Biz Tech Focus 2025

Mitsui & Co. Global Strategic Studies Institute
Technology & Innovation Studies Div.

Introduction

The development of new technologies is driven by various factors, including the creation of economic value, responses to market demands, solutions to social challenges, compliance with policies and regulations, and the efficient use of available resources. The path to social implementation of new technologies also varies with development progresses at different speeds. That’s why we continuously monitor key technological fields for signs of significant change.

From among these emerging technologies, we have identified nine that are expected to reach major milestones within the next two years—whether through social implementation, transition to commercial-scale development, large-scale funding, or development of related policy—and have compiled an overview of each.

Our concept is to provide a technology report that highlights near-term innovations, and is concise and easy to read.

We hope that Biz Tech Focus 2025 will contribute to your strategic planning.

Tetsuo Ogawa
Technology & Innovation Studies Div.

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Long Duration Energy Storage Technologies

─ Compressed Air Energy Storage and Thermal Energy Storage Show Potential for Widespread Adoption—

Yuji Inada
Industry Innovation Dept.
Ryusuke Ishiguro (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

The adoption of renewable energy is expanding as the push toward net-zero emissions accelerates. However, due to the inherent variability of renewable energy, sufficient storage capacity that can align with demand is essential for it to become a primary power source. Long Duration Energy Storage (LDES) enables extended storage of power and helps stabilize intermittent power supply when integrated with renewable energy. Technologies such as compressed air energy and thermal energy storage are being developed within the LDES field, offering low-cost solutions with substantial storage capacity.

Summary

- LDES technologies are essential for renewable energy to become a primary power source. In addition to conventional storage technologies such as batteries and pumped storage, advancements are being made in compressed air energy storage, thermal energy storage, flow batteries, and gravity-based storage.
- Among these LDES technologies, compressed air energy storage and thermal energy storage stand out for their cost-effectiveness and high safety. These technologies are transitioning from demonstration to commercialization, with widespread adoption expected within the next two to three years.

1. What is Long Duration Energy Storage (LDES)?

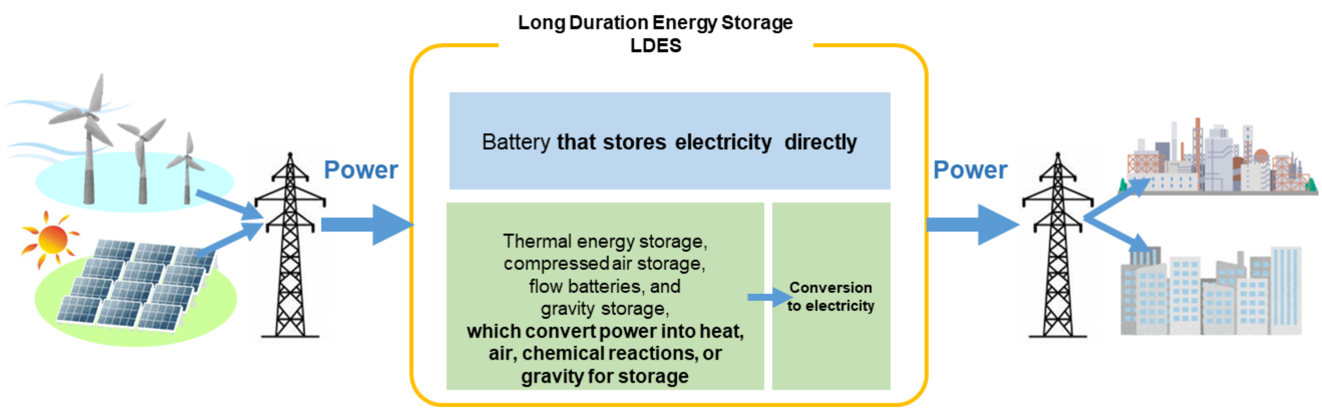
Renewable energy sources such as solar and wind can only generate electricity when conditions allow, making it difficult to adjust power output flexibly in response to demand, as is the case with thermal power generation. While renewables are a key solution for reducing CO_2 emissions, their lack of adjustability is a major drawback. As the share of renewable energy continues to grow, a significant surplus of electricity beyond actual demand is expected to occur. Therefore, there is an urgent need to establish storage systems that can temporarily store excess power and supply it as required.

1-1. Overview of LDES Technology

Figure 1 gives an overview of LDES technology and the technical challenges involved. LDES is defined as a technology capable of storing electricity for six hours or more. It allows electricity to be stored via the power grid for a certain period and then discharged in appropriate amounts according to demand, helping to balance supply and demand. Currently, the most widely used LDES technology is (1) batteries, which directly store electricity. However, there are also methods that convert electricity into other forms of energy for storage. Various types of LDES exist, including the following being typical examples. (2) Thermal energy storage: Converts electricity into heat for storage and reconverts it into electricity when needed. (3) Compressed air energy storage: Uses electricity to compress air, storing energy in the form of compressed air. (4) Flow batteries: Store and discharge electricity through chemical reactions. (5) Gravity energy storage: Lifts a heavy object to a high position, storing energy as gravitational potential energy[1].

Batteries store electricity directly with an efficiency exceeding 90%. In contrast, LDES technologies such as thermal energy storage and compressed air energy storage involve converting electricity into heat or compressed air and then back again into electricity, resulting in lower energy efficiency of approximately 50–70%, which is lower than batteries. However, for large-scale energy storage needs, these technologies offer the potential for cost-effective long-term storage, driving development toward social implementation. Additionally, patent applications related to LDES have been steadily increasing over the past decade, and there is particular attention on advancements in technologies that use air and heat as storage media.

Figure 1: Overview of long duration energy storage technologies

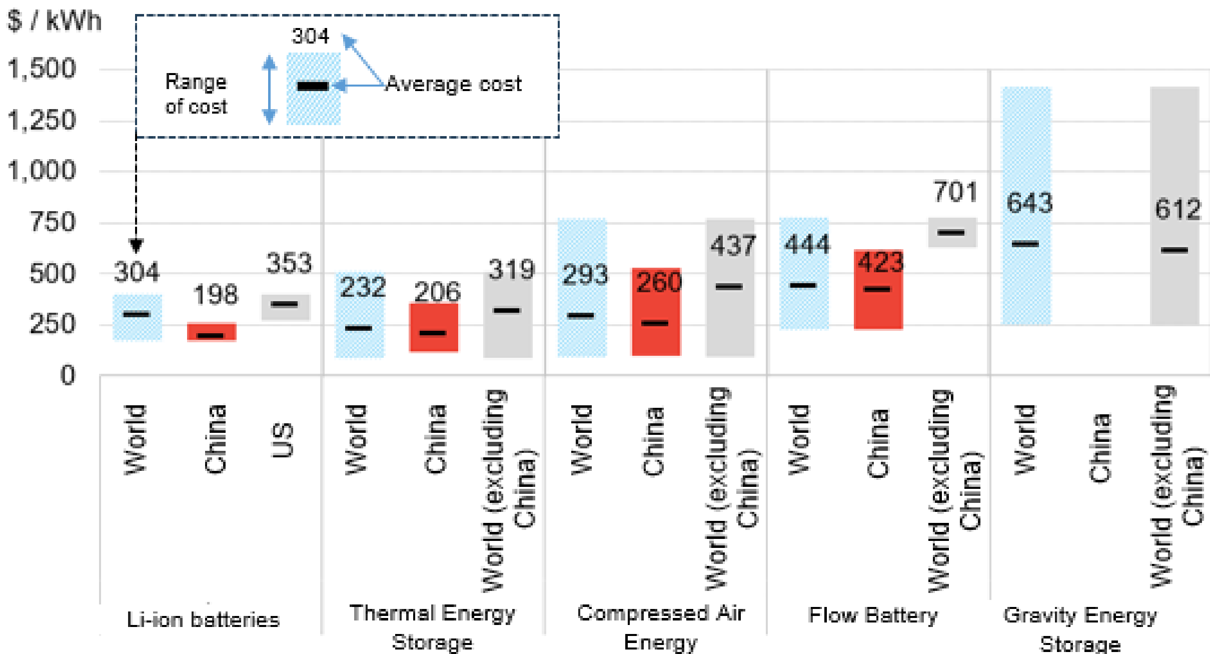


Energy storage technology	Technology overview	Technical issues, etc.
Batteries	■ Storage as chemical energy ■ Lithium-ion, flow, and many other varieties ■ Effective for relatively short-term fluctuations ■ Storage time: Minutes to hours	□ Lower cost and longer service life □ Economies of scale are not in place for long period / large capacity batteries.
Thermal Energy Storage (TES)	■ Storage of heat in materials. Sensible, latent, and chemical heat storage ■ Low cost of $15/kWh for thermal storage section ■ Electrothermal conversion, thermal storage, and thermoelectric conversion can be designed independently. ■ Storage time: Hours to days	□ Output variable speed is slow □ Large heat loss during power generation
Compressed Air Energy Storage (CAES)	■ Storage in underground spaces or tanks as compressed air ■ Some systems generate electricity by compressing and expanding air, while others use heat storage during compression and expansion. ■ Storage time: Hours to days	□ Commercialized plant utilizes underground cavities. □ Suitable locations are limited.
Flow Battery	■ System for storing electric power using liquid electrolyte ■ Liquid containing two dissolved chemicals is stored in tanks and circulated by pumps to facilitate charging and discharging. ■ Storage time: Hours to days	□ High initial cost □ Concerns about supply risk if vanadium is used □ Leakage prevention measures are necessary because the electrolyte is a liquid.
Gravity Energy Storage	■ An object is lifted to a higher position and its potential energy is used to store power. ■ A heavy object such as a concrete block is lifted to a high position by a crane, etc., and the kinetic energy generated when it is lowered is converted into electric power. ■ Storage time: Hours to days	□ Requires a certain amount of land and stable ground due to the need to lift a heavy object to a high elevation □ Installation can be difficult in areas with complex terrain.

Source: Compiled by MGSSI based on various data

[1] Pumped storage and hydrogen conversion, where electricity is stored by converting it into hydrogen, are also considered LDES technologies. However, these technologies are excluded from the scope of this report because pumped storage is an existing technology, and hydrogen conversion is unlikely to be commercially implemented within the next three to five years.

Figure 2: Cost of LDES



Source: Compiled by MGSSI based on BloombergNEF data

1-2. Cost of LDES

Figure 2 shows the costs of various LDES technologies as of 2023. Among them, gravity storage has the highest global average cost at USD 643 per kWh of storage[2].

The next highest is flow batteries at USD 444/kWh, followed by lithium-ion (Li-ion) batteries at USD 304/kWh and compressed air energy storage at USD 293/kWh. The lowest-cost technology is thermal energy storage at USD 232/kWh.

The costs of China-manufactured LDES technologies are below the global average, with lithium-ion batteries being the most affordable worldwide. As a result, even low-cost LDES technologies such as thermal energy storage and compressed air energy storage are unlikely to replace lithium-ion batteries in China.

2. Notable Trends

Currently, based on global average cost comparisons, the only LDES technologies that are cheaper or comparable to Li-ion batteries are thermal energy storage and compressed air energy storage. Thermal energy storage converts electricity into heat, storing it in materials such as rocks or molten salts. When electricity is needed, the stored heat is used to generate steam, which drives a turbine to produce power[3]. This section discusses compressed air energy storage as a notable trend. With this method, electricity powers compressors that compress air or CO_2, after which it is stored as a gas or liquid in underground spaces or tanks. When electricity demand

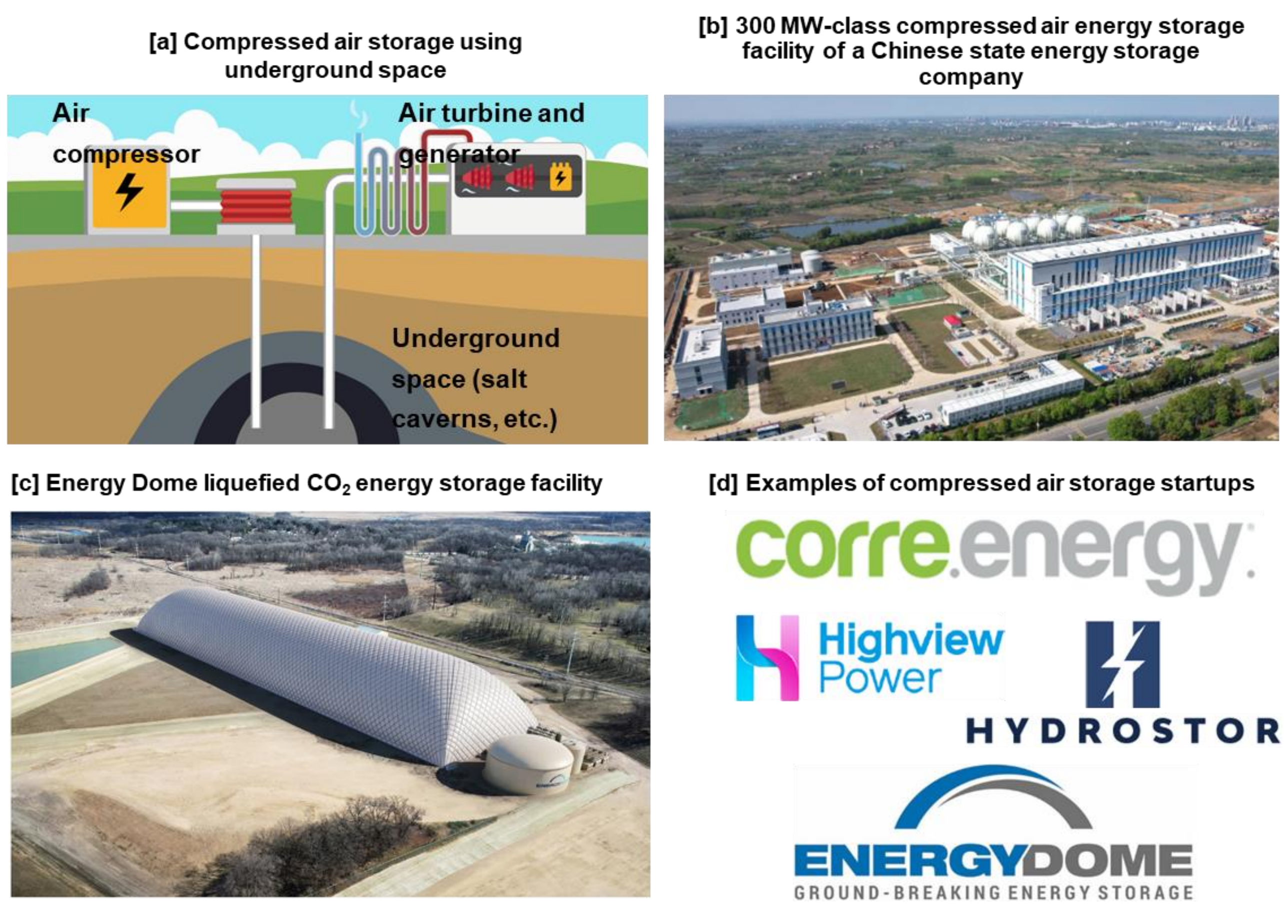
[2] Gravity storage does not include dam-based or pumped storage.
[3] For more details on thermal energy storage, see "Thermal Energy Storage Developing for a Decarbonized Society" (Mitsui & Co. Global Strategic Studies Institute, February 2021).

rises, the stored compressed energy is released and converted back into power using air turbines or other generators (Figure 3 [a]). This method is highly safe because air or CO_2 is used as the working fluid. Additionally, the technology of power generation through gas compression is well-established and simple. Wider adoption can be expected if suitable underground spaces can be secured and other necessary conditions for cost reduction could be met.

A Chinese national energy storage company began operating a 300 MW-class compressed air energy storage facility in April 2024 (Figure 3 [b]). This facility stores compressed air in a salt cavern extending approximately 1,000 meters underground. These caverns are formed after rock salt extraction and are highly sealed and stable, making them suitable for storing high-pressure air. Utilizing such natural formations reduces costs compared to installing above-ground storage tanks.

Energy Dome (Italy) has been operating a 2.5 MW-class liquefied CO_2 energy storage facility since 2022 (Figure 3 [c]). This technology stores gaseous CO_2 in a storage tank (dome) and uses electricity to pressurize and cool it, converting it into a liquid for storage. When electricity is needed, the liquefied CO_2 is boiled back to a gas, driving a turbine to generate power. Liquefying the CO_2 has the advantage of storing energy at a higher density than gas and reducing the volume of storage tanks. Energy Dome has also announced the construction of a 20 MW liquefied CO_2 energy storage facility in Wisconsin, US. Once completed, it is expected to be able to supply 10 hours of electricity to approximately 18,000 households. In addition to the above two companies, several startups are advancing the development of energy storage technologies that use gases or liquids such as air and water as storage media. These include Corre Energy (Netherlands), Highview Power (UK), and Hydrostor (Canada) (Figure 3 [d]).

Figure 3: Compressed air storage mechanisms and examples



3. Future Prospects

LDES technology is progressing from the initial development stage to demonstration and on toward commercial-scale implementation. This report has shown that compressed air energy storage in particular has demonstrated technical and cost advantages and is entering the practical application stage.

Recognizing the importance of LDES, the US Department of Energy announced in 2023 that it would provide up to USD 286 million in funding for LDES technology development[4]. Of this, six companies received USD 39 million to advance demonstration-scale technology development, including Energy Dome for the Columbia Energy Storage Project. With increasing government funding and growing investor interest, LDES development is accelerating, and full-scale social implementation is expected within the next two to three years.

