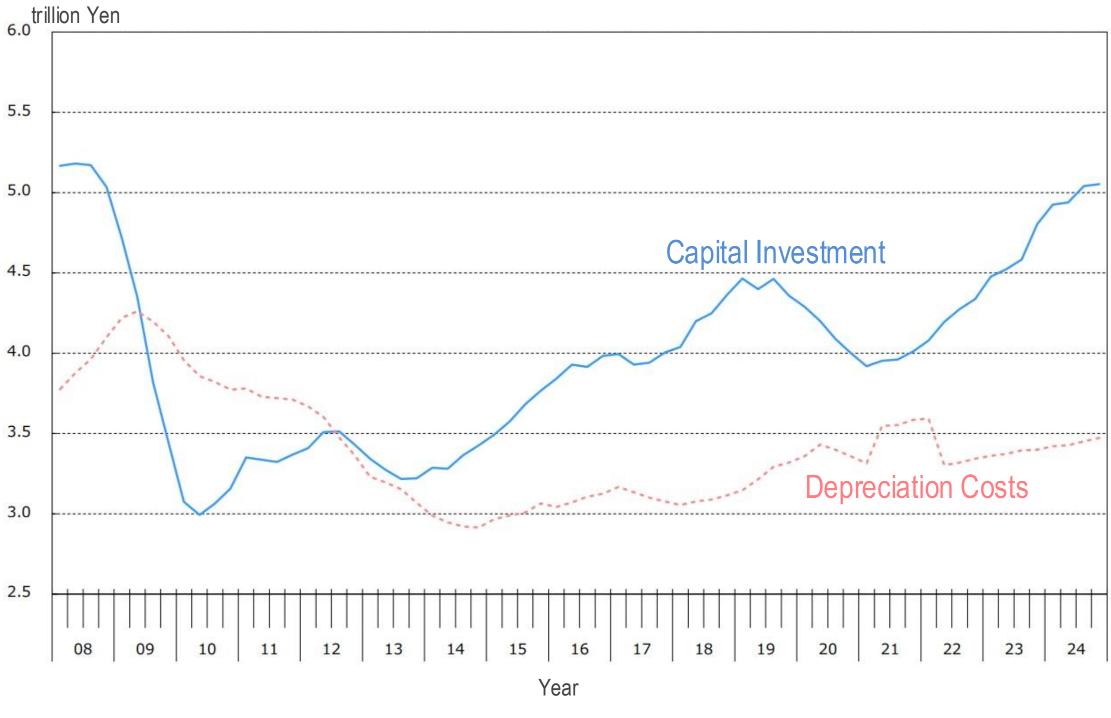


Figure 21 – Trends in capital investment and depreciation costs in the manufacturing industry [62]

To effectively promote the career development of workers within companies, subsidies are being provided to employers who have implemented vocational training for employees according to a plan, covering training expenses and a portion of wages during the training period[62]. To accelerate investment in people, the "Human Investment Promotion Course" and "Business Development Reskilling Support Course" will be established in FY2022, and will be supported with high subsidies until FY2026. In addition, from April 2024, the long-term education and training leave system of the human investment promotion course will be applicable to hourly leave so that workers can take leave flexibly, and the upper limit of the number of hours and amount of wage subsidy per person for small and medium-sized business owners will be raised. In addition, to promote the use of voluntary vocational ability development training, the minimum training time will be lowered from 20 hours to 10 hours, and the requirement that training be limited to work-related training will be accepted to include non-work-related training, making it easier to use in combination with the long-term education and training leave system.

In this way, the Japanese government continues to support employers who are working on human resource development. The number of grant applications approved for the 2023 Human Resource Development Support Subsidy (Human Resources Development Support Course, Education and Training Leave Grant Course, Human Investment Promotion Course, Business Development Reskilling Support Course) is 38,190, while the number of eligible workers is 136,909.

Additionally, the evaluation system and the promotion of skills have also been strengthened[62].

The Skills Testing System is a national certification program that assesses and verifies the skill levels of workers based on specific standards. As of April 1, 2025, 133 occupations are being implemented. It plays an important role in increasing the motivation of workers, including those in the manufacturing field, to acquire skills and in improving their social status. In fiscal year 2023, approximately 810,000 people applied to take the test nationwide, and approximately 360,000 passed. In total, approximately 8.72 million people have become skilled workers since the system began in fiscal year 1959. In addition, the Japanese government aims to promote vocational training and improve the skill levels of young skilled workers (generally under the age of 22) in participating countries and regions through skills competitions. Japan also participates in the World Skills Competition for the purpose of fostering international exchange and goodwill.

Labor productivity in Japan's manufacturing industry reflects the history and challenges of the sector's growth. After the dramatic growth leading up to the 1980s, the debate over what the growth drivers should be and how to implement measures to achieve a sustainable industry has been ongoing for the past few decades. Recent technological innovations and human resource strategies present promising paths for improvement, and the industry, academia, and government must work together to address the drastic changes in social conditions that occur every day.

3.3 U.S. Activities

3.3.1 Manufacturing Labor Productivity: A Comprehensive Analysis

Manufacturing productivity in the United States has been shaped by technological innovation, shifts in workforce dynamics, and policy interventions. Labor productivity in the U.S. is commonly defined as the ratio of total output, typically measured by GDP, to the total hours worked within the manufacturing sector. This key metric, reported by the Bureau of Labor Statistics (BLS), serves as a critical measure of labor efficiency in generating economic value. While global definitions of labor productivity generally align with the U.S. approach, they often integrate additional dimensions, such as energy use or environmental impact, to address regional priorities. Despite these variations, the fundamental goal remains consistent worldwide: to maximize output while minimizing inefficiencies in resource utilization.

3.3.2 Trends in Manufacturing Labor Productivity

Figure 22 – Manufacturing Sector: Output per Worker for All Workers [63]

The trajectory of U.S. manufacturing labor productivity reveals periods of growth and stagnation shaped by economic shifts, technological advancements, and external challenges. From 1973 to 1990, productivity growth slowed to 1.4% annually, as manufacturers faced economic restructuring, oil crises, and intensified global competition. This period highlighted inefficiencies as the sector adapted to a more interconnected global economy. The 1990 to 2007 technological resurgence marked a significant turnaround, with productivity averaging 4% annual growth. This was driven by the adoption of computer-aided design (CAD), robotics, and lean manufacturing techniques, alongside globalization and offshoring, which enabled firms to optimize production and reduce costs. However, the 2008–2019 post-recession period brought new challenges, with productivity growth falling to 0.9% annually due to reduced capital investments, labor market disruptions, and a shift toward service-oriented industries.

During the COVID-19 pandemic, U.S. manufacturing productivity experienced a sharp decline in early 2020, with output dropping by 20% in Q2 2020 as factories closed and supply chains were disrupted. However, a strong rebound followed, with productivity rising 10.1% in Q3 2020, as manufacturers rapidly adapted by implementing automation and digital technologies to maintain operations. Despite these gains, the sector faced persistent challenges. The pandemic accelerated the adoption of Industry 4.0 technologies, such as IoT and robotics, which helped offset labor shortages and improve efficiency, laying a foundation for long-term productivity growth even as global supply chain disruptions and workforce challenges continued.

In general, the slowdown in U.S. manufacturing productivity growth after the 2008–2010 financial crisis, despite investments in Industry 4.0 technologies, can be attributed to several factors: Research indicates that the productivity slowdown is widespread, affecting various industries and firms of different sizes. This suggests that the issue is not confined to specific sectors but is a broader phenomenon within the manufacturing landscape. Also, despite increasing R&D intensity—measured by the ratio of R&D expenditure to gross output—there has been a decline in the effectiveness of R&D in generating productivity growth. This indicates that additional investments in R&D are yielding lower incremental productivity gains than in the past. Another factor is that the rapid adoption of computer and electronic technologies between 1985 and 2005 significantly boosted productivity. However, as these technologies became ubiquitous, the marginal gains from further adoption diminished, leading to a slowdown in productivity growth. Also, the decline in capital investment post-financial crisis has limited the manufacturing sector's ability to modernize and enhance productivity. Lower levels of capital formation have constrained the adoption of new technologies and the replacement of outdated equipment. In summary, the post-crisis productivity slowdown in U.S. manufacturing is a multifaceted issue involving widespread industry effects, diminishing returns on R&D, technology saturation, and reduced capital investment.

Despite ongoing challenges, high-tech manufacturing sectors, particularly those in semiconductors and advanced electronics, have demonstrated robust productivity growth, showcasing the resilience and adaptability of U.S. manufacturing. The adoption of Industry 4.0 technologies—such as robotics, AI, and IoT—has been pivotal in driving efficiency, precision, and scalability. These advancements, bolstered by policies like the CHIPS Act, have enabled transformative gains in productivity by modernizing processes and enhancing global competitiveness. While certain industries still grapple with barriers to modernization, the integration of cutting-edge technologies and the support of forward-looking policies provide significant opportunities for sustained growth and innovation across the U.S. manufacturing landscape[64].

3.3.3 Factors Contributing to Productivity & Sustainability Trends

Labor productivity in U.S. manufacturing is shaped by a combination of technological innovation, strategic investments, workforce dynamics, and global trade considerations—all of which are increasingly interlinked with sustainability goals. Technological advancements remain a cornerstone of productivity growth, with the integration of robotics, AI, and IoT transforming traditional manufacturing processes. These technologies have enabled greater precision, minimized waste, and accelerated production cycles, contributing not only to efficiency but also to the environment. In 2022, capital investment to upgrade manufacturing infrastructure in the private nonfarm business sector grew at an annual rate of 2.8%[65]. These investments are essential for adopting efficient technologies, aligning productivity improvements with sustainability objectives.

Global trade and supply chains have long been pivotal to U.S. manufacturing productivity, providing access to cost-efficient raw materials and markets. However, recent trade tensions and supply chain disruptions have exposed vulnerabilities, prompting U.S. manufacturers to reconsider sourcing strategies. This has accelerated investments in domestic production capabilities and localized supply chains, supporting both resilience and environmental sustainability and reduced dependence on volatile global markets.

The capabilities of the workforce also play a critical role in U.S. labor productivity. While the U.S. benefits from a highly skilled labor pool, nearly 80% of manufacturers report difficulties in finding qualified workers, highlighting a persistent skills gap. The U.S. manufacturing industry faces a critical workforce challenge fueled by demographic shifts and skill shortages. A 2018 Deloitte report projected that by 2028, 2.4 million manufacturing positions—or 53% of open roles—would remain vacant due to a lack of skilled workers. A 2024 study estimates this figure will rise to 3.8 million unfilled positions within the next decade, highlighting the escalating issue[66]. Nearly 25% of the workforce consists of Baby Boomers (born 1946–1964), many nearing retirement. Already, 5% of the workforce is beyond retirement age, and an additional 20% is set to retire within 10 years, risking a significant loss of expertise. Simultaneously, the small number of Generation Z workers entering the sector compounds the problem, leaving manufacturers struggling to fill roles while managing the retirement of seasoned employees. Addressing this requires targeted strategies, including workforce development, advanced training, and technology-driven recruitment to secure the sector's future competitiveness.

By integrating technological innovation, capital investment, localized supply chains, and addressing workforce development, U.S. manufacturing can achieve productivity gains while advancing sustainability. These dual goals are essential for maintaining global competitiveness and addressing the environmental challenges of the 21st century.

3.3.4 Comparison of Global Productivity Trends

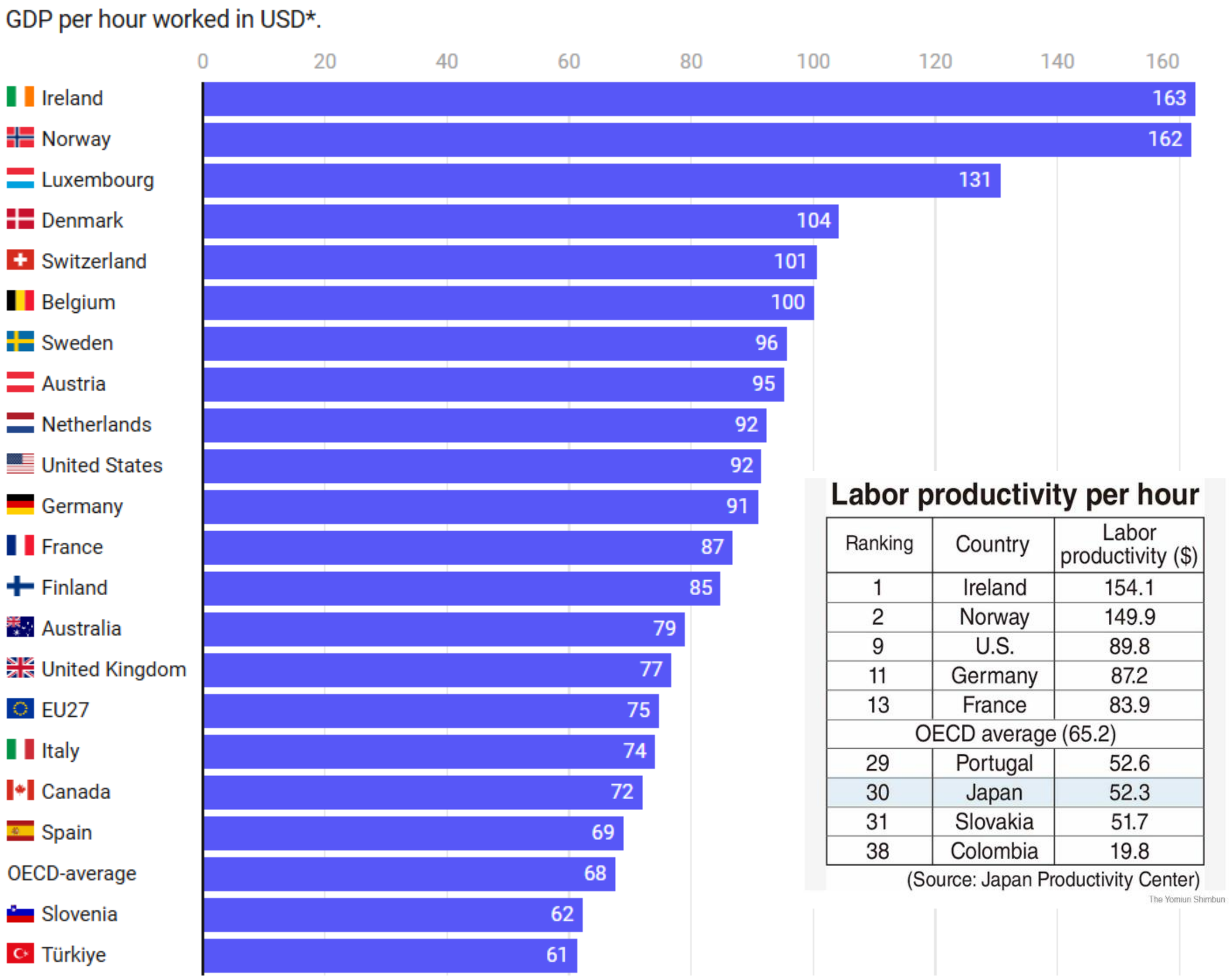


Figure 23 – Productivity levels in 2022[67]

The United States maintains a strong position in global manufacturing labor productivity, though it trails behind certain smaller, high-value, specialized manufacturing economies such as Ireland, Norway, Switzerland, etc. According to data from the Organization for Economic Co-operation and Development (OECD), in 2022, the U.S. achieved a GDP per hour worked of approx. $90, surpassing other major economies, including Germany and Japan, in this metric[68].

Manufacturing labor productivity in the United States reflects the sector's adaptability and resilience. While historical trends highlight periods of growth and stagnation, recent advancements in technology and workforce strategies offer promising pathways for improvement. Addressing challenges such as skill gaps, infrastructure limitations, and economic volatility will be essential to maintaining the sector's competitiveness in a rapidly evolving global landscape.

3.4 EU Activities

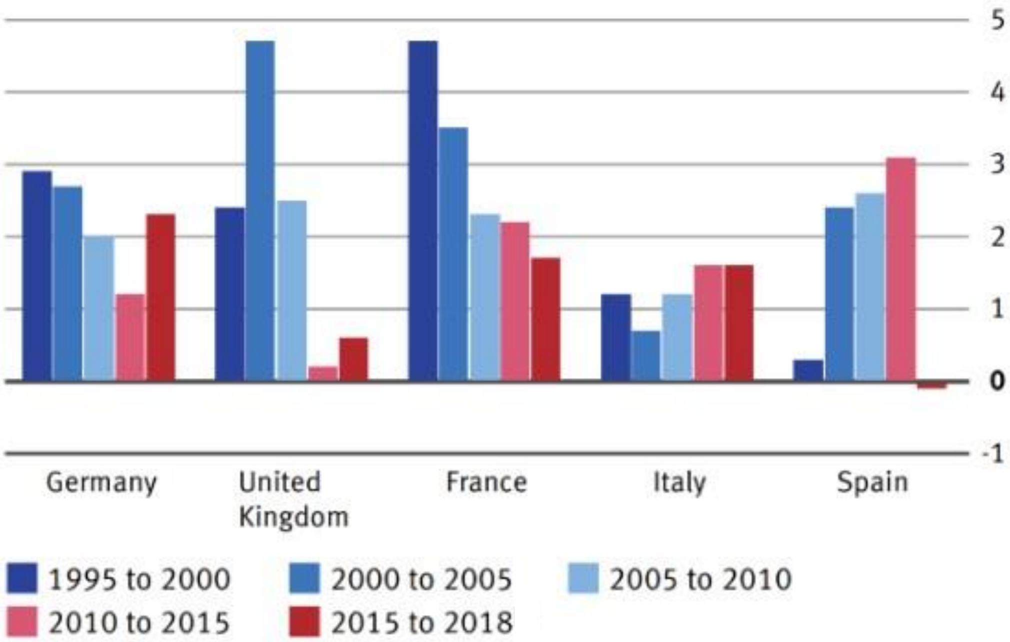


Figure 24 – Labor productivity in manufacturing,
Annual average change in the five-year intervals, percent [69]

As shown in Figure 24 the five largest economies in the EU (Germany, France, Italy, Spain and the United Kingdom) show different trends in labor productivity[69]. Germany has experienced slower productivity growth in recent years, which is partly due to demographic change and the increasing importance of the service sector.

Germany has experienced slower productivity growth in recent years. In this point, as shown in Figure 25, as the Statista chart with data from the Deutsche Bundesbank shows, both GDP per working day and GDP per working hour have been declining slightly since 2023[70]. According to the Federal Statistical Office (Destatis), an important reason for the slowdown in productivity development in Germany—considering the purely mathematical factor of a slight decline in economic output since 2023—is the structural change in the economy toward the service sectors. It is assumed that most activities in the service sector tend to offer less potential for productivity growth than is the case in the industrial sector. Production processes in the service sector are often labor-intensive and can be replaced to a lesser extent by technology.

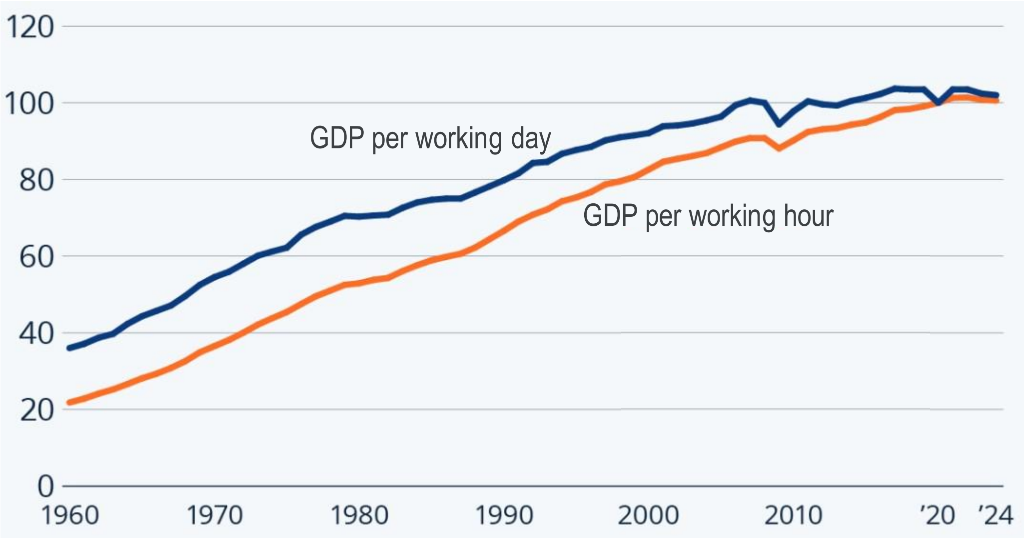


Figure 25 – Real GDP per working day/working hour in Germany in Germany (index, 2020=100)[70]

Another significant factor in the slow increase in productivity in the manufacturing industry to date is that Industry 4.0 applications have not yet been implemented across the board[71][72][73]. The associated implementation problems, often due to inadequate infrastructure, high initial investments, or the need for a fundamental rethink in established production processes, are hindering rapid adaptation. The integration of new technologies into existing operational structures is particularly challenging, presenting a considerable hurdle for SMEs. Here, there is often not only a lack of financial resources but also a lack of personnel capacity to make the transformation sustainable and efficient. Adapting operational structures to technological innovations requires extensive investment in both technical infrastructure and employee training. Careful planning is necessary to manage the transition without significant losses in production output.

Looking back at 2016, when Industry 4.0 initiatives began, Germany faced the problem that its labor productivity had not improved since 2007 as shown in Figure 26[74]. At that time, it was estimated that Industry 4.0 activities alone might increase the productivity of the German economy by 12% by 2025, solely through the added value from the digitalization of all production, supply, and distribution chains. However, even now, 10 years later, productivity has not increased, as discussed in Figure 24 and Figure 25.

The slowdown in labor productivity growth comes at a time of diverse and sometimes disruptive technological advances. In many areas, comprehensive IT networking gives rise to entirely new forms of organization in production and sales, while innovative business models challenge established structures. These developments, combined with buzzwords such as 'Industry 4.0,' 'Big Data,' and the 'Internet of Things,' suggest great potential for increasing productivity. It is therefore all the more surprising that the digitalization of the economy does not appear to be accompanied by significant productivity gains. This 'productivity paradox' is not entirely new; even the introduction of personal computers into economic life in the course of the 'third industrial revolution' in the 1980s did not lead to the expected advances in productivity[75].

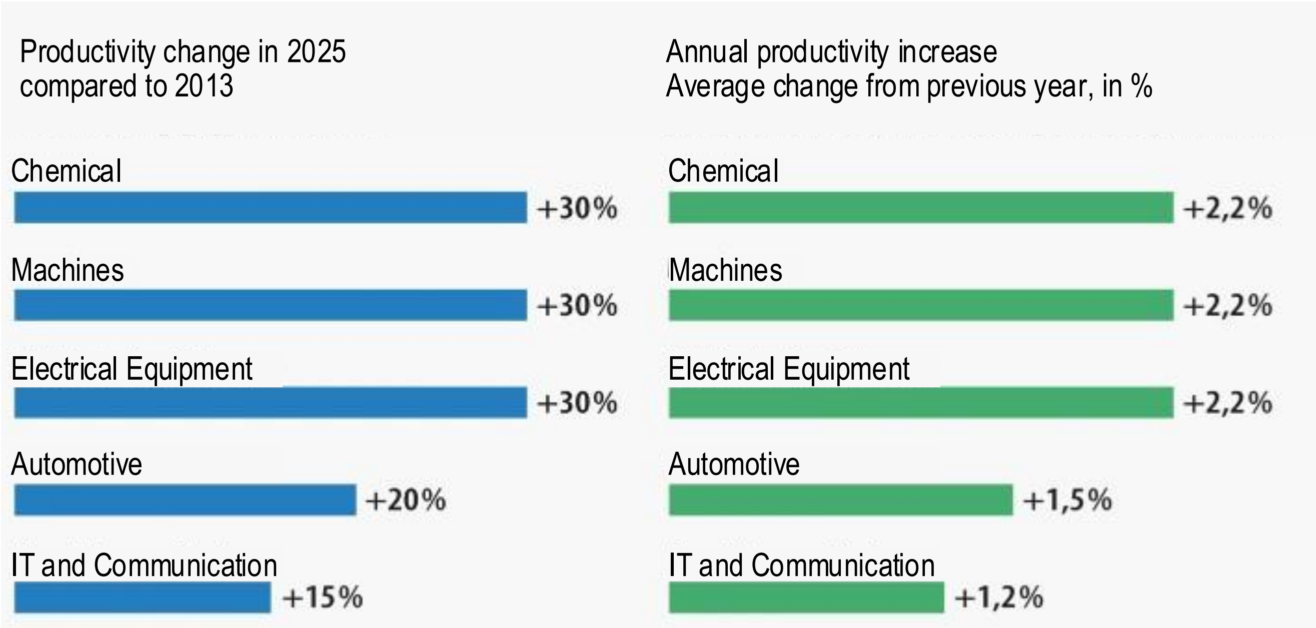


Figure 26 – Productivity growth rates by industry, as predicted by Frankfurter Allgemeine Zeitung GmbH in 2016[74]

3.5 Cross-regional Similarities and Differences

All three regions have seen productivity growth slow since the 2007 financial crisis. The practice of keeping only high-value-added processes in-country and offshoring the rest has been reconsidered since the financial crisis.

Instead, each region has been investing in digital technology and automation, but the benefits of this have yet to be seen in productivity gains. Also, each region shares the view that human resource development is essential to sustaining productivity gains, and each region is investing in education and training to strengthen human capital.

Additionally, each region acknowledges the need to realign labor market incentives and address demographic challenges, such as aging populations and labor shortages. Improving labor mobility and creating attractive career paths in manufacturing are shared policy priorities.

On the other hand, differences include the way each region responds to trade liberalization and its impact on productivity. Japan keeps high-value-added processes in Japan and outsources other processes overseas. It focuses on balancing domestic production with global trade opportunities through strategic trade policies. The United States, responding to trade tensions and supply chain disruptions, is shifting toward reshoring and strengthening domestic production capabilities. In the EU, trade liberalization trends are diverse, with some countries moving toward integration into global value chains. It focuses on balancing trade liberalization with domestic economic priorities and ensuring that trade policies support productivity growth across the region.

Also, incentive structures to attract talented people to manufacturing vary by region, affecting labor mobility and productivity. Wages in Japan's manufacturing industry are low compared to other industries, which may hinder the acquisition of talented people. It focuses on strengthening incentives to attract skilled workers to manufacturing and ensuring talent retention and maximization of productivity. In the United States, high-tech sectors offer competitive incentives, but skill gaps still exist. The focus is on addressing the skills gap and strengthening incentives to develop talent, to keep manufacturing competitive and innovative. EU incentives vary across countries, with some struggling to attract skilled workers due to stagnant wages and investment. The focus is on strengthening incentives to attract and retain talent across member states to keep manufacturing competitive and productive.

Labor mobility shows further divergence. Japan, while historically characterized by lifetime employment, is gradually shifting toward more flexible labor models. The U.S. labor market is generally fluid, with systems and employer expectations oriented toward rapid workforce reallocation. In the EU, labor mobility is supported through regional coordination, with an emphasis on cross-border skills recognition and workforce reallocation programs.

4 New Jobs/Lost Jobs, Gig Work, Workforce Strategies

4.1 Foreword

The World Economic Forum (WEF) published the "Future of Jobs Report 2025" in January 2025, outlining the outlook for the global labor market over the next five years (2025-2030). This was analyzed based on a survey of over 1,000 major companies around the world[76][77]. The report predicts that the rapid spread of generative AI will bring about major changes in industrial structure, employment, and required skills. It also states that the following five macro trends will significantly change the labor market by 2030.

1. Technological evolution: digitalization and the advancement of AI

   Expanding digital access, the evolution of AI and ICT, and the spread of robotics and automation will continue to have a major impact on the labor market. In particular, AI is ranked as the biggest trend that 60% of surveyed companies expect to transform their business, and its impact will be the largest in terms of both job creation and loss.

2. Economic uncertainty: rising cost of living and slowing growth

   Although global inflation is slowing down, rising living costs (50% of surveyed companies expect an impact) and slowing economic growth (42%) will continue to affect business activities in the future.

3. Green transition: accelerating climate change measures

   Increasing awareness of climate change measures is the third biggest change driver in the labor market. Increasing investment in decarbonization (47%) and adaptation to climate change (41%) will boost demand for renewable energy engineers and environmental engineers.

4. Demographic changes: aging populations in developed countries and increasing young workforces in emerging countries

   Aging and declining workforces in developed countries (40%) and increasing workforces in emerging countries (24%) will have a significant impact on the labor market, including increased demand for healthcare and education-related jobs.

5. Geoeconomic divisions: geopolitical tensions and protectionism

   Increasing geopolitical tensions (34%) and protectionist policies (tighter restrictions on trade and investment: 23%) will restructure supply chains and increase demand for security-related jobs, encouraging companies to transform their business models.

The report also predicts which occupations will grow fastest and decline fastest over the next five years with the following two figures.

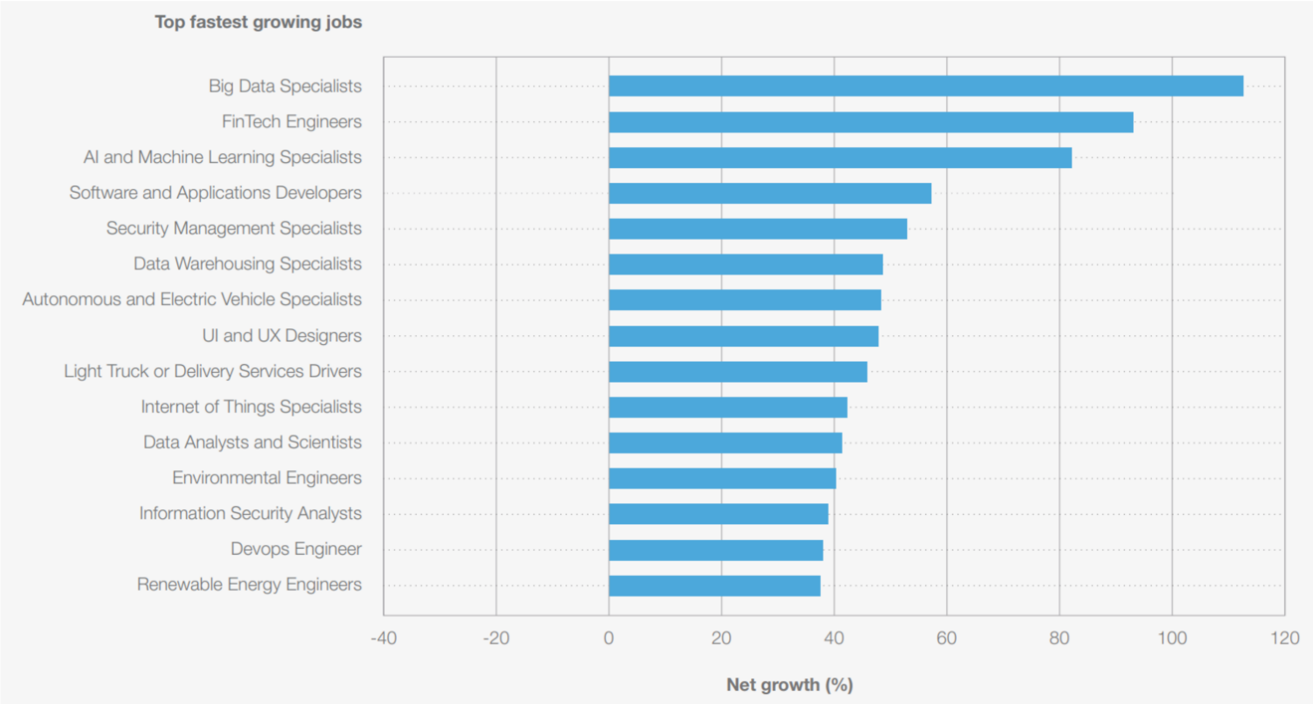


Figure 27 – Top fastest-growing jobs 2025–2030[76]

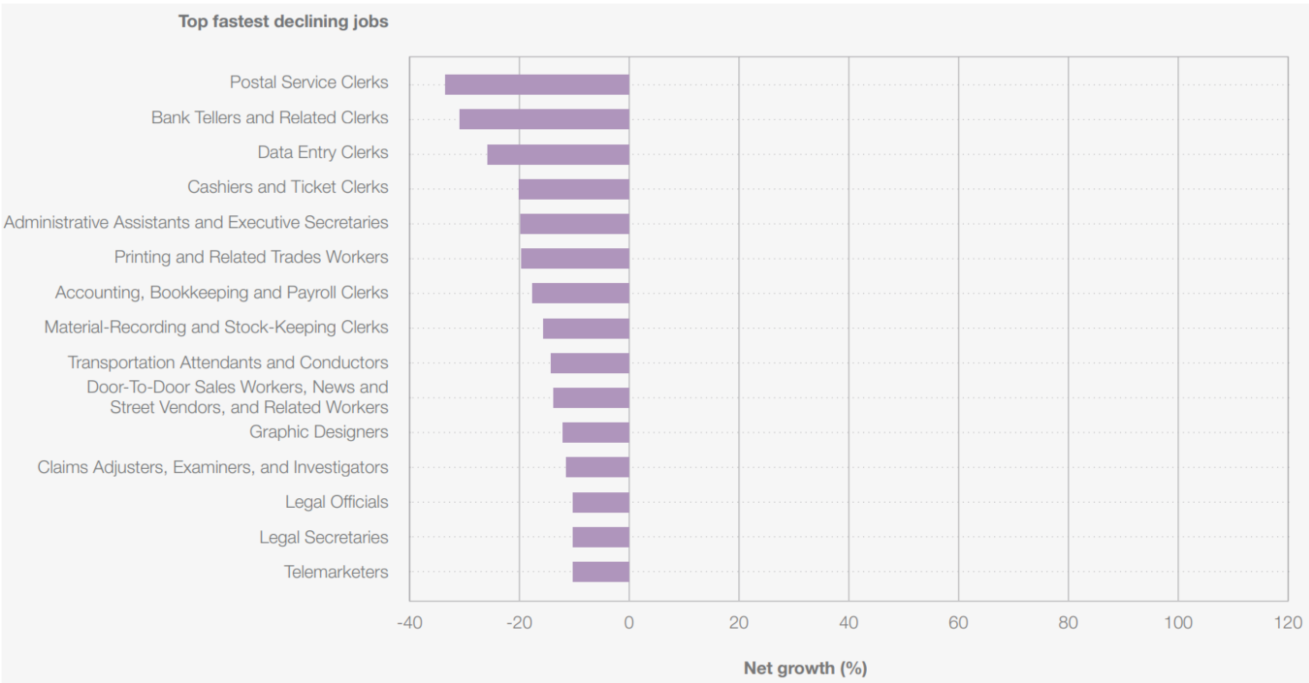


Figure 28 – Top fastest-declining jobs 2025–2030[76]

Figure 27 shows the growing jobs from 2025 to 2030. The horizontal axis shows the rate of increase/decrease, and the vertical axis shows jobs. Jobs such as Big Data Specialists, FinTech Engineers, and AI and Machine Learning Specialists are predicted to grow. On the other hand, Figure 28 shows the declining jobs from 2025 to 2030. The horizontal axis shows the rate of increase/decrease, and the vertical axis shows jobs. Jobs for Postal Service Clerks, Bank Tellers and Related Clerks, and Data Entry Clerks are predicted to decline. That is, most of the growing jobs are technology-related, with AI specialists and business intelligence analysts being the fastest-growing roles. And most of the fastest declining roles are administrative or secretarial roles, including bank tellers and related clerks.