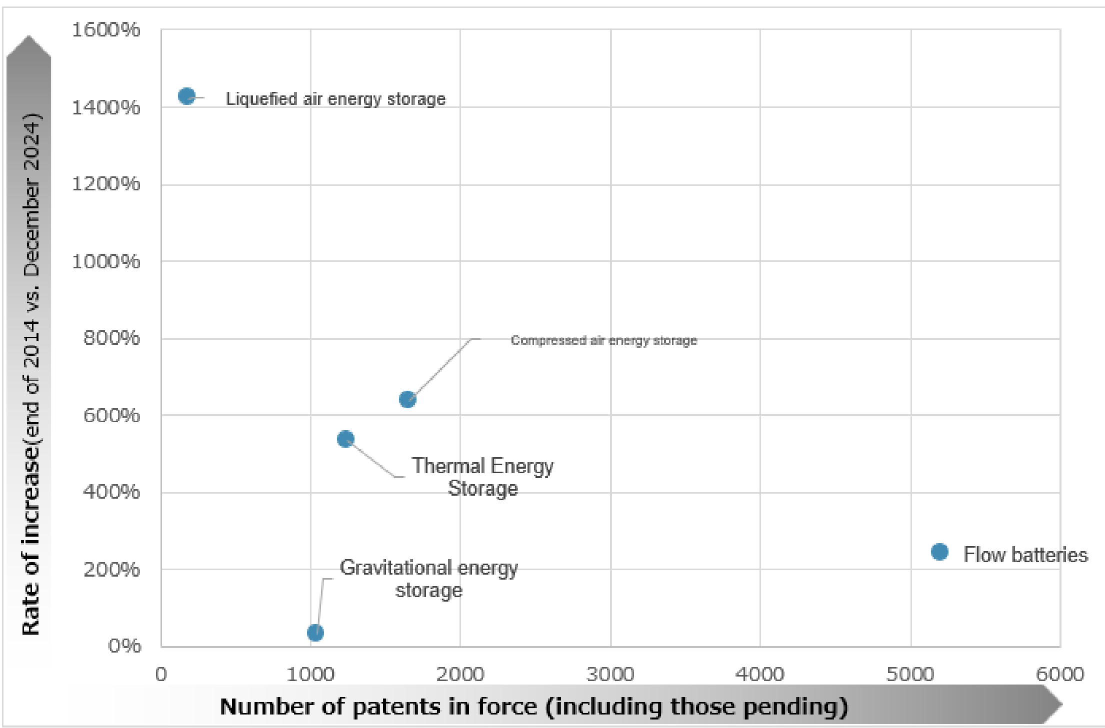
[4] US Department of Energy "Long-Duration Energy Storage Demonstrations Projects Selected and Awarded Projects"

IP Analysis of Long Duration Energy Storage (LDES) Technologies

Long Duration Energy Storage (LDES) technologies are categorized into five distinct types: flow batteries, compressed air energy storage, liquefied air energy storage, thermal energy storage, and gravity energy storage. Patents relevant to each type were identified (9,142 patents in force[5] including pending applications as of December 2024), and an analysis was conducted based on technology type and top players.

Figure 4 compares the number of patents in force for each LDES technology and their growth rates. The horizontal axis represents the number of patents in force, while the vertical axis shows the growth rate by comparing the number of patents in force as of December 2024 with those at the end of 2014. Among LDES technologies, flow batteries have the highest number of patents. Although the patent count for liquefied air energy storage, compressed air energy storage, and thermal energy storage is lower in comparison, these technologies have experienced significant patent growth in recent years.

Figure 4: Number of patents in force and growth rate (by technology category)



Source: Compiled by MGSSI based on data from LexisNexis PatentSight

[5] The total number of patents includes both filed patents and granted patents that have completed the examination process and are enforceable as intellectual property rights.

Figure 5 compares the top players in terms of the number of patents for each LDES-related technology, revealing the significant presence of Chinese research institutions across all fields. In the field of flow batteries, the Chinese Academy of Sciences (CAS) (China) holds the highest number of patents. Its affiliated Dalian Institute of Chemical Physics (DICP) (China), which ranks second in patent filings, announced in January 2024 the development of a vanadium flow battery stack with more than double the conventional power density.

Figure 5: Number of patents in force (top players by technology)

Flow batteries

#	Company / research institute	Number of patents
1	(China) Chinese Academy of Sciences	432
2	(China) Dalian Institute of Chemical Physics	290
3	(Japan) Sumitomo Electric	160
4	(China) DALIAN RONGKE POWER TECHNOLOGY DEVELOPMENT CO., LTD	128
5	(South Korea) LG Chem	90
6	(South Korea) Korea Institute of Energy Research	74
7	(South Korea) Lotte Chemical	72
8	(US) ESS Technology	63
9	(US) TRC COMPANIES INC	52
10	(China) Ansteel Group	50

Compressed air energy storage

#	Company / research institute	Number of patents
1	(China) Chinese Academy of Sciences	155
2	(China) China Huaneng Group	145
3	(China) State Grid Corp	130
4	(China) Tsinghua University	103
5	(China) Xi'an Jiaotong University	87
6	(China) PowerChina	86
7	(China) China Southern Power	66
8	(China) China Three Gorges	50
9	(China) State Power Investment	42
10	(China) North China Electric Power University	41

Liquefied air energy storage

#	Company / research institute	Number of patents
1	(China) Chinese Academy of Sciences	33
2	(China) Technical Institute of Physics & Chemistry	29
3	(China) State Grid Corp	12
4	(China) ZHONGLV ZHONGKE ENERGY STORAGE TECH	9
5	(China) China Huaneng Group	7
6	(China) Shijiazhuang Tiedao University	6
7	(China) ARREON ENTHALPY ENERGY TECH	5
8	(China) HEBEI HCIG GUORONG ENERGY SERVICE	5
9	(China) HEBEI JIANTOU ENERGY STORAGE TECH	5
10	(China) State Power Investment	5

Thermal Energy Storage

#	Company / research institute	Number of patents
1	(China) China Huaneng Group	98
2	(China) Xi'an Jiaotong University	66
3	(China) Chinese Academy of Sciences	59
4	(China) State Grid Corp	38
5	(China) Zhejiang University	30
6	(China) Huaneng Power International	24
7	(China) China Energy Investment	23
8	(China) Haier	23
9	(China) Tsinghua University	20
10	(China) North China Electric Power University	19

Gravitational energy storage

#	Company / research institute	Number of patents
1	(China) State Grid Corp	22
2	(China) Chinese Academy of Sciences	21
3	(China) China Huaneng Group	12
4	(China) Xi'an Jiaotong University	12
5	(China) State Power Investment	10
6	(China) China Southern Power	8
7	(Individual) YANG YIYONG	8
8	(France) CEA	7
9	(China) North China Electric Power University	7
10	(Individual) CHEN MING	6

Source: Compiled by MGSSI based on data from LexisNexis PatentSight

Small Modular Reactors
—Technological Trends in Molten Salt Reactors and High-Temperature Gas Reactors—

Takatoshi Asada
Industry Innovation Dept.
Yui Matsuura (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

Small Modular Reactors (SMRs) are attracting attention due to their compact size and various advantages compared to conventional large-scale nuclear reactors. Non-utility companies, such as Amazon (US), are considering adopting SMRs, and in 2024, Google (US) signed a contract to purchase electricity from an SMR operated by Kairos Power (US), raising expectations for commercial use. Such developments are accelerating SMR technology advancement and market adoption, potentially positioning it as a key clean energy option in the future. While SMR projects continue to advance worldwide, this report focuses on the United States, where many innovative projects are underway, detailing notable trends and future prospects.

Summary

- Kairos Power's Hermes demonstration reactor, a molten salt reactor, is scheduled to begin operation in 2027. In the field of high-temperature gas reactors, X-energy (US) plans to start construction of its Xe-100 reactor in 2026.
- As the number of SMRs increases globally, a wide variety of reactor designs are under development. However, only a limited number of reactor types can leverage economies of scale through the construction of multiple units, and many designs are likely to be phased out based on economic viability.

1. What is a Small Modular Reactor (SMR)?

A Small Modular Reactor (SMR) refers to a nuclear reactor with an output of 350 MW or less, compared to conventional reactors of 1,000 MW or more[6]. Nuclear energy has garnered attention as a means of decarbonization, and a “Declaration to Triple Nuclear Energy[7]” was announced at COP28. SMR development is accelerating alongside traditional large reactors in many countries due to its enhanced safety, greater site flexibility, and cost reductions through modular construction. The Draghi Report[8], published in Europe in September 2024, stated the need to establish a supply chain for nuclear reactors, including SMRs, in the mid-term[9]. As shown in Figure 1, a variety of SMRs are under development, broadly classified based on coolant type. (1) Light water reactors use pressurized or boiling water, similar to existing commercial reactors[10]. (2) Liquid metal-cooled reactors

[6] In the United Kingdom, liquid metal-cooled reactors, molten salt reactors, and high-temperature gas reactors are classified as advanced modular reactors regardless of their size. In some cases, reactors with an output of 300 MW or less are defined as SMRs.
[7] At the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) in 2023, a declaration was made to triple global nuclear power generation capacity from 2020 levels by 2050. According to estimates by the Japan Atomic Industrial Forum, Inc., achieving this goal would result in a total nuclear power capacity of over 1,200 GW. As of November 2024, 31 countries have signed the declaration.
[8] The official title of the report is “The Future of European Competitiveness,” and it was authored by Mario Draghi.
[9] In “The Future of European Competitiveness Part B, In-depth Analysis and Recommendations,” defines “new nuclear” as including advanced modular reactors and SMRs.
[10] Water that contains deuterium is referred to as heavy water.

utilize sodium or other liquid metals as coolant. (3) Molten salt reactors use chloride-based molten salts. (4) High-temperature gas reactors use gas as the cooling medium.

However, miniaturization reduces scalability, leading to higher power generation costs compared to conventional nuclear reactors[11,12]. This report focuses on (3) Molten salt reactors and (4) High-temperature gas reactors, which offer higher power generation efficiency through high-temperature operation in order to address the issue of power generation costs. Additionally, these reactors can directly supply high-temperature heat, making them suitable for applications where decarbonization is difficult, such as chemical manufacturing. Section 2-1 examines the trends in molten salt reactors and high-temperature gas reactors being advanced by two leading US-based companies. Section 2-2 covers trends in SMR fuel production, while Section 2-3 provides an overview of SMR heat utilization technologies.

Figure 1: Typical SMR specifications and operation start date

Reactor type	Model name	Manufacturer	Core coolant	Single unit output [MWe]	Core outlet temperature [°C]	Heat supply temperature [°C]	Operation start date
Pressurized water reactors	VOYGR	(US) NuScale Power	Light water	77	321	300	2029
Boiling water reactors	BWRX-300	(US) GE Hitachi Nuclear Energy (Japan) Hitachi-GE Nuclear Energy	Light water	300	288	-	2029
Liquid-metal cooled reactors	Natrium	(US) TerraPower	Sodium	345	500	-	2030
Molten salt reactors	KP-FHR	(US) Kairos Power	Molten salt	75	650	-	2030 or later
High-temperature gas reactors	Xe-100	(US) X-energy	Helium	80	750	565	2030

MWe: Electrical output

Source: Compiled by MGSSI based on various data

2. Notable Trends

2-1. Trends in Molten Salt Reactors and High-Temperature Gas Reactors

A leader in the field of molten salt reactors is the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)[13]. With support from the US Department of Energy (DOE), construction of the Hermes demonstration reactor began in Tennessee, US, in July 2024, with operations planned to commence in 2027[14]. Molten salt reactors face technical challenges, particularly concerning corrosion of structural materials. To address this issue, past reactors have used corrosion-resistant Hastelloy-based alloys[15]. However, Hermes has adopted 316H stainless steel[16], a lower-cost alternative, and has received construction approval from the US Nuclear Regulatory Commission (NRC).

A representative example of a high-temperature gas reactor is the Xe-100, a helium gas-cooled reactor

[11] NuScale Power (US) had planned to construct the VOYGR SMR in Idaho, US, but the project was abandoned due to rising construction costs and higher-than-expected power generation costs.
[12] In general, the cost of SMR power generation is estimated to be approximately twice that of conventional light water reactors.
[13] The KP-FHR uses a molten salt mixture of lithium fluoride and beryllium fluoride as a coolant. Construction of a high-purity molten salt production facility began in 2024, ensuring a stable supply of materials.
[14] Hermes is not designed for power generation but will instead verify 35 MW thermal energy output.
[15] Hastelloy-N was used as the structural material in the molten-salt reactor experiment at Oak Ridge National Laboratory, US.
[16] 316H stainless steel, which has been used in existing nuclear reactors, is recognized as a high-temperature material under ASME Section III Division 5.

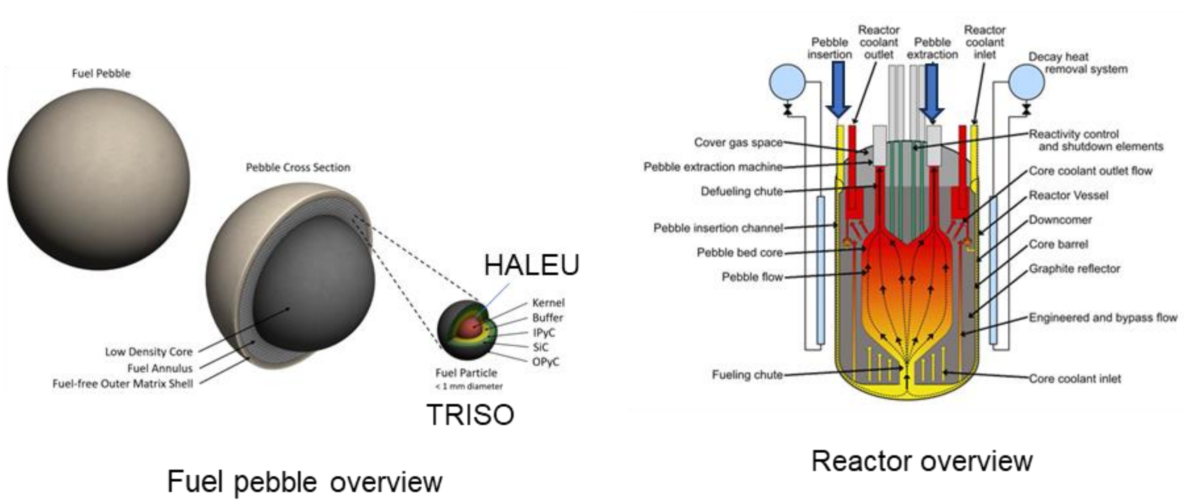
developed by X-energy. The company has signed a contract with the chemical manufacturer Dow (US)[17] to begin construction of a commercial reactor in Texas in 2026, with plans to supply low-carbon electricity and steam starting in 2030. Many high-temperature gas reactors are designed to operate at temperatures exceeding 950°C, which has led to higher structural material costs. There is also a risk of damage to the fuel particle coatings[18]. To address these challenges, the Xe-100 lowers the operating temperature to 750°C, enabling the use of a wider range of materials.

2-2. Trends in SMR Fuel Production

The SMRs mentioned above operate at high temperatures, requiring heat-resistant fuel to enhance safety. However, these advanced fuels necessitate the construction of new manufacturing facilities, making production infrastructure an important consideration. The SMRs developed by the two companies discussed above utilize spherical fuel pebble embedded with many fuel particles (TRISO[19]), each approximately 1 mm in diameter, made from triple-layered High-Assay Low-Enriched Uranium (HALEU[20]). This system is designed to enable continuous refueling during reactor operation (Figure 2).

HALEU is a fuel under consideration for use in various SMRs, and with the increasing demand for SMRs, potential supply shortages have become a concern[21]. Most recently, Centrus Energy (US) began manufacturing HALEU in October 2023. BWX Technologies (US) has started manufacturing of TRISO in Virginia, while X-energy plans to begin manufacturing in Tennessee in 2025. With these companies expanding their manufacturing capabilities, a stable fuel supply is expected to be secured by the time commercial reactors begin operations.

Figure 2: Conceptual fuel diagram and fuel supply system diagram



Source: Compiled by MGSSI based on US NRC data

[17] Dow plans to introduce an SMR at its UCC Seadrift Operations site, replacing the existing steam system while also supplying electric power.

[18] The AVR reactor (Germany) faced challenges regarding the high-temperature durability of its Bi-structural Isotropic (BISO) particle fuel.

[19] The uranium fuel is first coated with inner pyrolytic carbon, followed by a silicon carbide layer, and then outer pyrolytic carbon. This multi-layered coating structure does not melt even at temperatures up to 1600°C and prevents the release of fission products, making it very safe and enabling the further enhancement of SMR safety.

[20] HALEU refers to uranium-235 enriched between 5% and 20%.

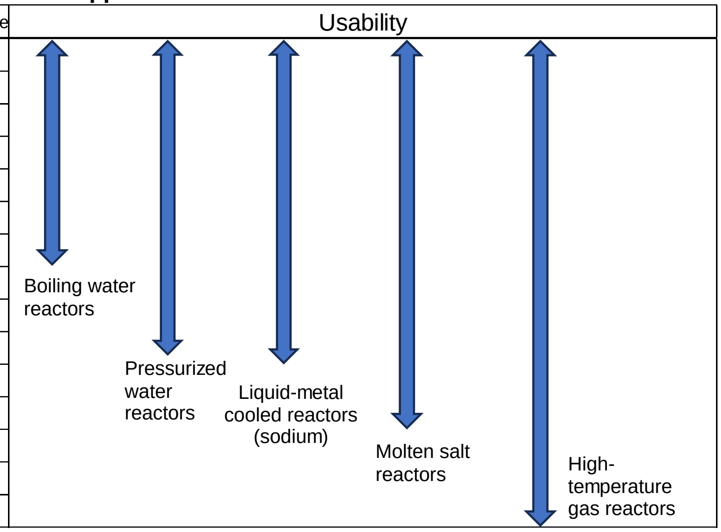
[21] In 2022, companies under Rosatom (Russia) accounted for 100% of the global market supply of HALEU. To reduce dependence on Russia, the US is supporting efforts to establish a domestic HALEU supply chain through the Inflation Reduction Act (IRA).

2-3. SMR Heat Utilization Technologies

The SMRs discussed above are capable of high-temperature heat supply, making them suitable for providing thermal energy to industrial sectors that are difficult to decarbonize, such as chemical plants. Intellectual property analysis has identified patent applications related to heat supply to methanol production systems, etc. Figure 3 summarizes the process temperatures of various industrial sectors and the corresponding SMR types that can be applied[22]. Additionally, the X-energy SMR is being considered for seawater desalination using high-temperature steam.

Figure 3: Process temperatures in industrial sectors and applicable SMRs

Industry	Process temperature
Seawater desalination	70~130℃
District heating	80~150℃
Aluminum production (alumina hydration)	100~300℃
Pulp and paper manufacturing	100~400℃
Chemical processing	250~600℃
Oil sand (SAGD process)	Approx. 300°C
Soda ash production (Solvay process)	300~400℃
Oil refining	350~550℃
Ammonia production (ammonia synthesis)	400~500℃
Oil shale processing	Approx. 500°C
Petroleum refining (catalytic cracking)	600~800℃
Ammonia production (natural gas reforming)	600~800℃
Hydrogen production (natural gas reforming)	Approx. 750°C
Chemical processing (naphtha cracking)	800~900℃
Aluminum production (alumina sintering)	800~1000℃



Source: Compiled by MGSSI based on data provided by Japan Atomic Industrial Forum, Inc.

3. Future Prospects

SMRs are gaining attention as a new development in nuclear energy, but the market competition is expected to be very intense. According to DOE, achieving cost reductions through economies of scale and learning effects requires the construction of at least 5 to 10 reactor units of the same design[23]. According to the IAEA[24] forecast for nuclear power deployment, in the "expected growth case," global nuclear power capacity will increase by 578 GW by 2050, with SMRs accounting for 24% of the total[25]. Based on this projection, assuming an average capacity of 350 MW per unit, approximately 390 SMRs are expected to be deployed worldwide.

Eighty different designs of SMR are under development[26] in 18 countries worldwide. However, some SMRs currently in development are likely to lose market competitiveness and be phased out due to several challenges[27]. These include unsustainable development costs due to longer-than-expected approval processes by the US Nuclear Regulatory Commission (NRC), rising construction costs exceeding initial estimates during detailed design

[22] Some liquid metal-cooled reactors are designed for higher operating temperatures, but the temperatures indicated are for typical liquid metal-cooled reactors.
[23] Based on the US Department of Energy report, "Pathways to Commercial Liftoff: Advanced Nuclear."
[24] International Atomic Energy Agency.
[25] According to the IAEA "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," global nuclear power capacity at the end of 2023 was 372 GW. By 2050, the high-case scenario estimates an increase to 950 GW, while the low-case scenario projects 514 GW. The share of SMRs is estimated to range from 6% to 24%.
[26] From "The Future of European Competitiveness," Part B, Section 1, Chapter 1
[27] In November, Ultra Safe Nuclear Corporation (US), which had been planning a micro-reactor smaller than an SMR, filed for bankruptcy. It was clear that the company had struggled to secure anchor investors.

stages, and the inability to achieve anticipated cost reductions through the introduction of new technologies.

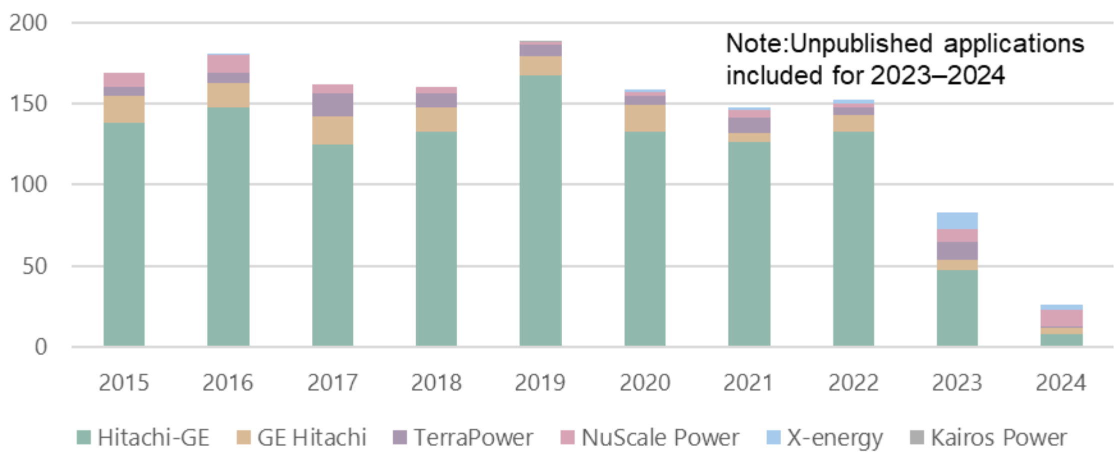
The first SMRs will be constructed by 2030, allowing for comparisons in terms of safety and cost. In the 2030s, commercial molten salt reactors and high-temperature gas reactors will commence operations. At that stage, the key factors driving the competitiveness of SMR manufacturers will include not only (1) fundamental safety assurance and (2) low costs, but also (3) reliable cost estimates, (4) high-temperature heat supply and expertise in its utilization, (5) partnerships with companies experienced in nuclear power plant construction (as the number of manufacturers has declined due to past phases of nuclear phase-out), and (6) the establishment of a highly reliable supply chain.

Despite the technical and economic challenges associated with SMRs, their ability to provide a stable supply of electricity and heat makes them an important option in the transition to a decarbonized society.

IP Analysis of Small Modular Reactors

For the intellectual property analysis of Small Modular Reactors (SMRs), patent data from six major developers listed in Figure 1 was extracted and analyzed to assess the technological landscape. The analysis covered 1,431 patent families filed between 2015 and 2024, identified using the global patent search tool PatSnap.

Figure 4: Annual patent applications by six SMR developers



Source: Compiled by MGSSI

As shown in Figure 4, while the number of patent filings varies by company, technology development has continued at a constant level. Among the companies analyzed, Hitachi-GE Nuclear Energy (Japan) had the highest number of filings over the entire period, averaging 138 patents per year. This was followed by GE Hitachi Nuclear Energy (US) with an average of 14 patents per year, TerraPower with 8 patents per year, and NuScale Power with 5 patents per year. X-energy has consistently filed patents since 2020, with a sharp increase to 10 filings in 2023. In contrast, Kairos Power has only one recorded patent filing in 2019.

Figure 5: Key focus areas and main filing countries by manufacturer (2015–2024)

Company name	No. of patents	Focus area	Main filing countries
(JP) Hitachi-GE	1,158	1. Nuclear technology | Reactor containment, nuclear facility safety 2. Infrastructure optimization and facilities management 3. Non-destructive testing and analysis techniques	Japan, US, Europe
(US) GE Hitachi	119	1. Nuclear technology | Cooling technology, next-generation reactor safety 2. Sensing and monitoring technology 3. AI & machine learning | Advanced system development based on data analysis	US, Europe, Japan, Canada, Mexico
(US) TerraPower	72	Sodium-cooled fast reactor technology	US, China, Europe, Canada, Japan, South Korea, Russia
(US) NuScale Power	59	1. SMR core power control and thermal cycle management 2. Reactor system safety and monitoring technology 3. Integrated energy system (IES) for nuclear reactors	US, Europe, Canada, South Korea, China, Japan
(US) X-energy	20	High temperature gas reactor technology | Fuel efficiency and safety improvement	US, Europe, South Korea, China, Canada, Japan, South Africa
(US) Kairos Power	1	Molten salt reactor technology | Impurity removal	US

Source: Compiled by MGSSI

Figure 5 summarizes the number of patent filings, key focus areas, and main filing countries for each manufacturer. Hitachi-GE had the highest number of filings, but approximately 85% of its patents were filed only in Japan. GE Hitachi is focusing on developing technologies to improve the safety and efficiency of next-generation reactors, including new designs for modular reactors. Additionally, AI-based failure prediction and operation management systems are expected to become important technological fields in the future. TerraPower is prioritizing sodium-cooled fast reactors, while X-energy is focusing on high-temperature gas reactors. While the patent filings of these companies are not exclusively for SMRs, they include technologies that can be applied to SMRs.

NuScale Power, in contrast, has filed patents explicitly mentioning “Small Modular Reactors” in their names, indicating a dedicated focus on SMR development. Furthermore, NuScale Power is notable for its patent filings related to Integrated Energy Systems (IES) for nuclear reactors, which aim to reduce environmental impact and carbon emissions. Patent filings related to IES include systems that utilize reactor-generated heat and electricity to capture CO_2 and utilize it for methanol production, as well as plants that produce hydrogen (H_2) from nuclear-generated steam and subsequently use it to synthesize nitric acid (HNO_3).

These patent data indicate that each manufacturer is strategically focusing on specific areas to realize next-generation nuclear technologies. Understanding future technological trends will be particularly interesting from the perspective of how nuclear technology evolves in response to environmental challenges and the need for efficient energy utilization.

Continuous Fermentation Technology
—Looking at the Innovative Technology that Holds the Key to Market Development for Precision Fermentation—

Takeshi Sawano
Consumer Innovation Dept.
Ryusuke Ishiguro (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

As climate change intensifies, biomanufacturing is being promoted worldwide, utilizing biological processes and biogenic resources to produce energy, chemicals, pharmaceuticals, food, and other products. In the food sector, precision fermentation—a process that uses genetically engineered microorganisms to produce animal proteins and other compounds—is gaining attention. However, scaling up and mass production, which directly impact the final product's cost, are proving to be bottlenecks in market development. The social implementation of continuous fermentation technology, which enables low-cost production without reliance on scaling up, has the potential to accelerate the formation of the precision fermentation market.

Summary

- Continuous fermentation is a technology that enables optimized fermentation reactions to be sustained over long periods, offering advantages in production efficiency and cost reduction compared to traditional batch and fed-batch fermentation. While challenges remain in terms of contamination control and stable operation, startups are developing technologies to address these issues. The social implementation of continuous fermentation technology is expected to enable the distribution of low-cost, competitive precision fermented foods, thereby accelerating market development.

1. What is Continuous Fermentation?

Continuous fermentation is a production method in which substrates and culture media are continuously supplied to a fermentation reactor, while the fermentation products are continuously separated. By real-time control of fermentation conditions based on various data collected from the reactor—including temperature, pH, oxygen concentration, substrate concentration, and cell density—optimized fermentation reactions can be sustained over long periods.

The differences between continuous fermentation and conventional fermentation methods were summarized (Figure 1). Batch fermentation is a production method in which microorganisms, substrate, and culture media are mixed at once and fermented under set conditions. After fermentation, the entire batch of fermentation products is separated at once. Fed-batch fermentation is also used, where substrate or fresh culture media are added during the fermentation process to extend the reaction time and increase the yield of fermentation products compared to batch fermentation. With these conventional methods, downtime for cleaning and preparation is inevitable when transitioning to the next production cycle. Therefore, in order to lower production costs, large-scale production per batch is required, which necessitates scaling-up fermentation conditions and using large fermentation reactors. In contrast, continuous fermentation allows the fermentation reaction to be sustained over long periods and the fermentation products to be continuously separated, making it possible to produce more than the reactor’s maximum capacity over time. As a result, continuous fermentation is typically adapted to smaller fermentation reactors, eliminating the need for scaling-up while still enabling low-cost production using compact reactors.

Figure 1: Conventional production methods (batch fermentation, fed-batch fermentation) and continuous fermentation

	Batch fermentation	Fed-batch fermentation	Continuous fermentation
Addition of substrate and culture medium	All added at once	Added during cultivation	**Added continuously**
Growth stage	Goes through all stages	Extends exponential period*	**Maintains exponential period***
Productivity	Low	Medium	**High**
Reactor size	Large	Medium to large	**Small**
Contamination risk	Low	Medium	**High**
Flexibility	High	Medium	**Low**
Necessity of scale-up	Necessary	Necessary	**None/little**
Issues at time of introduction	Can be handled by existing production systems	Can be handled by existing production systems	**Requires time and incurs cost during the transition of the production system**

*The period when microorganisms grow most actively and rapidly increase in number.

Source: Compiled by MGSSI

Despite its high production efficiency, continuous fermentation faces several challenges. In addition to the lengthy fermentation process, the microorganisms used in production are separated from the culture medium, recirculated, and reused, which increases the risk of productivity decline due to microbial mutations and contamination of the fermentation reactor. Additionally, the time and cost required to transition from existing production systems to continuous fermentation pose further challenges.

2. Notable Trends

In recent years, startups developing solutions for the challenges of continuous fermentation have begun to attract attention (Figure 2). Pow.Bio (US) is developing a continuous fermentation system integrating AI-driven advanced process control, which addresses microbial mutations and contamination issues by employing a dual-chamber system to separate the microbial growth process from the fermentation process. In the fermentation reactor where the target compound is produced, a nutrient-poor medium is used to inhibit the growth of unintended microorganisms, thereby reducing the risk of contamination. Pow.Bio has conducted demonstration experiments using 30L and 300L fermentation reactors, reporting a 2.5-fold increase in yield and a 40% reduction in production costs in the fermentation-based production of food proteins using yeast[28,29]. Enduro Genetics (Denmark) is using its proprietary genetic modification technology, Enduro Sense, to solve the problem of microbial mutation and develop microbial strains that can maintain high productivity throughout the continuous fermentation process. The company claims that this approach will improve the productivity of the fermentation process and enable stable production over the long term[30]. DAB.bio (Netherlands) has a technology that allows selective and continuous extraction of products from fermentation reactors, and is developing a continuous fermentation unit that enables a

[28] Pow.Bio | Continuous Fermentation for Biomanufacturing
[29] Pow.bio raises $9.5m to expand continuous fermentation platform | AgFunderNews
[30] Enduro Genetics: We can transform economics of biomanufacturing

seamless transition from existing production systems to continuous manufacturing. The company offers process development support services using this technology, claiming that it can reduce capital investment and operational costs by up to 70% and cut post-implementation production costs in half[31,32].

Figure 2: Notable startups developing continuous fermentation technology

Company name	Head office location	Issues expected to be resolved	Overview	Noteworthy trends
Pow.bio	US	Microbial mutation Contamination	Development of a support service for constructing fermentation production systems by combining continuous fermentation technology using a dual-chamber system with advanced fermentation condition control.	Completed Series A funding round, raising USD 9.5 million in October 2023. Aiming to establish a demonstration facility equipped with a 1,000L fermentation tank. Partnered with MeliBio (US) to launch an AI-driven precision fermented honey production initiative in March 2024.
Enduro Genetics	Denmark	Microbial mutation	Development of strain design services using proprietary genetic modification technology, “Enduro Sense.” Creation of microbial strains that maintain high productivity even during long-term fermentation processes.	Joined Agile BioFoundry, a consortium funded by the US Department of Energy’s Bioenergy Technologies Office in January 2022. Collaborating with multiple US national laboratories to demonstrate the scalability of the technology.
DAB.bio	Netherlands	Production system transition	Development of a continuous fermentation unit that enables seamless transition from existing production systems to continuous production, utilizing technology for selective and continuous extraction of products from fermentation tanks.	Joined the Ginkgo Technology Network, an ecosystem launched by Ginkgo Bioworks (US), and began efforts to support partner company R&D in May 2024.
Cauldron	Australia	Production system transition	Realization of cost reductions with minimal capital investment through leveraging proprietary continuous fermentation technology.	Announced the construction of “Cauldron Bio-Fab” with financial support from the Queensland government in October 2024. The facility will have an annual production capacity exceeding 1,000 tons. It will manufacture a diverse range of products, including food, animal feed, and chemicals. Has also received US bio-manufacturing grant funding.

Source: Compiled by MGSSI

3. Future Prospects

Thus, solving the challenges of continuous fermentation technology is beginning. Meanwhile, in the precision fermentation sector, which is a promising application for this technology, an increasing number of companies are obtaining Generally Recognized As Safe (GRAS) certification or self-GRAS certification[33] for food additives in the US (Figure 3).

For example, in November 2023, TurtleTree (Singapore) announced that it had become the first company in the world to obtain self-GRAS certification for precision fermentation-derived lactoferrin[34]. Similarly, in February 2024, New Culture (US) announced that it had become the first company in the world to obtain self-GRAS certification for precision fermentation-derived milk casein protein[35]. To drive market development for precision fermentation-based foods, these companies must achieve cost competitiveness against conventional products. Currently, conventional fermentation methods are used in almost all fermentation production facilities, and reducing production costs requires large-scale fermentation reactors for mass production. However, the number of accessible large fermentation reactors is limited, and building new large reactors requires enormous investment, making this the biggest bottleneck in market development. Under such circumstances, the demand for continuous fermentation technology is expected to grow naturally. If continuous fermentation technology is successfully implemented, it could eliminate the need for scale-up, enable low-cost production using small-scale equipment, and significantly accelerate market formation. Future developments should be closely monitored.