As the labor market changes, the skill sets required of workers will also change significantly. The report predicts that by 2030, 39% of workers' existing skill sets will be transformed or outdated. Companies are placing emphasis on continuous learning, reskilling, and upskilling programs. In addition, from the perspective of the diverse expertise and abilities of workers and diverse working styles, a social mechanism is required to match workers with the labor market more dynamically and in detail. This is due to the spread of a working style called "Gig work" in recent years in various countries, and this trend must also be considered.

In the following chapters, we will discuss how each country perceives such worker education and the matching of workers with the labor market and consider the workforce management.

4.2 Japan Activities

4.2.1 Estimated Labor Shortage

PERSOL Research Institute, the research institute of PERSOL, a major Japanese temporary staffing company, published Future Labor Market Projections 2035 in October 2024[78]. As a result of the estimate, it was found that in Japan in 2035, the daily labor demand will be 346.97 million hours, while the labor supply will be 329.22 million hours, resulting in a labor shortage of 17.75 million hours per day. This translates to a shortage of 3.84 million workers, and the labor shortage will be 1.85 times more serious than in 2023.

In 2035, the total population of Japan, including foreigners, is expected to decrease by about 7.7 million people compared to 2023, and the aging population will also progress. Considering these demographic trends as well as the state of the economy and wages, this estimate predicts that the number of employed people will increase by about 3.75 million, while the working hours per person are expected to decrease by about 163 hours per year.

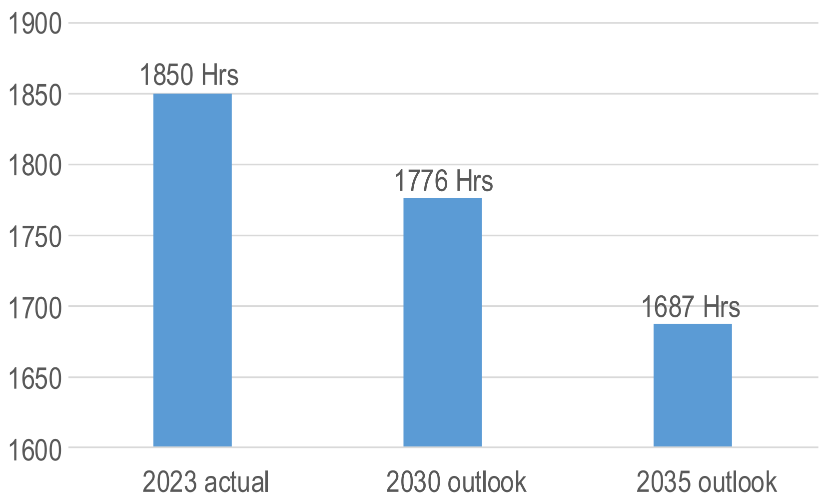


Figure 29 – Outlook for annual work hours per employed person in Japan[78]

Although the number of working people will increase as more women and seniors participate in the workforce, the number of working hours per person will decrease, coupled with the effects of work style reforms. As shown in Figure 29, the annual working hours per employed person is expected to decrease from 1,850 hours in 2023 to 1,776 hours in 2030 and 1,687 hours in 2035.

In other words, although Japan is transforming into a society that accepts diverse working styles, the labor force is not enough to meet the demand for labor required by society, and it is necessary to balance the supply and demand of labor by further improving productivity in existing industries and encouraging the transformation of individual industries to adapt to a changing society.

4.2.2 Future Human Resources Conference

The Future Human Resources Conference, organized by Japan's METI in 2022, invited presidents and executives of major globally competitive companies from various industries, including automobiles, electronics, industrial machinery, energy, retail, logistics, construction, and finance, to hear about "the type of human resources that will be needed in the future."[79]

As a result, it was said that unless everyone can sense changes in the times and constantly update their abilities and skills, they will not be able to adapt to the accelerating transformation of the industrial structure in the future. Based on this, the Future Human Resources Conference estimated Japan's labor demand in 2050.

In these estimates, they assumed changes in demand for skills, etc., due to digitalization and decarbonization, first estimated the extent to which each skill, etc., would be required in 2050, and then estimated the number of workers by job type and industry. And the following two scenarios were assumed when estimating labor demand.

- High growth scenario: A scenario in which digitalization and decarbonization progress and a high growth rate can be achieved
- Low-growth scenario: A scenario in which digitalization and decarbonization stagnate and a high growth rate cannot be achieved

Figure 30 shows the relative change in the number of workers required for each job type with the high growth scenario. The horizontal axis shows the rate of increase/decrease, and the vertical shows jobs. Jobs such as agriculture, forestry, and fishery workers, construction and mining workers, and office workers, are predicted to decline, and production process workers, professional and technical workers, and service workers, etc., are predicted to grow.

And Figure 31 shows the relative change in the number of workers needed by major industries with the high growth scenario. The horizontal axis shows the rate of increase/decrease, and the vertical shows industries. Industries such as agriculture, forestry and fisheries, mining and construction, public service, and multi-service, are predicted to decline, and medical care and welfare, education and learning support, and manufacturing, etc., are predicted to grow.

From this analysis, they predicted that in Japan, changes by occupation will decrease in occupations that are easily replaced by AI and robots but will increase in occupations that are difficult to replace, and occupations involved in new technological development. In addition, they predicted that changes by industry will be greatly influenced by the composition of occupations within each industry.

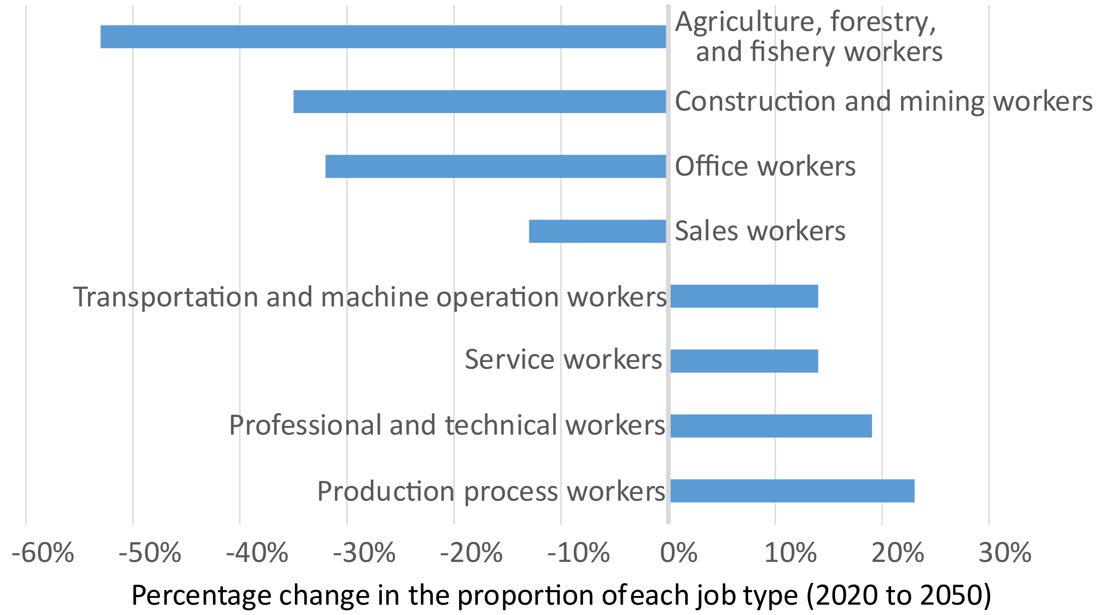


Figure 30 – Relative change in the number of workers required for each job type in Japan with the high growth scenario[79]

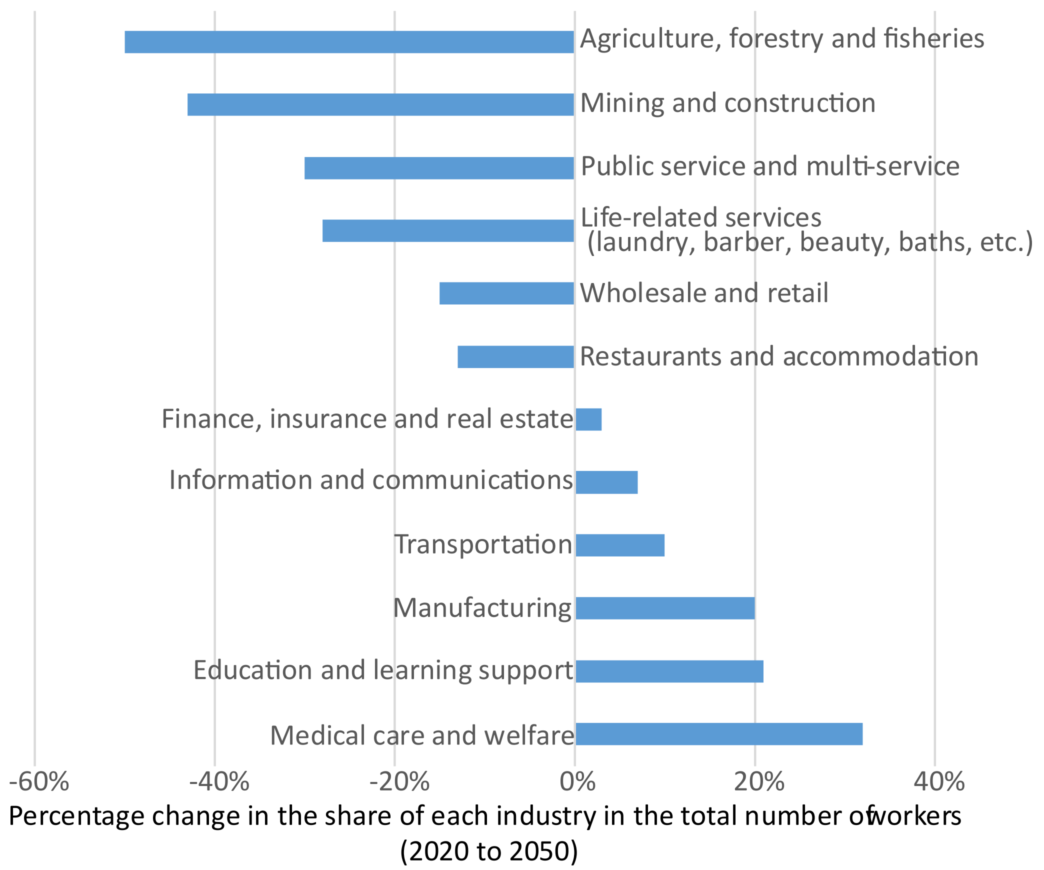


Figure 31 – Relative change in the number of workers needed by major industries in Japan with the high growth scenario[79]

Also, they looked back on Japan's employment system and considered future policies**[79]**.

In the past, the Japanese employment system was said to be a source of competitiveness, especially in the mass production model of manufacturing. Under the steady economic growth, the Japanese employment system developed human resources from a long-term perspective based on the premise of long-term employment, which contributed to fostering a sense of unity in the organization and accumulating company-specific capabilities. In addition, the lump-sum hiring of new graduates, which was established based on the premise of long-term employment, tended to enable many students to find employment after graduation, except for temporary exceptional periods, and led to social stability, such as keeping the youth unemployment rate at a low level.

However, as Japan's economic growth slowed and the "continued growth" that was the premise of the wage and personnel system unique to Japanese companies could no longer be expected, the limitations of the Japanese employment system have been pointed out since the 1990s.

Currently, employee engagement at Japanese companies is at the lowest level in the world. While few people believe they want to continue working at their current company, even fewer intend to change jobs or start their own businesses. In addition, compared to other countries, there is a strong tendency for job changes not to result in wage increases. And more than 40% of companies recognize the gap between the skills required by technological innovation and the skills of their current employees.

Based on these reflections, they asked Japanese society whether a review of the employment and human resource development system is required without any sacred cows. Specifically, it argued that the Japanese employment system represented by lifetime employment and seniority-based wages should be discussed, and the recruitment strategy that is the area connecting the Japanese employment system with the outside world. In other words, as shown in Figure 32, it was argued that the relationship between workers and organizations should change from a "closed" relationship to a "select and be selected" relationship through human capital management.

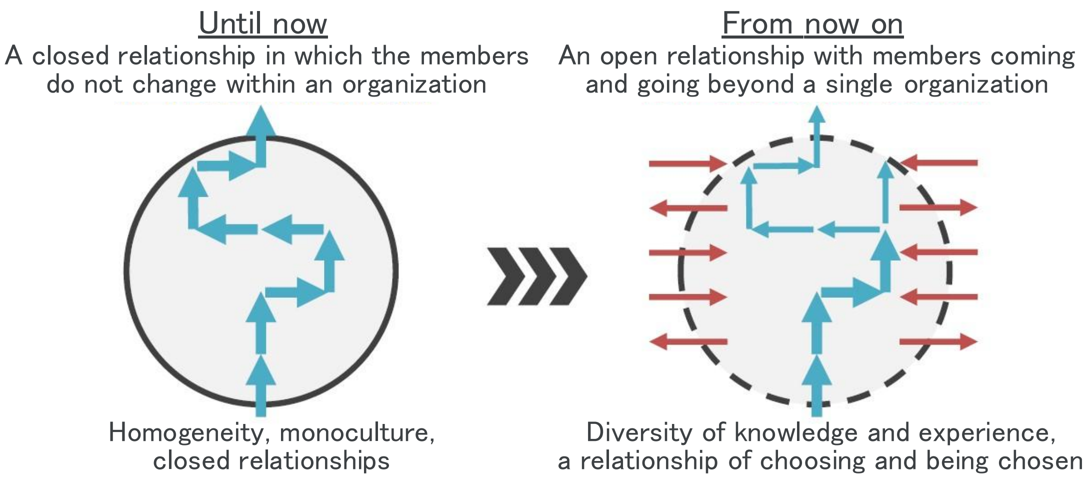


Figure 32 – The relationship between workers and organizations as advocated by METI, Japan[79]

In conclusion, they pointed out that megatrends such as digitalization and decarbonization will change the capabilities and skills required, and may significantly increase or decrease labor demand in certain occupations and industries. In this context, they pointed out that to develop and secure the human resources that will support the future, it is necessary to reconsider the entire social system, from employment and labor to education.

4.2.3 Status and Considerations on Gig Work

METI also analyzed the new digital-related work that emerging technologies have brought to the digital economy and the digital platforms that match these jobs[80]. It then categorized gig workers who obtain work opportunities through matching platforms in terms of the type of work and their relationships with companies, as shown in Figure 33.

Job		The dependency of Gig work on corporate workflow: Independent	The dependency of Gig work on corporate workflow: Subordinate
Job	Negotiation Type	Digital Nomad Worker	Jump-in Experts
Job	Allocation Type	Click Worker	Digital Servant

Figure 33 – Gig worker classification advocated by METI, Japan[80]

With this figure, METI notes that Gig workers range from those who are tied to a company's workflow and are assigned work through a platform, to more highly skilled gig workers who negotiate individually to secure work. They say that Gig work has the advantage of being able to secure personnel with the necessary skills at any given time, as a labor market that can meet the diverse working needs of workers, and that it reduces the burden of personnel training that was previously necessary. On the other hand, they say that there are disadvantages for workers, such as an unstable income because there is no guarantee of stable employment opportunities, and no opportunity to improve skills through training because skills are assumed.

In other words, they point out that technological innovation has polarized the labor market, and highly skilled workers have more options, which may reduce skill mismatches, leading to an expansion of the skill premium. Also, they point out that as the labor market has polarized, low-skilled workers have difficulty finding jobs that match their skills, even if they have acquired medium skills, as the number of medium-skill jobs has decreased in the labor market overall, and mismatched employment remains. To solve this problem, they point out, it is necessary to create a recurrent education system that allows people to continue learning throughout their lives, rather than simply acquiring the newly necessary knowledge and experience in compulsory education and higher education.

However, even if such educational opportunities are created, there will be a certain number of workers who are unable to acquire high skills. Enabling such workers to participate actively in society is an important perspective in building a human-centered sustainable society, but such discussion is yet to be seen from the Japanese government and related parties.

4.2.4 Expansion of Spot Work Market and Future Challenges

KPMG Japan focuses on Spot work market in Japan and analyzing how individual work style options are changing[81]. In this analysis, Spot work refers to “one-off, short-term work,” and is a concept that combines working under an employment contract with an employer said “one-off part-time work” and working as an individual on commission said “Gig work.”

According to them, the market size of Spot work intermediary services in Japan is growing at an average annual growth rate of nearly 30% from 2021 to 2023. Until now, Gig work, which involves working under contract for food delivery and other services, has attracted attention due to the COVID-19 pandemic, but recently there has been a noticeable increase in one-off part-time work under employment contracts.

They said the reasons for this market expansion include the decline in the productive population in Japan, the development of a technological infrastructure that can provide a one-stop service for matching jobseekers with employers on digital platforms, and the creation of guidelines by the Japanese government in 2018 to promote side jobs and part-time work, as well as efforts to foster an environment that supports employment in a wide range of areas. As a result, they point out that side jobs and part-time work are now possible even in cases where work outside of the main job was not previously permitted, and the number of people engaging in other forms of work is increasing.

They point out that in the future, the labor supply and demand will tighten and the competition to acquire talent will intensify, creating an overwhelming seller’s market, and an era will come in which individuals will be able to easily choose the company and work style they want to work for. The expansion of the spot work market will make it easier for individuals to secure multiple sources of income, achieve work–life balance, test-check their career aspirations and work content, and acquire the skills they need to get the job they want. At the same time, they point out that companies need to “promote the modularization of work” in order to turn work into spot work recruitment, “build internal systems that accept diverse working styles and career paths” in order to welcome jobseekers and support their success, and “provide opportunities to acquire and improve skills through spot work” in order to increase their attractiveness as companies that hire.

In other words, Japan’s immediate challenge is for both individuals and companies to reexamine traditional working styles in Japanese society, such as the seniority-based wage system and lifetime employment system, and to improve the sustainability of labor.

4.3 U.S. Activities

The U.S. labor market is undergoing profound transformation as digitalization, automation, and energy transition reshape the structure of work. The United States emphasizes adaptability and mobility as central features of its workforce system. This flexibility has historically enabled the U.S. to absorb shocks, but it also brings challenges: job creation and job loss occur simultaneously, gig and contingent work are expanding, and persistent skill gaps remain in manufacturing and advanced technology sectors.

In this context, U.S. workforce policy after 2025 has shifted toward a more integrated approach that connects industrial competitiveness, digital transformation, and workforce resilience. Federal initiatives and public–private partnerships are increasingly directed toward reskilling, upskilling, and preparing the next generation of workers for industries shaped by AI, clean energy, and advanced manufacturing. At the same time, gig work is playing a more visible role in manufacturing ecosystems, creating both opportunities for labor market participation and risks of precarity. This section examines these dynamics by reviewing U.S. trends in job creation and loss, the evolving role of gig work in manufacturing, and the strategies being pursued to ensure a skilled, adaptable, and inclusive workforce.

4.3.1 Trends in Job Creation and Job Losses

The U.S. industrial and manufacturing workforce is experiencing rapid shifts due to technological advancements, automation, and evolving economic policies. While some areas of manufacturing are seeing renewed investment and job creation, others are facing declining employment due to automation, AI-driven efficiencies, and shifting global supply chains. According to data from the BLS and the McKinsey Global Institute, these trends will significantly alter employment opportunities in industrial and manufacturing jobs by 2033. Total employment is projected to grow from 167.8 million in 2023 to 174.6 million in 2033, marking an increase of 4.0 percent over the decade. However, this growth will not be evenly distributed across industries, with sectors such as healthcare, professional services, and clean energy expected to see significant expansion, while manufacturing and retail trade will experience job declines or slower growth as shown Figure 34, Figure 35, Figure 36, and Figure 37[82].

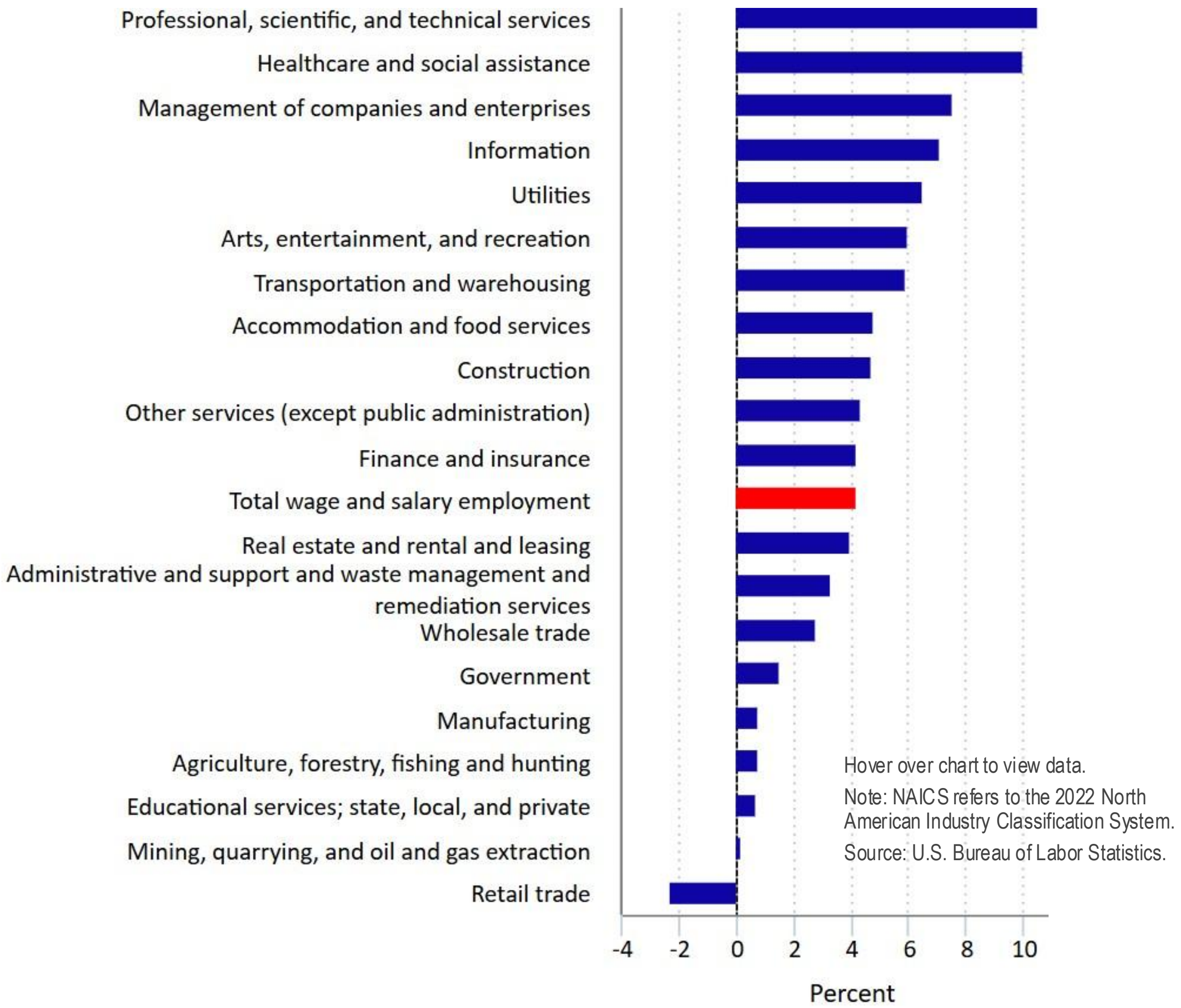


Figure 34 – Major Trends Shaping Employment (1), Percent Change in Wage and Salary Employment, by NAICS Sector, Projected 2023–33[82]

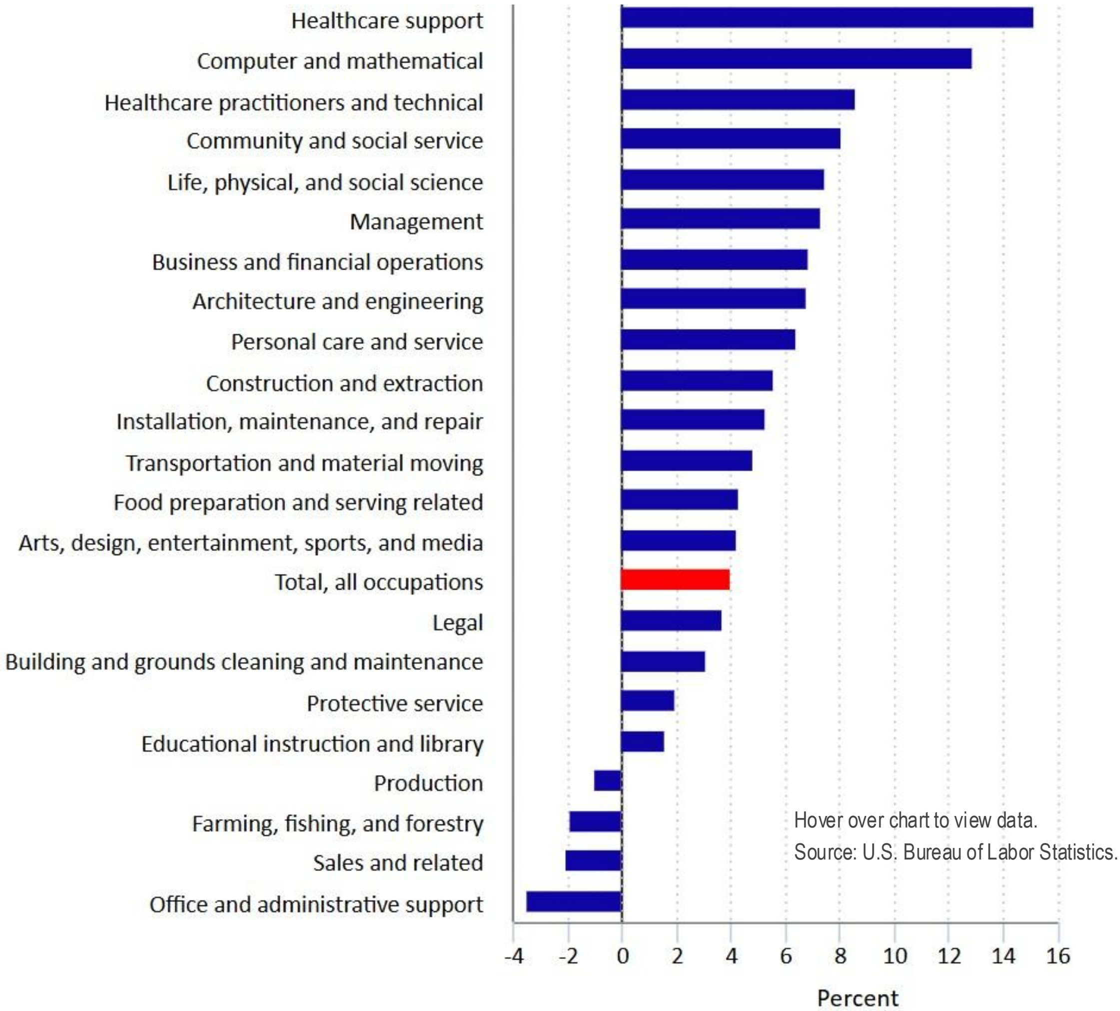


Figure 35 – Major Trends Shaping Employment (2), Percent Change in Total Employment, by Occupational Group, Projected 2023–33[82]

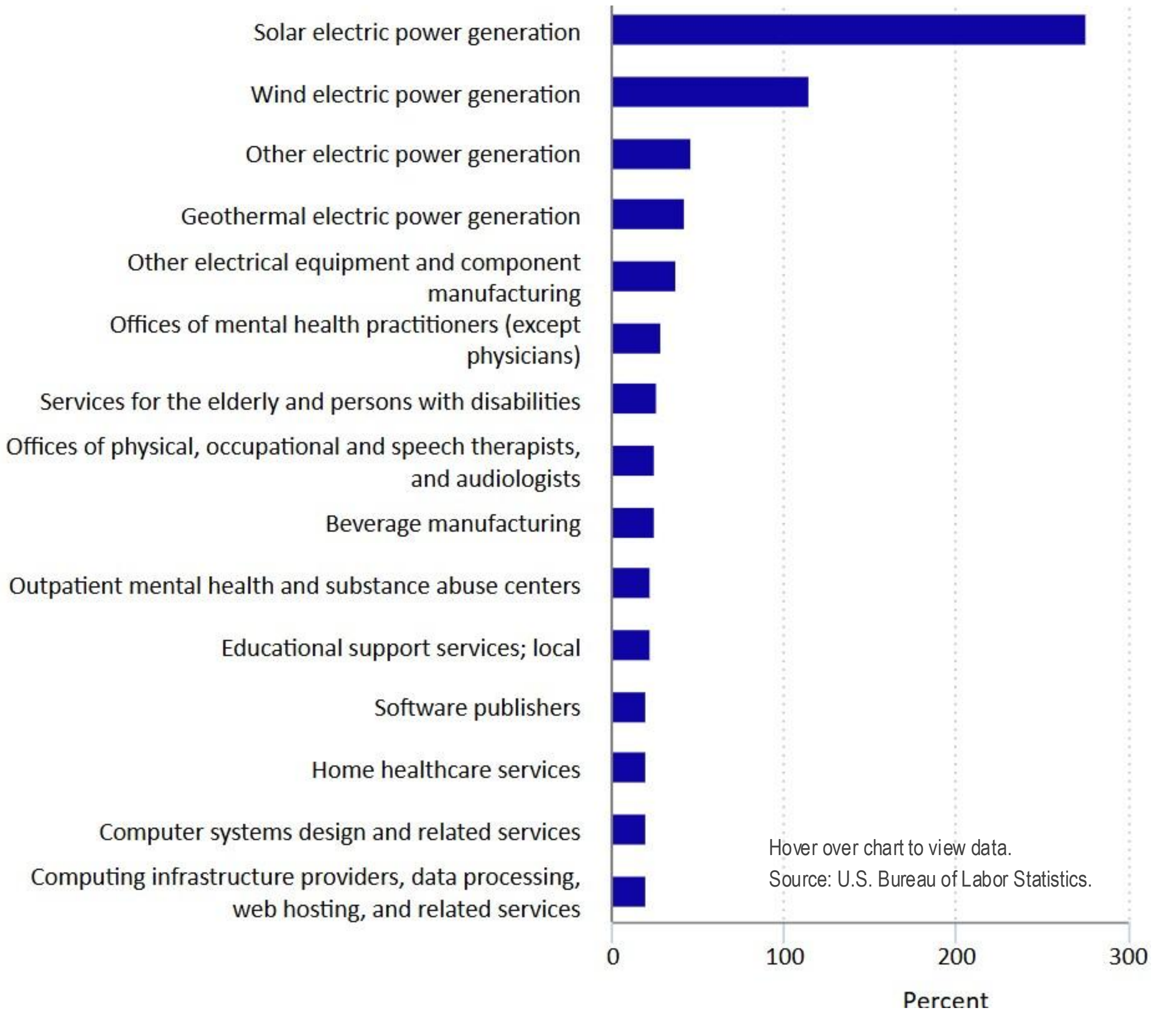


Figure 36 – Major Trends Shaping Employment (3), Fifteen Fastest-Growing Industries, Percent Change, Projected 2023–33[82]