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31 DAB.bio :: Lux Research
32 DAB | DAB.bio’s FAST Reduces Biomanufacturing Costs by 50%
33 Companies conduct expert panel evaluations to assess the safety of their own products and make a declaration to that effect. Typically, after obtaining self-GRAS certification, they notify the FDA and seek a “no objection” response.
34 TurtleTree obtains the world's first self-GRAS for animal-free lactoferrin, LF+™ now approved to commercialize in the U.S.
35 New Culture | "GRAS" for New Culture Animal-free Casein

Figure 3: Startups obtaining US GRAS certification for precision fermentation ingredients

Company name	Head office location	Ingredient produced by precision fermentation	Application examples	GRAS certification date	Market status
Impossible Foods	US	Soy leghemoglobin	Plant-based meat alternatives	July 2018	Commercially available
Perfect Day	US	Milk whey (β-lactoglobulin)	Dairy products	Mar 2020	Commercially available
		Sweet protein (brazzein)	Confectioneries	Pending certification	-
Remilk	Israel	Milk whey (β-lactoglobulin)	Dairy products	June 2022	Commercially available
Sweegen	US	Sweet protein (brazzein)	Confectioneries	May 2023	Commercially available
Imagindairy	Israel	Milk whey	Dairy products	Aug 2023 (self-GRAS)	Preparing for launch
The Every Company	US	Egg white protein	Bakery & confectionery products	Oct 2023	Commercially available
TurtleTree	Singapore	Lactoferrin	Functional foods Supplements	Nov 2023 (self-GRAS)	Preparing for launch
New Culture	US	Casein	Cheese	Feb 2024 (self-GRAS)	Preparing for launch
Vivici	Netherlands	Milk whey (β-lactoglobulin)	Dairy products	Feb 2024 (self-GRAS)	Preparing for launch
Oobli	US	Sweet protein (brazzein)	Confectioneries	Mar 2024	Provided exclusively for JAL in-flight meals
		Sweet protein (Monellin)	Confectioneries	Dec 2024	-
21st.BIO	Denmark	Milk whey (β-lactoglobulin)	Dairy products	Sept 2024 (self-GRAS)	-
Fermify	Austria	Casein	Cheese	Oct 2024 (self-GRAS)	-
Onego Bio	Finland	Egg white protein	Bakery & confectionery products	Submission planned	-

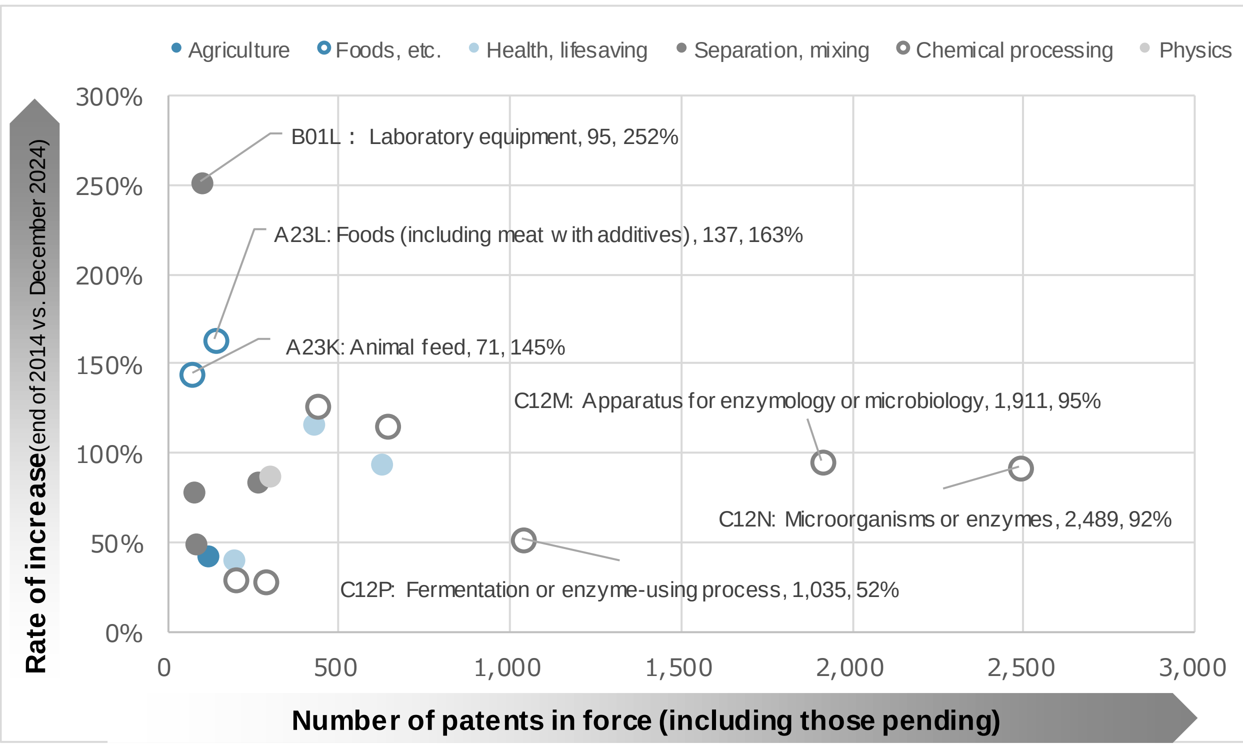
Source: Compiled by MGSSI

IP Analysis of Continuous Fermentation Technology

Keywords closely related to this technology, such as “multi-chamber” and “continuous fermentation,” as well as International Patent Classification (IPC) codes associated with microorganisms, enzymes, and fermentation, were identified (3,371 in force as of December 2024, including pending applications[36]), and an analysis was conducted based on technology classifications and top players.

Figure 4 compares the number of patents in force by technology classification and their growth rates. The horizontal axis represents the number of patents in force, while the vertical axis shows the growth rate by comparing the number of patents in force as of December 2024 with those at the end of 2014. The results indicate a stronger focus on technologies related to microorganisms, enzymes, and fermentation, which have been increasingly applied to foods and animal feed in recent years. Among the food-related technologies with significant growth in recent years, there has been a particularly notable growth in the number of patents related to meat products containing additives.

Figure 4: Number of patents in force and growth rate (by technology category)

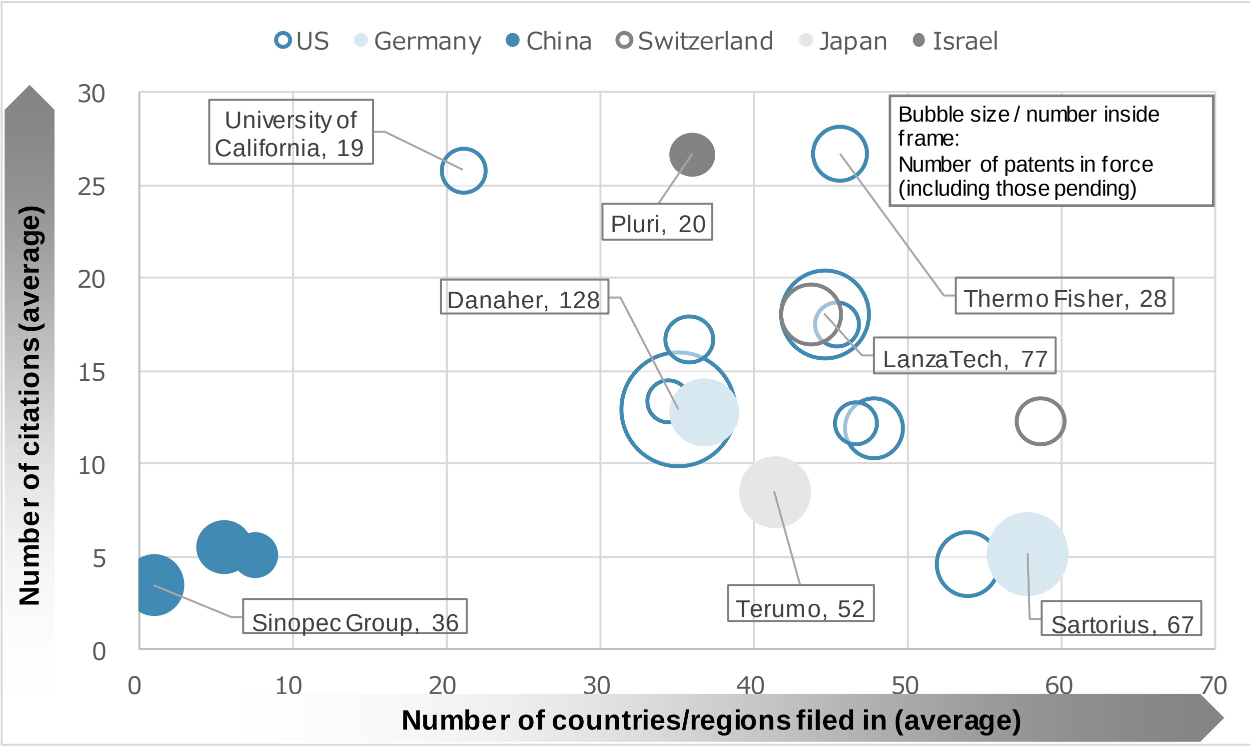


Source: Compiled by MGSSI based on data from LexisNexis PatentSight

Figure 5 compares the top players in terms of the number of continuous fermentation-related patents. The bubble size represents the number of patents in force, the horizontal axis indicates the average number of countries or regions where applications were filed, and the vertical axis represents the average number of citations, reflecting the technological impact. The results highlight the prominence of US companies, such as Danaher (US) and LanzaTech (US). Additionally, major players across multiple industries, including healthcare and chemicals, dominate the top ranks.

[36] The total number of patents includes both filed patents and granted patents that have completed the examination process and are enforceable as intellectual property rights.

Figure 5: Number of patents in force, number of countries/regions filed in, and number of citations (by top players)



Source: Compiled by MGSSI based on data from LexisNexis PatentSight

Smart Hospitals

—How Digital Twin Technology is Shaping the Future of Hospitals—

Takako Kato
Industry Innovation Dept.
Yui Matsuura (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

Smart hospitals that utilize digital technology and data are expected to help improve hospital operational efficiency and the quality of patient care. In recent years, the application of digital twins in the medical field has been attracting attention, with advanced projects such as DIGIPREDICT (EU), FDT-BioTech (US), CVD-Net (UK), and BRiDGE (Japan) currently in progress. As a result, the number of patents and academic publications[37] is also on the rise. Supported by government funding and private investment, R&D and social implementation are accelerating, positioning digital twins as a key technology in shaping the future of hospitals.

Summary

- The introduction of digital twins to hospitals is still in its early stages, with progress expected through small-scale pilot experiments.
- Integration of digital technologies and assurance of data quality and reliability are essential for the construction of digital twins.
- In the future, digital twins are expected to be utilized in various areas, including enhancing hospital functions, improving personalized care, and increasing the efficiency of clinical trials. However, addressing ethical challenges such as privacy protection and transparency will be important.

1. Smart Hospitals

The smart hospital is a concept that aims to improve hospital operational efficiency and enhance the quality of patient care by utilizing the latest digital technologies and data. The key technologies supporting this concept include IoT, AI, robotics, automation, sensing, big data analytics, and augmented/virtual reality (AR/VR). Among these, **digital twins** are gaining increasing attention. A digital twin is a technology that replicates the real-world environment of hospitals and patients in a virtual environment, enabling real-time data analysis. When combined with **AI**, it can support decision-making on complex issues, and **predict future scenarios** to facilitate early intervention, prevention, and corrective measures. Patent filings in this field have surged, signaling that digital twin technology has moved beyond the research phase and is now rapidly advancing toward practical implementation.

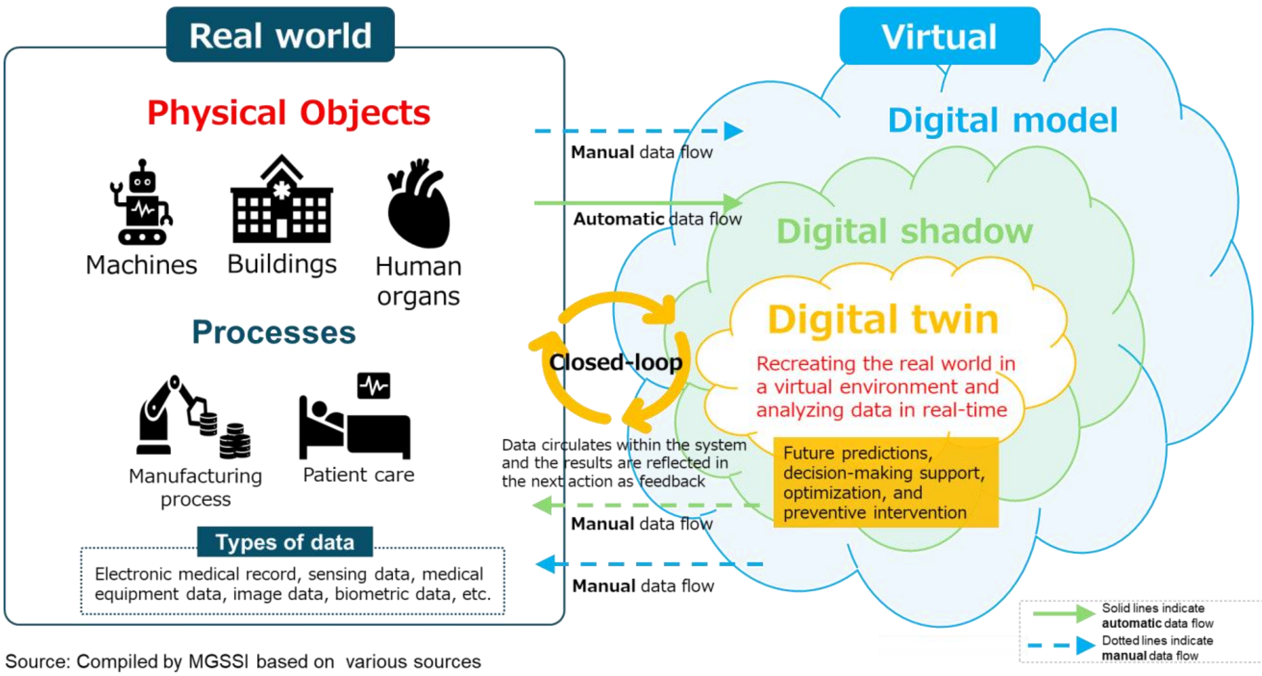
1-1. Digital Twins

A digital twin digitally represents real-world objects (e.g., machines, buildings, human organs) and processes (e.g., manufacturing workflows, patient care) by creating a mathematically constructed **digital model** in a virtual environment. This model is continuously updated using real-time data collected from the physical world, a concept

[37] Evangelia Katsoulakis et al., Digital twins for health: a scoping review Check for update, npj Digital Medicine | (2024) 7:77 (Digital twins for health: a scoping review | npj Digital Medicine)

referred to as a “**digital shadow**.” In addition to the digital shadow, a **digital twin** incorporates a **closed-loop**[38] feedback mechanism, which reflects the simulation results generated in the virtual environment to the real world. This system enables future predictions, decision-making support, optimization, and preventative interventions (Figure 1).

Figure 1: Conceptual diagram of a Digital Twin



Source: Compiled by MGSSI based on various sources

1-2. Elemental Technologies Supporting Digital Twins

The construction of digital twins requires a framework that integrates various advanced technologies. First, data is collected from (1) sensors such as wearable and implantable devices, as well as (2) IoT devices. This data is then processed locally and in real time using (3) edge computing, before being transmitted via (4) real-time data streaming to (5) cloud computing for application as (6) integrated data. For effective processing, learning, and prediction, based on the integrated data, (7) multimodal AI plays an important role in handling diverse data sources. (8) 3D/4D modeling is necessary for intuitive visualization and (9) cybersecurity ensures data security. Additionally, (10) large-scale quantitative models are indispensable for supporting complex predictive analyses. These technologies collectively form the foundation of digital twin construction (Figure 2).

[38] In the context of digital twins, a closed-loop system refers to a process where simulation results obtained in a virtual environment are applied to the real world, and the outcomes are continuously fed back into the system for further learning and improvement.

Figure 2: Key Technologies Supporting Digital Twins

Technology	Explanation
(1) Sensors	Devices that collect information from the physical environment. Capable of detecting temperature, pressure, motion, etc.
(2) IoT devices	Physical devices connected to the internet that handle data collection and transmission.
(3) Edge computing	Technology that processes data in real-time at the collection site, reducing latency.
(4) Real-time data streaming	A technology that continuously transmits large volumes of data in real time.
(5) Cloud computing	Technology for storing, processing, and analyzing data via the internet.
(6) Integrated data	A unified dataset that consolidates data from multiple sources.
(7) Multimodal AI	Artificial intelligence technology that supports multiple data formats (e.g., text, images, audio)
(8) 3D/4D modeling	A technology that visualizes information in 3D or 4D (including time axis) formats.
(9) Cyber security	Technology for protecting the confidentiality, integrity, and availability of data.
(10) Large-scale quantitative models	Numerical models used for predicting and simulating complex phenomena.

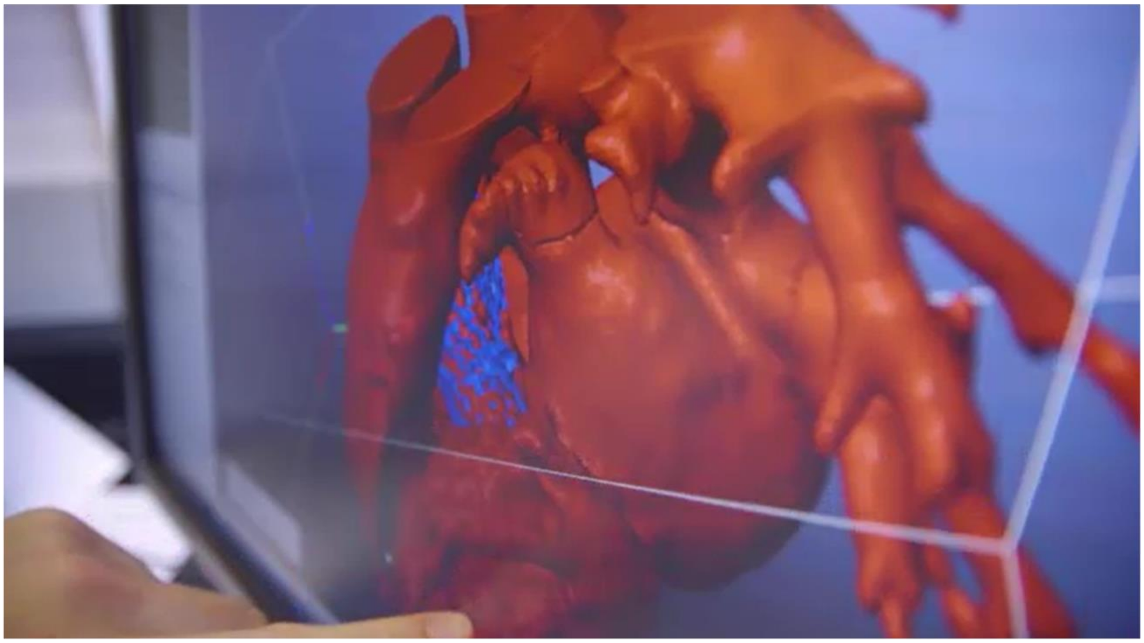
Source: Compiled by MGSSI based on various sources

1-3. Current Status and Objectives of Digital Twins in Smart Hospitals

The implementation of digital twins in smart hospitals is still in its early stages. Interviews with experts have confirmed that many current cases remain at the level of digital models or digital shadows, rather than fully integrated digital twins. In the medical field, building advanced models capable of processing thousands of biometric and environmental data points per second faces several challenges, including a lack of data standardization and the need to protect medical information privacy.

The main objectives of introducing digital twins in hospitals are (1) improving hospital operations (e.g., optimizing workflows for medical staff and patients, preventing medical equipment failures) and (2) enhancing patient care (e.g., determining optimal treatment plans, providing personalized care, and implementing proactive interventions based on individual patient data). Since the construction of a digital twin is time-consuming and costly, development efforts are being focused on specific applications, such as optimizing ICU operations, optimizing hospital resource management, maintaining medical equipment, and utilizing simulations of organs such as the heart (Figure 3) and diseases such as diabetes for treatment optimization.

Figure 3: Illustration of development of a Digital Twin Heart



Source: Excerpt from a video posted on the Dassault Systèmes website (accessed December 5, 2024)

2. Notable Trends

Notable trends in this field were categorized into five categories: large-scale projects, consortiums, standardization and standards organizations, hospitals and research institutions, and companies. These are summarized in Figure 4. In the medical field, digital twins are being applied in advanced projects, including DIGIPREDICT (EU), FDT-BioTech (US), CVD-Net (UK), and BRiDGE (Japan). These projects aim to realize personalized and predictive medicine through collaboration among academia, industry, and government. Significant advancements in the practical implementation of digital twins are expected over the next five years, making this a crucial period for their adoption.

Figure 4: Key Trends in the Application of Digital Twins in Hospitals

Category	Region	Name	Overview
Large-scale projects	EU	DIGIPREDICT	A project aimed at building a digital twin platform for predicting COVID-19 complications and optimizing the prevention, diagnosis, and treatment of cardiovascular diseases**.** Supported by the **EU Horizon 2020 program** (launched in 2021), the project also focuses on the development of technologies such as digital biomarkers, organ-on-chip, AI.
	EU	Neurotwin	A project supported by EU Horizon 2020 that aims to construct a **personalized brain digital twin** to optimize non-invasive electrical stimulation-based treatment for **Alzheimer's disease**.
	US	FDT-BioTech	In October 2024, the US National Science Foundation (NSF), in collaboration with the National Institutes of Health (NIH) and the Food and Drug Administration (FDA), announced research funding for a project promoting the development of **digital twins for biomedical applications**. This initiative is part of the Foundations for Digital Twins as Catalyzers of Biomedical Technological Innovation (FDT-BioTech).
	UK	CVD-Net	A project funded by an £8 million grant from the Engineering and Physical Sciences Research Council (EPSRC). It aims to create a **digital twin of the heart** to track disease progression and treatment responses in real time for patients with **pulmonary arterial hypertension (PAH)**.
	Japan	BRiDGE (Programs for Bridging the gap between R&D and the ideal society (society 5.0) and generating economic and social value)	In July 2023, this project was launched to establish a digital medical data bank aimed at advancing medical digital twins. Led by the **National Cancer Center**, the initiative seeks to build the data bank by digitizing, structuring, and collecting various medical information, including clinical data, genomic data, medical imaging data, and pharmaceutical information.
Consortiums	Global	Digital Twin Consortium	An international organization dedicated to the promotion and advancement of digital twin technology. Experts from industry, academia, and government collaborate to drive the development of digital twins, enhance awareness, encourage adoption, and improve interoperability.
Standardization & standards organizations	US	The American Society of Mechanical Engineers (ASME)	The **American Society of Mechanical Engineers (ASME)** has established the **V&V 40 standard** for medical devices. In the field of digital twins, V&V 40 plays a crucial role and is widely applied to ensure the reliability of computational modeling.
	Europe	Avicenna Alliance	An organization advocating for the regulation and adoption of **computer modeling and simulation (in silico methods)**. It develops guidelines on the concept, definition, and implementation of digital twins. Based on the V&V 40 standard established by ASME, the organization is working to establish a framework for the verification and validation of digital twins in Europe.
Hospitals & research institutions	US	Cleveland Clinic	In February 2023, leveraging a $3.14 million grant from the U.S. National Institutes of Health (NIH), a model called **"Digital Twin Neighborhoods"** is being developed to analyze and address regional health disparities based on electronic health records from over **250,000 individuals**. Additionally, digital twin technology is being applied to cardiac surgery planning and patient monitoring.
	US	Johns Hopkins	A **"Genotype-specific digital twin (Geno-DT)"** is being developed to create a virtual replica of a patient's heart. Additionally, digital twin technology is being integrated into cardiac surgery and pediatric surgical planning.
	Sweden	Karolinska Institute	In March 2024, a method was developed to identify the **optimal medication for autoimmune disease treatment** using individual patient digital twins.
	Singapore	Singapore General Hospital	As part of its smart hospital strategy, a digital twin is being developed. The initiative includes the **4D Disease Occurrence Surveillance System (4D-DOSS) project**, which integrates clinical data, test results, and patient movement history onto a digital replica of the hospital's physical space.
	Singapore	Changi General Hospital	According to reports, the hospital is developing a digital twin model to predict staffing and resource needs in **emergency departments** and to support the redesign of workflows.
Companies	Netherlands	Phillips	Creating detailed **digital models for CT, MRI, ultrasound systems**, and other medical devices, and simulations conducted to aid in device design and performance evaluation. Additionally, patient data is collected and analyzed, integrating it with digital twin models to enable personalized diagnosis and treatment planning.
	Germany	Siemens Healthineers	A **heart model** has been developed, enabling simulation-based diagnostics and treatment planning based on a detailed 3D model. This model is integrated into the **"teamplay" platform**, which allows interoperability with software from other vendors.
	France	Dassault Systèmes	The **"Living Heart Project"** is being promoted to develop a detailed 3D heart model for simulation-based applications in clinical settings. In recent years, efforts have expanded to include models of other organs, such as the lungs, brain, and kidneys, indicating a broader vision for integrating digital twin technology across entire hospital systems.
	UK	AnyLogic	A hospital digital twin project was implemented at two NHS-affiliated hospitals—**Cheltenham General Hospital and Gloucestershire Royal Hospital**. By simulating hospital operations, the project led to resource optimization and reduced patient wait times.
	US	ANSYS (a Synopsys company)	Leveraging its expertise in simulation technology, the organization is actively developing medical devices and patient physiological models. It specializes in constructing **biological models of the heart, blood vessels, and respiratory system**.
	France	Sim&Cure	A **digital twin technology for brain aneurysm treatment** planning has been developed. Specifically, a 3D model is created based on patient imaging data, allowing for simulations to evaluate optimal treatment strategies and surgical procedures.

Source: Compiled by MGSSI based on interviews with experts and various corporate websites

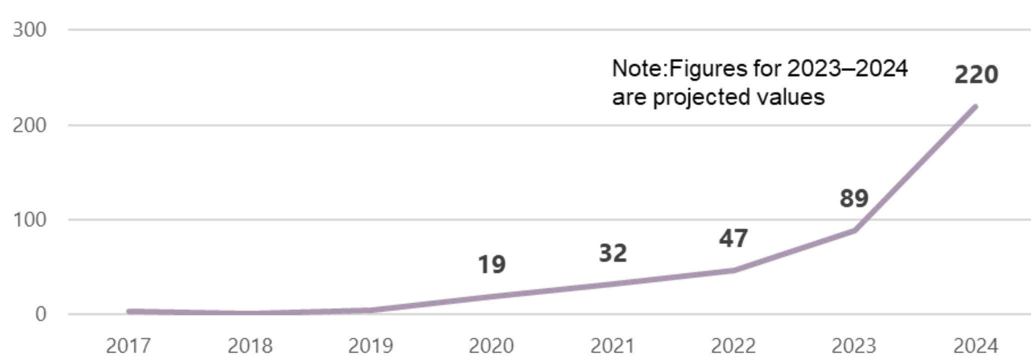
3. Future Prospects

The implementation of digital twins in smart hospitals is expected to progress through small-scale pilot experiments with clearly defined purposes of use. Building a highly accurate digital twin requires the integration of cutting-edge digital technologies, with data quality and reliability being key to success. In particular, constructing digital twins for entire hospitals or entire human bodies presents significant challenges due to the vast amount of data and high costs involved. A system in which hospitals build digital twins at the structural or organ level, and share them on a common platform is necessary. Hospitals will not only serve as testing grounds but will also play a crucial role as data providers. In the future, the use of digital twins will promote a "shared reality within hospitals[39]", which is expected to drive the transformation of siloed structures and hierarchical organizations. Additionally, the development of individual patient-specific digital twins will contribute to advancements in personalized care. In the long term, the integration of digital twins for both objects and processes will enhance hospital functions based on treatment strategies. Digital twins are also expected to be utilized in various other ways, including improving the efficiency of clinical trials in the pharmaceutical sector. At the same time, addressing ethical challenges such as privacy protection and ensuring transparency will be important.

IP Analysis of Smart Hospitals

For the IP analysis of smart hospitals, patent data related to the application of digital twins in healthcare was extracted and analyzed to assess the technological landscape. The analysis covered 211 patent families filed between 2017 and 2024, identified using the global patent search tool PatSnap.

Figure 5: Number of patent filings per year for digital twin × medical technology



Source: Compiled by MGSSI

[39] Shared reality refers to the real-time and accurate digital replication of the medical environment, allowing all relevant stakeholders to access and share the same information.

Figure 6: Top ranking of patent applicants by number of filings (2017–2024)

Source: Compiled by MGSSI

As shown in Figure 5, a turning point occurred in 2020, with a sharp increase in patent filings. This growth trend is continuing, indicating intensifying competition for patents driven by accelerated innovation. Figure 6 illustrates the major patent applicants, which include large healthcare corporations (Philips, Siemens Healthineers), IT companies (IBM), academic institutions (Shanghai Jiao Tong University School of Medicine), and emerging companies(Twin Health). The diversity of applicants shows that technological development is being promoted by a wide range of actors. This trend demonstrates that technological development is not concentrated in a specific country or company but is advancing globally across various sectors.

Figure 7: Invention category classifications

Invention category	Category description	No. of patents
Diagnosis & treatment support	Creation of virtual patient models to simulate the diagnosis and treatment process	**76**
Management & optimization of medical devices	Use of virtual models of medical devices to simulate operational conditions and predict failures	**48**
Rehabilitation & movement assistance	Reflection of patient body movements in the digital twin to visualize progress and effectiveness	**26**
Virtual medical services	Use of virtual patient models to predict treatment outcomes and enable remote monitoring	**13**
Education & training	Construction of virtual hospitals and surgical environments to provide realistic training scenarios	**12**

Source: Compiled by MGSSI

Figure 7 summarizes patent data related to the application of digital twins in healthcare when broken down by invention category. The largest number of inventions fall under diagnostic and treatment support, including systems that utilize digital twins to predict treatment outcomes and customize treatment plans, technologies for personalized treatment such as assisting in cancer prognosis prediction, and simulation technologies that virtually replicate and optimize human and work environments such as body temperature regulation and safety management.

The patent data indicate that digital twin technology is being applied to address specific challenges in the medical field, such as personalization, efficiency, accuracy improvement, and regional disparities. Additionally, the presence of patent filings in emerging markets suggests that digital twins could contribute to improving healthcare quality in these regions and narrowing the healthcare gap between developed and developing countries.

Targeted Protein Degradation (TPD) Technology

—Delivering a Novel Therapeutic Approach for Intractable Diseases—

Yu Toguchi
Industry Innovation Dept.
Yui Matsuura (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

Targeted protein degradation (TPD) technology is attracting attention for expanding drug discovery possibilities for “undruggable[40]” molecules, which have been difficult to target using conventional small molecule or antibody drugs. PROTAC (Proteolysis Targeting Chimeras), one of the TPD technologies, has several candidate compounds currently advancing through clinical trials, and the social implementation of these novel drugs is approaching. This report describes the background and mechanism of TPD technology, and discusses company trends, challenges, and its significance in drug discovery.

Summary

- Progress in clinical trials for drug discovery using TPD technology and regulatory developments are bringing the technology closer to practical application.
- As the technology advances, interest in small molecule drugs is increasing, raising expectations for more efficient drug discovery.
- The development of oral drugs using small molecular compounds is expected to improve treatment adherence and reduce patient burden, leading to better chronic disease management.

1. Targeted Protein Degradation (TPD) Technology

TPD (Targeted Protein Degradation) is a novel drug discovery technology that selectively degrades designated proteins within cells to control their functions. First developed at the California Institute of Technology in 2001, this technology has the unique ability to address undruggable proteins, which are difficult to target with conventional drugs[41].

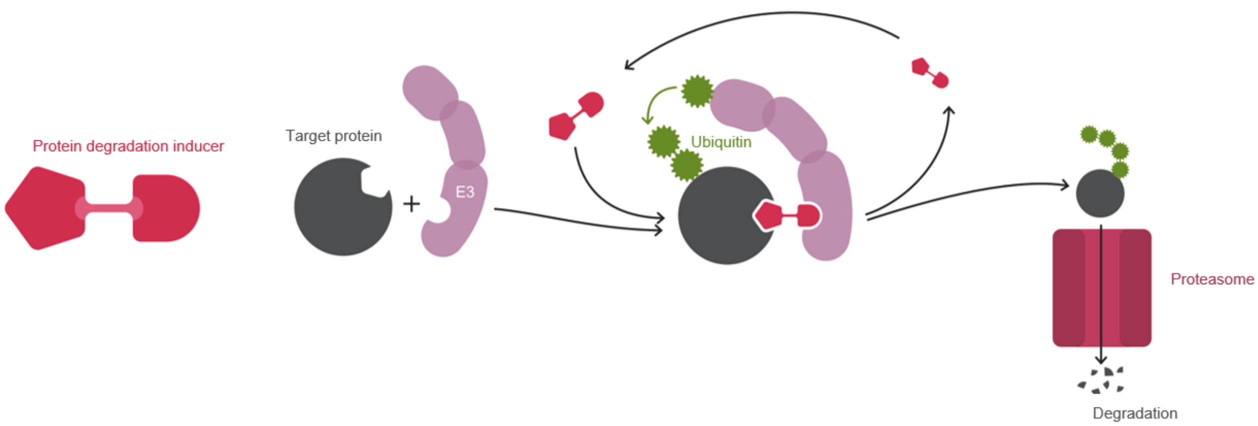
Drug development has conventionally focused on proteins that have "pockets" to which drugs can bind, and enzyme proteins and receptor proteins that exert their effects when drugs bind to these pockets. On the other hand, proteins that are considered undruggable have been excluded from drug discovery because their molecular structures have no or very small pockets for drug binding. These proteins account for approximately 80% of all proteins, and many are closely linked to difficult-to-treat diseases[42,43]. By degrading these proteins, TPD technology offers new therapeutic possibilities for cancer and immune diseases, and is expected to serve as a foundational technology for the next generation of drug development.

[40] Undruggable refers to molecules (or the concept of molecules) that have been considered difficult or impossible to target using conventional drug discovery techniques. These include target molecules that, due to their structural or functional characteristics, cannot be effectively acted upon by conventional small molecule or antibody drugs (Nature Digest 12, 7 (2015)).
[41] Proc. Natl. Acad. Sci. 98, 15 (2001)
[42] Astellas Pharma R&D meeting (12/9/2022)
[43] Harvey Lect. 102 (2006)

1-1. Mechanism of TPD Technology

TPD technology is a collective term for therapeutic approaches that leverage the “proteolytic system” of cell to selectively degrade designated proteins and thereby regulate their functions. A representative example is proteolysis targeting chimeras (PROTAC) (Figure 1). In PROTAC, a protein degradation inducer links the designated protein (target protein) with an E3 ubiquitin ligase, which plays a role in attaching ubiquitin, a marker for degradation. This action adds ubiquitin to the target protein, which is then sent to the proteasome, the cell’s degradation machinery, where it is broken down. Because the drug functions in a catalytic manner, it can be repeatedly used to facilitate the ubiquitination of target proteins, thereby enabling the efficient degradation of proteins.