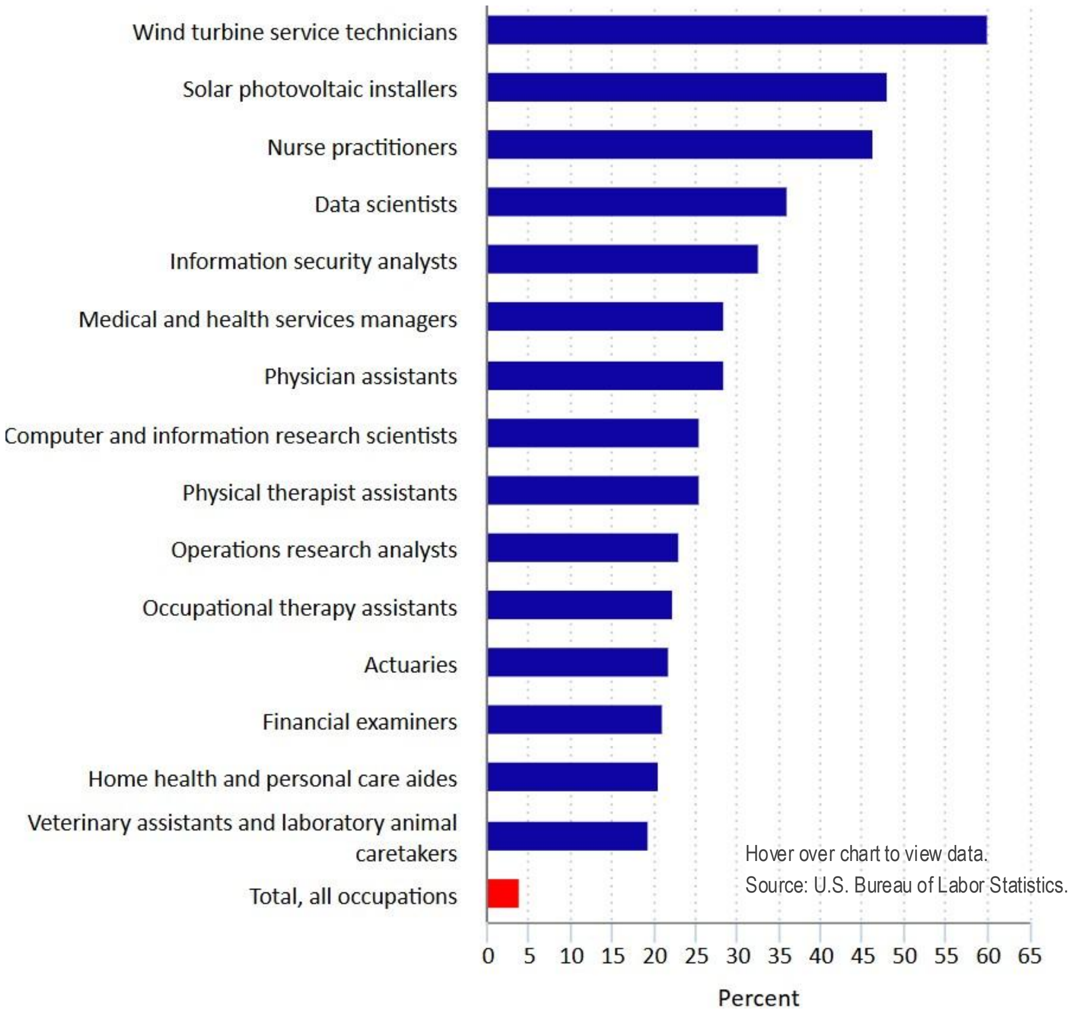


Figure 37 – Major Trends Shaping Employment (4), Fifteen Fastest-Growing Occupations, Percent Change, Projected 2023–33[82]

The BLS Employment Projections for 2023–2033 outline key trends in industry and occupational employment based on anticipated economic, technological, and demographic shifts. The report highlights four major factors shaping employment trends: AI, Clean Energy, Electric Vehicles (EVs), and Information Technology (IT). It also provides projections for various sectors, including healthcare, education, leisure and hospitality, retail trade, and transportation and warehousing. The following is a summary of the key findings from industry and occupational employment projections:

Key Employment Projections (2023–2033)

- Total employment is projected to grow by 4.0%, adding 6.7 million jobs from 167.8 million in 2023 to 174.6 million in 2033.
- Healthcare and social assistance will add the most jobs (2.3 million new positions), accounting for over one-third of all new jobs.
- Professional, Scientific, and Technical Services will be the fastest-growing sector, driven by strong demand for IT and AI-related services.
- Retail Trade is the only major sector projected to lose jobs, reflecting e-commerce expansion and automation.

1. AI and Automation

- AI is expected to enhance productivity but reduce employment demand in administrative, sales, and customer service roles.
- Paralegals, graphic designers, and broadcast announcers will see slow growth or job losses due to AI automation.
- Demand for AI-skilled professionals (e.g. software developers, cybersecurity analysts, and data scientists) will grow significantly.

2. Clean Energy and Sustainability

- The solar electric power industry is projected to grow by 275.9%, adding 35,700 jobs.
- The wind power industry will increase employment by 115.1%, with wind turbine technicians experiencing the fastest job growth (+60.1%).
- Nuclear and fossil fuel power generation will decline, losing 5,900 jobs (-15.9%) and 24,900 jobs (-32.6%), respectively.

3. EVs

- EV production is expected to increase to 40% of all new vehicles by 2033.
- EV battery manufacturing will grow by 37.7%, adding 62,200 jobs.
- Motor vehicle parts manufacturing will shrink by 21.5%, leading to 123,300 job losses.

4. IT

- Demand for software developers (+17.9%) and information security analysts (+32.7%) will rise due to AI adoption and cybersecurity needs.
- Cloud computing and data analytics jobs will see rapid growth.

The transition to advanced manufacturing technologies, aimed at enhancing productivity while prioritizing sustainable practices, has profoundly reshaped the job landscape, creating new opportunities while also presenting significant challenges. Traditional manufacturing roles, such as machine operators and assemblers, are projected to experience declines or slow growth over the next decade, according to a 2023 BLS report. Meanwhile, positions in advanced manufacturing areas, such as robotics, AI, sustainability analysis, are expected to grow by over 20%[83]. Also, industries adopting green technologies, such as renewable energy manufacturing and electric vehicle production, are among the key drivers of this transformation. For instance, as shown in Figure 38, the U.S. DOE reports that employment in wind turbine and solar panel production has grown by 12.8% annually since 2020[84].

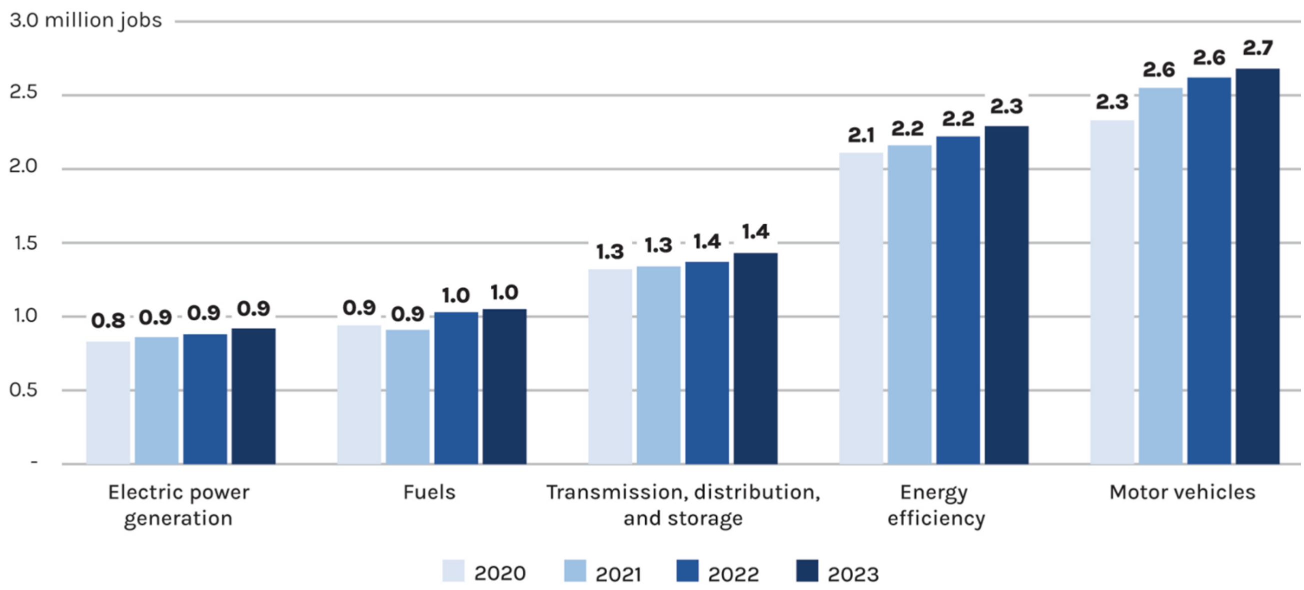


Figure 38 – Energy Employment by Technology, 2020–2023 (Millions of Jobs)[84]

In response to these shifts, the workforce will need to adapt by acquiring new skills. Jobs requiring STEM expertise, digital literacy, and technical problem-solving will see the greatest growth. Industrial engineers, automation specialists, and robotics technicians will be in high demand as manufacturing becomes more technology-driven, while electricians and electrical contractors will experience job growth of 10.8% and 6.6%, respectively, due to the expansion of EV charging infrastructure.

Overall, the U.S. labor market is evolving rapidly, with high demand for healthcare workers, AI and tech professionals, and clean energy specialists, while industries reliant on fossil fuels, traditional retail, and manual assembly line production face declines. The industrial and manufacturing job market is undergoing a profound transformation, with high-tech, automation-driven, and clean energy-related jobs expanding, while traditional, labor-intensive roles are shrinking. As AI-driven automation, renewable energy manufacturing, and advanced digital fabrication redefine employment landscapes, reskilling and workforce training will be critical in ensuring that displaced workers can transition into emerging fields. The next decade will require strategic workforce development efforts to prepare for an increasingly automated and technology-driven industrial economy[85][86].

In the post-2025 model, fossil fuel employment declines steadily despite energy abundance policies—coal facing the steepest losses and oil and gas contracting more gradually, cushioned by LNG exports and petrochemical demand. By contrast, nuclear power emerges as a growth engine for high-skill, long-tenure jobs, with SMRs and advanced nuclear projects driving workforce expansion through 2050. This divergence underscores the U.S. strategy of managing fossil fuel decline while investing in nuclear and clean energy as pillars of industrial sustainability and workforce resilience.

4.3.2 Role and Trends of Gig Work in U.S. Manufacturing

As the U.S. manufacturing sector experiences a fundamental transformation driven by technological advancements, shifting workforce dynamics, and an increasing reliance on alternative employment models. One of the most significant changes shaping the industry is the rise of gig work. Once associated primarily with app-based services, gig work has now become a key component of manufacturing operations, helping companies address labor shortages, meet skill demands, and enhance operational agility[87][88].

The Growing Role of Gig Work in Manufacturing

Gig work is not new to manufacturing, but its scope and significance have expanded in recent years. Traditionally, companies have relied on temporary and contract workers for short-term projects or seasonal labor needs. Today, manufacturing firms are integrating gig workers into their core operations, including production, maintenance, and supply chain management. The demand for these workers is increasing as businesses struggle to fill permanent roles due to labor shortages and a widening skills gap[89].

A major driver of this trend is the persistent difficulty in attracting and retaining full-time employees. The U.S. manufacturing industry faces a projected shortfall of 2.1 million workers by 2030, largely due to the retirement of experienced workers and a lack of interest among younger generations in pursuing careers in manufacturing. Baby Boomers, who have long constituted a significant portion of the manufacturing workforce, are leaving the industry at a rapid rate, and younger workers often perceive manufacturing jobs as outdated, monotonous, or lacking in career growth potential. Despite efforts to modernize and promote high-tech roles in manufacturing, companies continue to face recruitment challenges.

At the same time, the rise of smart manufacturing and Industry 4.0 technologies is reshaping job requirements. Automation, robotics, AI, and IoT are becoming essential in modern manufacturing environments, creating new opportunities for highly skilled gig workers. Instead of relying solely on full-time employees, manufacturers are increasingly turning to independent contractors with expertise in robotics, digital manufacturing, and sustainability analysis. These workers bring specialized skills to the industry, often on a project-by-project basis, making gig work an attractive solution for both employers and skilled professionals seeking flexible work arrangements[87].

Economic and workforce trends have also contributed to the expansion of gig work. Rising wages and benefits costs for full-time employees have led manufacturers to explore alternative workforce models that provide greater financial flexibility. The COVID-19 pandemic accelerated the adoption of remote and flexible work arrangements, making gig work more appealing for workers seeking autonomy and work–life balance. Digital platforms and AI-driven staffing tools have further facilitated this shift, enabling companies to efficiently match independent workers with short-term job opportunities[90].

Trends in Gig Work Adoption

The share of gig workers in the U.S. manufacturing industry has steadily increased over the past decade. Research shows that one in six workers in large organizations is now a gig worker, and in some manufacturing segments, the proportion is even higher. Between 2010 and 2019, the share of gig workers in traditional companies grew from 14.2% to 16.4%, with every indication that this upward trend will continue. By 2025, as much as 20% of manufacturing roles could be filled by gig workers, reflecting a fundamental shift in employment practices within the industry[89].

The nature of gig work in manufacturing is evolving as well. Unlike in the past, when temporary workers were typically assigned low-skill, repetitive tasks, today's gig workforce includes highly specialized professionals. Robotics technicians, data analysts, and AI engineers are among the growing ranks of independent workers who contribute to manufacturing innovation. These workers often have advanced degrees and extensive experience in emerging technologies, allowing manufacturers to leverage their expertise without committing to long-term employment contracts.

Companies are also adopting new workforce management strategies to integrate gig workers more effectively. Online talent marketplaces and digital staffing platforms have streamlined the hiring process, allowing manufacturers to quickly identify, onboard, and manage contract workers. AI-driven workforce planning tools are used to predict labor demand, optimize scheduling, and ensure that gig workers are deployed efficiently. Many manufacturers are restructuring job roles to accommodate flexible staffing models, blending full-time employees with on-demand talent to create a more dynamic and responsive workforce.

Despite these advantages, integrating gig workers into manufacturing operations presents several challenges. One major concern is workforce management and compliance, as many companies lack structured HR policies for temporary workers. Unlike full-time employees, gig workers are often not covered by traditional benefits programs, which leads to potential legal and ethical concerns. Companies must also navigate complex labor laws governing independent contractors, ensuring compliance with regulations while maintaining operational flexibility[87].

Another challenge is knowledge retention and training. High turnover rates among gig workers can lead to the loss of institutional knowledge, making it difficult for companies to maintain consistency in their production processes. Traditional employees often undergo extensive training programs, while independent contractors may not have access to the same resources. Without adequate training, there is a risk of skill mismatches, which could impact efficiency and product quality[87].

Cultural and organizational resistance also remains an obstacle to widespread gig work adoption. Some manufacturing firms are hesitant to embrace a contingent workforce model, fearing disruptions to workplace cohesion and productivity. Long-term employees and labor unions have expressed concerns about job security and the potential erosion of traditional employment benefits. Overcoming these challenges requires a balanced approach that integrates gig work without undermining workforce stability[87][89].

Outlook: The Evolving Role of Gig Work in Manufacturing

As the gig economy continues to expand, manufacturers will need to adapt their workforce strategies to remain competitive. The use of on-demand talent pools is expected to increase, with companies developing dedicated gig worker pipelines to ensure access to specialized skills. Workforce analytics and AI-powered staffing solutions will play a larger role in optimizing labor management, enabling companies to forecast demand and deploy gig workers more effectively.

Regulatory changes may also reshape the gig work landscape in manufacturing. Policymakers are considering new labor laws that could redefine independent contractor status, ensuring greater protections for gig workers while providing clarity for employers. These changes could influence how companies structure gig work arrangements, potentially leading to new models that balance flexibility with worker rights[87].

In the long term, manufacturers are likely to adopt hybrid workforce models that blend full-time and gig workers in a seamless manner. Cloud-based collaboration tools and virtual manufacturing environments will facilitate this integration, allowing independent contractors to contribute remotely to production planning, maintenance, and quality control. Companies that successfully navigate this transition will gain a competitive advantage, as they will be better equipped to respond to fluctuating market demands and emerging industry trends[87].

The rise of gig work in U.S. manufacturing marks a significant shift in how companies approach labor and workforce management. Faced with persistent labor shortages, evolving skill requirements, and the pressures of DX, manufacturers are increasingly turning to gig workers to fill critical roles. While challenges remain in workforce integration, compliance, and knowledge retention, the strategic adoption of gig work offers a pathway to greater flexibility and efficiency. Moving forward, manufacturers that embrace innovative workforce models and leverage technology to optimize gig worker management will be well positioned to thrive in an increasingly digital and dynamic manufacturing landscape[87][88][89].

4.3.3 Upskilling, Reskilling, and Preparing the Next-Generation U.S. Manufacturing Workforce

Despite the trends observed in gig work, the U.S. is also actively investing in workforce development to prepare its manufacturing sector for the demands of Industry 4.0 and sustainability-driven production. Through robust public–private partnerships involving academia, industry, and government, several initiatives are shaping the future of the manufacturing workforce. Key programs such as the Manufacturing USA Institutes, NIST MEP, and the CHIPS and Science Act, among others play central roles in equipping workers with the skills needed to drive innovation, enhance productivity, and promote sustainability. At the forefront of this effort, the Manufacturing USA Institutes ensure that workforce development is aligned with emerging technologies, enabling the U.S. to maintain its industrial sustainability and global competitiveness.

The Role of Manufacturing USA in Advanced Manufacturing Workforce Development

The Manufacturing USA network, consisting of 17 specialized institutes, focuses on cutting-edge manufacturing technologies such as robotics, AI, additive manufacturing, and advanced materials. By conducting industry-driven research and development, these institutes define the essential skills needed to operate, maintain, and innovate within high-tech manufacturing environments. Each institute specializes in a transformative area, ensuring that workforce training aligns with industry needs:

- **CESMII:** Focuses on smart manufacturing by training workers in IoT-enabled systems, real-time data analytics, and energy-efficient processes.
- **REMADE Institute:** Emphasizes recycling, remanufacturing, and circular economy practices, preparing workers for sustainability-driven manufacturing roles.
- **America Makes:** Specializes in additive manufacturing, equipping workers with skills in 3D printing technologies for prototyping, production, and repair.

These institutes collaborate directly with employers to develop programs that equip workers with the skills required for advanced manufacturing. To ensure that the U.S. workforce remains competitive in Industry 4.0, the Manufacturing USA Institutes integrate technological advancements into training programs. Key areas of focus include, but are not limited to:

- **AI**: Integrating AI into advanced manufacturing that equips employees with AI-driven process optimization, predictive maintenance, and smart automation skills.
- **Digital Twins and Smart Factories:** Training workers to utilize digital twins and smart factory technologies for process optimization, real-time monitoring, and waste reduction.
- **Sustainability and Circular Economy Practices:** Incorporating lifecycle assessments, recycling technologies, and resource-efficient production methods into workforce training, aligning with the U.S.'s industrial sustainability goals.

- **Advanced Materials and Additive Manufacturing:** Equipping workers with materials science innovations, enabling them to develop and use lighter, stronger, and more sustainable materials.

The Manufacturing USA Institutes leverage partnerships with federal agencies and collaborations with industry to maximize the impact of workforce training. Programs funded by the Department of Defense (DOD), the Department of Energy (DOE), and the Department of Commerce (DOC) ensure that national priorities such as clean energy, decarbonization, and industrial resilience are reflected in workforce development. Additionally, collaborations with manufacturing companies provide real-world applications of skills through internships, co-op programs, and hands-on training, ensuring that workers gain practical experience in high-tech manufacturing environments.

The Role of NIST MEP in Advanced Manufacturing Workforce Development

Unlike the research-intensive Manufacturing USA Institutes, NIST MEP focuses on providing practical workforce solutions for small and medium-sized manufacturers (SMMs). By working directly with SMMs to identify skills gaps, the MEP National Network provides tailored training programs that emphasize:

- Lean manufacturing practices
- Quality assurance and process control
- Energy efficiency and cost optimization

These hands-on training programs ensure that SMM employees develop foundational skills that improve production efficiency and business resilience. Additionally, the MEP supports reskilling initiatives to help workers transition into roles in automation, robotics, and data analytics, enabling smaller manufacturers to compete in a technology-driven economy. While the Manufacturing USA Institutes focus on high-tech solutions like AI and additive manufacturing, the MEP ensures that smaller manufacturers can integrate these technologies gradually. By providing training in DX, data management, and cybersecurity, the MEP helps SMMs adopt Industry 4.0 technologies without disrupting production processes. This support is critical for ensuring that all manufacturers—regardless of size—benefit from digitalization and automation.

From this perspective, the adoption of collaborative robots in manufacturing is also expanding in the U.S., see Annex B.

The Complementary Roles of Manufacturing USA & NIST MEP

The Manufacturing USA Institutes and NIST MEP play complementary roles in advancing U.S. workforce development.

- Manufacturing USA Institutes focus on cutting-edge workforce training for advanced technologies, such as AI, digital twins, and additive manufacturing.
- NIST MEP provides practical, cost-effective training for small and medium-sized manufacturers, ensuring that they can gradually implement Industry 4.0 innovations without major disruptions.

Together, these programs form a holistic workforce ecosystem, with Manufacturing USA driving innovation and NIST MEP enabling scalable, practical implementation. This synergy ensures that the entire manufacturing workforce, from high-tech specialists to shop-floor technicians, benefits from industrial advancements.

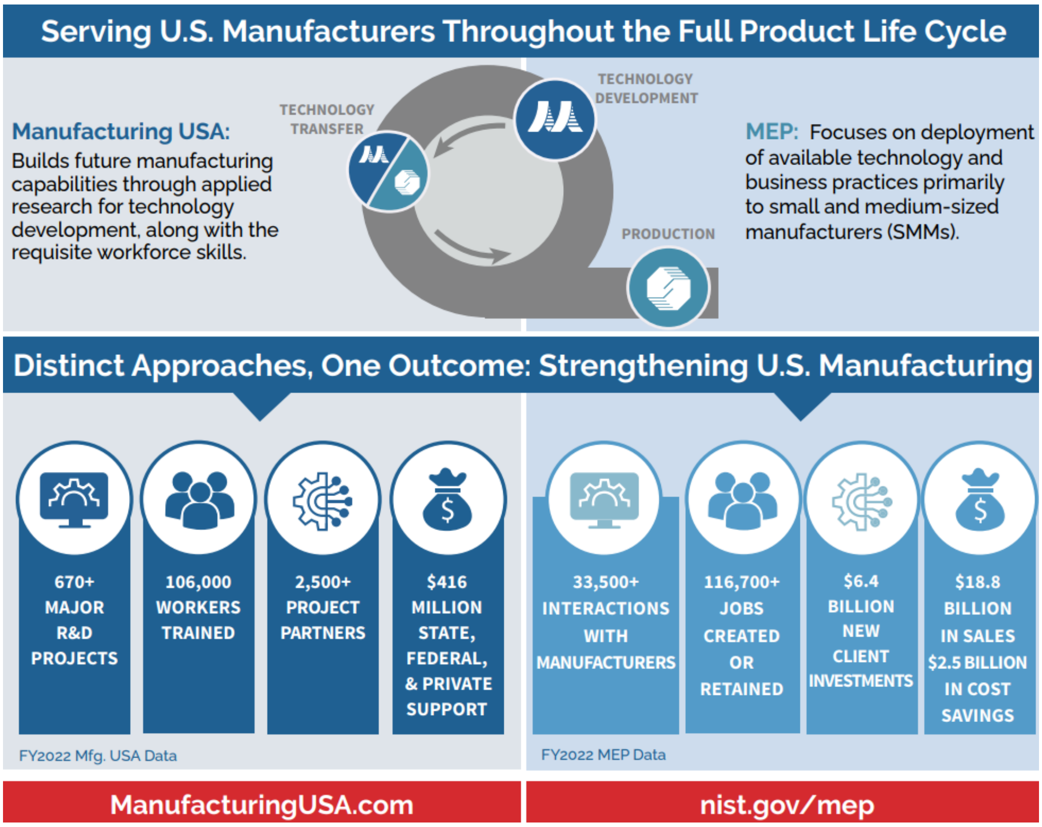


Figure 39 – Strengthening U.S. Manufacturing: Manufacturing USA® and the MEP[91]

The synergy between these initiatives exemplifies the effectiveness of public–private partnerships in workforce development. For instance, the CHIPS and Science Act's funding supports the establishment of new Manufacturing USA Institutes focused on semiconductor manufacturing, which in turn collaborate with NIST MEP to provide targeted training and support to small and medium-sized manufacturers. This integrated approach ensures that workforce development efforts are comprehensive, addressing the needs of the entire manufacturing ecosystem.

By leveraging the strengths of academia, industry, and government, the U.S. is making significant strides in preparing its manufacturing workforce for future challenges. These collaborative efforts not only enhance manufacturing productivity but also promote industrial sustainability, positioning the nation to maintain its competitive edge in the global market.

4.4 EU Activities

4.4.1 Replacement Demand Versus Employment Change, 2021-35

For several decades a significant part of the demand for skills in Europe has represented replacement needs, which emerge because people leave the labor market to retire or for another reason or because they transition between jobs[93]. The growing share of replacement demand in job openings mirrors the aging population and workforce, which is viewed as an acute challenge in several member states. Toward 2035, replacement demand is expected to provide the bulk of job opening across sectors in Figure 40. Job openings are also positive in agriculture and mining and quarrying—sectors where employment is expected to shrink—because replacement demand more than compensates for the anticipated decline in employment in these sectors.

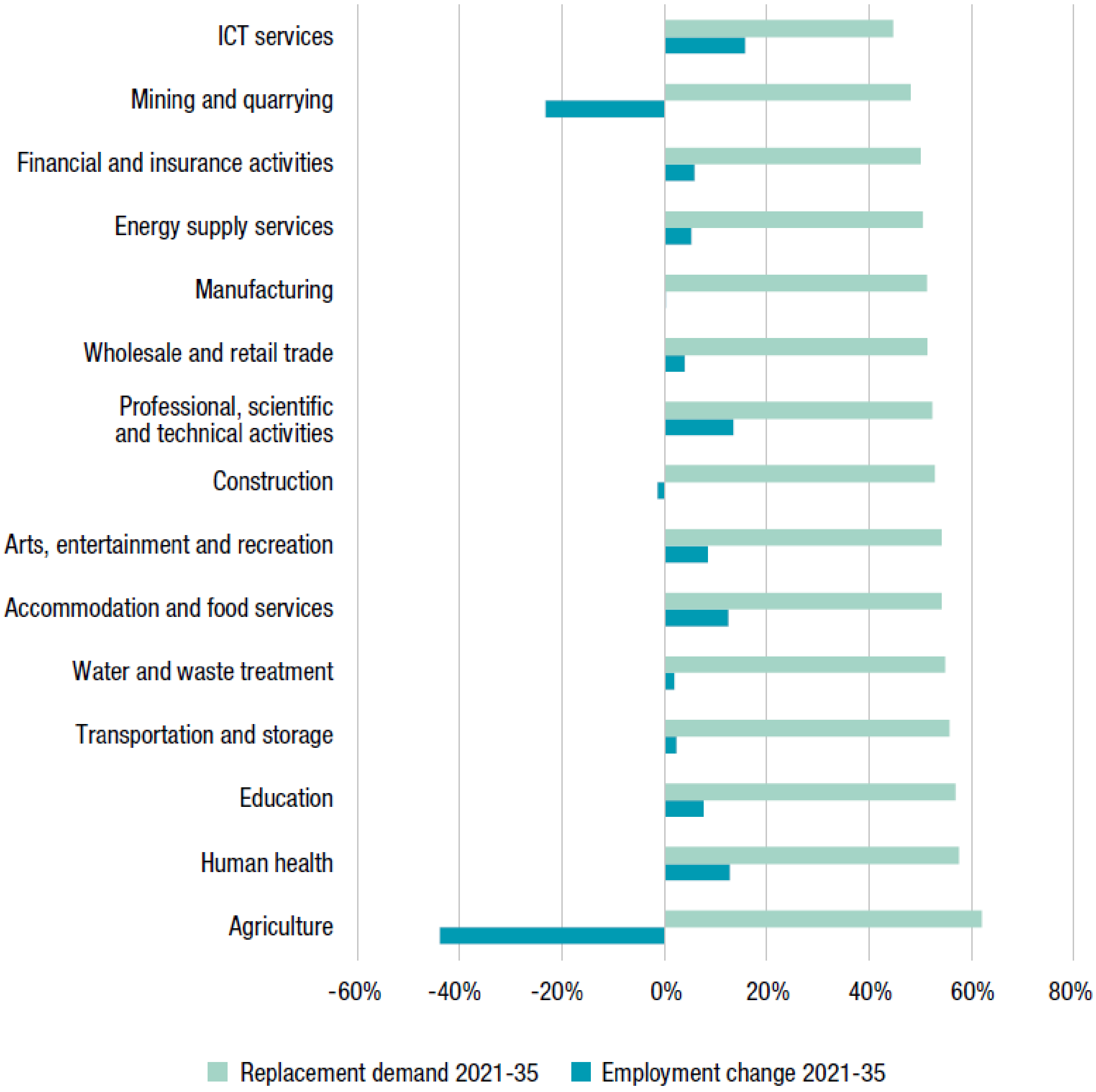


Figure 40 – Replacement demand versus employment change in selected sectors, 2021–35, EU-27[93]

As replacement demand does not only reflect vacancies arising from aging employees leaving the labor market, measures aimed at addressing it should also consider other factors that contribute to this demand. For example, the green transition is expected to become a driver of occupational and, in some cases, sectoral transitions for energy workers. Regional and sectoral-level analysis of current and expected shifts of that sort will help shape targeted policy implementation approaches, which go beyond training provision.

4.4.2 Policies Toward Digital Platform Workers Including Gig Workers

Platform work is a form of employment in which organizations or individuals use an online platform to access other organizations or individuals to solve specific problems, or to provide specific services in exchange for payment[92]. Platform work is on the rise, with hundreds of digital platforms active in the EU and millions of workers earning some income by working for them[94]. And EU policy toward digital platform workers has evolved during COVID-19.

According to a statement from the European Parliament in 2019, obtaining work opportunities from digital platforms poses a significant risk to workers' rights. At that time, they stated that individuals who offer their services through these platforms are often not protected by standard labor contracts, which makes them more vulnerable. The EU wants to change this with the EU platform workers directive.

In 2019, members of the European Parliament adopted new rules introducing minimum rights for all employees. This legislation granted new rights to the most vulnerable employees on atypical contracts and in non-standard jobs, such as gig economy workers. The rules included measures to protect workers by ensuring more transparent and predictable working conditions, providing free mandatory training, and setting limits on working hours and the length of the probationary period.

A 2021 European Commission analysis found more than 500 digital labor platforms active in the EU, from international companies to small national or local start-ups. Accelerated by the pandemic, the switch to digital has made their revenue grow spectacularly, by around 500 % over the past 5 years. In the EU, digital platforms employ more than 28 million people, a figure expected to reach 43 million by 2025. While most platform workers are formally self-employed, about 5.5 million people, providing mostly on-location services, may be misclassified. The situation varies across the EU. More than 100 court judgments in EU countries have already addressed the employment status of platform workers, mostly reclassifying independent contractors as workers and 'gig' platforms as employers, thereby imposing legal responsibility for their workers.