Figure 1: Mechanism of target protein degradation by PROTAC



Source: Astellas Pharma R&D meeting (12/9/2022)

1-2. Major Approaches in TPD Technology

Various approaches to induce protein degradation exist within TPD technology. Each approach has characteristic mechanisms and application ranges, and the most suitable is selected based on the treatment target and issue (Figure 2).

Figure 2: Main approaches in TPD technology

Approach	Mechanism	Characteristics
PROTAC (Proteolysis Targeting Chimeras)	Ubiquitin is added to target proteins, which are degraded via the proteasome	- Compatible with a wide range of proteins, including undruggable proteins - Catalytically acts to induce repeated degradation with small amounts of agent
Molecular Glue (Molecular Glue)	Small molecules link target proteins to E3 proteins for degradation	- Single molecule that acts as an intermolecular adhesive - Simple design that acts on specific proteins
LYTAC (Lysosome Targeting Chimeras)	Utilizes a mechanism that delivers target proteins to lysosomes (intracellular degradation systems) for degradation	- Primarily targets membrane and extracellular proteins - Uses lysosomes instead of the proteasome
AUTAC (Autophagy Targeting Chimeras)	Uses autophagy (cellular autodegradation mechanism) to break down abnormal proteins	- Targets abnormal proteins and aggregates

Source: Compiled by MGSSI based on *Signal Transduction and Targeted Therapy* 7, 113 (2022), *Signal Transduction and Targeted Therapy* 9, 308 (2024)

2. Notable Trends

2-1. Strategies and Pipelines of Major Companies

In recent years, drug development utilizing TPD technology has progressed, with several therapeutic candidates advancing to the clinical trial stage, including PROTAC. Patent filing trends in TPD technology, particularly PROTAC, have shown a significant increase since 2020. Many pharmaceutical and biotechnology companies are leveraging TPD technology to develop new treatments for cancer and immune disorders, which have been historically difficult to treat (Figure 3).

Notably, the American company Arvinas (US) is leading this technology. In collaboration with Pfizer (US), Arvinas has developed ARV-471, a drug candidate for breast cancer, which has already demonstrated promising results in Phase 1 and 2 trials. According to Dr. Cacase, the company's CSO, the primary results of the Phase 3 trial are expected to be published in early 2025, raising expectations for the first commercial launch of a drug using TPD technology[44].

Figure 3: Strategies and development pipelines of major companies focusing on TPD technology

Companies	Main approach	Strategic trend	Main pipeline/phase	Main therapeutic areas
Arvinas (US)	PROTAC	Expanding market share through partnerships with major pharmaceutical companies such as Pfizer and Novartis	ARV-471 (Breast cancer/P3) ARV-110 (Prostate cancer/P2)	Cancer
C4 Therapeutics (US)	Molecular Glue PROTAC	Utilizing a proprietary degradation induction technology platform	CFT7455 (Multiple myeloma/P1) CFT8634 (Soft tissue sarcoma/P1)	Cancer
Kymera Therapeutics (US)	PROTAC	Expanding applications to immune diseases in collaboration with Sanofi (France)	KT-474 (Atopic dermatitis/P2) KT-413 (Hematological cancer/P1)	Immunology, cancer
Monte Rosa Therapeutics (US)	Molecular Glue	Targeting cancer-causing genes	MRT-2359 (Hematological cancer/P1)	Cancer
Astellas Pharma (Japan)	PROTAC	Designated as a priority area, aiming for commercialization leveraging core strengths	ASP-3082 (Solid cancer/P1)	Cancer
Novartis (Switzerland)	PROTAC Molecular Glue	Partnering with Arvinas and Monte Rosa Therapeutics Strengthening internal technology base	DYK709 (Solid cancer/P1)	Cancer
Nurix Therapeutics (US)	PROTAC	Expanding into a wide range of indications	NX-5948 (B-cell lymphoma/P1) NX-1607 (Solid cancer/P1)	Cancer
Foghorn Therapeutics (US)	PROTAC	Promoting development leveraging epigenetics expertise related to gene expression regulation	FHD-609 (Soft tissue sarcoma/P1)	Cancer

Source : Compiled by MGSSI based on Frost & Sullivan, "Top 5 Growth Opportunities for the Pharmaceutical Industry, 2024," *Nature Medicine* 30, 3030-3031 (2024), *Signal Transduction and Targeted Therapy* 9, 308 (2024), and company websites (accessed: December 4, 2024)

[44] Nature Medicine 30, 11 (2024)

2-2. Regulatory Easing, Market Trends, and Challenges

The development of new drugs utilizing TPD technology has significantly benefited from regulatory easing, improving the environment for practical implementation. In particular, an increasing number of TPD-based drugs have been selected for the US FDA's Breakthrough Therapy and Fast Track expedited approval programs, accelerating the approval process. This is facilitating the rapid commercialization of new drugs, reducing the time required to bring treatments to patients. Additionally, partnerships between pharmaceutical companies have become more active, particularly between large pharmaceutical firms and biotech ventures with TPD technology, reflecting the growing interest in this field.

However, challenges remain. In the US, safety evaluation standards are currently under review, with a key concern being off-target effects, where drugs unintentionally act on proteins other than their intended targets. Overcoming this challenge is expected to further expand practical applications and drive the broader adoption of TPD technology for a wider range of diseases.

3. Future Prospects

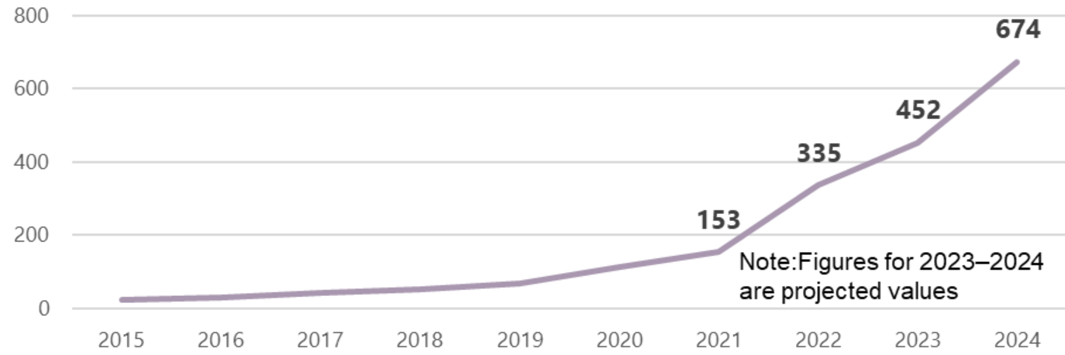
TPD technology opens new possibilities in drug development by enabling the targeting of undruggable proteins. As this technology advances and its applications broaden, it might alter the current biopharmaceutical trend favoring medium- and large-molecule drugs. The use of small molecules in TPD technology may reignite interest in small molecule drugs and compound libraries. Additionally, in AI-driven molecular screening and protein property analysis, small molecular compounds have an advantage over biopharmaceuticals, as they have abundant research data and are easier to process computationally, making them more applicable to AI-based drug discovery processes.

Furthermore, TPD-based therapeutics offer significant advantages from the patient's perspective. Many small molecule drugs are developed as oral medications, which reduce the patient burden compared to biopharmaceuticals, which require injections or intravenous infusions. This is particularly beneficial for chronic diseases and long-term treatments, where the convenience of at-home oral medication greatly contributes to treatment adherence. TPD technology will serve as a key foundational technology that provides new treatment options for intractable diseases, contributes to the efficiency of healthcare economics, and improves patients' quality of life (QOL), playing a crucial role in advancing medical innovation.

IP Analysis of TPD Technology

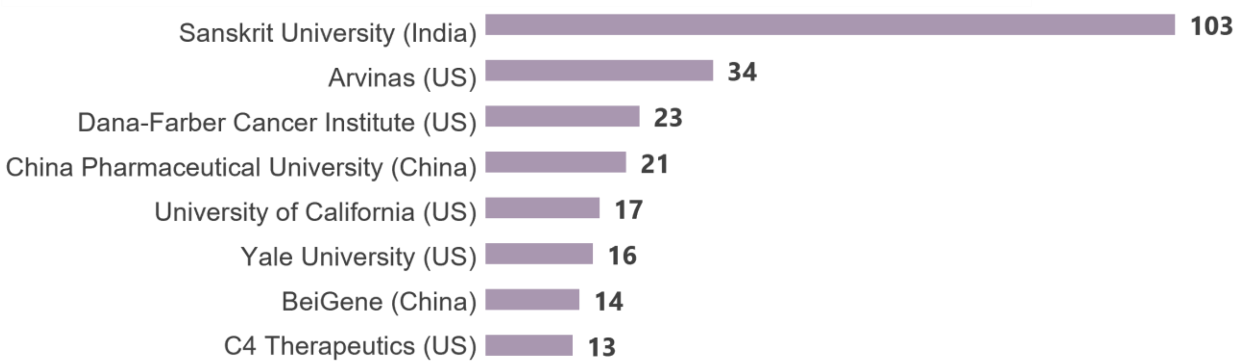
For the IP analysis of TPD technology, patent data related to this field was extracted and analyzed to assess the technological landscape. The analysis covered 1,359 patent families filed between 2015 and 2024, identified using the global patent search tool PatSnap.

Figure 4: Annual patent filings related to TPD technology



Source: Compiled by MGSSI

Figure 5: Top ranking of patent applicants by number of filings (2015–2024)



Source: Compiled by MGSSI

As shown in Figure 4, the number of patent filings increased at a moderate annual growth rate of approximately 30% from 2015 to 2019. However, since 2020, the annual growth rate has surged to around 57%, indicating a rapid increase in filings. Possible factors behind this surge include the entry of new players and strengthened IP strategies by existing players. Among the major applicants shown in Figure 5, Sanskrit University and BeiGene have emerged since 2020. These new players reflect the intensification of regional competition in China and India. Arvinas has continued patent filing activity throughout the period, with 7 filings up to 2019 and 27 filings since 2020, clearly ramping up its IP activity.

Figure 6: Major applicant focus areas (2015–2024)

Applicant	Focus area	Main filing countries	Characteristics
Sanskrit University	Protein target design and drug binding site discovery Technology development related to medicinal chemistry and molecular modeling	India	Focusing on academic research with the aim of leading technology development within India
Arvinas	PROTAC Development of cancer treatments and hormone receptor-related drugs	US, Europe, Japan, China, Australia, Brazil, Canada, India	Aggressively expanding patent portfolio to enhance competitiveness
Dana-Farber Cancer Institute	Basic research and clinical applications aimed at cancer treatment Development of new therapeutic approaches utilizing TPD technology	US, Europe, Australia, Canada, China, Japan	Filings in diverse regions, with an eye on markets in Asia and Europe
China Pharmaceutical University	Drug development utilizing ubiquitin ligase Research on therapeutics for liver diseases and infectious diseases	China	Many applied research projects focused on domestic medical needs, with a strong emphasis on fundamental research
University of California	Basic research on WASP proteins and oligomers associated with immune function Visualization of intracellular processes and diagnostic technologies	US, Europe, Australia, Canada, China, Japan	Technology transfer and licensing activities in the global market also envisioned
Yale University	Novel protein degradation technologies for cancer treatment Ongoing research partnership with Arvinas	US, Europe, Japan, China, Australia	Strengths in academic research and industry collaboration
BeiGene	Research and development of cancer therapeutics Design of protein-targeted compounds	China, US, Taiwan, Europe, Argentina, Japan	Patent strategy with a view to global expansion
C4 Therapeutics	In vivo degradation modulators utilizing PROTAC technology Therapeutic approaches for cancer and inflammatory diseases	US, China, Europe	Multinational filings cover a wide range of markets

Source: Compiled by MGSSI

Figure 6 summarizes the focus areas of the major applicants and the characteristics of their patent filings. Sanskrit University and China Pharmaceutical University are focusing on the domestic market and are advancing technology development tailored to local needs. US companies and BeiGene are securing the US domestic market while also expanding into global markets, including Europe, Japan, and China. While being grounded in academic research, Yale University and the University of California are engaging in strong collaboration with industry. For example, Yale University has been identified as a co-applicant with Arvinas, demonstrating a successful industry-academia collaboration where Arvinas aims to commercialize PROTAC technology, a research outcome from Yale.

Patent data also indicates that US companies such as Arvinas and C4 Therapeutics are utilizing AI to advance TPD technology. The application of AI technology is advancing molecular design and pharmacological modeling, and is expected to lead to the discovery of new therapeutic targets and the development of more efficient molecular designs.

Semi-Solid-State Battery Technology

—Driving the Development of Solid Electrolytes, High-Performance Anodes, and Other Technologies for All-Solid-State Batteries—

Jian Zhao
Consumer Innovation Dept.
Ryusuke Ishiguro (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

Semi-solid-state batteries are positioned between liquid-based lithium-ion batteries (LIBs), which use flammable liquid electrolytes, and all-solid-state batteries. They offer higher safety and energy density than liquid-based LIBs while having lower mass-production challenges compared to all-solid-state batteries. As a result, battery companies worldwide are working to implement semi-solid-state batteries as an interim solution until all-solid-state batteries become commercially viable. The implementation of semi-solid-state batteries is driving the development and integration of solid electrolytes, high-performance cathodes, and anodes, not only accelerating all-solid-state battery development but also holding the potential to expand market share of semi-solid-state batteries beyond just serving as an interim solution, depending on performance and cost.

Summary

- By utilizing solid electrolytes and high-performance anodes, semi-solid-state LIBs can achieve an energy density exceeding 300 Wh/kg, which is considered the upper limit of liquid-based LIBs. The hurdle for mass production is also low because they can be manufactured on existing liquid-based LIB production lines.
- Many Chinese companies are developing semi-solid-state batteries with oxide-based solid electrolytes for EV applications. Some next-generation battery startups in the US and other regions are entering the semi-solid-state battery sector, targeting aerospace and other high-added-value applications.

1. Semi-Solid-State Battery Technology

1-1. Semi-Solid-State Batteries

There is no clear definition of a semi-solid-state battery. As shown in Figure 1, they are generally classified as solid-liquid hybrid type, which utilizes both liquid and solid electrolytes, and gel polymer type or clay type, where electrolytes and electrode materials are gelled or made clay-like.

Figure 1: Definition and classification of semi-solid-state batteries

Classification	Definition	Characteristics	Representative companies
Solid-liquid hybrid type	A technology that uses different electrolytes for the cathode and anode, such as employing a solid electrolyte on the anode side and a liquid electrolyte on the cathode side	Enables the use of high-performance anodes, achieving higher energy density. Offers higher safety while utilizing existing liquid-based LIB manufacturing technologies	WELION (China), SES AI (US)
Gel-polymer type, clay type	A type where conventional electrolytes are gelled or where electrolytes are mixed into the electrode materials on the cathode or anode to form a clay or gel-like structure	Lowers the risk of leakage and ignition compared to conventional liquid-based batteries by reducing fluidity	Kyocera (Japan), 24M Technologies (US)

Source: Compiled by MGSSI based on various data

The solid-liquid hybrid type can leverage existing LIB manufacturing processes and offers higher energy density than liquid-based LIBs, making it a focus of development and implementation, particularly among Chinese companies. The gel polymer and clay types offer higher safety, lower raw material costs, and simplified manufacturing processes. A representative company in the space is 24M Technologies (US), which has developed a thick-film electrode using clay-like materials in a simple structure. By eliminating binders and reducing the volume of current collectors and separators, the company has increased energy density per unit volume of battery cells.

1-2. Performance and Main Benefits

Figure 2 shows a comparison of key materials and performance between semi-solid-state LIBs, liquid-based LIBs, and all-solid-state LIBs.

Figure 2: Comparison of liquid-based LIB, semi-solid-state LIB (Note 1), and all-solid-state LIB

	Liquid-based LIB	Semi-solid-state LIB	All-solid-state LIB
Cathode	NMC (Note 2), LFP (Note 3)	NMC, high-nickel NMC (Note 4), LFP	NMC, high-nickel NMC, LMR (Note 5)
Anode	Graphite, silicon-based	Graphite, silicon-based, lithium metal	Graphite, silicon-based, lithium metal
Separator	Required	Required	Not required
Electrolyte	Comprises more than 10% of battery weight. Includes lithium ion salts, flammable organic solvents, and additives.	Mixture of solid electrolytes and a small proportion of liquid electrolyte (less than 10% of battery weight)	100% solid electrolytes (mainly sulfide, oxide, and polymer)
Energy density	Up to 300 Wh/kg	300 Wh/kg or more	350 - 500Wh/kg
Voltage range	2.7 - 4.2V	2.7 - 4.2V	5V or more
Safety	Risk of ignition	Higher than liquid-based LIB	Highest
Implementation stage	Implemented	Initial stage	Expected implementation after 2027
Cost	Low	High	High
Advantages	Mature technology; low-cost large-scale production possible	Higher performance and safety than liquid-based LIBs; some existing liquid-based LIB production lines can be used.	Significantly higher performance and safety compared to current liquid-based LIBs possible
Disadvantages	Uses organic electrolytes, posing ignition risk; energy density nearing its limit	Performance is inferior to all-solid-state batteries; ignition risk not fundamentally eliminated.	New materials with higher performance are under development. Large-scale mass production technology is still being established as manufacturing process differs from liquid-based LIBs.

Note 1: Example based on solid-liquid hybrid type
Note 2: NMC: A ternary cathode material primarily composed of Nickel (Ni), Manganese (Mn), and Cobalt (Co)
Note 3: LFP: Lithium iron phosphate ($LiFePO_4$) cathode
Note 4: High-nickel NMC: A ternary cathode with a high nickel content
Note 5: LMR: Lithium-rich manganese-based cathode
Source: Compiled by MGSSI based on various data

Generally, batteries with liquid electrolyte content of 10% or less of the total battery weight are classified as semi-solid-state LIBs. By reducing the use of liquid electrolytes, semi-solid-state LIBs lower the risk of ignition. Additionally, the use of solid electrolytes and high-performance anodes is expected to enable an energy density exceeding 300 Wh/kg, which is considered the upper limit of liquid-based LIBs. Another advantage is that semi-solid-state LIBs can be manufactured using existing liquid-based LIB production lines, making mass production easier. However, semi-solid-state LIBs use an electrolyte containing a small amount of flammable organic solvent, meaning that the risk of ignition under abnormal heat conditions cannot be completely eliminated. Additionally, the increased cost of solid electrolytes and high-performance anode materials is expected to be a bottleneck for widespread adoption. For example, the semi-solid-state LIB package adopted by Chinese EV startup NIO is estimated to cost 1.7 to 2.2 CNY/Wh (approx. 36 to 46 JPY/Wh[45]), which is significantly higher than mainstream nickel manganese cobalt (NMC) batteries at around 0.73 CNY/Wh (approx. 15 JPY/Wh). Due to this high cost, NIO has opted not to sell the battery but to provide it exclusively on a rental basis.

2. Notable Trends

As of 2024, many Chinese companies, along with some US and South Korean firms, have announced plans to implement semi-solid-state LIBs (Figure 3).

Figure 3: Development status of semi-solid-state batteries by major companies

Battery manufacturer	Mass production	Main component			Cell energy density (Wh/kg)	EV battery pack development status		
		Cathode	Anode	Electrolyte		Capacity (kWh)	Range (km)	Partnerships, etc.
WELION (China)	2023	High-nickel NMC	Si/C anode	Oxide and polymer-based	360	150	1,000	Installed in the NIO ET7, a premium model from the Chinese EV startup NIO
	2025	High-nickel NMC	Si/C anode	Oxide and polymer-based	300	n/a	600 - 1,000	Planned for a new model from, Lutetium Wei Technology, an EV subsidiary of JAC (a mid-sized Chinese state-owned automaker)
GanFeng Lithium (China)	2023	NMC	Graphite	Oxide-based	240 - 270	90	530	Installed in export EV models from SERES (China)
	TBD	NMC	Li metal	Oxide-based	400	n/a	n/a	This is its second-generation semi-solid-state battery under development
Qingtao Energy Development (China)	2024	High-nickel NMC	Si/C anode	Oxide and polymer-based	368	130	1,000	Installed in IM L6 from SAIC Motor (China). Developing a second-generation version using oxide, halide, and polymer electrolytes
Dongfeng Motor (China)	2025	NMC	Graphite	Oxide-based	350	n/a	n/a	Plans to implement in own vehicles
	TBD	High-nickel NMC	Li metal	Unknown	405	n/a	n/a	
FARASIS (China)	2025	NMC	Si/C anode	Unknown	300 - 400	n/a	n/a	Strategic partnership with FAW (China) and JAC (China)
24M Technologies (US)	2025	NMC	Si-based / Li	Unknown	391	n/a	1,600	Proprietary dry electrode, cell & packaging technology, and electrolyte/separator integration
QuantumScape (US)	2025	LFP/NMC	Li metal	Oxide-ceramic	300	n/a	n/a	Mass production planned in collaboration with Volkswagen (Germany)
Enpower Greentech (US)	2025	NMC	Li metal	Sulfide-based	292 - 320	n/a	n/a	Targeting industrial, drone, eVTOL*, and other applications
LG Energy Solution (South Korea)	2026 - 2027	Unknown	Unknown	Oxide and polymer-based	n/a	n/a	n/a	Adopting a bipolar structure
SVOLT (China)	2026	NMC	Graphite	Sulfide-based	266	n/a	n/a	For vehicles with large-capacity battery packs
Talent New Energy (China)	2027	NMC	Graphite	Oxide-based	n/a	n/a	n/a	Development with Changan Automobile (China)
StoreDot (Israel)	2028	High-nickel NMC	Si-based	Organic-inorganic composite solid electrolyte	400	n/a	n/a	Joint development with Polestar (Sweden). Aiming for 100 miles (about 160 km) of range with a 3-minute charge
Gotion (China)	TBD	NMC	Graphite	Unknown	360	160	1,000	Said to be developing in collaboration with EV and eVTOL (electric vertical takeoff and landing) companies
ZENERGY (China)	TBD	NMC	Si-based	Unknown	300 - 330	170	1,000	Conducting EV tests and collaborating with eVTOL companies
LISHEN (China)	TBD	High-nickel NMC	Si-based	Oxide-based	402	n/a	n/a	Development underway for long-range EVs and eVTOLs

Note: eVTOL：Electric Vertical Take-Off and Landing aircraft
Source: Compiled by MGSSI based on various company materials

[45] Exchange rate: 1 CNY = 21 JPY

Chinese companies, which already hold a significant share in the liquid-based LIB market, perceive breakthroughs in all-solid-state batteries by foreign companies as a major threat, as they could disrupt the market where liquid-based LIBs remain the dominant product. However, Chinese battery manufacturers lag behind Japan and South Korea in solid electrolyte development, making it difficult to compete in the race for all-solid-state battery commercialization. Accordingly, they are adopting a two-step strategy: first, implementing semi-solid-state batteries, which have relatively low mass-production hurdles, to enhance their technological capabilities, and then ultimately achieving all-solid-state battery commercialization. Also, many Chinese companies are focusing on oxide-based solid electrolytes, which offer high stability and safety. However, these electrolytes have low ion conductivity and rigid material properties, making it challenging to bond them with active materials, thereby delaying full commercialization of all-solid-state batteries. Semi-solid-state batteries that incorporate liquid or polymer electrolytes can overcome these challenges more easily, enabling earlier practical implementation. Envisaging use in EVs, many Chinese companies are working alongside EV manufacturers to implement semi-solid-state batteries using oxide-based electrolytes, which offer longer driving ranges than liquid-based LIBs.

Some next-generation battery technology startups in the US and other regions are entering into semi-solid-state battery development, leveraging their proprietary technologies such as solid electrolytes and high-performance lithium metal anodes, while also preparing for the full-scale roll-out of all-solid-state batteries in the future. The expected applications for these semi-solid-state batteries under development extend beyond EVs to include high-added-value sectors such as eVTOL and aerospace applications.

On the other hand, sulfide-based solid electrolytes, in which Japanese companies lead globally, have high ionic conductivity and soft material properties, making it largely unnecessary to develop them into semi-solid-state batteries, as they are often directly implemented as all-solid-state batteries.

3. Future Prospects

According to the Chinese market research firm GGII, China's semi-solid-state battery shipments in 2024 are expected to reach 7 GWh (million kWh), equivalent to 117,000 EV[46], and grow to 65 GWh by 2030. While it remains to be seen how much market share can be expanded due to cost-related and other challenges, industry efforts are driving the development of solid electrolytes, high-performance anodes, and other technologies that can later be applied to all-solid-state batteries, while also contributing to the prolongation of the existing liquid-based LIB industry, ultimately benefiting the evolution of the Chinese battery industry. On the other hand, unlike Chinese companies, which focus on incremental improvements, Western, Japanese, and other foreign battery companies aim to differentiate themselves through higher performance, making the creation of demand for high-performance batteries a key competitive factor.

Furthermore, if future technological advancements enhance the safety and cost-effectiveness of semi-solid-state batteries, they could secure a stable market share in the mid-to-long term, potentially delaying the adoption of all-solid-state batteries. As a result, close attention should be paid to the implementation and technological development of semi-solid-state batteries.

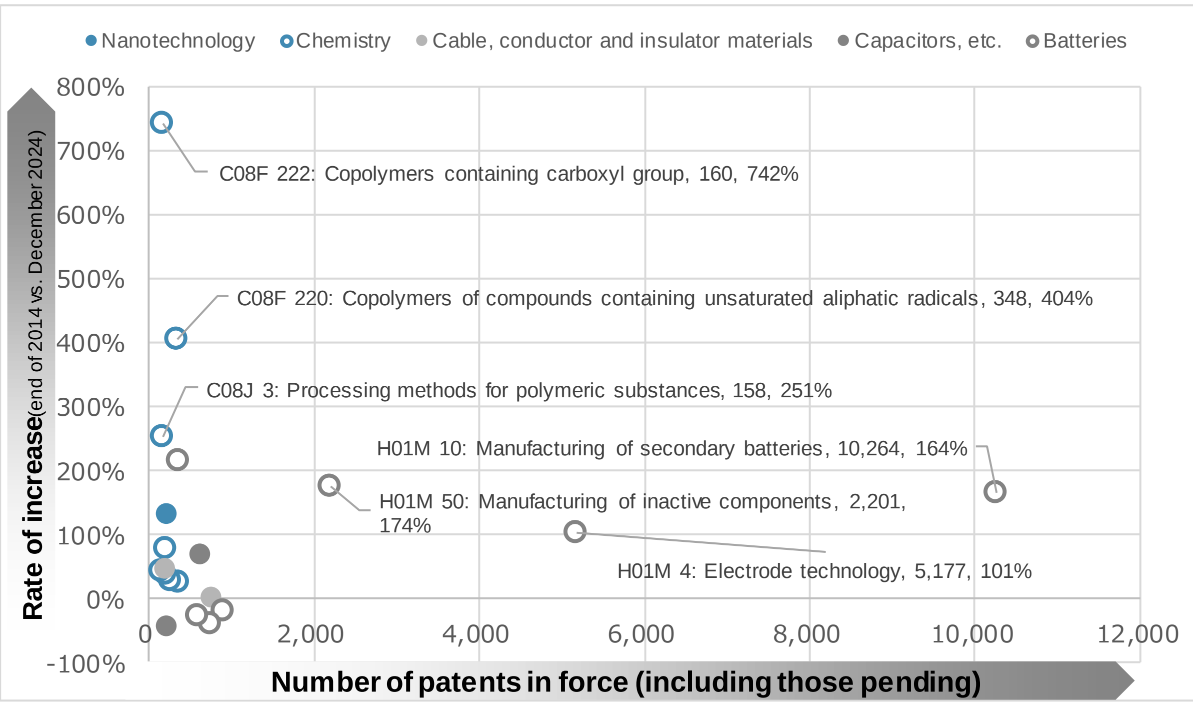
[46] Assuming a battery package capacity of 60 kWh.

IP Analysis of Semi-Solid-State Battery Technology

Keywords closely related to this technology, such as “(semi) polymer,” “gel,” and “electrolyte,” as well as International Patent Classification (IPC) codes related to secondary batteries, were identified (11,030 in force as of December 2024, including pending applications[47]), and an analysis was conducted based on technology classifications and top players.

Figure 4 compares the number of patents in force related to semi-solid-state batteries and their growth rates. The horizontal axis represents the number of patents in force, while the vertical axis shows the growth rate by comparing the number of patents as of December 2024 with those at the end of 2014. The results indicate that interest is increasing, particularly in secondary batteries and electrodes.

Figure 4: Number of patents in force and growth rate (by technology category)

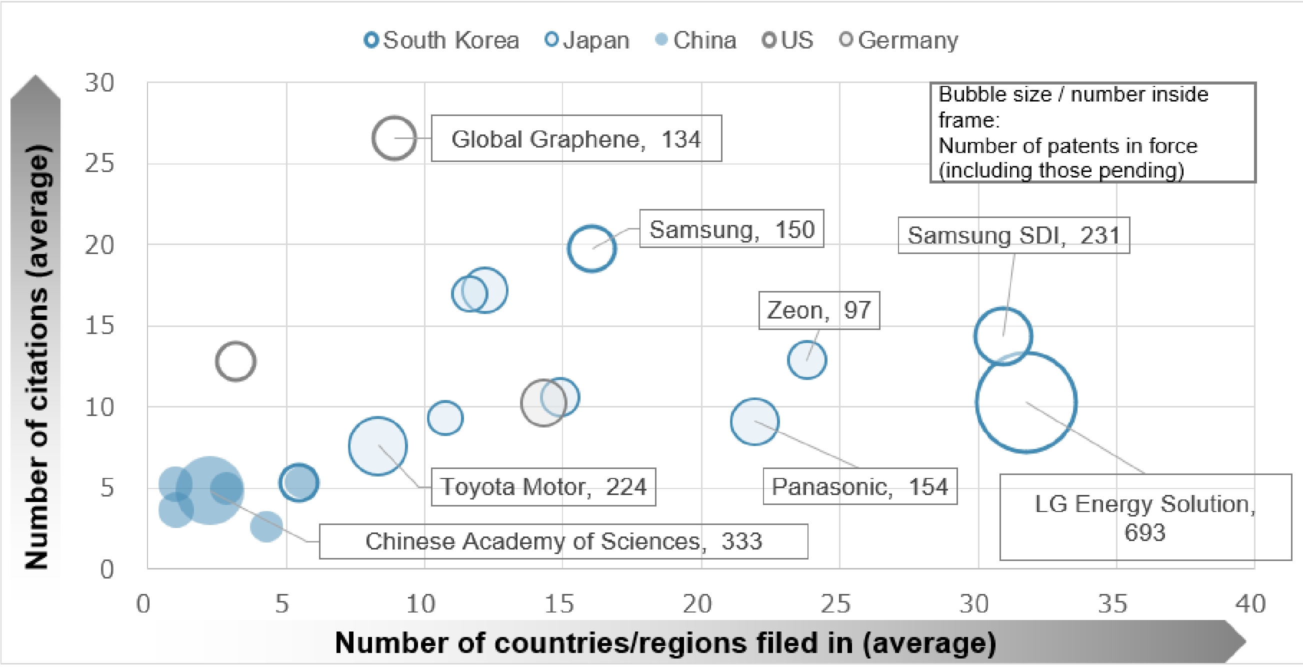


Source: Compiled by MGSSI based on data from LexisNexis PatentSight

Figure 5 compares the top players in terms of the number of patents related to semi-solid-state batteries. The bubble size represents the number of patents in force, the horizontal axis indicates the average number of countries or regions where applications were filed, and the vertical axis represents the average number of citations, reflecting the technological impact. The results reveal that LG Energy Solution (South Korea) leads significantly, surpassing the second-ranked company by a wide margin in patent count, demonstrating its aggressive investment in R&D. The company is also engaged in intellectual property activities in battery technology, such as strengthening patent protection, enforcing patent infringement measures, and leading a patent pool initiative to ensure fair patent licensing.

[47] The total number of patents includes both filed patents and granted patents that have completed the examination process and are enforceable as intellectual property rights.

Figure 5: Number of patents in force, number of countries/regions filed in, and number of citations (by top players)



Source: Compiled by MGSSI based on data from LexisNexis PatentSight

Chiplets
—How New Semiconductor Architectures Are Reshaping the Competitive Landscape—

Reina Ogawa
Industry Innovation Dept.
Ryusuke Ishiguro (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

Entering 2024, a series of product announcements reflected advancements in chiplet technology, including Intel's (US) Gaudi 3, a semiconductor for generative AI, and Apple's (US) R1 chip for the Apple Vision Pro headset (manufactured by TSMC (Taiwan)).

With the release of the UCIe 2.0 specifications in August and support from key industry players such as ARM (UK), Intel, and TSMC, die-to-die and chip-to-chip connection standards have been established, lowering the barriers to adopting the technology, marking the beginning of its full-scale proliferation.

Summary

- The spread of chiplet technology is progressing, starting with high-performance computing, due to the balance between required functionality and cost.
- Chiplet technology is oriented toward development through standardization and cross-industry collaboration, leading to shifts in the supply chain and opportunities for non-linear growth for new entrants, particularly in design and front-end processes.

1. What is a Chiplet?

Chiplet is defined by IEEE[48] as a semiconductor industry standard as follows: "Chiplet is not a package type, it is part of a packaging architecture. It is an integrated circuit block that has been specifically designed to communicate with other chiplets, to form larger more complex ICs.[49]"[50] Since chiplets may be difficult to visualize by this definition alone, the following section provides additional context and explains the evolution leading up to chiplet technology.