March 2024, the Employment and Social Affairs Committee of European Parliament endorsed a political deal on a new bill aiming to improve the working conditions of platform workers[95]. The new rules, agreed upon by Parliament and the Council in February, aim to ensure that platform workers have their employment status classified correctly and to address bogus self-employment. They also regulate, for the first time ever in the EU, the use of algorithmic management and AI in the workplace. The directive obliges EU countries to establish a rebuttable legal presumption of employment at the national level, aiming to correct the imbalance of power between the platform and the individual performing platform work. The burden of proof lies with the platform, meaning that it is up to the platform to demonstrate that there is no employment relationship. The new rules ensure that a person performing platform work cannot be fired or dismissed based on a decision made by an algorithm or an automated decision-making system. Also, the directive improves transparency by obliging platforms to inform workers and their representatives about how their algorithms work and how a worker's behavior affects the decisions made by automated systems.

4.4.3 Challenge of Human Capital in EU

In the context of the global competition for talent, and a shrinking working age population in the EU, Europe's competitiveness relies on future-oriented skills, contributing to economic social and territorial cohesion[96]. Human capital is also essential for promoting preparedness and security in the current geopolitical situation.

To be competitive and prepared for the future, the EU needs to support and prepare its people with the skills and competences needed for success in learning, work, and life, as highlighted by the Competitiveness Compass for the EU[97].

Skills shortages and gaps, insufficient transformation speed and fragmented and inefficient governance are hampering the EU's competitiveness, as underlined by the Draghi[98], Letta[99] and Niinistö[100][101] reports. They are a barrier to productivity growth and innovation, hindering decarbonization and digitalization efforts.

Education and training systems in Europe are lagging behind the rapid technological transformations and the changing skills needed to take forward the decarbonization of the economy and to reduce dependencies in strategic sectors. Europe faces a growing challenge in meeting the demand for skilled talent in STEM fields, especially in strategic sectors like clean and circular technologies, digital technologies, aerospace, and defense, including in traditional sectors increasingly relying on digital tools requiring STEM skills.

Figure 41 – Key Figures about the Union of Skills[102]

While we produce highly qualified professionals, their quantity is insufficient to bridge the gaps. As shown in Figure 41, nearly four out of five SMEs in the EU struggle to find workers with the necessary skillsets—with start-ups and scale-ups severely impacted—particularly in breakthrough technologies such as AI, semiconductors and quantum computing. These shortages impact all sectors, including transport, food, and energy, limiting economic growth and stifling innovation. The decline in basic skills among 15-year-olds is closely linked to the lack of specialist teachers in mathematics and science, highlighting the urgent need to attract teachers and trainers and support them better through continuous professional development in these critical areas. Also, as younger generations' needs and expectations evolve, a fresh vision for education and career pathways may be necessary to align with the changing landscape of work and innovation.

4.4.4 The Union of Skills

The Union of Skills aims to ensure that everyone in Europe, no matter where they are, is empowered to build solid skills foundations and engage in lifelong upskilling and reskilling, in line with the European Pillar of Social Rights[96].

Its goal is to support European education and training systems to provide equal opportunities for everyone, including all young people, regardless of their background and place of residence, to access education, lifelong learning, quality jobs and navigate transitions and crises.

The second objective is to support companies to be competitive and resilient, making it easier for employers and particularly for SMEs to find people with the skills they need to create sustainable growth and quality jobs. It is also a call for companies to invest in upskilling and reskilling their workers of all generations to adapt to ever-changing challenges and opportunities. At the same time, it recognizes that companies—especially SMEs and start-ups/scale-ups—need the right incentives and support to make these investments feasible.

Finally, the Union of Skills will work to make skills and qualifications—regardless of where they are acquired in Europe—transparent, trusted, and recognized across the single market, allowing individuals to exercise their right to free movement and enabling employers, notably SMEs, to recruit effectively across borders.

As shown in Figure 42, key strands of the Union of Skills will

- build skills for quality jobs and lives through a strong educational foundation, with an inclusive lifelong learning approach
- upskill and reskill an agile workforce mastering the digital and clean transition, notably those with lower and middle skills
- circulate skills with the free movement of people across the EU, unlocking the single market's full potential
- attract, develop and retain talent.

Figure 42 – The Union of Skills[96]

Described in Figure 42, key components of the union of skills are[102]:

<u>**Building skills for quality lives and jobs**</u>

Building skills, education, and training is essential for creating good jobs and improving lives. The union of skills aims to

- pilot a basic skills support scheme, so that every young person has strong reading, math, science, and digital skills
- improve skills in science, technology, engineering, and mathematics (STEM), promote STEM careers, attract more women, and prepare people for digital and clean-tech transitions, with the STEM education strategic plan
- introduce a new EU vocational education and training (VET) strategy to make vocational education and training more attractive, innovative, and inclusive.

Regular upskilling and reskilling

Learning new skills should be a regular part of people's professional lives to keep up with evolving economies and ensure lifelong learning.

The Commission will

- propose to expand the use of micro-credentials as flexible learning solutions
- reinforce the Pact for Skills to help more workers gain new skills in strategic sectors
- pilot a skills guarantee to offer workers at risk of unemployment the opportunity to gain new skills.

The EU will support the roll-out of EU skills academies to provide businesses with the skills needed for the green transition and the Clean Industrial Deal.

Helping the free movement of workers

Circulating skills across the EU will unlock the full potential of the single market. The union of skills focuses on

- a skills portability initiative, to enhance the portability of skills and qualifications across the EU, independently of where they were acquired
- working toward a European degree to facilitate the development of innovative joint study programs across the EU
- a new European VET diploma
- strengthening European universities alliances and centers of vocational excellence
- European school alliances to enhance teacher and student mobility.

Attracting, developing, and retaining talent

Europe must attract, develop, and keep top talent crucial for innovation, growth, and competitiveness.

The Commission will

- set up an EU talent pool for the recruitment of jobseekers from outside the EU at all skills levels, especially for jobs facing skill shortages
- present a visa strategy to make it easier for top students, skilled workers, and researchers to come to the EU
- launch a 'Choose Europe' initiative under Marie Skłodowska-Curie Actions to attract and retain talent.

The Union of Skills proposes a new approach, combining education, training, and employment policies, united around a common vision of competitiveness. The challenge ahead is enormous and can only be tackled if all actors assume collective responsibility and step up in a whole-of-government approach addressing both the supply and demand side of skills (including skills development, recognition, the links with working conditions, demography, company practices), including member states, social partners, the business community, universities, and schools.

4.5 Cross-regional Similarities and Differences

In this chapter, we have looked at human resource strategy efforts in Japan, the United States, and Europe.

All three regions recognize that the era of high productivity due to the so-called demographic bonus characteristic of developed countries has already passed, and that a common challenge is to ensure a balance between labor supply and demand in line with changes in social conditions. In other words, although the three regions have differences in regulations, rules, and cultural backgrounds, they have many commonalities in the maturity of their societies, and from the perspective of human resources, they share a common understanding that technological advances, including digitalization, will transform the future labor force.

In particular, from the perspective of HMI, manual labor such as inputting data into machines and checking information output from machines will continue to decrease in the future, so retraining human resources for digitalization-related occupations, for which demand is expected to increase in the future, is a common challenge. Furthermore, gig work, which is increasingly being used on digital platforms, is recognized in all three regions as useful in terms of increasing labor force dynamics as social conditions change.

Thus, although awareness of the problem and the desire for industry–academia–government collaboration are common to all regions, priorities and approaches to specific measures differ from region to region, considering their respective economic situations.

In Japan, prior to the expansion of reskilling and gig work, emphasis has been placed on increasing the mobility of human resources by reviewing traditional employment systems, such as lifetime employment and seniority-based wages, that accompanied economic growth up until the 1980s. In the United States, human resource mobility is relatively high across a wide range of occupations, including professional fields. Public–private collaboration and federal government efforts are focused on workforce transformation policies through digitalization, which are based on human resource mobility. In Europe, efforts are being made to build mechanisms that promote relationship building through industry–academia–government collaboration and access to necessary resources to support the DX of small and medium-sized enterprises.

As mentioned above, each region has a common awareness of the issues and is eager to work toward industrial sustainability through industry–academia–government collaboration, but regarding specific measures, each region has its own priorities and approaches, considering the regional economic situation, etc. We aim to achieve industrial sustainability on a global scale by mutually understanding these similarities and differences and promoting international cooperation. In the next chapter and beyond, we will delve deeper into topics related to energy security, decarbonization, and waste, and explore the possibility of international collaboration.

5 Energy/Decarbonization/Waste Issue

5.1 Foreword

In the wake of the COVID-19 pandemic, the global landscape has shifted dramatically, underscoring the critical importance of energy security and sustainable practices. The invasion of Ukraine by Russia in 2022 further highlighted these challenges, prompting nations to reevaluate their energy strategies and consider the role of nuclear power in achieving decarbonization goals.

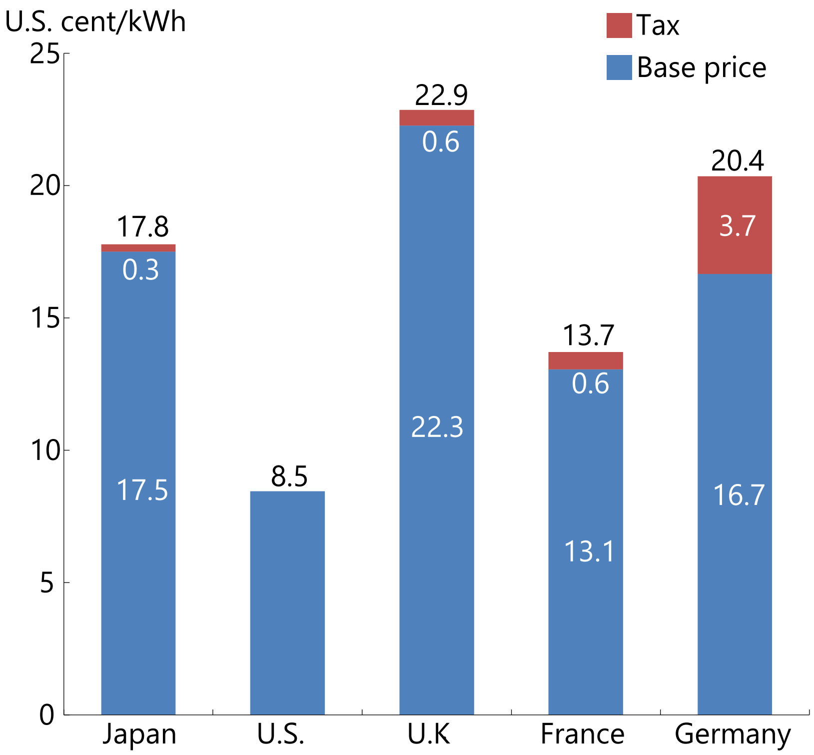


Figure 43 – Electricity Charges (Industrial) 2022, Energy White Paper 2024, Agency for Natural Resources and Energy, METI, Japan[103]

Looking at the comparison of industrial electricity rates by country in Figure 43, the United States is overwhelmingly cheaper, while Japan and Germany are in a similar situation[103]. From the perspective of industrial sustainability, energy costs are directly linked to the promotion of manufacturing in the region, and various measures are being taken in each country.

Also, from the perspective of the relationship between industrial sustainability and planetary boundaries, for example, semiconductor manufacturing and steel manufacturing are industries that consume large amounts of energy. However, these industries are the foundation that supports human society, and decarbonization and energy conservation in these industries have the potential to balance the relationship between industrial sustainability and planetary boundaries to a high degree.

From this perspective, what efforts are being made in Japan, the United States, and Europe in the areas of energy, manufacturing, and sustainable human society, and what challenges do they face? The following chapters will delve deeper into this point and explore opportunities for international collaboration.

5.2 Japan Activities

5.2.1 Green Growth Strategy

In October 2020, the Japanese government declared to realize “Carbon Neutrality by 2050” [104]. In addition, in April 2021, a new policy was announced to set a new GHG reduction target for FY2030[105], aiming to reduce GHG emissions by 46% from FY2013 levels while continuing strenuous efforts in its challenge to meet the lofty goal of cutting its emissions by 50%.

Based on these policies, various future scenarios are being considered to formulate a strategy for achieving the Carbon Neutrality by 2050[106]. For example, the following reference indicators have been presented:

- Approximately 50–60% of power generation in 2050 will be covered by renewable energy sources such as solar power, wind power, hydropower, geothermal power, and biomass.
- Approximately 10% will be covered by hydrogen and fuel ammonia power generation.
- Approximately 30–40% will be covered by nuclear power and thermal power generation with CO_2 capture.

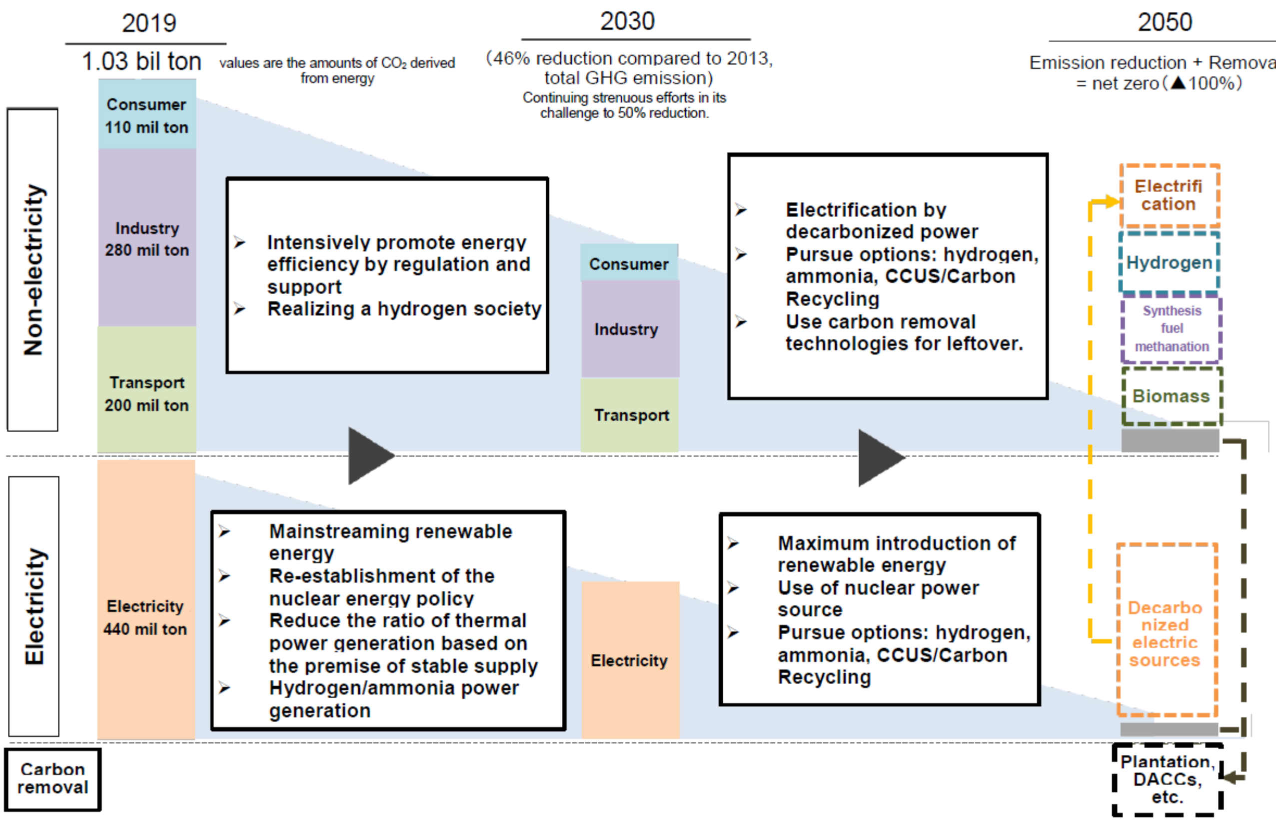


Figure 44 – GHG reduction target in 2030 and 2050 in Japan[106]

To achieve these reference indicators, each power source is defining issues such as natural conditions, social constraints, and technical challenges, and considering measures to resolve them. To address the issue of electricity demand being expected to increase by around 30 to 40% in the future due to the progress of electrification, we are considering all options for decarbonization, such as nuclear power, hydrogen and ammonia, CCUS/carbon recycling, and maximizing the use of renewable energy, without narrowing down the policy options. Figure 44 organizes these options to achieve the goal, considering the mid-term goal in 2030.

As for the progress of this policy, it has been reported that steady progress has been made toward the intermediate target of reducing GHG emissions by 22.9% compared to fiscal 2013 levels by fiscal 2022. This has been praised for being consistent with Japan's energy policy, which aims to achieve and maintain the 3E+S (energy supply, economic efficiency, and environment based on safety).

Furthermore, this policy aims to create a cycle of economic growth and environmental conservation together with the business community. As shown in Figure 45, 14 industrial sectors expected to grow are identified, and policies for growth that combine the efforts of industry, academia, and government are being considered.

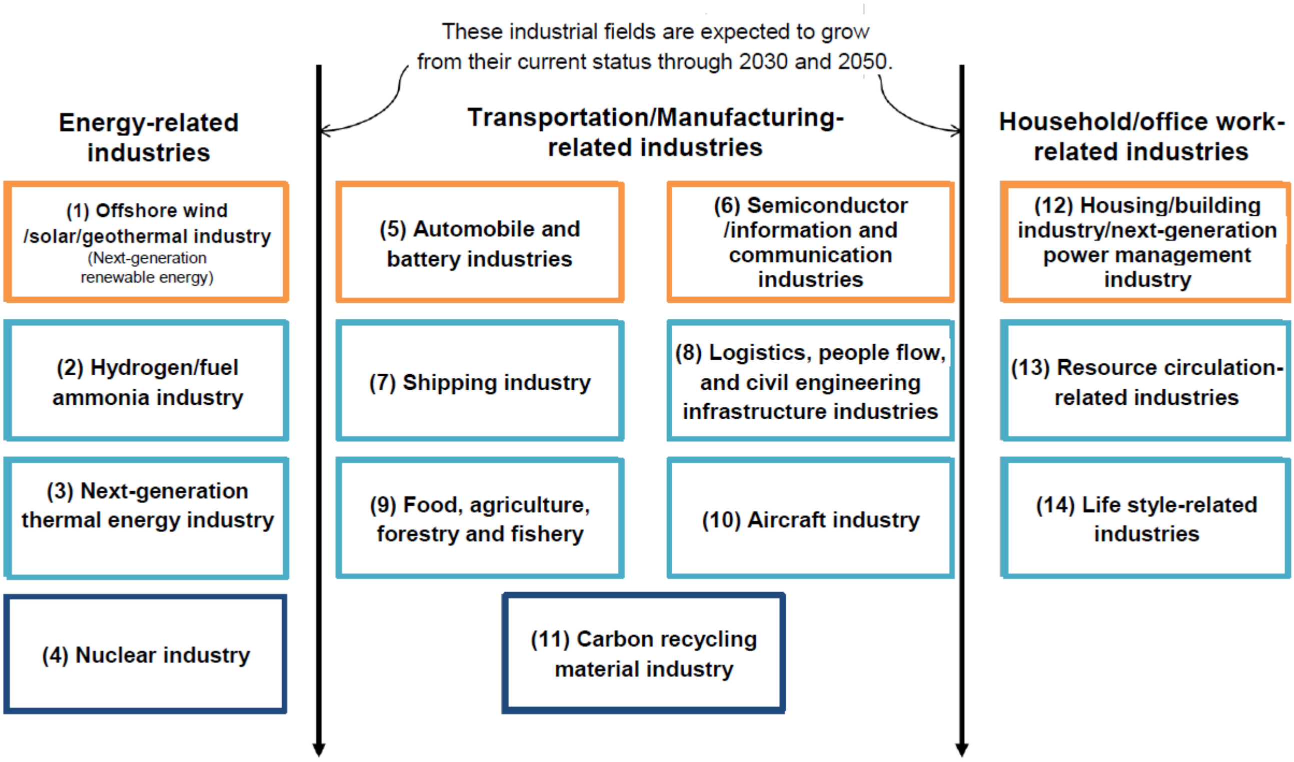


Figure 45 – Industrial fields expected to grow by Green Growth Strategy in Japan[106]

5.2.2 Green Innovation Funds

To achieve carbon neutrality by 2050, METI established a 2 trillion-yen fund as part of NEDO and provides continuous support for R&D projects, demonstrations, and social implementation projects for up to 10 years to companies that commit to ambitious goals(300 billion yen has been added to the second supplementary budget for FY2022, and 456.4 billion yen will be added to the initial budget for FY2023 (as of July 2023))[107][108].

The support targets are profiled with the following:

- Should be the average size of a conventional R&D project (20 billion yen) or more.
- Projects for which short-term government support programs are sufficient are not eligible.
- The main implementers should be companies or other profit-making businesses capable of carrying out the entire process of public implementation (participation of SMEs and venture companies is encouraged; participation of universities and research institutions is also anticipated).
- The project must include innovative and fundamental R&D elements that are worthy of being commissioned by the government.

To steadily translate the results of research and development into social implementation, METI requires company managers to commit to persistently addressing this issue as a long-term management priority. For example, METI requires company managers to submit a long-term business strategy vision when applying, to attend and explain in field-specific working groups, and to submit a management sheet showing the status of their efforts. Furthermore, as mechanisms for seeking this commitment, METI has introduced measures such as the suspension of projects and the partial refund of commission fees if the status of efforts is insufficient, along with the introduction of a system (incentive measures) that allows the government to bear more of the burden depending on the degree of achievement of goals.

The projects must include innovative and fundamental R&D elements that are worthy of being commissioned by the government. Currently a number of projects are launched, including:

- Cost Reductions for Offshore Wind Power Generation
- Development of Next-Generation Solar Cells
- Achieving Carbon Neutrality in Waste and Resource Circulation
- Large-scale Hydrogen Supply Chain Establishment
- Hydrogen Production through Water Electrolysis Using Power from Renewables
- Hydrogen Utilization in Iron and Steelmaking Processes
- Fuel Ammonia Supply Chain Establishment
- Development of Technology for Producing Raw Materials for Plastics Using CO_2 and Other Sources
- Development of Technology for Producing Fuel Using CO_2, etc.
- Development of Technology for Producing Concrete and Cement Using CO_2
- Development of Technology for CO_2 Separation, Capture, etc.
- Next-generation Storage Battery and Motor Development
- Development of In-vehicle Computing and Simulation Technology for Energy Saving in Electric Vehicles
- Smart Mobility Society Construction
- Next-generation Digital Infrastructure Construction
- Next-generation Aircraft Development

· Next-generation Ship Development

· Development of Negative Emissions Technologies in Agriculture, Forestry, and Fisheries Industries

· Promotion of Carbon Recycling Using CO_2 from Bio-manufacturing Technology as a Direct Raw Material

· Decarbonization of Thermal Processes in Manufacturing

5.2.3 Circular Economy and Microplastic Issues

In addition to working on the cycle of economic growth and environmental conservation from the perspective of supplying resources such as energy to the economy, Japan is also working to establish a circular society regarding waste generated by economic activity.

Based on the results of the second progress review of the 4th Fundamental Plan for Establishing a Sound Material-Cycle Society (approved by the Cabinet in June 2018), the Ministry of the Environment formulated and announced the Circular Economy Roadmap in September 2022 as shown in Figure 46, which set the direction toward a circular economy for the first time in Japan after the declaration of net-zero GHG emissions by 2050[109].

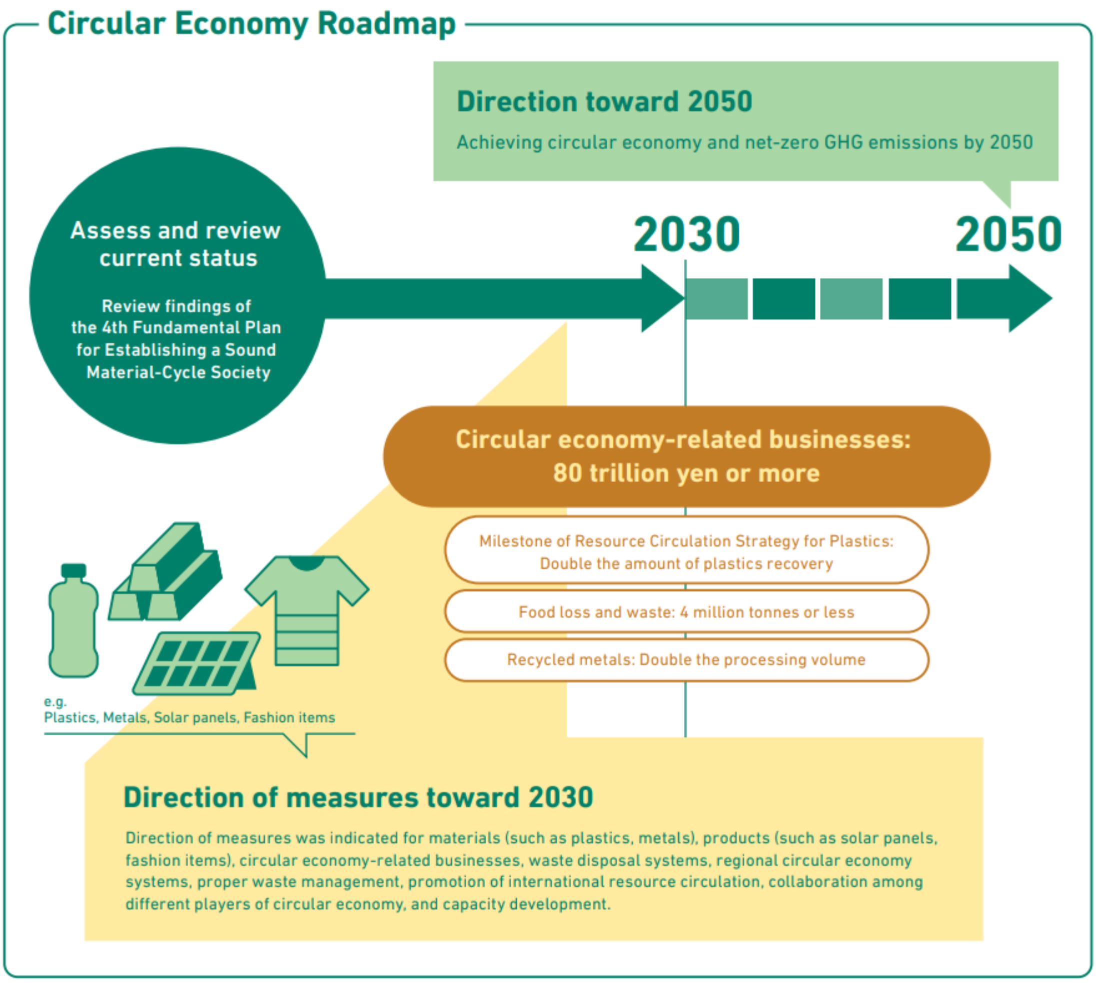


Figure 46 – Overview of the Circular Economy Roadmap[109]

The Circular Economy Roadmap sheds light on the direction of the circular economy that should be pursued with a view toward 2050, as well as the directions for measures to be taken toward 2030 in the materials, products, and other fields. Based on this, the public and private sectors will work together to promote decarbonization based on resource circulation throughout the life cycle.

An analysis of Japan's GHG Inventory estimated that approximately 36% of the total emissions correspond to sectors where resource circulation can contribute. The 3Rs + Renewable and other efforts for the transition to the circular economy need to be promoted, especially in the context of achieving net-zero GHG emissions by 2050.

3Rs + Renewable is a policy approach to ensure the widespread practice of the 3Rs and encourage replacement by renewable resources. It is based on the fundamental principles stipulated in the Basic Act on Establishing a Sound Material-Cycle Society (Act No. 110 of 2000). It not only calls for GHG emission reduction by minimizing incineration and landfilling of carbon-containing substances, but also for reducing energy consumption in production processes, increasing use of biomass as feedstock and other material switch-over, and a shift to renewable energy in the processing/treatment steps. 3Rs + Renewable is a foundational approach that will contribute broadly to the realization of a decarbonized society.

The Home Appliance Recycling Law (Specific Home Appliance Recycling Law) is an example of a system that was enacted into law in 2001 and implemented in society more than 10 years before the Circular Economy Roadmap was defined[110]. This aims to reduce the amount of waste by recycling useful parts and resources from specific home appliances discarded by ordinary households and offices. Air conditioners, televisions, refrigerators/freezers, washing machines/clothes dryers, etc. are subject to the law, and manufacturers, retailers, and waste generators are obligated to handle them.

In this field, plastic waste has become a global issue. The amount of plastic produced has been increasing worldwide, with over 8.3 billion tons of plastic produced since 1950. In addition, as production has increased, the amount of waste has also increased, and it is said that 6.3 billion tons have been discarded as garbage. At the current pace, it is predicted that 25 billion tons of plastic waste will be generated by 2050, and more than 12 billion tons of plastic will be landfilled and dumped in nature. In 2021, Japan produced approximately 10.45 million tons of plastic. Domestic consumption was 9 million tons, while the total amount of plastic waste generated was 8.24 million tons. Of this waste, approximately 25% was recycled and reused as materials. And approximately 63% was recovered as energy.

Also, marine plastic waste discharged into the ocean has become a global issue. The amount of marine plastic waste is extremely huge, and it has been reported that approximately 8 million tons of plastic waste are discharged into the ocean every year worldwide. In recent years, fine plastics smaller than 5 mm have generally been called microplastics, and there are concerns about the impact of this on the marine ecosystem. Microplastics are generated when plastic waste becomes smaller due to the effects of waves and ultraviolet rays, or from plastic particles that have been used as scrubbing agents in facial cleansers and toothpastes, or from washing synthetic fiber clothing. Regarding the issue of marine plastic litter, at the G20 Osaka Summit in 2019, the G20 leaders shared the "Osaka Blue Ocean Vision," which aims to reduce additional pollution to zero by 2050[111].

In response to this issue, Japan has implemented the following laws and initiatives:

Basic Law for Promoting the Creation of a Recycling-Based Society (2001)

This law promotes the reduction of natural resource consumption and environmental impact. Certain product categories, such as home appliances, automobiles, and packaging materials, are required to be recycled under the relevant laws.

Act on Promotion of Plastic Resource Circulation (2022)

Unlike previous laws that focus on specific product categories, this law targets the entire life cycle of plastics and places emphasis on material recycling and the use of renewable plastics[112]. The main measures are as follows:

- Promotion of 3R + Renewable Plastics: Promoting waste reduction, reuse, recycling, and the use of biodegradable alternatives.
- Charges for plastic bags: Retailers are required to charge for plastic bags to curb disposable consumption.
- Milestone targets: For example, reduce disposable plastics by 25% by 2030.

Regarding primary microplastics, the use of microbeads is not explicitly prohibited in Japan. However, due to voluntary efforts by manufacturers, the use of microbeads has been reduced. Furthermore, in 2019, the Marine Litter Processing Promotion Act was revised to address microplastic pollution. The revised law stipulates that companies should strive to reduce the use of microbeads and minimize their discharge into the marine environment[113].

Japan faces significant challenges in achieving comprehensive plastic life cycle management. Although recycling rates are high, much of this is energy recovery rather than material reuse, highlighting the need for innovation in recycling technology[114]. In addition, addressing microplastic pollution requires:

- further development and widespread use of biodegradable plastics
- raising public awareness and participation in reducing plastic consumption.

In response to these societal challenges, the field of mechanical engineering has an important role to play in addressing the microplastic problem. Innovations in materials science, waste treatment technology, and product design can lead to reduced plastic waste and improved recyclability. Interdisciplinary collaboration with environmental science and policymaking is essential to developing sustainable solutions[115].

5.2.4 Economic Security and Regional Economic Revitalization

A large portion of energy is consumed in industry, especially by production facilities for the manufacturing industry. Locations of production facilities are preferred to regions and countries with low energy costs. On the contrary, from the perspective of economic security, production facilities of some product groups are maintained or expanded domestically. For instance, according to the Cabinet Office, large semiconductor foundries have been recently launched in the southern and northern regions in Japan[116]. Around these facilities, additional jobs are created for operators and process engineers for the foundries, as well as equipment manufacturers and parts and material suppliers to strengthen the supply chain. Furthermore, additional investment has been made by other industry sectors such as education and housing. However, in general, automation and digitalization of the operations in production facilities decrease the number of workers needed.

Due to the rapid introduction of generative AI technology in the market, the number of data centers has been dramatically increasing in Japan. Increase in the number of data centers is a reason for intensive energy usage in recent years. Even in the manufacturing industry, digitalization of product development operations and analysis of usage data of products in the market require computational resources and data storage. Data centers are concentrated in the city areas such as Tokyo and Osaka, where the power supply is more robust, and the risks of natural disaster are relatively low. Recently, the advancement of cloud computing has accelerated the further concentration of new investment in data centers in these areas. However, to prevent disparity between these areas and other regions, the development of core bases in the north and south regions of Japan has been promoted as a supplement for or alternative to those in these areas. Furthermore, according to METI, the decentralized location of data centers in regional areas as a foundation that supports regional ecosystems has been in progress.

That is, the type and location of production facilities and the location of data centers have a significant impact on the characteristics of energy use and GHG emissions in Japan. Furthermore, location also affects the geographic distribution of workers with diverse skills. At this time, the basis for these decisions regarding the type and location of renewable energy power plants, production facilities, and data centers varies depending on the background of national and regional industrial policies, demographic trends, educational levels, technology (including research and development directions), etc. Figure 47 summarizes the relationship between large-investment decision variables to reach national goals and their reasoning.

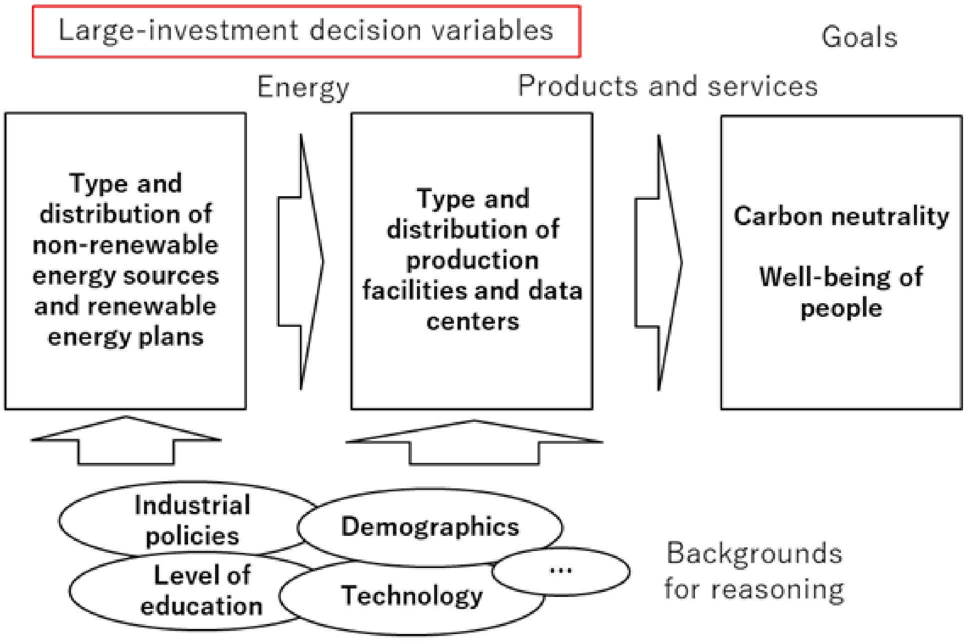


Figure 47 – Reasoning of large-investment decision variables to reach national goals[117]

5.2.5 Digital Infrastructure

With the digitalization of society and the expansion of business applications of AI, energy demand is increasing dramatically and the impact of related businesses on local economies is becoming more pronounced. With this in mind, the Japanese government is implementing several measures.

For example, manufacturing bases for the semiconductor-related industry are located in a wide range of regions in Japan and account for a certain proportion of the local economy. In particular, device manufacturers that manufacture semiconductors are making large-scale investments in JASM (Kumamoto Prefecture) for advanced semiconductors and Rapidus (Hokkaido) for next-generation semiconductors, as shown in Figure 48[118]. These regions are seeing rising wages and have begun regional efforts to develop semiconductor-related human resources, and are expected to become the center of the regional economy in the future.

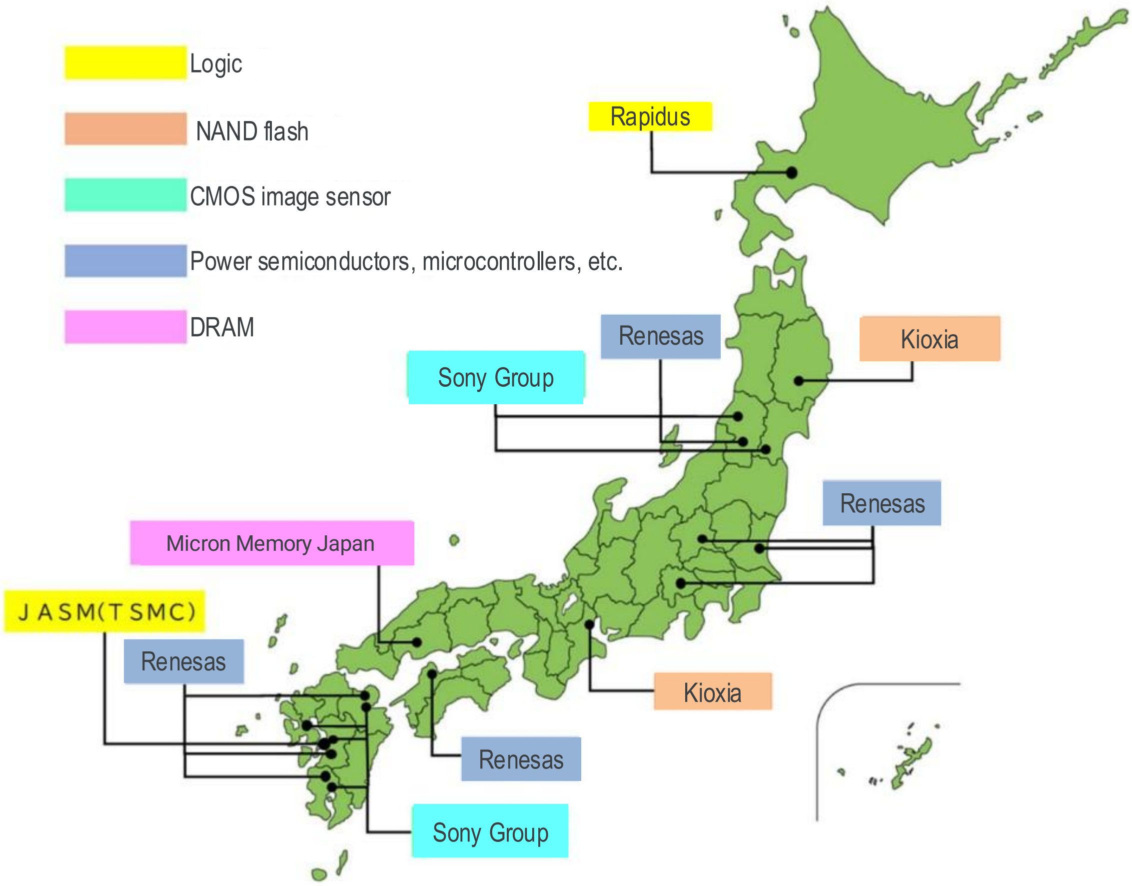


Figure 48 – Major semiconductor-related manufacturing bases in Japan[118]

In order for such large-scale investments to be made in rural areas, it is important not only to accumulate related technologies, but also to develop infrastructure such as electricity and communications in the region.

From this perspective, if we look at the location of data centers in Japan, we can see that new investments in data centers are accelerating in the Tokyo and Osaka areas.

In response to this, the Japanese government is promoting policies to promote the decentralization of digital infrastructure such as data centers, based on requirements such as (1) strengthening resilience in the event of natural disasters, (2) efficient use of renewable energy in rural areas, and (3) streamlining of communication networks that enable "local production for local consumption" of data generated in rural areas[119].

Specifically, from the perspective of strengthening reliable connectivity with countries in the Asia-Pacific region and Europe and the United States, the government is considering strategically developing data centers as a backbone that supports Japan's digital society. For the time being, the government is promoting the development of third and fourth core bases in areas such as Hokkaido and Kyushu to complement and replace the Tokyo and Osaka areas, and is promoting the multi-route of international undersea cables linked to these.

In particular, with regard to the relationship between information processing and electricity and communication infrastructure, the government has shown its recognition that, since communication costs are much cheaper than the transportation costs of electricity, it is more important to process data in a data center located near the electricity infrastructure and then transmit the processing results to the demand area via a communication network, rather than locating a data center near the demand area for the data processing results. Currently, the government has indicated that it is even more important to promote the decentralization of data centers from the perspective of local production and consumption of electricity, including carbon-free sources.

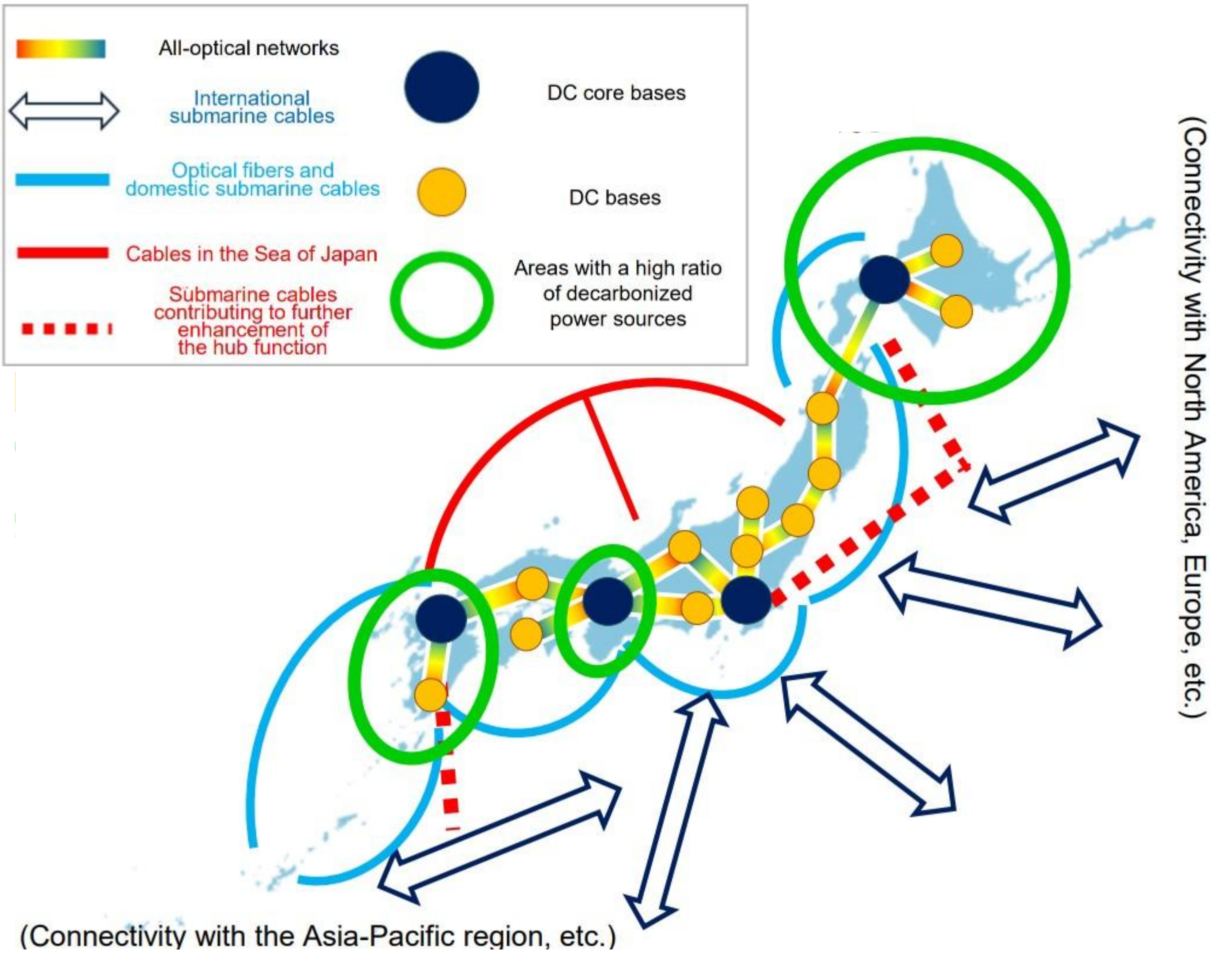


Figure 49 – Conceptual diagram of Japan's digital infrastructure in the 2030s[119]

5.3 U.S. Activities

5.3.1 Overview

The U.S. approach to industrial sustainability has evolved through several distinct phases, reflecting both domestic priorities and global pressures. For much of the early 21st century, the strategy was framed around climate mandates and emissions reduction targets, supported by major pieces of legislation such as the Energy Policy Act (2005), the America COMPETES Act (2007, 2010), the Bipartisan Infrastructure Law (2021), the CHIPS and Science Act (2022), and the Inflation Reduction Act (2022). These initiatives laid the groundwork for renewable energy deployment, clean energy incentives, industrial reshoring, and large-scale investment in infrastructure. They also established the first systematic attempts to align U.S. industrial competitiveness with environmental objectives.

Yet, by the mid-2020s, it became clear that this regulation-first, climate-centric model was not sufficient to address the full scope of industrial sustainability challenges. The U.S. industrial sector remained highly energy-intensive, accounting for nearly a third of national energy use, while reliance on fossil fuels persisted despite growth in renewables and nuclear. At the same time, structural changes in the global economy — including the rise of data centers and AI computing, industrial reshoring of semiconductors and batteries, and the electrification of transport and buildings — began to reshape demand in ways that existing frameworks had not fully anticipated.

Compounding these shifts, external shocks such as the COVID-19 pandemic, global supply chain disruptions, and the energy crisis triggered by geopolitical tensions highlighted vulnerabilities in both U.S. energy security and industrial resilience. Policymakers and industry leaders recognized that sustainability could no longer be defined solely in terms of carbon accounting. Instead, it required an integrated framework that balanced environmental responsibility with energy abundance, competitiveness, and innovation capacity.

Against this backdrop, the U.S. has broadened its approach to industrial sustainability. While climate goals remain central, they are now pursued within a pragmatic balance-of-priorities model that situates decarbonization alongside energy security and industrial strength. This reframing sets the stage for the sections that follow: an examination of the current state of U.S. energy demand (5.3.2), the drivers of consumption (5.3.3), the long-term outlook to 2035 and 2050 (5.3.4), and the strategic role of decarbonization and circular economy models (5.3.5–5.3.7).

5.3.2 The Current State of U.S. Energy Demand (2024–2026)

The trajectory of U.S. energy demand is best understood through the framework of the current administration's three interlocking pillars of industrial sustainability: Energy Security, Economic Vitality, and Innovation Pathways. Each pillar provides a framework for interpreting not just the balance of energy supply and demand, but also how short-term dynamics position the U.S. for long-term resilience.

From the standpoint of energy security, the U.S. remains a net energy exporter, with production exceeding consumption by nearly 9 quadrillion Btu in 2023, underscoring the abundance that anchors national resilience. Fossil fuels—petroleum and natural gas in particular—continue to dominate the mix, yet renewables and nuclear are expanding, reflecting the "energy addition, not subtraction" philosophy that defines this pillar.

On the dimension of economic vitality, energy demand growth is now closely tied to structural drivers such as digital infrastructure, industrial reshoring, and electrification. Electricity consumption, which had been flat for nearly a decade, accelerated by ~3% in 2024, with the International Energy Agency (IEA) and U.S. Energy Information Administration (EIA) projecting continued growth through 2026, concentrated in the commercial and industrial sectors. These trends highlight how energy abundance underpins competitiveness, job creation, and protection of strategic industries from offshoring pressures.

Finally, innovation pathways frame how short-term demand shifts intersect with technological transformation. The rapid scaling of data centers, LNG exports, and the adoption of electrification in transport and buildings all signal how innovation is reshaping demand profiles. Rather than being managed through prescriptive mandates, the U.S. strategy emphasizes technology-neutral solutions — from AI-driven grid optimization to small modular reactors — that allow market signals to drive the next wave of efficiency and decarbonization.

Against this backdrop, the following subsections provide a snapshot of U.S. energy demand in the near term (2024–2026), highlighting the balance of primary energy, electricity, natural gas, and liquid fuels, and situating these trends within the broader framework of the three pillars.

Primary Energy:

U.S. total primary energy consumption stood at about 94 quadrillion Btu in 2024, still below the historical peak reached in 2007[120]. In 2023, production outpaced consumption for the fourth consecutive year, reaching 102.83 quadrillion Btu of output against 93.59 consumed, a record surplus that cemented U.S. net exporter status. The mix continues to be dominated by petroleum (~38%) and natural gas (~36%), with nuclear (~9%) and coal (~7%) still contributing alongside a growing renewable share (~9%). This balance reflects both the strength of fossil fuel supply and the steady, but incremental, expansion of renewables as part of an “energy addition, not subtraction” approach.

Electricity Demand:

After nearly a decade of flat demand, U.S. electricity consumption accelerated in 2024, rising by roughly 3% year-on-year, driven by data centers, industrial reshoring, and electrification of transport and buildings. This upward trajectory is expected to continue, with the International Energy Agency (IEA) projecting growth of ~2.3% in 2025 and ~2.2% in 2026, while U.S. Energy Information Administration (EIA) short-term outlook attributes much of this expansion to the commercial (+3.0% in 2025, +4.5% in 2026) and industrial (+2.0%, +3.5%) sectors. These gains underscore how new digital infrastructure and clean-tech manufacturing are reshaping U.S. load growth dynamics, reversing years of stagnation and creating regional hotspots of demand growth (e.g., Texas and the Mid-Atlantic)[121].

Natural Gas Demand:

According to EIA’s August 2025 outlook, U.S. natural gas consumption will reach a record ~91.4 bcf/d in 2025, before easing slightly in 2026 as efficiency improvements offset some industrial and power sector gains. A significant share of demand growth is tied to LNG exports, which are projected to expand nearly 10% annually through 2030, reinforcing the role of natural gas as both a domestic baseload fuel and a geopolitical export lever. While natural gas continues to underpin electricity generation (around 40% of supply), its role is increasingly linked to America’s energy abundance strategy and global competitiveness.

Liquid Fuels Demand:

Near-term liquid fuels demand is under pressure from efficiency gains, electrification, and macroeconomic headwinds. Gasoline consumption in May 2025 fell to its lowest seasonal level since 2020, highlighting the combined effects of improved vehicle efficiency, rising EV adoption, and consumer behavior shifts. Petroleum remains the single largest energy source, but its growth trajectory is flattening, with jet fuel and petrochemical feedstocks showing relative resilience compared to road fuels. This suggests a gradual rebalancing of the liquid fuels market, with structural declines in gasoline demand partially offset by other sectors.

5.3.3 Factors Driving the Demand Curve

Data Centers & AI Computing:

Electricity demand from data centers has become one of the most transformative forces in the U.S. power system. According to DOE the Lawrence Berkeley National Laboratory (DOE/LBNL) 2024 assessment, data center load has tripled over the past decade and could double or even triple again by 2028, driven by explosive growth in cloud services, artificial intelligence, and high-performance computing. The EPRI/DOE joint analysis projects that U.S. data centers could consume up to 9% of total U.S. electricity by 2030, compared to ~4% in 2023. Globally, the IEA expects data center electricity use to more than double by 2030, underscoring the international dimension of this trend. U.S. forecasts also highlight structural change: EIA's Annual Energy Outlook 2025 projects that commercial computing's share of commercial sector electricity will rise from ~8% in 2024 to nearly 20% by 2050[122][123][124].

Industrial Reshoring & Semiconductor Manufacturing:

A second major driver is the wave of industrial reshoring and new manufacturing investment, much of it catalyzed by federal incentives and supply chain security priorities. The buildout of semiconductor fabs, battery plants, and clean-tech manufacturing facilities is creating large, steady baseload demands unlike the cyclical loads of older industries. Sector studies identify these three sectors—chips, batteries, and clean energy equipment—as the biggest contributors to manufacturing electricity growth over the next decade. Industry trackers show a pipeline of projects, with dozens of semiconductor fabs and gigafactories under construction or in planning stages. Beyond sheer load growth, these facilities also demand high-quality, reliable power and are concentrated in specific regions, further amplifying local grid stress and the need for accelerated infrastructure upgrades[126][127].

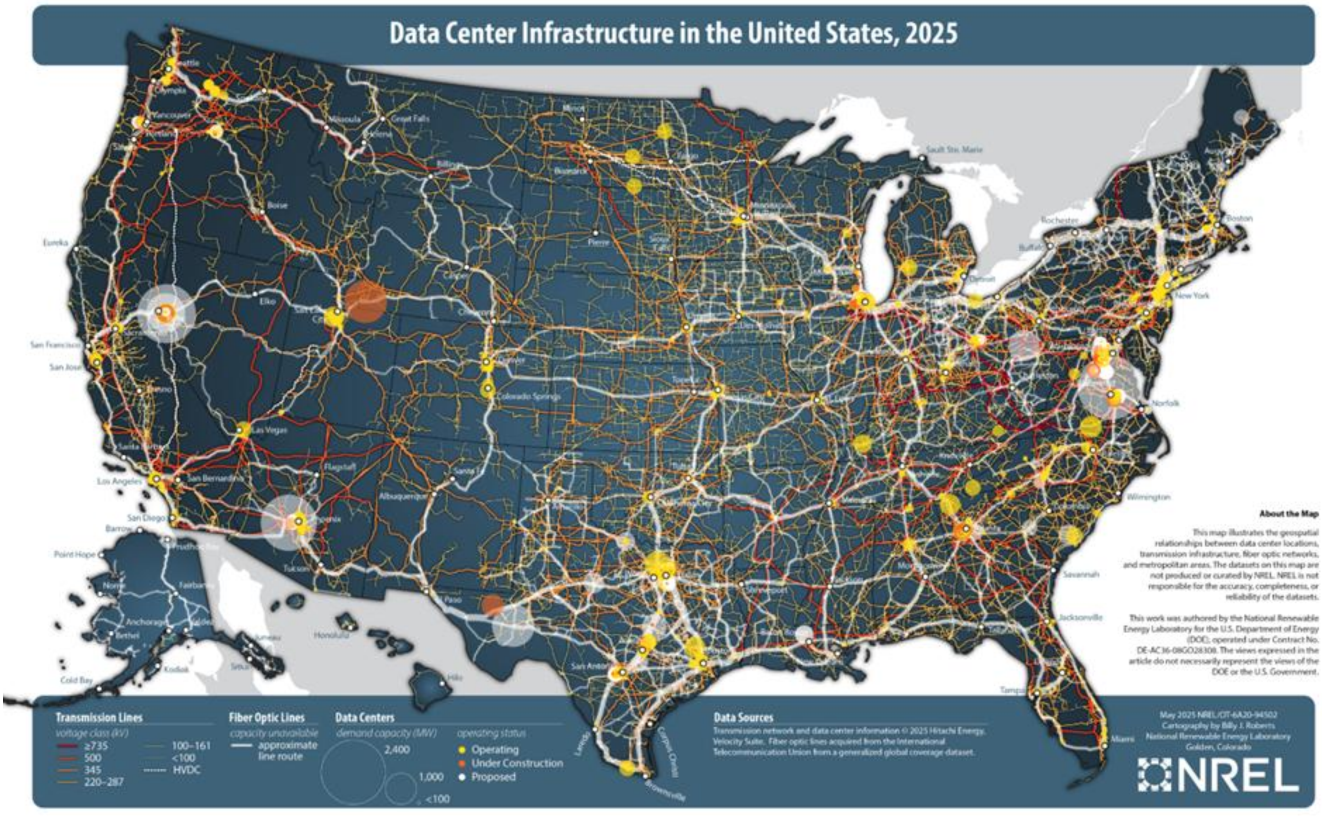


Figure 50 – Data Center Infrastructure in the United States[125]

Transport & Buildings Electrification:

Electrification in transport and buildings is another long-term growth vector. Heat pumps have outsold gas furnaces every year since 2021, and the gap widened further in 2023–2024. This signals a structural shift in heating loads toward electricity, though efficiency gains partially offset the rise. Building electrification trends are reinforced in EIA's Annual Energy Outlook 2025[124], which incorporates stronger policy support, technology cost reductions, and consumer adoption momentum. In transport, the steady increase in EV adoption is reshaping demand curves. EVs reduce gasoline consumption, but they also shift significant energy use onto the power grid, increasing residential and commercial charging demand. Studies note that while gasoline demand has softened, electricity load growth linked to EV penetration is set to accelerate in the late 2020s, especially in states with aggressive zero-emission vehicle mandates. Collectively, transport and building electrification embody the structural reallocation of energy demand from fossil fuels to the grid, reshaping both utility planning and long-term fuel mix trajectories.

Weather & Climate Volatility

Weather and climate-related volatility is an increasingly important factor shaping U.S. energy demand. Hotter summers are driving record levels of cooling load, particularly during prolonged heat waves that strain regional grids and push peak demand higher than historical norms. Similarly, severe winter storms and cold snaps amplify heating requirements, leading to sharp spikes in natural gas and electricity consumption. These conditions not only increase average demand but also elevate the scale and frequency of peak load events, which require additional generating and transmission capacity to maintain system stability. Beyond direct temperature-driven demand, the frequency of severe events—hurricanes, floods, wildfires, and polar vortices—creates resilience-driven energy needs, as households, businesses, and industries invest in backup generation, on-site storage, and demand-response systems. These resilience measures themselves add to overall energy demand profiles.

The North American Electric Reliability Corporation (NERC), in its 2024 Long-Term Reliability Assessment (LTRA), warned that accelerating load growth, coupled with the retirement of firm generation resources and transmission constraints, is amplifying reliability risk across multiple regions[128]. This is especially acute in areas experiencing simultaneous pressures from data center buildouts, electrification, and extreme weather exposure.

5.3.4 The Long View (2035–2050)

In the U.S., the total primary energy demand is projected to decline modestly through the 2030s, not rising again until the early 2040s, and anticipated to remain below 2024 levels by 2050 (U.S. EIA). In contrast, electricity demand will grow steadily, driven by data centers, industrial reshoring, and electrification of transport and buildings, though growth is regionally concentrated and uncertain in timing. Natural gas remains critical in the near term for power and industry, but renewables are expanding rapidly, with wind and solar surpassing coal in 2024 and continuing to gain share. Over time, electrification will move liquid fuels demand downward, while nuclear and emerging technologies (hydrogen, storage) will reinforce the low-carbon supply mix. The result is a long-term outlook where overall energy use is flat-to-declining, however electricity will continue to play an increasingly central role in U.S. industrial sustainability and competitiveness. Below is a table contrasting the near-term (2024–2026) and long-term (2035–2050) U.S. energy demand outlook.

Near-Term (2024–2026)	Long-Term (2035–2050)
Primary energy: ~94 quads in 2024; production (~103 quads) exceeds consumption; U.S. remains a net exporter (EIA, 2023).	**Primary energy:** Annual Energy Outlook 2025 projects total demand declining in the 2020s–30s; in most scenarios 2050 levels remain below 2024 (EIA).
Electricity demand: Re-accelerated growth (~+3% in 2024), led by data centers, electrification, and reshoring. IEA forecasts +2.3% (2025) and +2.2% (2026).	**Electricity demand**: Structural growth continues, driven by AI/data centers, clean-tech manufacturing, EVs, and heat pumps. Regional concentration (TX, Mid-Atlantic) creates planning challenges.
Natural gas: Consumption reaches 91.4 bcf/d in 2025, a record, then eases slightly in 2026. LNG exports are a major driver (EIA, Reuters).	**Natural gas**: Remains pivotal for balancing renewables and meeting industrial demand, but relative share declines as renewables and nuclear expand.
Liquids: Gasoline demand weakens (May 2025 lowest seasonal level since 2020), reflecting efficiency gains and EV adoption (Reuters).	**Liquids:** Structural decline in gasoline demand from electrification; petrochemicals and jet fuel remain resilient.
Renewables & nuclear: Solar capacity additions strong (66% of new capacity in 2024); wind and solar reach 17% of generation, surpassing coal for first time (Ember, Wikipedia).	**Renewables & nuclear**: Wind/solar share grows steadily; U.S. plans to triple nuclear capacity by 2050 (DOE). Emerging hydrogen and storage technologies reinforce grid reliability.
Climate & reliability: NERC (2024 LTRA) warns of reliability risks from rising load, generator retirements, and transmission bottlenecks under hotter summers and extreme weather.	**Climate & reliability**: Sustained investments in transmission, grid flexibility, and resilience needed to cope with load growth, extreme weather, and geopolitical risks.
Fossil fuels: Still provide ~84% of U.S. primary energy in 2023, dominated by petroleum (38%) and natural gas (36%), with coal (~7%) (EIA, 2023). The administration emphasizes expanded production alongside renewables ("Energy addition, not subtraction")	**Fossil fuels**: Continue to underpin energy security and export strength (e.g., LNG capacity approved up to 48 bcf/d) while gradually declining in domestic share. Used strategically to sustain industrial resilience, with growth in nuclear and renewables gradually reshaping the mix

5.3.5 U.S. Decarbonization and Industrial Sustainability Strategy

In the post-2025 model, decarbonization is embedded within a broader strategy that links climate action with industrial resilience and growth. Rather than treating emissions reduction as an isolated mandate, the current U.S. administration situates it within three interlocking pillars: **Energy Security, Economic Vitality, and Innovation Pathways.**

- **Energy Security** is advanced through an "energy addition, not subtraction" philosophy, expanding oil, gas, nuclear, geothermal, and renewables while securing LNG and nuclear exports that displace higher-emission fuels abroad.
- **Economic Vitality** emphasizes affordability, job creation, and reshoring of strategic industries such as semiconductors, batteries, and clean-tech manufacturing, ensuring industrial strength while minimizing carbon leakage.

- **Innovation Pathways** prioritize technology neutrality — supporting carbon capture, hydrogen, small modular reactors, geothermal, and AI-enabled digitalization — so that market signals and private investment drive the next wave of decarbonization.

This innovation-first approach marks a departure from pre-2025 regulation-heavy models. By combining energy abundance, competitive industry, and technology-neutral innovation, the U.S. strategy demonstrates that sustainability can reinforce, rather than constrain, industrial leadership in the decades ahead.

5.3.6 Looking Ahead: Pathways to 2035 and 2050

If the current administration's approach continues, U.S. decarbonization will be pursued through a strategy that combines energy abundance, technological innovation, and industrial competitiveness. Climate goals are not treated as stand-alone mandates, but as outcomes of a system designed to expand supply, modernize infrastructure, and accelerate private-sector deployment of clean technologies.

By 2035, the United States is expected to remain a leading global energy exporter while reducing the carbon intensity of its domestic system. Natural gas will continue to provide stability for electricity and industry, but its relative share will gradually decline as renewables expand and the first small modular nuclear reactors enter service. Large-scale investments in semiconductors, batteries, and clean-tech manufacturing will add substantial load, yet these facilities will operate on increasingly cleaner power. Emerging technologies such as carbon capture, hydrogen, geothermal, and advanced storage are expected to move from pilot stages into early commercial deployment. At the same time, digital tools like AI-driven optimization, digital twins, and smart grids will improve efficiency, reduce waste, and provide the flexibility needed to integrate higher shares of variable renewable energy. Collectively, these shifts will drive significant reductions in power-sector emissions while ensuring reliability and affordability.

By 2050, the U.S. system is projected to evolve into a diversified low-carbon mix anchored by renewables, nuclear, and natural gas with carbon capture. Nuclear capacity is expected to triple, providing a dependable backbone of zero-carbon generation, while hydrogen and CCUS are widely adopted in hard-to-abate industries such as steel, cement, and chemicals. Overall primary energy demand is expected to remain flat or slightly below 2024 levels due to efficiency gains, but electricity demand will continue to rise as electrification deepens across transport, buildings, and manufacturing. Advanced digitalization will link energy and industrial systems into adaptive, highly efficient networks, further lowering emissions intensity. By mid-century, the U.S. would demonstrate that it is possible to achieve a low-carbon, globally competitive industrial base not through scarcity or restrictive mandates, but by leveraging innovation, resilience, and energy abundance.

5.3.7 Decarbonization Outlook: Pre-2025 vs. Post-2025 Strategies

Pre-2025: Regulation-First, Climate-Mandate Model

Before 2025, U.S. industrial sustainability was largely framed around net-zero targets and carbon accounting. Decarbonization was pursued primarily through:

- Binding federal or state emissions targets (e.g., Clean Power Plan frameworks, net-zero executive orders).

- Mandated fossil fuel retirements, particularly coal, with renewables prioritized as the default replacement.
- Subsidies and incentives (e.g., IRA 2022, BIL 2021) directed mainly toward wind, solar, EVs, and storage.
- Regulatory oversight emphasizing compliance and prescriptive technology choices.

Decarbonization Outlook under this model:

- Faster early-stage emissions reductions in the power sector from coal-to-renewables switching.
- High reliance on renewables + storage for decarbonization, with limited role for natural gas, nuclear, or carbon capture.
- Increased exposure to supply-chain vulnerabilities tied to critical minerals and solar/battery imports.
- Carbon leakage risk: stricter domestic rules risked driving energy-intensive industries offshore, undermining net gains.
- Innovation constrained: R&D favored select technologies, limiting investment in nuclear SMRs, CCUS, or hybrid solutions.

In short, the pre-2025 model emphasized rapid compliance-driven carbon cuts, but at the cost of resilience, supply security, and broader industrial competitiveness.

Post-2025: Abundance, Resilience, and Innovation Model

Since 2025, U.S. policy has shifted to a broader framing of sustainability, where decarbonization is achieved through energy security, economic competitiveness, and innovation pathways. Climate goals remain central but are pursued through expansion and diversification of energy supply rather than constraint.

Key features of the post-2025 model:

- Energy addition, not subtraction: expanded oil, gas, nuclear, geothermal, and renewables, with LNG exports rising ~10% annually through 2030.
- Technology neutrality: R&D and deployment for carbon capture, hydrogen, SMRs, geothermal, renewables, and digitalization, without favoring one pathway.
- Innovation-driven decarbonization: DOE Lab modernization, permitting reform, and AI/digital twins accelerating commercialization of clean technologies.
- Industrial integration: reshoring of semiconductors, batteries, and clean-tech manufacturing powered by increasingly clean and reliable energy.
- Export-linked decarbonization: U.S. LNG and nuclear exports displace coal and higher-emission fuels abroad, contributing indirectly to global CO_2 reduction.

Decarbonization Outlook under this model:

- Steady long-term emissions reductions as renewables and nuclear expand, natural gas is paired with CCUS, and hydrogen penetrates hard-to-abate industries.
- Lower carbon intensity across sectors while sustaining affordability and industrial strength.
- Greater system resilience due to diversified energy mix, reduced import reliance, and stronger supply chains.

- Innovation as multiplier: digitalization and cross-sector integration reduce energy waste and optimize carbon outcomes.

5.3.8 Decarbonization – Comparative Trajectories

Aspect	Pre-2025 Model (Regulation-First)	Post-2025 Model (Abundance & Innovation)
Approach	Compliance-driven; carbon mandates; prescriptive technology choices	Technology-neutral; innovation-driven; energy addition & diversification
Near-term power sector decarbonization	Rapid coal retirements: renewables + storage dominates	Renewables expand, but nuclear, gas + CCUS, hydrogen, and geothermal play parallel roles
Energy security	Greater reliance on imported critical minerals and clean-tech supply chains	U.S. as net exporter of LNG/nuclear; diversified domestic energy base
Industrial competitiveness	Risk of carbon leakage： higher compliance costs	Reshoring and expansion of semiconductors, batteries, clean-tech plants under affordable energy
Innovation pathways	Narrow focus (renewables, storage, EVs)	Broad portfolio (renewables, SMRs, CCUS, hydrogen, digitalization)
Long-term emissions profile	Faster early cuts, but plateauing if storage/renewables bottleneck	Gradual but more resilient cuts; lower carbon intensity by 2050 with diversified mix
Global impact	Domestic-focused; weaker role in shaping external energy markets	Global decarbonization via LNG/nuclear exports displacing higher-carbon fuels

Under the Pre-2025 Regulation-First, Climate-Mandate Model, the U.S. would place emissions reduction at the center of all policy design. Stronger federal regulations would impose binding emissions caps, accelerate fossil fuel retirements, and direct investment primarily into renewables and storage. Energy security would rely more heavily on renewable deployment and imports of critical minerals, potentially exposing the system to new vulnerabilities. Economic vitality could face greater risks if regulatory burdens outpace the ability of U.S. industries to remain competitive, raising concerns about carbon leakage as production migrates overseas. Innovation would still occur, but within narrower, prescribed technology channels, favoring renewables, electrification, and storage while reducing investment in nuclear, fossil-based technologies with carbon capture, or hybrid solutions.

5.3.9 Decarbonization and Circular Economy

The U.S. approach to industrial sustainability is not limited to expanding energy supply and modernizing infrastructure; it also encompasses the circular economy, where resource efficiency and material recovery are central to long-term decarbonization. This dimension is increasingly articulated through the Re-X framework — a set of strategies that include reuse, remanufacturing, recycling, refurbishment, and recovery. By extending the useful life of products and materials, the Re-X model reduces the energy and carbon intensity of industrial production while creating new economic opportunities in design, logistics, and advanced manufacturing.

Circularity and Decarbonization

The circular economy represents a critical lever for reducing emissions associated with energy-intensive sectors such as steel, aluminum, plastics, and cement. Roughly 30% of U.S. greenhouse gas emissions are tied to industrial production, with a significant share linked to raw material extraction and processing. Applying the Re-X framework lowers demand for virgin resources, thereby decreasing both upstream emissions and energy requirements. For example, remanufacturing components in automotive or aerospace sectors typically uses 80–90% less energy compared to producing new parts, while advanced recycling technologies can capture high-value materials otherwise lost to landfill. In this way, the circular economy directly supports the three pillars of the U.S. sustainability model: it strengthens energy security by reducing import dependence, enhances economic vitality through cost savings and job creation, and accelerates innovation pathways by fostering new technologies for material recovery and reuse.

The Role of the REMADE Institute

At the center of U.S. circular economy efforts is the REMADE Institute, one of the 17 Manufacturing USA institutes. Funded by the Department of Energy and supported by industry, academia, and government partners, REMADE focuses on technologies that reduce embodied energy and emissions in manufacturing by developing scalable solutions for recycling, remanufacturing, and materials efficiency. Research areas include:

- Design for reuse and remanufacturing, enabling products to be disassembled and upgraded rather than discarded.
- Systems for recycling polymers, metals, and fibers, advancing closed-loop supply chains.
- Process innovations that reduce waste, recover critical materials, and optimize energy use in material production.

REMADE also has a strong emphasis on workforce development, preparing engineers and technicians with the skills needed to implement Re-X practices across U.S. industry. By linking applied R&D with training and commercialization, REMADE exemplifies the collaborative public–private partnership model that underpins the U.S. industrial sustainability strategy.

Integrating the Re-X framework into mainstream industrial practice is essential for meeting long-term decarbonization goals. As electricity demand grows from new data centers, EVs, and clean-tech manufacturing, reducing the energy embedded in materials offers a parallel pathway to sustainability. If supported by permitting reforms, investment incentives, and expanded collaboration through Manufacturing USA and MEP networks, the Re-X model could cut industrial sector emissions substantially while enhancing resilience against supply chain shocks. In this vision, circularity is not an adjunct to sustainability but a core strategy for building an industrial system that is low-carbon, resource-efficient, and globally competitive.

Circularity and Addressing the Microplastics Challenge

While circular economy strategies such as reuse, remanufacturing, and recycling can reduce industrial emissions and material waste, they also play a pivotal role in addressing one of the most pressing environmental issues in the United States: microplastic pollution. Microplastics originate from degraded consumer products, synthetic textiles, tire wear, and mismanaged waste streams. In the U.S., the EPA reported 35.7 million tons of plastic waste generated in 2018, while more recent studies from NREL estimate the figure closer to 44 million metric tons annually, much of which ends up landfilled, incinerated, or leaked into natural ecosystems due to insufficient recycling infrastructure. sources[129].

Microplastics are now found in U.S. waterways, agricultural soils, and even in human bloodstreams, raising concerns about long-term ecological and health impacts. Their persistence undermines ecosystem resilience and imposes hidden costs on fisheries, agriculture, and public health. Moreover, producing virgin plastics is energy-intensive, often relying on petrochemical feedstocks that add to industrial greenhouse gas emissions. Addressing plastic waste is therefore not only an environmental imperative but also an industrial

The proliferation of microplastics is closely linked to the massive production and disposal of plastic materials. In 2018, the United States generated approximately 35.7 million tons of plastic waste, accounting for 12.2% of all municipal solid waste. Notably, the recycling rate for plastics remained low, with only 8.7% (approximately three million tons) being recycled. Much of this plastic waste was either landfilled or incinerated, leading to environmental pollution and the fragmentation of plastics into microplastics[130].

Figure 51 – U.S. Initiatives for Building a Circular Economy[133]

The microplastics problem in the United States is a multifaceted issue stemming from extensive plastic production and inadequate waste management. The widespread presence of microplastics in the environment and their potential implications for human health underscore the urgency for effective interventions to address this growing concern[131]. The environmental impact of microplastics is significant. These particles have been detected in various ecosystems, including freshwater bodies and marine environments. Studies have found microplastics in lakes, rivers, and aquatic organisms, raising concerns about the health of wildlife and the potential for bioaccumulation in the food chain[132]. Addressing the microplastics problem requires comprehensive waste management strategies, including improving recycling rates, reducing plastic production, and implementing policies to limit the use of single-use plastics, which are critical steps.

Addressing the microplastics crisis will require collaborative action from policymakers, industries, researchers, and consumers alike. A multifaceted approach that prioritizes innovation, regulation, and behavioral change is essential to mitigate the long-term environmental and health impacts of plastic pollution and to transition toward a more sustainable and plastic-conscious future.

To address this issue, the United States is implementing various sustainability initiatives, including circular economy models and enhanced materials recycling, aimed at reducing plastic waste and mitigating the proliferation of microplastics.

The U.S. EPA Initiatives

EPA is actively advancing a circular economy to address plastic pollution. In November 2024, the EPA released the "National Strategy to Prevent Plastic Pollution," outlining objectives such as reducing pollution from plastic production, innovating material and product design, and improving waste management practices[134]. The strategy outlines a comprehensive plan to address plastic pollution across the entire lifecycle of plastic products. This strategy aims to eliminate the release of plastic waste into the environment by 2040, focusing on six key objectives:

1. Reduce Pollution from Plastic Production
    - Enhance Regulatory Measures: Review and update regulations for fossil fuel extraction, petrochemical, and plastic production facilities to minimize environmental and health impacts.
    - Promote Environmental Standards: Explore the creation of voluntary certifications to recognize plastic products manufactured under rigorous environmental standards.
    - Address Environmental Justice: Identify and mitigate environmental injustice and public health impacts associated with plastic production facilities.
2. Innovate Material and Product Design
    - Design for Circularity: Encourage the development of products that are reusable, recyclable, or compostable, thereby extending their lifecycle and reducing waste.
    - Support Sustainable Materials: Invest in research and development of alternative materials that have a lower environmental footprint compared to traditional plastics.
3. Decrease Waste Generation
    - Promote Reuse and Reduction: Encourage consumer behaviors and business practices that prioritize the reduction of single-use plastics and the adoption of reusable products.
    - Implement Extended Producer Responsibility: Develop policies that hold producers accountable for the entire lifecycle of their products, incentivizing waste reduction and improved product design.

4. Improve Waste Management
    - Enhance Recycling Infrastructure: Invest in modernizing recycling facilities to handle a broader range of plastic materials efficiently.
    - Standardize Recycling Practices: Develop uniform guidelines for recycling to reduce contamination and increase the quality of recyclable materials.
5. Improve Capture and Removal of Plastic Pollution
    - Develop Cleanup Technologies: Invest in innovative technologies and methodologies for effective removal of plastic waste from terrestrial and aquatic environments.
    - Support Community Cleanup Efforts: Provide resources and support for local initiatives aimed at removing plastic pollution from communities and natural habitats.
6. Minimize Loadings and Impacts on Waterways and the Ocean
    - Implement Source Reduction Strategies: Identify and control sources of plastic pollution entering waterways, including stormwater management and wastewater treatment enhancements.
    - Protect Marine Ecosystems: Develop and enforce regulations to prevent plastic waste from entering marine environments, safeguarding aquatic life and habitats.

This strategy emphasizes a collaborative approach that involves businesses, governments, non-governmental organizations, academia, and consumers in transitioning the United States toward a circular economy. This approach focuses on designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.

NIST Initiatives

In March 2024, NIST awarded nearly $3 million to six universities to develop educational programs that promote a circular economy for plastics. This initiative, part of NIST's Training for Improving Plastics Circularity (TIPC) Grant Program, is designed to equip students with the skills necessary to tackle challenges related to plastic production, consumption, and waste management[135].

The funded programs aim to integrate various disciplines, including materials science, economics, business, and engineering, to provide a well-rounded approach to plastic circularity. By incorporating these interdisciplinary perspectives, students will gain a deeper understanding of the economic, technological, and environmental factors that influence plastic waste management and recycling. A key focus of this initiative is shifting from a linear economy, where plastics are produced, used, and discarded, to a circular economy that emphasizes reuse, repair, and recycling. This transition aims to extend the lifecycle of plastic materials, reduce environmental pollution, and foster the development of more sustainable manufacturing practices. Each participating university will tailor its program to address various aspects of plastic circularity. Some will focus on developing new recycling technologies, while others will work on designing sustainable materials or creating business models that support circular practices. By fostering collaboration between industry leaders, researchers, and students, NIST's initiative is expected to drive innovation and support U.S. industries in implementing sustainable plastic management strategies that reduce waste and enhance environmental responsibility.

DOE Initiatives

Pre-2025, the U.S. DOE allocated $13.4 million to seven projects aimed at advancing technologies for plastic recycling, reducing plastic waste, and lowering the carbon footprint of plastic production. The selected projects, led by industry and universities, focus on converting plastic films into more valuable materials and designing new plastics that are more recyclable and biodegradable. This investment supported the Biden Administration's efforts to build a clean energy economy and achieve net-zero carbon emissions by 2050. Single-use plastics, such as plastic bags, wraps, and films, are energy-intensive to produce, accounting for more than 3% of total U.S. energy consumption. Despite their high embodied energy, many of these materials end up in landfills or the environment, with less than 10% currently being recycled[136].

The funded projects aim to develop affordable solutions for upcycling plastic films into more valuable materials and designing new plastics that are more recyclable and biodegradable, innovating both the processes of single-use plastics recycling and the plastics themselves. This funding opportunity builds on DOE investments, including the Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (BOTTLE) Consortium and the REMADE Institute[137]. DOE's Office of Energy Efficiency and Renewable Energy's Advanced Manufacturing Office and Bioenergy Technologies Office oversee these investments, with DOE's Office of Science, Office of Fossil Energy and Carbon Management, and ARPA-E also playing key roles in supporting plastic research and development efforts.

5.4 EU Activities

5.4.1 The European Green Deal

The European Green Deal is a comprehensive EU strategy to combat climate change and promote a more sustainable economy[139]. The Green Deal includes numerous initiatives, from reducing CO_2 emissions to investing in renewable energy and environmentally friendly technologies. The European Green Deal is also our lifeline in the fight against the COVID-19 pandemic. One-third of the €1.8 trillion investments from the NextGenerationEU Recovery Plan and the EU's seven-year budget will finance the European Green Deal.

The aim of the European Green Deal is to make the European Union climate-neutral by 2050, meaning it will no longer produce any net GHG emissions. This is a comprehensive strategy that affects all areas of the economy and society, from energy production and industry to transport, agriculture, and biodiversity protection. The Green Deal pursues the long-term goal of transforming the EU into a more environmentally friendly and sustainable economic region.

The first climate-neutral continent	At least 55% less	3 billion
by 2050	net greenhouse gas emissions by 2030, compared to 1990 levels	additional trees to be planted in the EU by 2030

Figure 52 – Key Figures of the European Green Deal[139]

As shows in Figure 52, the main objectives of the European Green Deal are:

1. Climate Neutrality by 2050

The EU aims to achieve net-zero GHG emissions by 2050, which means that all emissions must be offset through measures such as reforestation, carbon capture or other technologies. This is the core objective of the Green Deal and is to be achieved through far-reaching political measures, investments and innovations.

2. Reduction of GHG Emissions

By 2030, the EU's GHG emissions are to be reduced by at least 55% compared to 1990 levels. This is to be achieved through stricter emissions regulations, the expansion of renewable energies, the transition to cleaner transport technologies and the promotion of energy efficiency.

3. Promotion of Renewable Energies

An important part of the Green Deal is the promotion of renewable energies such as solar, wind and water energy to reduce dependence on fossil fuels and decarbonize the energy sector.

4. Protection of Biodiversity

The Green Deal also aims to protect biodiversity and conserve the EU's natural resources. This includes measures to combat pollution, restore ecosystems and protect habitats and biodiversity.

5. Circular Economy

Another goal is to promote a circular economy in which resources are used more efficiently and waste is reduced. Products should be used for longer periods and be easier to recycle or reuse, resulting in less waste and a reduced environmental impact.

6. Sustainable Mobility

The EU is planning a comprehensive transformation of the transport sector to make it more climate-friendly. This includes measures such as the promotion of electric vehicles, the expansion of public transport systems and the reduction of CO_2 emissions in aviation and shipping.

7. Fair Economic Transformation

The European Green Deal ensures that the transformation of the economy is socially just. This includes support for regions and sectors that are particularly affected by the transition, for example, through the Just Transition Fund. The aim is to create jobs and prevent economic imbalances.

6. Green Investment and Innovation

Massive investment in green technologies and innovation is needed to support the Green Deal. The EU will therefore create incentives for companies and investors to invest in sustainable projects, for example through green bonds and support programs.

Notable initiatives include[139]:

- REPowerEU
- The Green Deal Industrial Plan
- EU action to address energy crisis

5.4.2 REPowerEU

In response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine, the European Commission is implementing its REPowerEU Plan to phase out Russian fossil fuel imports[140]. Launched in May 2022, REPowerEU is helping the EU save energy, diversify energy supplies, and produce clean energy. Thanks to REPowerEU, the European Commission has safeguarded EU citizens and businesses from energy shortages, supported Ukraine by weakening Russia's war chest, accelerated the transition to clean energy, and stabilized prices. EU countries will prepare national plans by the end of 2025 outlining how they will contribute to phasing out imports of Russian gas, nuclear energy, and oil. At the same time, efforts will continue to accelerate the EU's energy transition and diversify energy supplies to eliminate risks to supply security and market stability.

Securing Affordable Energy

Energy prices in Europe have declined substantially compared to the peaks of 2022, thanks to the coordinated European response and the REPowerEU Plan. Europe is investing in the production of clean and affordable energy to secure its energy independence. Following the Russian full-scale invasion of Ukraine, the EU proposed common gas procurement to ensure that Europeans have access to affordable energy and to avoid any energy supply disruptions. This system allowed us to start purchasing a portion of our gas needs collectively as Europeans, rather than competing against one another for scarce supplies. In place since April 2022, the EU Energy Platform plays a crucial role in diversifying our energy supply. The Platform helps coordinate infrastructure investments and negotiations with external gas suppliers to prevent EU countries from outbidding one another. The Platform also leverages the weight of the EU single market to achieve better conditions for all EU consumers.

Accelerating the Clean Energy Transition

The REPowerEU Plan is accelerating the green transition and promoting massive investment in renewable energy. In November 2023, the revised Renewable Energy Directive entered into force. This new legislation aims to increase the share of renewables in the EU's overall energy consumption, raising the binding target for 2030 to 42.5% with the ambition of reaching 45%. This would almost double the existing share of renewable energy in the EU.

To support the clean transition, we must improve our ability to nurture our own industry. To achieve this, we proposed a Green Deal Industrial Plan for Europe in February 2023. The Plan will help enable the EU's manufacturing industry to scale up its production of the net-zero technologies and products required to meet Europe's ambitious climate targets.

At the end of 2023, the Commission presented an action plan to accelerate the rollout of electricity grids. With the EU markets fully integrated, a modernized infrastructure network ensures that citizens and businesses benefit from cheaper and cleaner energy. In the same year, we also revised the Energy Efficiency Directive along with other energy and climate regulations. The new rules establish an ‘energy efficiency first’ principle, meaning that, in practice, energy efficiency must be considered by EU countries in all relevant policy and major investment decisions made in both the energy and non-energy sectors. The rules also contribute to ensuring that we meet our climate ambition of reducing GHG emissions by at least 55% by 2030, compared to 1990.

In July 2024, the reform of the EU electricity market design entered into force. This helps to make the EU energy market more resilient and benefits citizens and companies by making their energy bills less dependent on the short-term market price of electricity. The reform also helps accelerate the integration of more renewable energy sources into the energy system and enhances protection against market manipulation.

A large-scale business plan to further support the competitiveness and resilience of EU industry, called the Clean Industrial Deal, was put forward in early 2025. The Deal will accelerate decarbonization while simultaneously boosting EU manufacturing by lowering energy prices, creating quality jobs, and providing the right conditions for companies to thrive.

5.4.3 The Green Deal Industrial Plan

The Green Deal Industrial Plan enhances the competitiveness of Europe’s net-zero industry and is accelerating the transition to climate neutrality[141]. It does so by creating a more supportive environment for scaling up the EU’s manufacturing capacity for the net-zero technologies and products required to meet Europe’s ambitious climate targets.

On the road to net-zero, the EU Commission lists the following key figures shown in Figure 53:

Over €100 billion is the value of EU’s net-zero start-ups ecosystem in 2021, doubling since 2020	**More than 400 GW** of wind and solar renewable energy production capacity in the EU in 2022, an increase of over 25% compared to 2020	**4.5 million** green jobs in the European economy in 2019 up from 3.2 million in 2000

Figure 53 – Key Figures of the Green Deal Industrial Plan[141]

To secure Europe’s place as the home of industrial innovation and clean tech, the Green Deal Industrial Plan will cover following four key pillars:

1. Predictable and Simplified Regulatory Environment

This pillar of the plan focuses on the regulatory environment. This means creating a simpler, faster, and more predictable framework, securing the volumes needed for raw materials, and ensuring users can benefit from the low costs of renewables. There are three initiatives to support this work, as follows:

- Offshore Wind Turbines Net-Zero Industry Act
  Identifying goals for net-zero industrial capacity and provide a regulatory framework suited for its quick deployment
- Critical Raw Materials Act

Ensuring sufficient access to those materials, like rare earths, that are vital for manufacturing key technologies

- Reform of Electricity Market Design
  Helping consumers benefit from the lower costs of renewables

2. Faster Access to Funding

The second pillar of the plan will speed up investment and financing for clean-tech production in Europe.

Under competition policy, the Commission aims to guarantee a level playing field within the Single Market while making it easier for member states to grant the necessary aid to fast-track the green transition. To that end, and in order to speed up and simplify aid granting, the Commission consulted member states, amended the Temporary State Aid Crisis and Transition Framework, and revised the General Block Exemption Regulation in light of the Green Deal.

The Commission will also facilitate the use of existing EU funds to finance clean-tech innovation, manufacturing, and deployment, with a focus on REPowerEU, InvestEU, and the Innovation Fund. The Commission will also seek to establish the European Sovereignty Fund as a mid-term structural solution for investment needs.

3. Enhancing Skills

With a significant growth in new technologies, we will need a corresponding increase in skills and skilled workers in this sector. To develop the skills needed to facilitate the green transition, the Commission will propose establishing Net-Zero Industry Academies that will help roll out upskilling and reskilling programs in strategic industries. This proposal will consider how to combine a 'skills-first' approach, recognizing actual skills, with existing approaches based on qualifications. Additionally, it will explore ways to facilitate the access of third-country nationals to EU labor markets in priority sectors and will examine measures to foster and align public and private funding for skills development.

4. Open Trade for Resilient Supply Chains

The fourth pillar focuses on global cooperation and making trade conducive to the green transition, adhering to the principles of fair competition and open trade, while building on engagements with the EU's partners and the work of the World Trade Organization (WTO). To that end, the Commission will continue to develop the EU's network of Free Trade Agreements and other forms of cooperation with partners to support the green transition. It will also continue to defend the Single Market from unfair trade practices.

5.4.4 EU Action to Address Energy Crisis

Russia's military aggression against Ukraine and its weaponization of gas supplies have provoked an unprecedented energy crisis for the EU. This has led to a sharp rise in energy prices and brought hardship to Europeans[142].

In response, the EU implemented emergency measures in 2022 to stabilize energy prices and ensure access to gas supply during the winter. Looking ahead, the Commission is now focusing on addressing persistently high energy costs that impact EU citizens and businesses. To this end, in February 2025, the Commission presented a new action plan aimed at reducing energy costs, completing the energy union, attracting investments, and enhancing preparedness for potential energy crises.

In June and July 2022, the Commission proposed new rules to ensure that Europe had sufficient gas supplies to withstand any sudden disruptions from Russia during the winter months. With the new gas storage rules, EU countries must fill storage facilities to 90% by November 1 of each year. At the beginning of the 2024-2025 winter season, the gas storages were 95% full, with the 90% threshold having been reached as early as August 2024. Furthermore, in August 2022, the EU countries agreed on a regulation to voluntarily reduce natural gas demand by 15% for the 2022/2023 winter season, later extending it to cover the winter of 2023/2024. In March 2024, the Council adopted a recommendation to continue taking voluntary measures until March 2025 to maintain a collective 15% reduction in gas demand compared to the average demand between April 2017 and March 2022. In April 2022, the Commission also launched the EU Energy Platform to help EU countries collaborate on global markets. The goal is to avoid competition between EU countries, use the EU's influence to secure diverse energy sources, encourage competition among major suppliers, and achieve better conditions for consumers.

A key part of ensuring secure and affordable energy supplies involves diversifying supply routes. In recent years, the EU has been working with international partners to diversify supplies. Since 2022, the Commission has established agreements with Egypt, Israel, and Azerbaijan to export natural gas to Europe. The EU has also increased liquefied natural gas (LNG) imports from North America, Australia, Qatar, and East Africa, as well as through pipelines from Norway, the United Kingdom, Azerbaijan, and North Africa. Investments in LNG terminals and gas interconnectors have ensured that every EU country can now receive gas from at least two sources, and reverse flows are possible between neighboring countries. For example, in May 2022, the Poland-Lithuania gas interconnector began operations, reinforcing the optionality and resilience of the Baltic gas market. Similarly, in October 2022, the Greece-Bulgaria gas interconnector was launched, playing a key role in diversifying gas supplies in Southeast Europe.

Besides securing sources abroad, we must use as much homegrown energy as possible. The EU is already a global leader in the development of technology for renewable energies. In 2023, the share of renewables in the EU's energy consumption was 24.5%. With the revised Renewable Energy Directive in November 2023 as shown in Figure 54, EU countries agreed on an overall renewable energy target of at least 42.5% at EU level by 2030, with the aim to reach at least 45%. To speed up the deployment of renewable energy, EU countries agreed in December 2022 on temporary rules that allow for streamlined permitting processes.

Figure 54 – Key Figures of Developing Renewable Energy[142]

In response to Russia's use of energy as a weapon, EU countries agreed in October 2022 to implement an emergency intervention aimed at reducing energy bills for European households and businesses. It included following measures:

- Reducing electricity demand (10% overall, with an obligatory 5% reduction during peak hours)
- Capping revenues (€180 per MWh) from low-cost energy producers (nuclear, lignite, renewables) and

redistributing the surplus to costumers

- Introducing a temporary solidarity contribution on excess profits in the oil, gas, coal and refinery sectors, redirecting funds to energy consumers.

The emergency measures expired in 2023.

In February 2023 EU countries also agreed on a Market Correction Mechanism to avoid disruptions to the energy and financial market. In case of need, it would have been automatically activated:

- If the month-ahead Title Transfer Facility (TTF) price exceeded €180/MWh for 3 working days and,
- If the TTF price was €35 higher than a reference price for liquefied natural gas (LNG) on global markets for the same 3 working days.

The mechanism was in force until January 2025 and never needed to be triggered, thanks to factors such as a decline in structural demand, reliable LNG and pipeline imports from trusted partners, and enhanced import infrastructure.

Nevertheless, energy prices in the EU remain structurally high, which harms EU citizens and the competitiveness of EU industry. The Commission therefore proposed the Affordable Energy Action Plan in February 2025, which outlines concrete short-term measures to lower energy costs for citizens, businesses, industry, and communities across the EU, complete the energy union, attract investments, and be better prepared for potential energy crises. This will allow for an overall estimated savings of €45 billion in 2025, with a progressive increase of up to €130 billion annually by 2030, and €260 billion annually by 2040.

5.4.5 Microplastic Issues

Microplastics are plastic particles of various shapes that are present in the air, soil, freshwater, seas, biota, and several components of our diet. Because of the fragmentation and degradation of larger plastic items and microplastics, it is plausible that nanoplastics will be formed. Scientists, policymakers, and the public are becoming increasingly concerned about both the ubiquity of nano- and microplastics (collectively referred to as ‘NMPs’) and the uncertainties surrounding their impacts, hazards, and risks to our environment and human health.

NMPs are less than 5 mm in size (Arthur, 2009; Thompson et al., 2004) and originate from a variety of sources, including fisheries, products and textiles (use and breakdown), agriculture, industry, waste, litter, and others. The scientific evidence base and policy context was reviewed by the European Commission’s Scientific Advice Mechanism, and they published a report on January 2019[143]. The absence of concrete evidence of microplastic risks at the time of the report did not allow us to conclude with sufficient certainty either that the risk was present or that it was absent in nature. On the other hand, the working group of the European Commission’s Scientific Advice Mechanism found that there was a need for more inquiry into these future socioeconomic scenarios, as well as the environmental ones.

The working group’s key conclusions were[144]:

- Microplastics—tiny particles under 5 mm in length—are already present across air, soil and sediment, freshwaters, seas and oceans, plants and animals, and in several components of the human diet.
- These particles come from a variety of sources, including plastic products, textiles, fisheries, agriculture, industry and general waste.

- In controlled experiments, high concentrations of these particles have been shown to cause physical harm to the environment and living creatures, including inducing inflammation and stress.
- However, the concentration levels measured in many real-world locations are well below this threshold—though there are also limitations in the measurement methods currently available.
- Meanwhile, in other parts of the environment, there is no reliable evidence about the levels or effects of these particles. This is true especially of nano plastics, which are very difficult to measure and evaluate.

After that, on October 17, 2023, Commission Regulation (EU) 2023/2055 restricting synthetic polymer microparticles on their own or intentionally added to mixtures—better known as “the microplastics restriction”—began to apply[145]. On April 8, 2025, the Council and the European Parliament provisionally agreed on a regulation to prevent the loss of plastic pellets—the industrial raw materials used to make plastic products—into the environment[146].

5.5 Cross-regional Similarities and Differences

In this chapter, we have looked at efforts regarding energy, decarbonization, and environmental issues in Japan, the United States, and Europe.

All three regions are committed to achieving carbon neutrality by the middle of this century through strategies that include reducing GHG emissions and promoting renewable energy. To balance economic growth with reducing environmental impact, all regions are promoting measures such as technology development and tax incentives to expand renewable energy sources. Furthermore, all regions are working toward a transition to a circular economy by improving resource efficiency and reducing waste.

As for the differences in energy, decarbonization, and environmental issues in the three regions, as mentioned above, the recognition of the issues is generally the same, but there were some differences in the specific measures, reflecting the economic and cultural backgrounds.

For example, measures against microplastic pollution vary from region to region, and the degree of emphasis and level of regulation also seem to differ. In Japan, the emphasis is on voluntary reduction efforts and recycling laws, and efforts against microplastic pollution have only recently begun. The U.S. strategy on microplastics and plastic waste emphasizes a science-based, lifecycle approach led by the EPA and supported by state-level initiatives, voluntary industry actions, and investments in recycling and sustainable materials. This decentralized, innovation-driven model integrates stakeholder collaboration and aligns with broader circular economy and environmental goals. In the EU, strict regulations on microplastics, including measures to prevent the loss of plastic pellets, are being disseminated based on scientific analysis and recommendations.

In addition, from the perspective of energy strategies and regional revitalization, management policies differ in their discussions on regional decentralization. In Japan, decentralization is being promoted for semiconductor manufacturing and data center construction in accordance with regional energy mix strategies. In 2025, the U.S. redefined industrial sustainability through a practical model centered on resilience, abundance, and innovation. In this model, the U.S. emphasizes “energy addition, not subtraction” and shifting to a decarbonized energy mix over the long term, achieving both industrial sustainability and decarbonization while reinforcing global energy leadership by energy exports. The EU, facing higher energy costs and geopolitical risks, is focused on reducing its dependency on Russian fossil fuels through the REPowerEU plan, integrating renewable energy, and harmonizing infrastructure development across member states.

Despite the policy differences mentioned above, this discussion has clarified common challenges and solutions related to energy, decarbonization, and environmental issues, demonstrating that international cooperation can lead to rapid and effective results.

Column: Balancing Energy Security and Industrial Promotion

Energy security and industrial promotion are closely linked, with significant challenges arising in both areas. The fluctuation in energy trading prices is recognized as a problem, prompting discussions on digital solutions for stabilization. Industries such as steel and chemicals, which are heavily reliant on a stable energy supply, face significant challenges. Additionally, SMEs in the Factory Automation (FA) sector, particularly those using automated equipment like machine tools, are highly sensitive to energy issues. This column introduces the respective initiatives of Japan, the EU, and the U.S. in balancing energy security and industrial promotion.

Japan's Initiatives:

In Japan, following the Fukushima incident during the Great East Japan Earthquake, there is a movement to reassess nuclear power as part of the energy policy. While natural energy faces geographical constraints and is not yet fully operational, nuclear power is being reconsidered as a base load. The government has provided a safety net for SMEs from an energy perspective in response to disasters like the Great East Japan Earthquake and COVID-19. However, this is a short-term measure. In the long term, Japan plans to leverage its rich communication network, including fiber optics, to revive industries such as semiconductors and to locate data centers. The government aims to form ecosystems in areas like Kitakyushu and Hokkaido, where natural energy can be relatively stable and a strong technological base, supported by universities, exists. This indicates that long-term industrial promotion strategies are beginning to incorporate energy considerations.

EU's Initiatives:

The EuroHPC initiative represents Europe's ambitious push to develop world-class supercomputing capabilities, establishing a network of high-performance computing (HPC) infrastructure crucial for AI development. This initiative directly supports Europe's vision of becoming an "AI Continent" by providing the necessary computational power for advanced AI research and applications.

The initiative synergizes with the Important Project of Common European Interest on Cloud Infrastructure and Services and Horizon Europe CEI Pilot projects such as O-CEI, which aim to develop sovereign cloud and data infrastructure. Together, these programs create a robust ecosystem where AI applications can be developed, tested, and deployed securely within European frameworks.

Environmental sustainability, as measured by the Green Deal initiatives, is fundamentally integrated into both programs. The supercomputing centers under EuroHPC are designed with energy efficiency in mind, often using renewable energy sources and innovative cooling solutions. For instance, the LUMI supercomputer in Finland uses 100% hydroelectric power and its waste heat is repurposed for local district heating.

The integration of these initiatives demonstrates Europe's comprehensive approach to technological advancement while maintaining environmental responsibility. The programs work together to ensure:

- sovereign computing capabilities
- sustainable infrastructure development
- competitive AI innovation
- compliance with EU values and standards.

This coordinated strategy positions Europe as a leader in sustainable, high-performance computing for the AI age.

U.S.'s Initiatives:

In the post-2025 model, the U.S. links energy security, industrial resilience, and sustainability into a single strategy. Abundant and diversified supply—including natural gas, nuclear, renewables, and emerging technologies such as carbon capture and storage (CCUS), hydrogen, geothermal, advanced energy storage, and small modular reactors (SMRs), underpins energy security by ensuring long-term stability, short-term system reliability, and steady progress toward decarbonization. Stable, affordable energy supports heavy industries and SMEs, and digital tools such as AI, digital twins, and smart grids improve operations, and strengthen resilience in the system. Decarbonization is pursued through technology-neutral innovation—from CCUS and hydrogen to AI-enabled grids—ensuring emissions reduction without undermining competitiveness. In this way, the U.S. advances sustainability not through scarcity or mandates but through abundance, resilience, and technological innovation that reinforce its industrial and global leadership.

6 Human-Machine Interaction in the Future

In order to realize the goal image of Multiverse Mediation shown in Figure 1 that was discussed and established in the last Japan-Germany project, it is necessary to consider not only technical issues but also the cultural background and economic situation of each region, thoroughly consider ELSI, and discuss the steps to achieve this.

For example, in Japan, as part of NEDO SIP program, the development and social implementation of Human-Cyber-Physical Space (HCPS) collaborative robotics are being advanced[138]. This project aims to create a society where humans and technology coexist harmoniously, known as a Technopia Support Society, contributing significantly to the realization of Society 5.0. Specifically, it seeks to enhance the independence and freedom of people across generations by adapting to diverse lifestyles through support for the elderly, vulnerable individuals, and childcare. By the fiscal year 2025, the project will evaluate the foundational technologies of HCPS and assess the operation of integrated systems. By 2027, it aims to begin actual operations at more than 10 locations both domestically and internationally. Ultimately, by 2033, the project plans to expand to over 30 locations and extend into other areas, establishing a sustainable economic cycle. There is a growing discussion that this activity should also be viewed from the perspective of citizens and socially vulnerable groups, taking into account the cultural background and economic situation of each region in Japan.

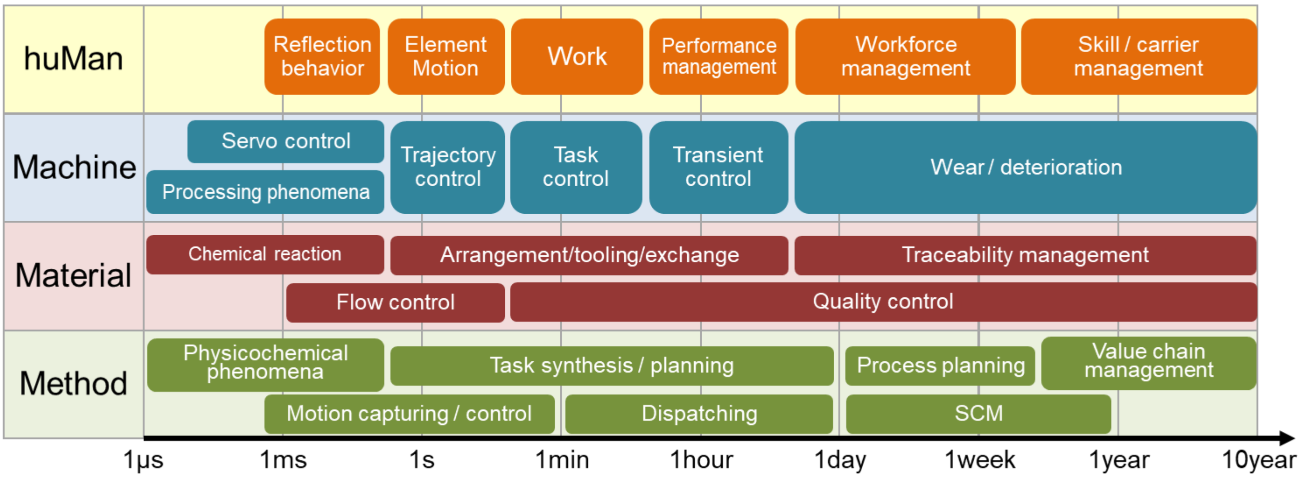


Figure 55 – Limitations of current technologies related to the HMI[147]

Furthermore, when industry, academia and government collaborate in such a broad range of fields, technological development initiatives tend to take the lead, but there is a fundamental problem in that the performance limits of technology do not cover the requirements in HMI. That is, machines, including AI, do not yet have the capability to imitate human senses and knowledge, nor to transmit knowledge and experience from humans with various cultural backgrounds to other humans. Figure 55 shows a logarithmic time from microseconds to several decades on the horizontal axis and illustrates the main behaviors from the perspectives of human, machine, material, and method, which are said to be the four basic elements of HMI. For example, within the microsecond time domain, human reflex movements, chemical reactions of objects, and physicochemical phenomena have not yet been formalized as data. In the decades time domain, there are still many challenges, such as how to transfer personal knowledge and experience accumulated over many years to other humans and machines, how to monitor machine wear and tear over the long term, and how to maintain and manage data for more than several decades.

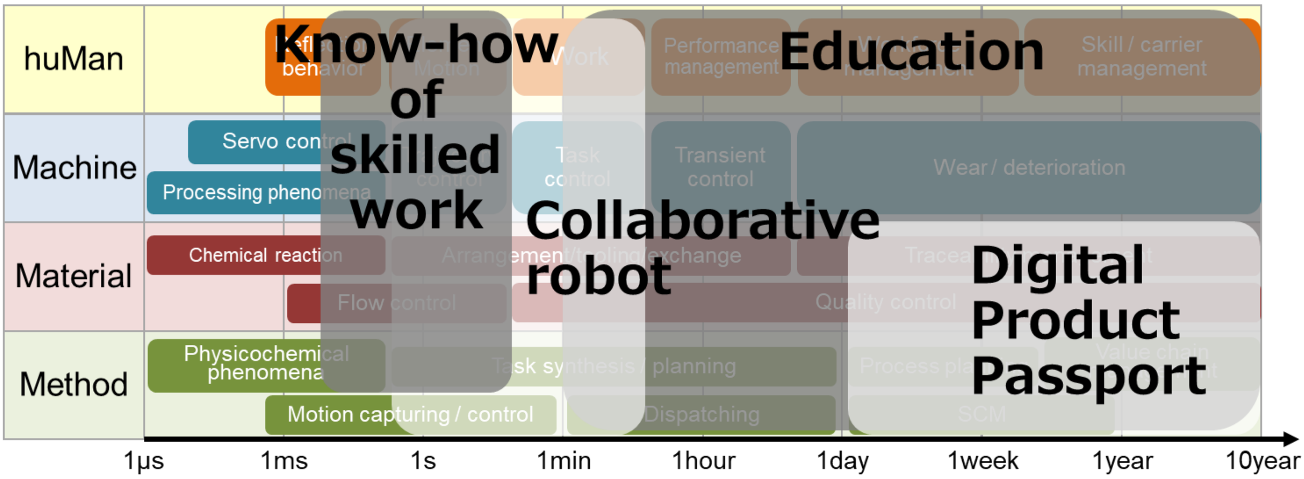


Figure 56 – Related initiatives[147]

Figure 56 overlays examples of HMI initiatives on top of Figure 55. What is important about this figure is that no initiative has the technical capability to cover the entirety of the figure. In other words, to realize Multiverse Mediation, which is defined as the goal image of symbiosis between humans and machines, it is important to combine multiple initiatives organically and systematically, apply them appropriately as a human society, and maintain and manage them in a permanent manner. This is one of the motivations for Japan's Society 5.0 and Europe's Industry 4.0 to repeatedly emphasize that the concept of System of Systems is essentially important not only technologically but also socially, and that international collaboration is essential.

Column: Strengthening Resilience in Manufacturing through AI in the U.S.

The U.S. government is also actively advancing AI-driven solutions to enhance manufacturing resilience and sustainability. On July 22, 2024, NIST announced a funding opportunity of up to $70 million to establish a new Manufacturing USA Institute dedicated to integrating AI technologies in U.S. manufacturing[148]. This initiative will build on the existing Manufacturing USA Institutes and will focus on applications such as predictive maintenance, which reduces downtime, minimizes resource waste, and extends the life cycle of manufacturing equipment, ultimately fostering greater sustainability. Moreover, generative AI plays a pivotal role in improving manufacturing resilience by enabling predictive maintenance. Its ability to analyze multi-modal data, including machine status and operational conditions, facilitates comprehensive assessments and accurate failure predictions. By anticipating maintenance requirements, manufacturers can avoid costly equipment breakdowns, reduce production interruptions, and optimize the longevity of their equipment. This proactive maintenance approach not only reduces the need for new equipment but also decreases energy waste associated with inefficient machine operation, contributing to improved industrial sustainability through optimized resource utilization and minimized environmental impact.

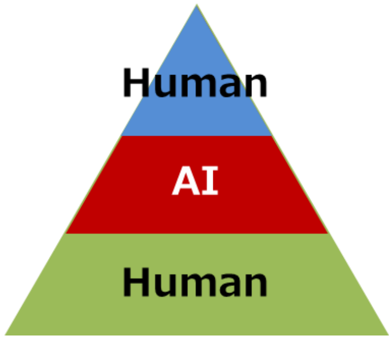


Figure 57 – Sophisticated Slavery[149]

Regarding ELSI in each region, one of the topics being discussed in Japan's Society 5.0 is the assumption by Mr. Kobayashi, lawyer, in 2018[149]. He proposes that as machines become more intelligent, changes will occur in the human labor structure. In other words, he predicts that the process of accumulating the knowledge necessary for work and presenting knowledge that is useful in each situation will be replaced by machines, including AI. Humans will be divided into two types: those who provide knowledge and instructions to the machines, and those who receive instructions from the machines and perform simple physical labor. This hypothesis suggests that the middle tier of the triangle in shown in Figure 57, for example, middle-skilled workers who do a lot of routine work such as insurance clerks and accounting clerks, will be replaced by machines, including AI. He calls this hierarchical structure "Sophisticated Slavery."

Furthermore, he argues that such a change does not immediately result in misery for people, as those who previously had difficulty participating in the labor force due to differences in cultural background or economic situations will be able to do so. However, he states that the income of humans who receive instructions from machines and perform simple physical labor will decrease, widening the economic gap between them and those who provide knowledge and instructions to machines. He argues that choosing a position at the bottom of this hierarchy may not necessarily be the wrong choice. He argues that work requiring 100% compliance with the instructions of an AI involves no judgment or hesitation and can be considered work with little occupational stress, that AI "bosses" are free from sexual harassment and power harassment, and that as long as they are programmed to comply with the law, they will never instruct illegal overtime work.

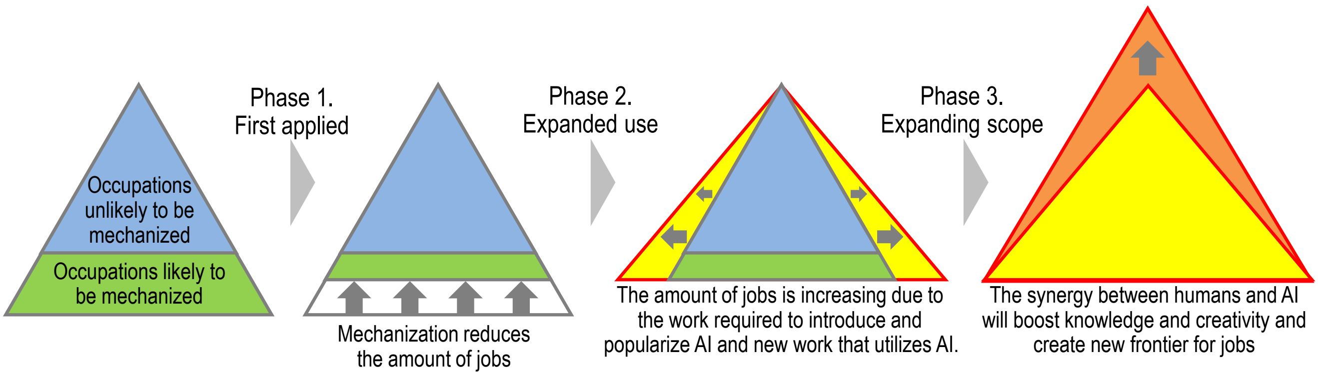


Figure 58 – An evolution of jobs with the introduction of AI

created by the authors based on "Figure 4-5-2-1 Changes in jobs due to the introduction of AI,"

2018 White Paper on Information and Communications in Japan, Ministry of Internal Affairs and Communications[150]

A similar argument is also made in the white paper of the Ministry of Internal Affairs and Communications of Japan as a requirement for realizing Society 5.0. Figure 58 shows an evolution of jobs with the introduction of AI, the left and the middle two figures are quoted from “Figure 4-5-2-1 Changes in jobs due to the introduction of AI” in the 2018 White Paper on Information and Communications in Japan, Ministry of Internal Affairs and Communications[150]. According to them, as shown in the figure on the far left, the labor structure can be divided into parts that are likely to be mechanized (the lower green part of the figure) and parts that are unlikely to be mechanized (the upper blue part of the figure). With the application of AI, as shown in the second figure from the left, the green part will be replaced by machines, leading to a decrease in the number of human tasks. Furthermore, as shown in the third figure from the left, the work required to introduce and popularize AI and new work that utilizes AI will increase the overall number of tasks. The figure on the far right illustrates how the HMI discussed in this book will further expand human knowledge and creativity, opening up entirely new industries and jobs while transforming the workplace into a new labor structure. And this machine’s domain will encroach upon the domain of intellectual labor, which provides knowledge and instructions from higher levels. Statistical predictions based on the analysis of big data, such as stock prices, exchange rates, corporate performance, traffic congestion, and weather, are among AI’s specialties, and sooner or later, it will surpass human predictive capabilities.

Rather than engaging in a binary debate about whether this hierarchical structure should be called a dystopia or a utopia, there are future predictions based on these thought experiments, and it is important to discuss what kind of social system should allow people to live happy lives, and what kind of HMI there should be.

Figure 59 shows the chart in a McKinsey’s report in 2017, which is consistent with Kobayashi’s hypothesis stated previously in 2018. They predict that between 2016 and 2030, jobs requiring medium skills (like “cognitive skills”) will be replaced by machines and decline, while jobs requiring specialized knowledge will increase. They also predict that jobs requiring less skill will either decline or increase slightly. In other words, they are consistent with Kobayashi’s hypothesis in predicting the point at which labor polarization will occur.

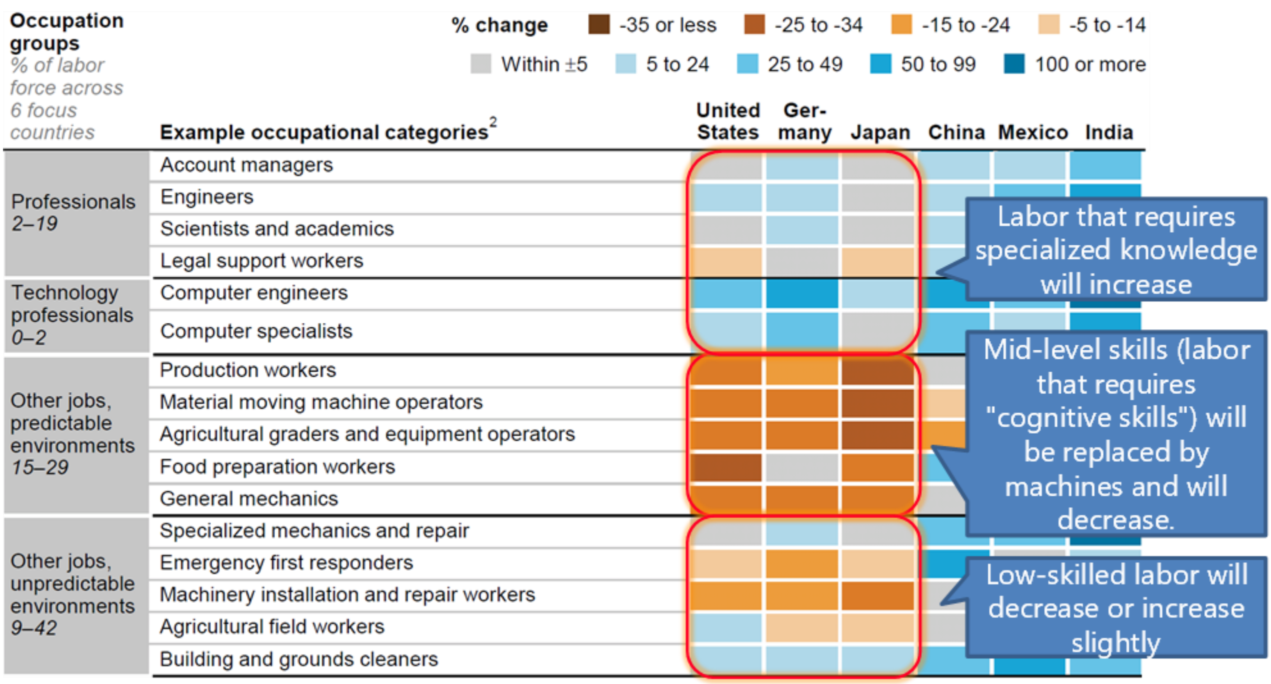


Figure 59 –Jobs lost, jobs gained: Workforce transitions in a time of automation[151]

This is also pointed out in the IMF report[152]. Figure 60 shows the contribution of skills to changes in the total labor distribution rate in the period between 1995 and 2009, and there are three categories, High Skill, Middle Skill, and Low Skill which include percentages for each major factor. This figure claims that the increase in the share of high-skilled labor and the decrease in the share of low-skilled labor are caused by policies promoting more advanced education, while the negative impact on the share of medium-skilled labor is attributed to technological change and the integration of global value chains. In other words, advanced education and globalization reduce the number of medium-skilled jobs, and it is inevitable, from the perspective of the development and maintenance of human society, that machines, including AI, will replace those jobs.

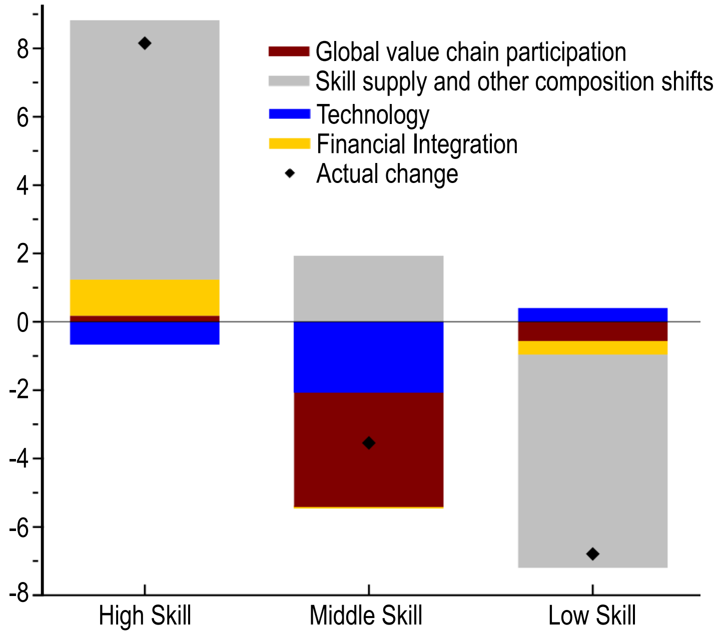


Figure 60 – Contributions to aggregate labor share change by skill, 1995–2009[152]

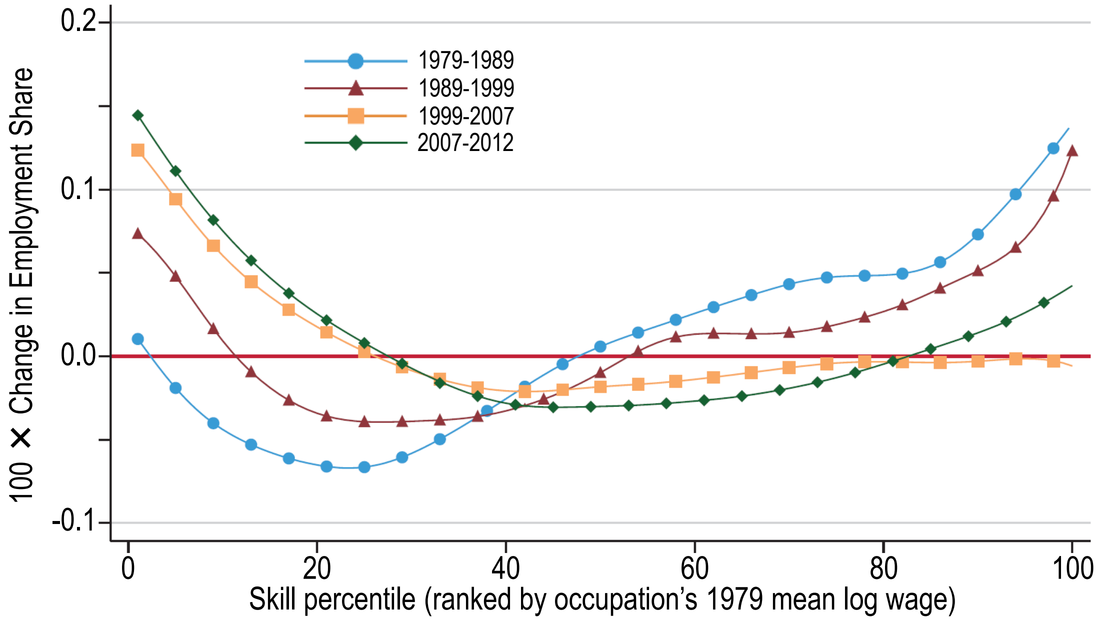


Figure 61 – Smoothed employment changes by occupational skill percentile in the U.S. labor market, 1979–2012[153]

Regarding the transition of the labor structure by skill level, there is a well-known paper by Autor that analyzed the U.S. labor market[153]. A representative example is Figure 61, in which the vertical axis shows the percentile value of change in employment share, the horizontal axis shows the skill percentile ranked by occupation's 1979 mean log wage, and multiple line graphs show the situation at each period. This figure shows that the U.S. labor structure by skill level is gradually polarizing into low-skilled and high-skilled labor.

Based on Figure 61, Figure 62 shows the current and future trend image of the labor structure. What should be discussed in this figure is what value the ideal form of HMI should bring to the labor structure change.

The red area in the upper left of the diagram, "Difference A," represents the increase in low-skilled labor, the yellow area in the center of the diagram, "Difference B," represents the decrease in middle-skilled labor, and the green area in the upper right of the diagram, "Difference C," represents the increase in high-skilled labor. And as we have discussed so far, difference A arises as automation and digitalization permeate society. Difference B is not only diminishing with the globalization of the economy through the construction and operation of global supply chains, but is also arising as humans are replaced by machines, including AI. Also, Difference C is arising as human activities and knowledge expand further with the help of machines in some advanced technological developments.

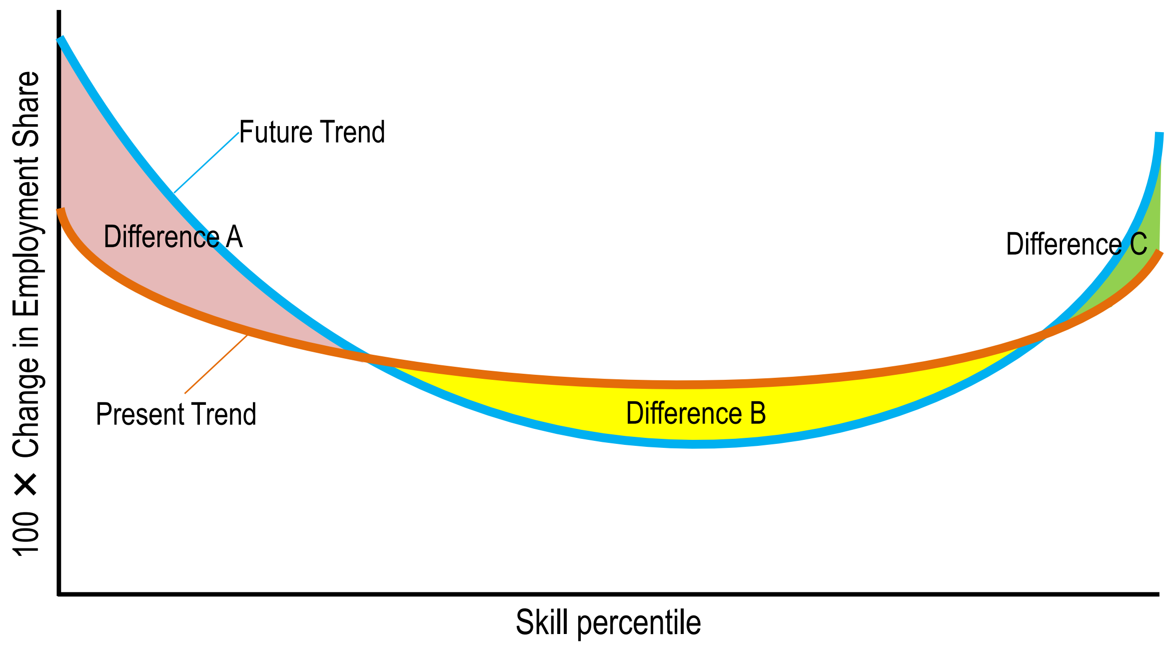


Figure 62 – Current and future trend image of the labor structure based on Figure 61[147]

There are two points to be discussed regarding the transition of the labor structure in Figure 62 as shown in Figure 63. First, how can workers who lose their jobs in Difference B move to Difference C and play an active role? Second, how can we enable humans to participate in society with a lively spirit in Difference A to which workers who lose their jobs in Difference B also move?

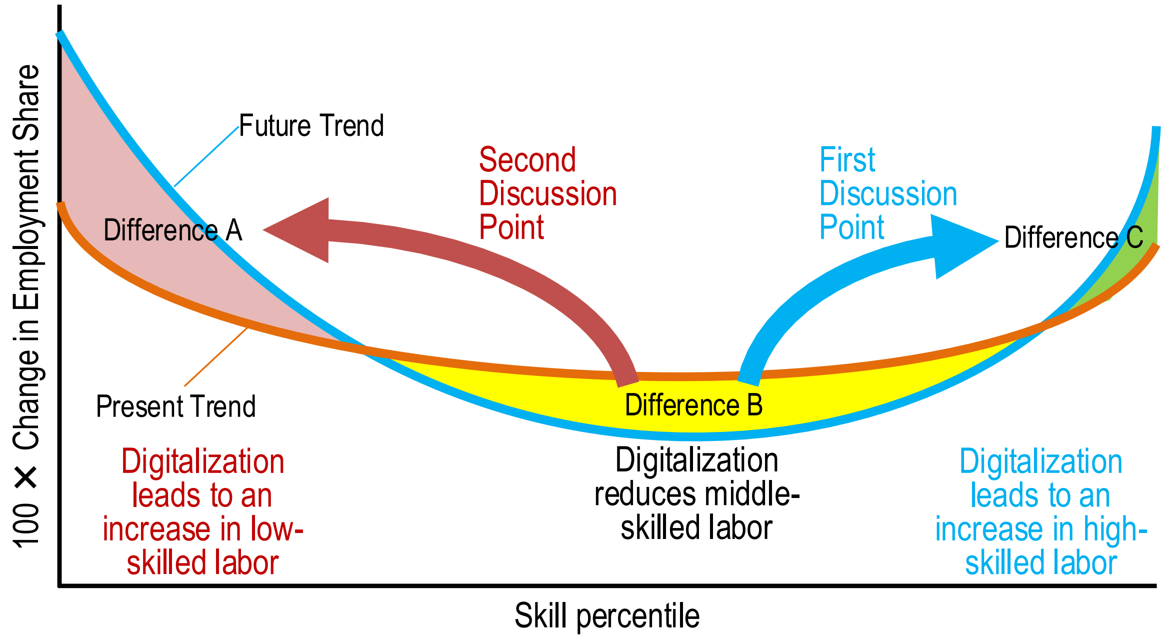


Figure 63 – Two discussion points[147]

That is, regarding the first discussion point indicated by the blue arrow in Figure 63, digitalization will reduce mid-skill labor in Difference B, such as data entry and checking, so there is a need to transform it into high-skill labor in Difference C, through lifelong education and other means. For this, various measures need to be expanded, such as STEM education, which is updated in line with the evolution of humans and society, lifelong education to cultivate diverse values and abilities, and individual education according to individual growth and circumstances. This is also important from the perspective of On-the-Job Training (OJT) in manufacturing, retail, and service sites, and it is necessary to effectively and efficiently provide appropriate awareness and know-how according to individual growth and circumstances.

Advanced HMI is expected to contribute to the provision of individual education, awareness, and know-how tailored to the growth and circumstances of individuals. Even now, in the field of education, the enhancement of interfaces is spreading, such as distributing tablet devices to elementary and junior high school students, and education tailored to the growth and circumstances of individuals is beginning to be started. In addition, in the service fields of manufacturing and retail, efforts have begun to use tablet devices not only to confirm work content and report completion, but also to call attention to points to note when carrying out work and to view past trouble cases.

In addition, automation of programming using generative AI is becoming the key to transforming engineers' work into more productive and creative. In the short term, this automation of programming may take away the labor of engineers. However, from a medium- to long-term perspective, it will further promote the reuse of documents and source codes that have been cultivated so far, allowing engineers to focus their labor on essential tasks, and should be an important enabler that contributes to industrial sustainability based on HMI.

What is globally needed now is a systematic identification of the issues and measures to transform mid-level skilled workers who have lost their jobs in Difference B into highly skilled workers in Difference C.

Regards to the second discussion point as the red arrow in Figure 63, low-skill labor of simple tasks such as cleaning, in difference A, will not disappear, and as the red arrow in the diagram indicates, there is a possibility that workers due to the decrease in mid-skill labor, in difference B, will move to low-skill labor in Difference A.

For the second discussion point, the following two aspects should be emphasized.

Firstly, most low-skill labor is not particularly profitable but is considered essential for supporting society. In the near future, it may be difficult to achieve complete automation due to insufficient technology and high costs. Participation of human workers, possibly through versatile collaborations with machines, is necessary.

Secondly, the abilities and preferences of humans are diverse and cannot be captured by high-skill labor alone. For social sustainability and well-being, every individual should be accepted and experience psychological satisfaction by participating in the roles of society. Reconsideration of low-skill labor is important for this aspect.

In other words, **to transform society through digitalization and ensure industrial sustainability, collaboration between humans and machines in low-skill labor is the most important issue. The essential challenge for the future is finding ways to solve this problem and enable low-skilled workers to participate vibrantly in society.**

Discussions from this perspective do not seem to have progressed in any country yet. At the very least, in a society where workers who have lost their jobs in Difference B also move to difference A, it should be important to build a social system that accepts diverse values and diverse working styles so that human can participate in society with a lively attitude. To achieve this, it is necessary to realize **a social system in which people who want to work can work as much as they want in appropriate working environments and conditions by further segmenting and dynamically evolving the matching of labor and employment.**

It is also necessary to focus on employment that cannot be addressed by such labor alone and to create a mechanism to promote automation. At the very least, in a society where workers who have lost their jobs in Difference B also move to Difference A, it is important to build a social system that accepts diverse values and various working styles so that individuals can participate in society with a lively attitude. We need to tackle this issue internationally from the perspective of **identifying the simple, repetitive tasks that humans cannot perform with enthusiasm, and determining what measures can be taken to automate these tasks at a low cost and with a quality equal to or higher than that of humans.**

Column: The Role of the Medium-Skilled Labor Market and Adapting Technological Changes

The medium-skilled labor plays an important role in society and the economy and will never be completely eliminated. This market serves as a foundation for the livelihoods of many people, including university graduates. However, these workers are constantly under pressure from the threat of job loss and lead lives dominated by routine work.

It is important to reassess the role of this labor market and investigate the extent to which AI and automation technologies can replace it. Specifically, it is necessary to clarify what can and cannot be replaced by AI, as well as the determining factors that vary based on social context. In Japan, the U.S., and the EU, research focusing on the medium-skilled labor market is advancing, and it is essential to utilize these insights to consider strategies for adapting to changes in the labor market. [154][155][156][157][158]

Regarding the two points discussed above, since the requirements of such a social system cannot be met by employment and technology developed from a simplistic capitalist perspective, it will be necessary to build a new social infrastructure that includes new HMI as a public function.

In other words, one of the issues is how to create a social system that can share knowledge and experience over an overwhelmingly wide dynamic range in time and space as shown in Figure 55, and greatly expand human capabilities, including creativity. On the other hand, when examining the real world, the methods and steps for achieving this should differ from region to region due to cultural differences and variations in economic conditions. Therefore, what should be discussed and collaborated on internationally is not only how to determine the desired outcome regarding this issue but also what the mechanism for achieving that outcome should be.

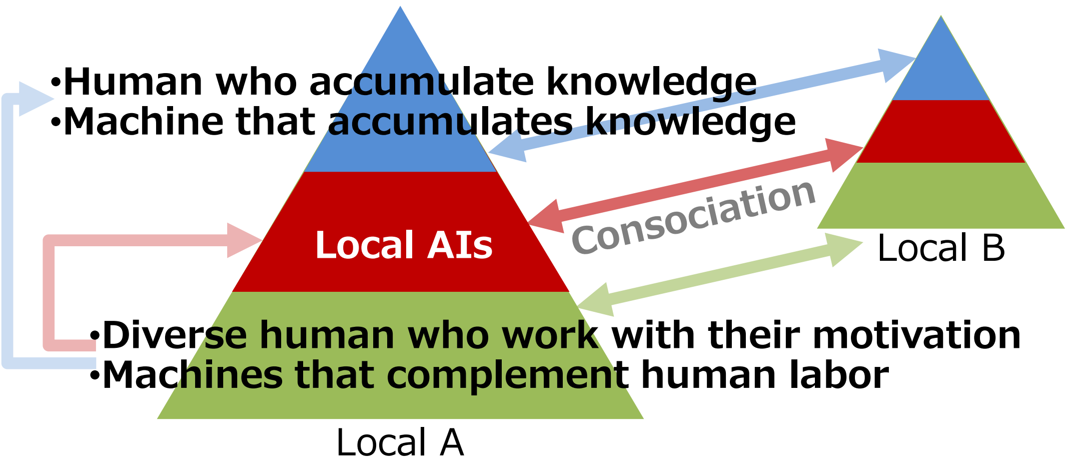


Figure 64 – Harmonized Symbiotic Society [147]

Instead of a social structure in which human labor is divided between machines and humans, as proposed in the discussion of Sophisticated Slavery shown in Figure 57, it should be important to build a system in which not only are there laws and standards appropriate for each region with its unique culture and economic situation, but machines in each region have the role of accumulating knowledge and experience and presenting them as appropriate, and both humans and machines accumulate their own knowledge and experience in their functions and use them effectively in accordance with the laws and cultural background of each region. In other words, we do not believe that a single data space or AI can achieve our goal because real society is diverse, with different cultures and economic situations, and because operational know-how is unique to each industry sector. We call this image Harmonized Symbiotic Society as shown in Figure 64.

In this image, Local A and Local B represent the formation of separate ecosystems for collaboration between individual humans and machines, where “local” refers to different countries, cultural spheres, and industrial sectors. In each locality, AI and the intelligent machines that utilize it contribute to human society, where diverse human efforts thrive alongside their motivation, and machines supplement the labor force that cannot be met by human workers. Furthermore, the experience and knowledge gained through the labor of these humans and machines are used in the AI developed in each locality.

And with other locals, such as Local B, which represents a different country or industrial sector, a loose consociation based on social rules, regulations, and standards should be formed. This would create a sustainable human society as a whole while maintaining the uniqueness and specificity of each local.

For implementation, application plans must be developed that consider the ELSI of each region and include existing assets and economic conditions. See Annex C for a discussion of this.

As described above, we hope to contribute to the realization of the Harmonized Symbiotic Society in which the environment, happiness, and economic growth are in harmony.

Column: Expanding the Application of DX Cases by Utilizing Knowledge Reuse Through Metamodeling

As we have discussed in this book, the challenges faced by each region are becoming increasingly diverse and complex. A successful DX case somewhere in the world is not just an outcome but a valuable asset that can provide benefits to other regions. In other words, how to reuse successful DX cases worldwide and how to address the technological and social acceptance of them are becoming urgent issues globally.

For this reason, in these DX cases, systems engineering is attracting attention as it analyzes the causal relationships between stakeholders and localizes interfaces and operations for each region, taking into account the ELSI of each area, even though the essential components of DX are common.

To scale DX cases to other regions, it is essential for systems engineering to extract and systematize the individual knowledge used in each case as a model. The key here is the use of "metamodels." A metamodel is a high-level model that defines the structure, rules, syntax, and semantics for creating specific models described in Systems Modeling Language (SysML), Unified Modeling Language (UML), Business Process Model and Notation (BPMN), etc. By using metamodels, models that express knowledge in a specific environment or domain can be converted into a format suitable for other environments or domains, and can be applied as reusable knowledge across different use cases, as shown in Figure 65.

In the future, it is expected that knowledge reuse mechanisms using metamodels will expand to a wider range of industries and business domains. For example, developing metamodels optimized for each industry, such as manufacturing, logistics, finance, services, and the public sector, will further promote the sharing and horizontal deployment of knowledge in each field.

Furthermore, by introducing a mechanism that uses digital technologies such as AI to automatically extract and model on-site know-how and insights into a knowledge reuse mechanism using metamodels, it will be possible to prevent knowledge from becoming personal and realize efficient accumulation and reuse.

On the other hand, there are still many issues to be resolved, such as adjusting the abstraction level of models that express knowledge, the difficulty of designing metamodels, establishing them in the field, and flexible response to individual requirements. To address these issues, it is important for each region to cooperate to create a common mechanism, such as developing guidelines and templates for metamodel design, introducing knowledge-sharing tools, and strengthening education and support systems for field personnel.

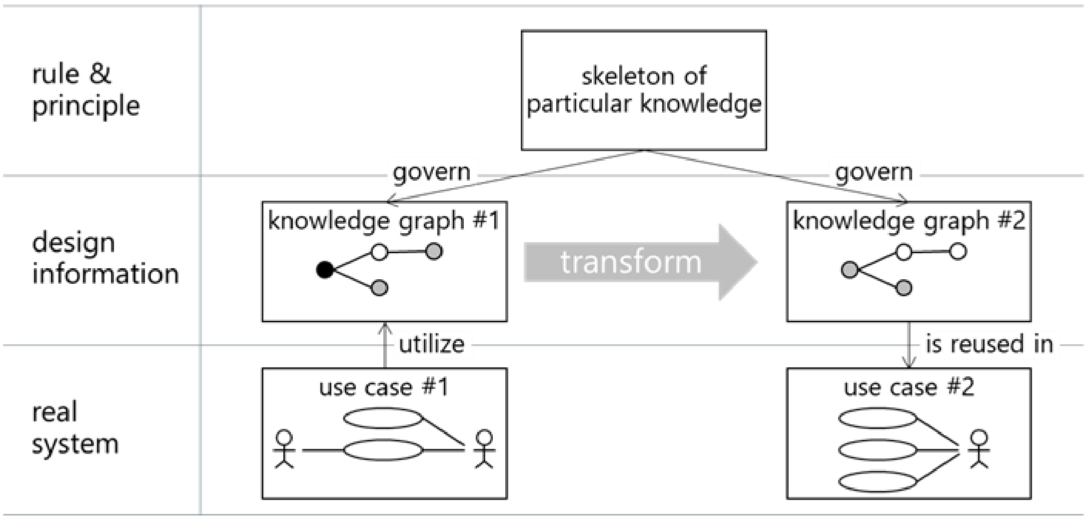


Figure 65 – Reusing accumulated design information through a meta-model[159]

7 Recommendation

In this document, we shared the current efforts of Japan, the U.S., and the EU toward industrial sustainability, addressing key challenges such as shifts in labor structures, evolving work styles, and the environmental impacts of industrial activity, including decarbonization and microplastic pollution.

Emerging from this discussion is the role of HMI as one of the important and unifying frameworks through which these complex issues can be addressed. Building on this perspective, we present three strategic recommendations aimed at business executives engaged in Smart Manufacturing, government policymakers, and researchers focused on the future of work and industrial sustainability. These recommendations are intended to guide the evolution of human-machine collaboration in support of sustainable and inclusive industrial development. Collectively, they outline a trilateral pathway for Japan, the U.S., and the EU to shape a more equitable and resilient future of work—grounded in innovation, worker equity, and environmental responsibility.

7.1 First Direction (Proposal 1)

Enhancing Human-Centered Work Through Digital Transformation

As digital technologies—including automation and AI—reshape global labor markets, there is a growing need to redefine the role of work in a sustainable, equitable, and human-centric industrial system. Rather than merely replacing labor, these technologies have the potential to augment human capabilities, expand access to meaningful employment, and increase individual motivation to participate in the workforce. In this direction, we propose a joint international effort to clarify the challenges and solutions for building an industrial society where people can work with enthusiasm in environments that are safe, inclusive, and purpose driven.

Digital technologies—including generative AI, automation, and smart systems—are rapidly reshaping labor markets, accelerating job polarization, and fundamentally transforming the nature of work. This project examined global megatrends, such as the digitalization of production, the globalization of value chains, demographic shifts, and the acceleration of automation. We categorized human labor into three domains: (1) simple labor requiring limited training, (2) skilled labor that can be developed through structured education and experience, and (3) highly creative and analytical labor. Our findings align with recent studies indicating that automation and AI are rapidly transforming or replacing many mid-skill roles while creating new demand for both high-skill cognitive roles and low-skill service roles, contributing to a polarization of the labor market.

Generative AI, in particular, is expected to automate up to 30% of current work activities by 2030, primarily affecting routine office, administrative, and customer service roles, while enhancing productivity in knowledge-intensive professions such as STEM, business, law, and healthcare. At the same time, investments in infrastructure, clean energy, and manufacturing modernization—especially in the U.S., Japan, and the EU—will generate demand for new occupations and skills. However, these emerging roles may not align with the existing geographic or demographic distribution of today's workforce.

To support sustainable and inclusive transitions, we recommend the following strategic actions:

- Implement human-centric design standards across manufacturing and service sectors, ensuring that HMI systems enhance worker autonomy, creativity, learning, and purpose—especially for mid- and low-skill roles.
- Boost motivation and job satisfaction even in low-skill occupations by leveraging digital platforms for dynamic task assignment, feedback, and human-AI collaboration.
- Tailor educational and upskilling programs using AI to align with individual aptitudes, life stages, and local labor demands—turning lifelong learning into a driver of long-term employment resilience.
- Reduce entry barriers for underserved populations by expanding skill-based hiring and promoting inclusive digital literacy programs.

Importantly, maximizing the benefits of automation and AI requires us to view labor not merely as a cost to be minimized but as a source of societal well-being, innovation, and economic resilience. As MIT economist David Autor notes, while machines substitute routine tasks, they also complement and elevate uniquely human capabilities such as judgment, adaptability, and creativity. Therefore, increasing human participation—even in roles once deemed low-value—can ultimately enhance long-term sustainability when designed with equity and dignity in mind.

This transformation must not be confined to national boundaries. Rather, it presents a critical opportunity for international collaboration among Japan, the U.S., and the EU. Together, we can build frameworks for responsible AI deployment, coordinated workforce policies, and cross-border knowledge exchange to ensure that work remains a central and fulfilling part of the human experience—even as its structure evolves.

7.2 Second Direction (Proposal 2)

Essential Labor That Machines Should Support

As automation and AI reshape the labor landscape, a crucial priority for sustainable industrial development is to define and support the category of socially essential labor—tasks that cannot be fulfilled by human workers alone, particularly in light of the polarization and displacement of middle-skilled occupations identified in Proposal 1. These roles include public and environmental services that contribute directly to industrial sustainability and societal resilience.

Many forms of socially essential labor remain undervalued despite being foundational to industrial resilience and societal well-being. These roles are often labor-intensive, low-wage, and difficult to fully automate due to their dependence on contextual judgment, empathy, and adaptability. However, they hold substantial potential to benefit from targeted HMI support, particularly when designed to augment human strengths rather than displace workers.

To achieve well-being within planetary boundaries, it is imperative to systematically assess the division of labor between humans and machines. This assessment must balance technical feasibility with the social desirability of automation, ensuring that it supports rather than undermines human dignity and community resilience. Machines should not merely replace labor but augment and complement it, particularly in domains where human labor is insufficient, undesirable, or inefficient. For example, repetitive or hazardous tasks, such as materials sorting in recycling, environmental cleanup, or data-intensive monitoring, can be effectively addressed through AI and robotics without undermining the human-centric foundation of employment.

At the heart of this proposal is the need to align technical innovation with human values and societal priorities.

Rather than deploying machines as job eliminators, future workforce development strategies must treat automation as a tool for expanding human capability, extending the reach of essential services, and enabling broader participation in addressing the complex challenges of our time—such as aging populations, environmental degradation, and burdens on health systems. By elevating essential labor through the thoughtful integration of HMI, these initiatives can transform socially critical roles into sustainable, high-impact career pathways, while simultaneously improving public outcomes and supporting regional economic revitalization.

In this context, there is substantial potential for cross-regional collaboration among experts in Japan, the U.S., and the EU to co-develop frameworks for identifying essential labor categories, optimizing machine-human task allocation, and embedding inclusive design principles into HMI technologies. Shared knowledge and best practices will be critical for navigating this transformation equitably and effectively across diverse industrial, cultural, and geopolitical landscapes.

7.3 Third Direction (Proposal 3)

ELSI for Human-Machine Collaborations

As the integration of AI, automation, and HMI deepens across global industrial systems, it is increasingly essential to address the ELSI that arise in different regions. In this proposal, we emphasize the need to identify, categorize, and align the ELSI concerns of Japan, the United States, and Europe—particularly as they relate to Proposals 1 and 2—so that inclusive and interoperable systems can be designed for sustainable and equitable industrial development.

The rapid deployment of advanced HMI systems—driven by generative AI, robotics, and automation—raises profound ELSI that vary across regions due to differences in cultural values, regulatory frameworks, and governance philosophies. As these technologies reshape both high-precision and low-complexity tasks, new ethical concerns emerge regarding job displacement, fairness in algorithmic decision-making, data privacy, and the long-term social cohesion of diverse labor markets.

According to research from Brookings and McKinsey, generative AI will significantly alter occupational skill requirements, reducing demand for routine cognitive labor while increasing reliance on advanced cognitive, technological, and social-emotional capabilities[160][161]. These transitions cannot be responsibly managed through traditional compliance models alone. Instead, they demand new ethical frameworks that are adaptive, inclusive, and regionally sensitive. For instance, Japan's Society 5.0 emphasizes harmonizing AI with human well-being and social inclusion[31], while the EU often adopts precautionary legal frameworks focused on trust, transparency, and accountability[162]. The U.S., by contrast, emphasizes innovation and market-driven adoption, albeit with increasing interest in responsible AI governance through initiatives such as the NIST AI Risk Management Framework[163].

To build a resilient architecture for human-machine collaboration, the future industrial system must fulfill three key criteria:

1. Human-Centric Design: Embed principles of dignity, autonomy, and diversity into system design. HMI technologies, including generative AI, should augment and not replace human potential, ensuring that all individuals, including those displaced by labor transitions, can find meaningful, aligned roles.

2. Distributed Governance Models: Given diverse regulatory landscapes, ELSI considerations must be modular, addressing common concerns (e.g. data protection, safety) while allowing flexibility to reflect regional attitudes toward automation and AI ethics. A “system of systems” approach should enable localized implementations that respect both global norms and national regulations.
3. Transparency, Accountability, and Data Sovereignty: HMI systems must include mechanisms for explainability, auditability, and human-in-the-loop oversight, particularly in high-stakes industrial applications. Ensuring traceability and intervention rights reinforces trust, worker agency, and regulatory confidence.

In addition to these foundational elements, economic equity must be integrated into ELSI governance. As generative AI enables dynamic scheduling and autonomous operations, it simultaneously transforms how economic value is generated and shared. There is a risk of reinforcing inequality if new value flows are not equitably distributed, particularly between those designing intelligent systems and those subject to their control.

Afterword

For developed countries such as Japan, the United States, and Europe, the period of economic growth opportunities due to demographic dividends is long gone. Over the past decade, industry, academia, and government have been working together to actively promote digitalization as a new driver of societal growth.

Living in a post-COVID-19 pandemic world, far from reaping the benefits of these digitalization efforts, we find ourselves in a "polycrisis" characterized by worsening environmental disasters such as typhoons, floods, and droughts, worsening environmental pollution from man-made objects such as microplastics, and the impact of geopolitical risks, including nationalism, on the real economy.

We must take a moment to review the digitalization efforts of the past decade, reflect on what needs to be learned to achieve sustainable industry and society, and realize a society in which the environment, social well-being, and economic growth are in harmony.

Cooperation among Japan, the United States, and Europe should provide a unique opportunity to collectively address the economic, ethical, legal, and social complexities brought about by the rise of advanced HMI systems. Through this partnership, we will be able to establish a joint ELSI task force to align fundamental principles such as transparency, accountability, algorithmic fairness, and data governance. Furthermore, by building an international knowledge-sharing platform, a federated AI system will enable each region to operate based on shared standards while maintaining regulatory autonomy, promoting collective learning, proactive risk mitigation, and the responsible global expansion of AI technology.

We hope that readers of this paper will actively participate in future discussions and activities.

Annex A: The RoX Project: Pioneering Data-Driven Robotics for Enhanced Efficiency and Sustainability

RoX (AI-based Robotics) is a transformative industrial automation project that combines advanced AI with robotics to create adaptive, intelligent manufacturing systems capable of enhanced perception, cognitive decision-making, and seamless human-robot collaboration. Ultimately, it aims to revolutionize production environments through flexible, efficient, and safe automation solutions.

The comprehensive use of robotic systems enables a significant strengthening of numerous industries, such as manufacturing companies and those with extensive logistical operations or service components (loading/unloading, order picking, etc.) As a result, the market for robotic systems will be characterized by significant growth potential in the future. In order to fully exploit the resulting opportunities and potential, robotic systems must be elevated to a new level of performance, for example, through the development of advanced robotic components, the widespread use of AI, and the possibilities offered by digital ecosystems to shorten innovation cycles and improve system integration and commissioning. In the RoX project, this is addressed by an application-oriented industrial consortium consisting of both industrial and scientific partners.

Due to the strong emphasis on AI-based technologies and the realization of central software aspects of robotic solutions in iterative development approaches (especially DevOps), the RoX project focuses on data-centric, data-driven and AI-driven approaches that are implemented with complex multi-vendor tool landscapes in cloud/edge environments[164]. The entire area of value creation in connection with robotic solutions is addressed via the direct connection of these solutions to application and development environments. In addition to established business models, this also enables new entry points for companies with innovative product ideas.

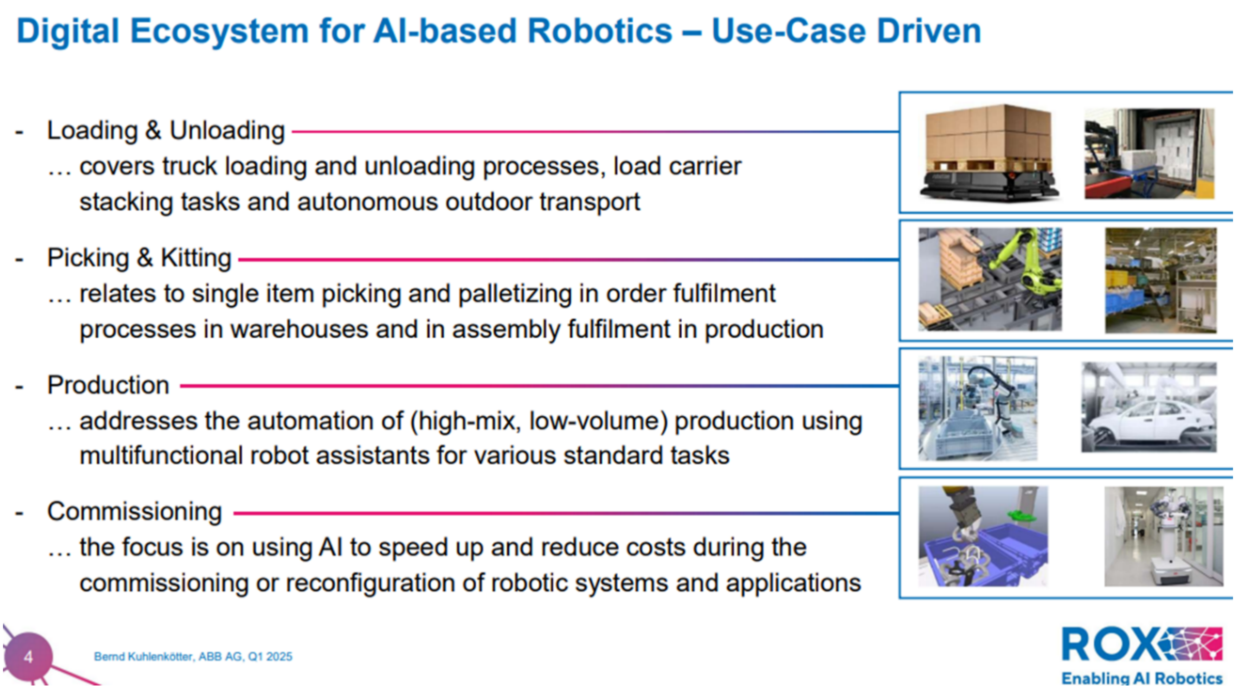


Figure 66 – Digital Ecosystem for AI-based Robotics – Use-Case Driven[164]

Annex B: The Impact of Collaborative Robots in the U.S.

Cobots have revolutionized sustainable manufacturing by working safely alongside human operators and enhancing efficiency, precision, and flexibility across various industrial processes. In material handling, cobots optimize workflows by automating tasks such as picking, placing, and transporting components, which reduces manual labor and minimizes errors. In terms of segment, up to 5 kg was the largest revenue generating payload capacity in 2024[136] via integrating the complementary strengths between humans and machines. The U.S. collaborative robot market generated a revenue of USD 284.0 million in 2024 and is expected to reach USD 1,401.5 million by 2030. The U.S. market is expected to grow at a CAGR of 29.5% from 2025 to 2030.

These advancements are reshaping manufacturing processes, particularly those related to sustainable goals, enabling more efficient resource utilization, process precision, operational efficiency, and enhanced decision-making. In assembly and disassembly, cobots ensure precision in component alignment, fastening, and product disassembly for repair or remanufacturing, while their aptitude for repetitive tasks enhances accuracy in applications like screwdriving and welding. Additionally, in pick-and-place operations, cobots accelerate production lines by seamlessly transferring parts between processes, thereby improving throughput and consistency. Beyond material handling and assembly, cobots play a crucial role in high-precision applications such as welding, grinding, polishing, and deburring, where they enhance consistency and reduce human exposure to hazardous conditions. In quality control and inspection, cobots equipped with advanced sensors and vision systems enable real-time defect detection and ensure product compliance.

Cobots are transforming a wide range of industries by enhancing automation, efficiency, and workplace safety. In automotive manufacturing, cobots assist with assembly, welding, painting, and quality inspections, ensuring precision and productivity. The electronics industry relies on cobots for delicate tasks such as circuit board assembly, micro-welding, and testing. In metals and machining, they are widely used for CNC machine tending, grinding, polishing, and die-casting, optimizing workflow and reducing manual labor. The plastics and polymers sector integrates cobots into injection molding, trimming, and quality control to ensure consistency and minimize waste. Beyond manufacturing, cobots play a vital role in the food and beverage industry for packaging, sorting, and quality inspection, as well as in furniture and equipment production for drilling, fastening, and assembly. In healthcare, cobots support pharmaceutical packaging, laboratory automation, and patient assistance, thereby improving operational efficiency. The logistics sector benefits from cobots in warehouse automation, material handling, and order fulfillment, streamlining supply chains. As cobots continue to advance with AI and machine learning, their adoption across industries will further drive innovation and operational excellence.

Annex C: Balancing Corporate Readiness and Dataspace Strategy

At the RRI Symposium held in Tokyo in the fiscal year 2024, we discussed the balance between companies' readiness and data space strategy[165][166]. We organized the discussion using a four-quadrant diagram, shown in Figure 67, composed of dimensions representing the characteristics of the data space and the situations of companies utilizing that data space.

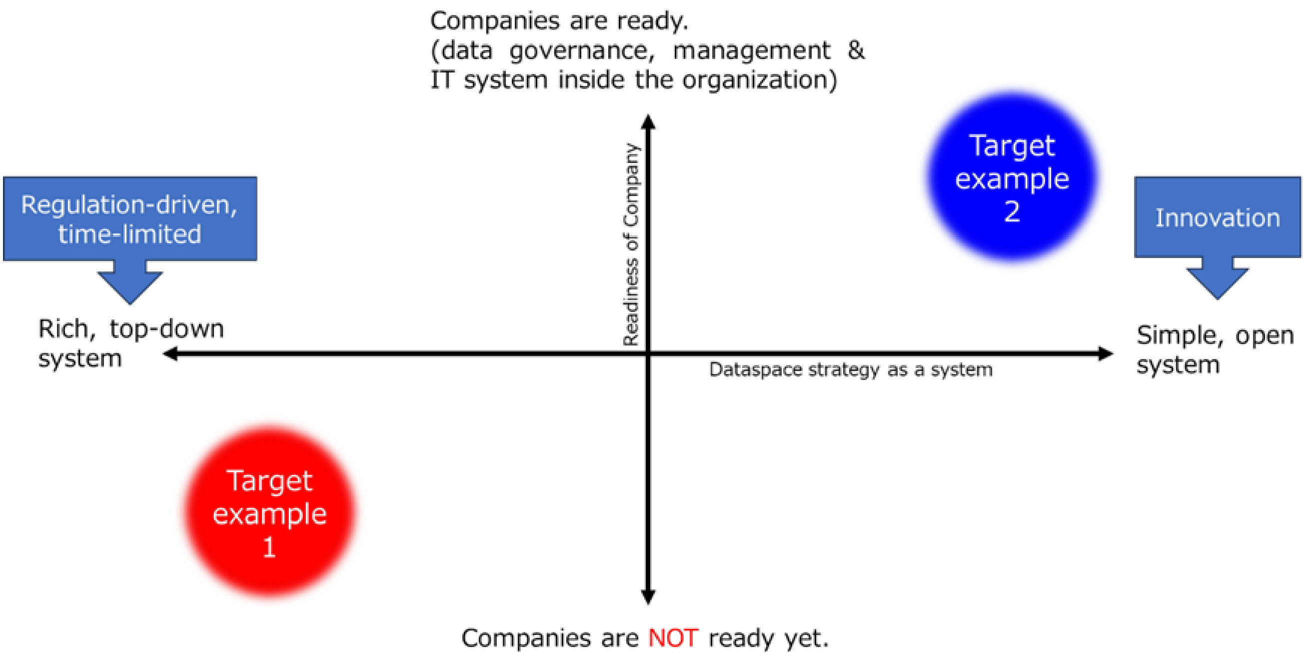


Figure 67 – The relationship between data space and companies' readiness levels[165][166]

In Figure 67, RRI considers two target approaches. Target 1 indicates a situation where companies are not ready but must utilize the data because regulatory requirements are imminent. In this case, the data space system needs to have more features to support these companies. Target 2 indicates a situation where companies are ready, and the data space is simple and open enough to invite many innovations from participants. This is an example of a data space, but since the situation of companies utilizing advanced technologies is expressed in readiness levels such as Technology Readiness Level (TRL) and Business Readiness Level (BRL), it seems possible to organize the concept of HMI using a similar analogy.

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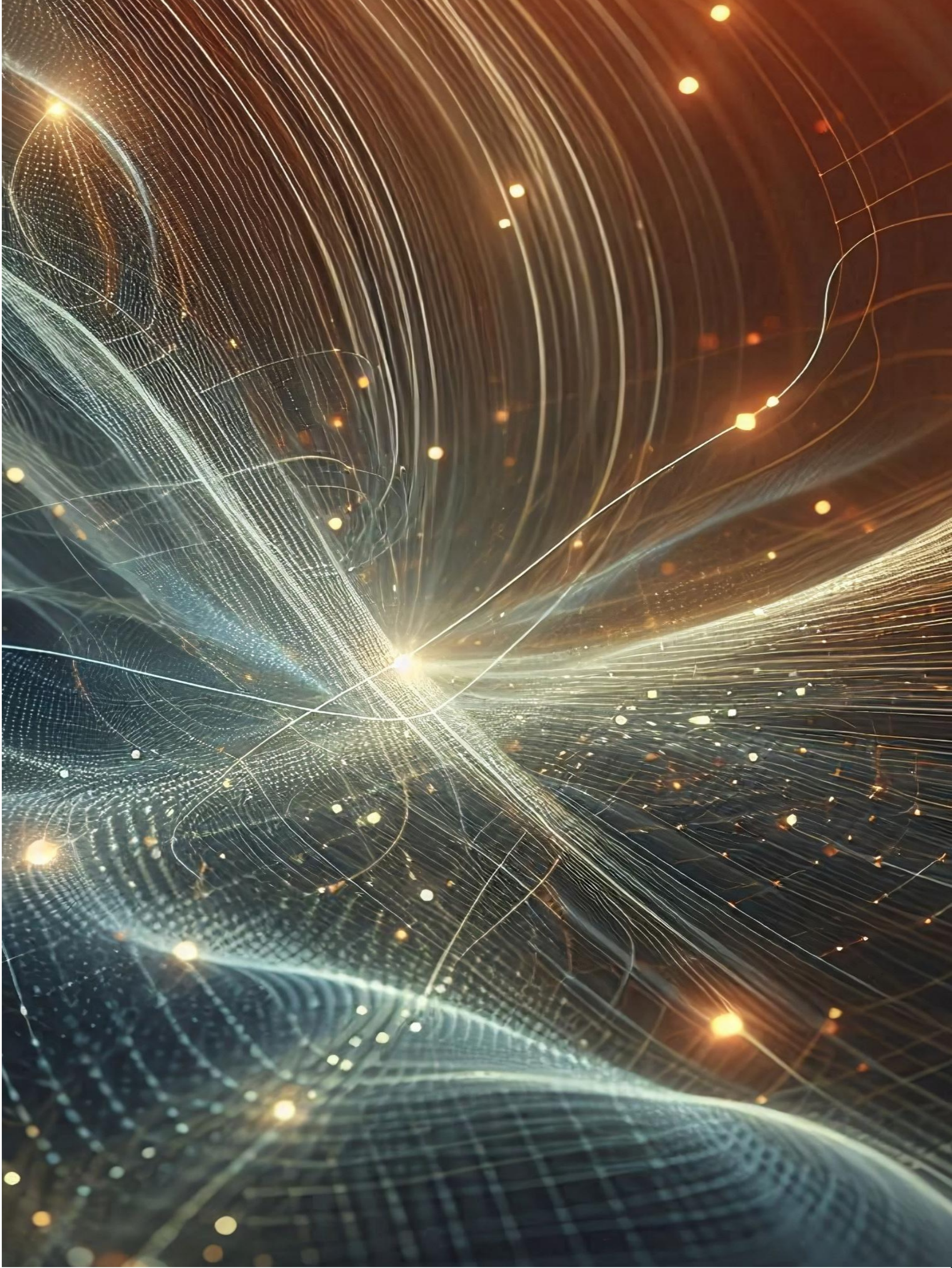

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