1-1. Semiconductor Integrated Circuit Blocks and SoCs[51]

A semiconductor integrated circuit block is a collection of circuits designed to perform a specific function. In conventional smartphones, semiconductors enable functions such as communication essential for network and phone use, data storage (memory), and information processing (processor). For applications where size and communication latency are not major concerns, each semiconductor

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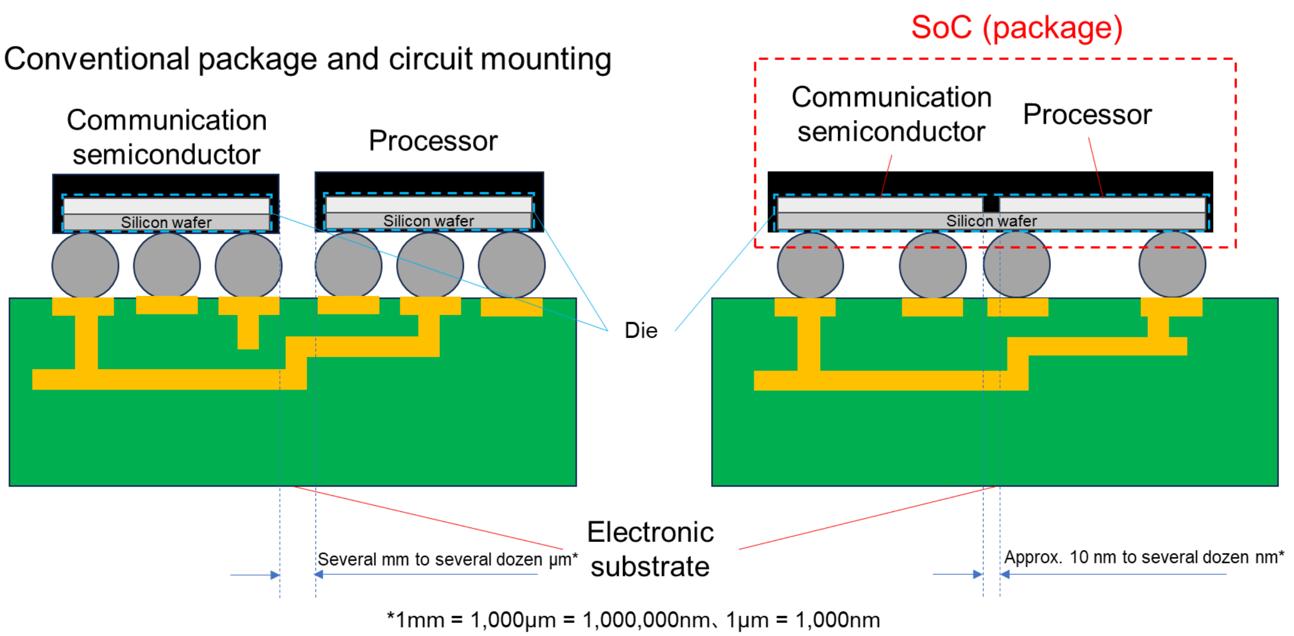
48 The Institute of Electrical and Electronics Engineers, Inc. This is the world's largest nonprofit organization for electrical and electronics professionals, dedicated to research in electronics and related fields.
49 The Japan Electronics and Information Technology Industries Association (JEITA) defines a chiplet as "a silicon (Si) component, typically ranging in size from a few millimeters to several tens of millimeters square, on which transistors, diodes, resistors, capacitors, and other circuit elements are integrated and interconnected to function as an electronic circuit with a specific purpose." (tentative translation from Japanese source) This definition is adopted and used in this report.
50 Chiplet Definition from the IEEE Electronics Packaging Society website
51 System-on-Chip

integrated circuit block is individually packaged and mounted on an electronic substrate (Figure 1, left). However, in smartphones and other applications requiring compact size and high-speed processing, semiconductor miniaturization has advanced to the point where the communication distance between circuit blocks (i.e., speed) has become a bottleneck to improve performance. This has created a need for greater integration of these functions. System-on-chip (SoC) technology became widely adopted to address this issue. SoCs integrate multiple semiconductor integrated circuit blocks with different functions onto a single silicon wafer (Figure 1, right).

Figure 1: Illustration of conventional packaging and mounted circuit, and SoC

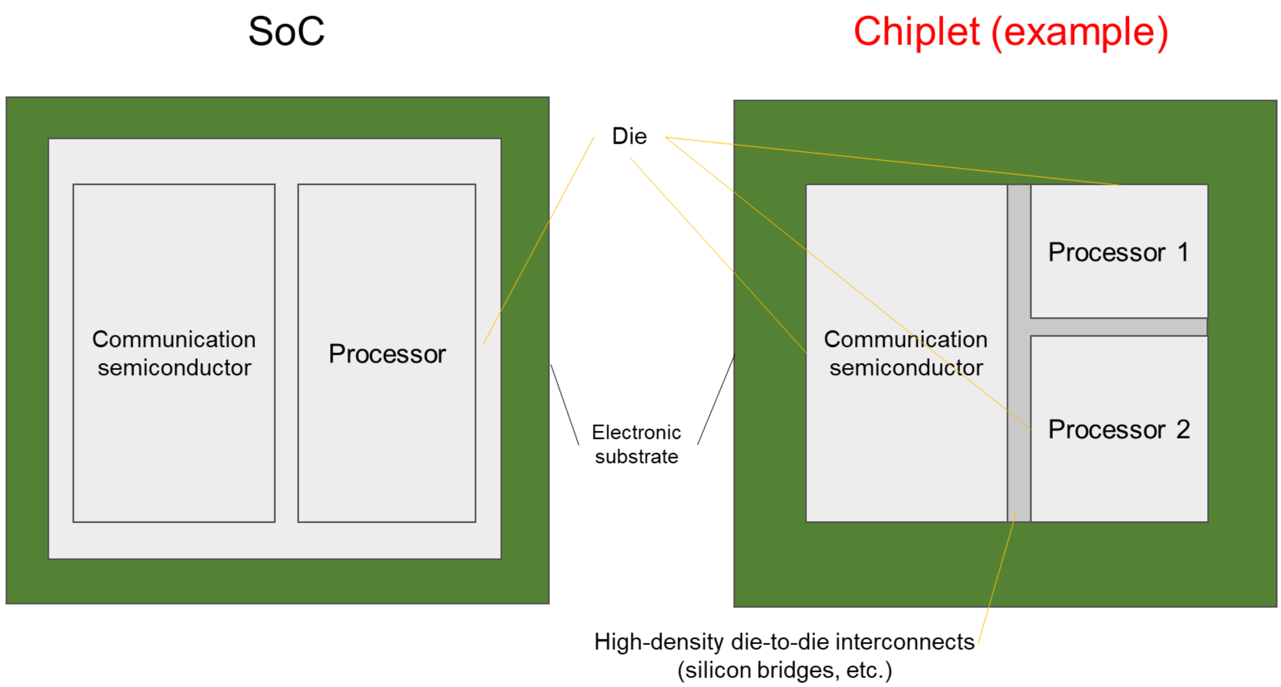


Source: Compiled by MGSSI based on various sources

1-2. From SoCs to Chiplets

While SoCs integrate all functions into a single die[52], chiplets take a modular approach by manufacturing separate dies for each function and connecting them with high-density interconnects on a scale comparable to SoC communications (Figure 2).

Figure 2: Illustration of SoC and chiplet

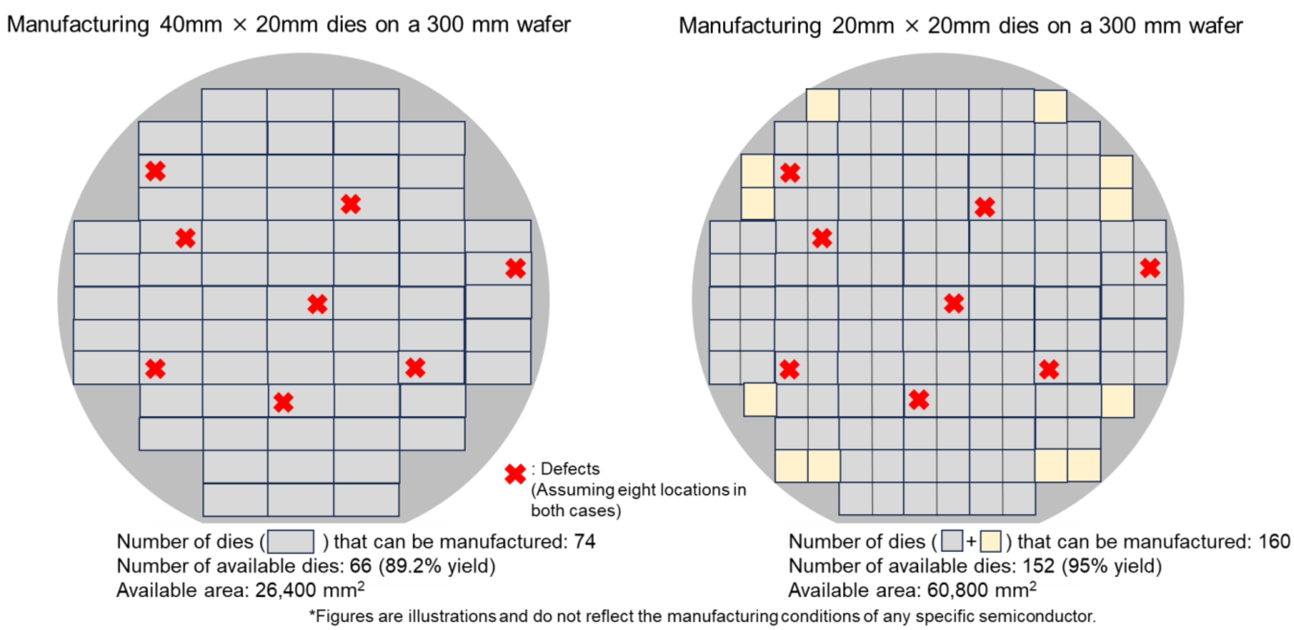


Source: Compiled by MGSSI based on various sources

[52] This report adopts the term die, a term that predates the emergence of chiplet technology. Intel refers to the dies that make up a chiplet as "tiles" (example). Meanwhile, IEEE, academia (example) etc. use the term "functional block" to contrast with chiplets, which are semiconductor integrated circuit blocks.

In the semiconductor industry, new technologies are only adopted if they provide cost-effective functionality. However, the benefits of miniaturization, which have historically driven both size and cost reduction, have been diminished by the rapid rise[53] in design and manufacturing costs. Additionally, the rapid spread of generative AI and the arrival of the CASE[54] era for automobiles have led to an increase in SoC sizes. This has introduced new challenges, including rising design costs, fewer dies per wafer reducing manufacturing efficiency, and a larger die area discarded per defect (Figure 3). Against this backdrop, chiplets, which involve manufacturing dies separately using the most suitable process for each function and then interconnecting them, are becoming advantageous in terms of both performance and cost.

Figure 3: Illustration of die size, number of dies per wafer, and yield loss due to defects



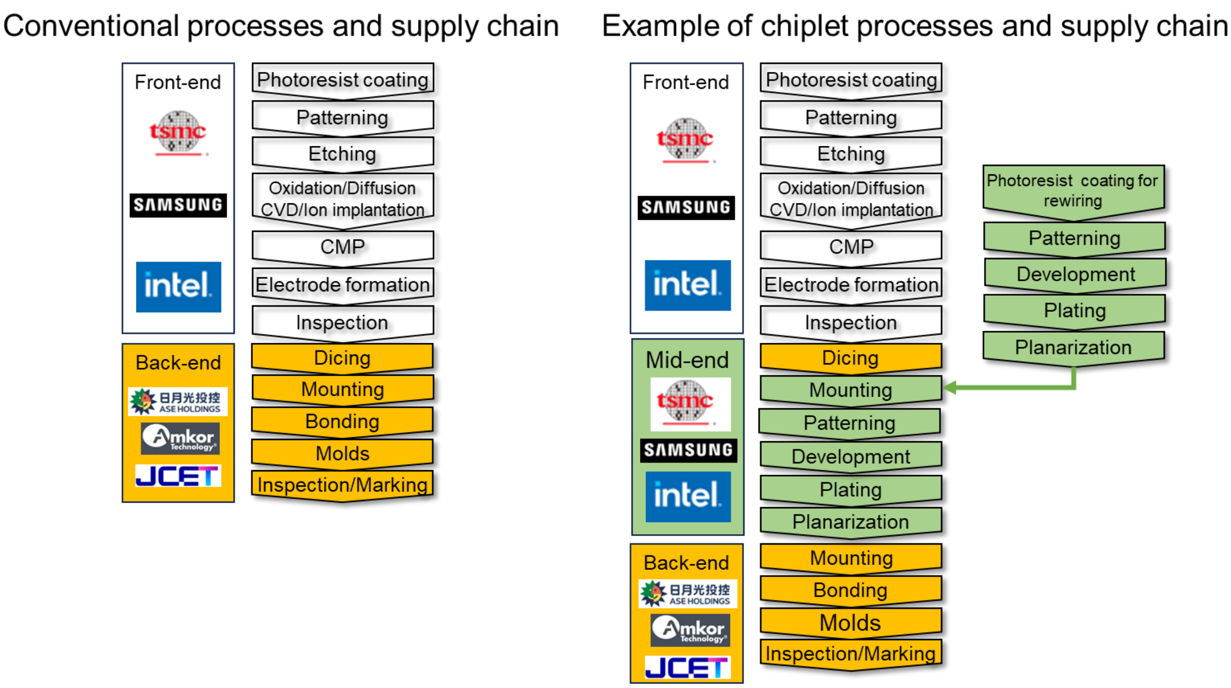
Source: Compiled by MGSSI based on various sources

[53] A representative value is TSMC's price per wafer by process node (generation). See articles by Tech Power Up and Tom's Hardware for data. Data on design costs are available in Semiconductor Engineering.
[54] The emerging trend in the automotive industry for vehicles to be connected (wireless communication with the cloud and other vehicles), autonomous/automated, shared/service (mobility services and car-sharing), and electric.

1-3. Changes Brought About in Packaging Structure, Processes, and Supply Chain by Chiplets

Usually, each die cut from a wafer is encapsulated in resin or ceramic and electrically connected to external components via conductors such as pins in a later stage. In contrast, chiplet technology first establishes die-to-die electrical connections before encapsulation. As a result, new mid-end processes are required between the front-end and back-end processes, which were conventionally separated in semiconductor manufacturing (Figure 4). These mid-end processes are handled by front-end players such as TSMC, Samsung (South Korea), and Intel. In 2024, software vendors focusing on front-end processes, such as Cadence (US), moved to acquire CAE[55] software companies to support mid-end process design.

Figure 4: Process and supply chain changes due to chiplets



Source: Compiled by MGSSI based on various sources

2. Notable Trends

Established in 2022, the Universal Chiplet Interconnect Express (UCIe) Consortium released the UCIe 2.0 specifications in August 2024 to standardize die-to-die and chip-to-chip connections. With specifications now established for both horizontal and vertical (stacked) connections as well as for product management, the barriers to chiplet adoption have been significantly lowered, marking the beginning of widespread adoption. In addition to Intel, which has been at the forefront of launching related products, companies such as Cadence; the fabless

[55] CAE (Computer-Aided Engineering) is widely used in large-scale design fields larger than the semiconductor front-end process, such as mechanical and equipment engineering. CAE software is commonly used for simulations involving temperature changes due to heating and structural deformation under applied loads. On January 16, 2024, Synopsys (US) announced the acquisition of Ansys (US), and Cadence (US) announced its acquisition of BETA CAE (US) on March 5, 2024.

companies[56] AMD (US), ARM (UK), Alphawave Semi (UK), Global Unichip[57] (Taiwan), Google (US); and semiconductor testing equipment manufacturer Advantest (Japan) have issued statements in support of this advancement[58]. Alongside these eight companies, the growth of six startups that have also expressed support (Figure 5) is highly anticipated.

Figure 5: Notable startups in chiplet technology

Company name	Headquarters location	Overview	URL
Astera Labs	Santa Clara, California, US	Founded by Jitendra Mohan, Sanjay Gajendra, and Casey Morrison, formerly of Texas Instruments. A fabless company that provides technology to maintain and streamline data flow for data centers. Selected as one of the "Next Billion-Dollar Startups" in 2022.	https://www.asteralabs.com/
Ayar Labs	San Jose, California, US	A fabless company that has developed TeraPHY™, a chiplet for optical data transfer. By integrating optical communication within the chiplet, it claims to achieve 5–10 times the bandwidth of conventional data transfer. It also reduces latency to one-tenth while consuming one-quarter to one-eighth of the power. Nvidia has invested in this company.	https://ayarlabs.com/
Blue Cheetah	Sunnyvale, California, US	Offers the BlueLynx D2D IP, which flexibly supports chip-to-chip interconnects for 16nm to 3nm process nodes. Tom Kelly, the company's COO, is among several members from Cadence's analog division.	https://www.bcanalog.com/
Eliyan	Santa Clara, California, US	Developed NuLink™, a technology that enables high-speed chiplet interconnects on standard organic substrates without using an interposer. Completed designs for 5 nm and 3 nm process nodes and offering IP solutions.	https://eliyan.com/
eTopus	San Jose, California, US	Offers ePHY™, a solution for minimizing data transfer losses at different data transfer and interconnect points for data centers, 5G communications, and enterprise IT infrastructure.	https://etopus.com/
Kandou Bus	Saint-Sulpice (suburb of Lausanne), Switzerland	Provides technology to minimize data transfer errors and latency between electronic components. Offers high-speed transmission technologies for the latest USB standards and PCIe, a high-speed transmission standard for external memory, etc., as well as Glasswing™ IP, which enables highly efficient interconnections between electronic components in AR/VR glasses.	https://kandou.com/about/

Source: Compiled by MGSSI based on company websites

3. Future Prospects

The first-generation chiplet technology, which connects CPU and GPU dies, memory, and multiple dies using silicon interconnects, is already being adopted in high-performance computing semiconductors[59], including those for generative AI by Nvidia (US), AMD (US), and Intel (US). As die interconnects transition from the current 16nm to 12nm process to the 7nm process, the industry is expected to shift toward "ghiplets," a model in which GPUs are functionally partitioned and manufactured as chiplets[60].

Within five years, chiplet adoption in automotive semiconductors is also expected to begin. Advanced SoC Research for Automotive (ASRA)[61] is developing automotive semiconductors that apply chiplet technology, aiming

[56] A fabless semiconductor company designs and sells semiconductor products or licenses intellectual property (IP) relying on contract manufacturers, without owning its own manufacturing facilities. Companies that specialize exclusively in licensing IP are referred to as IP vendors/partners, but for simplicity, this report includes them under the term fabless.

[57] Taiwan Semiconductor Manufacturing Company (TSMC) is its largest shareholder. Leveraging a close partnership with TSMC, it leads the industry in design using cutting-edge process and packaging technologies.

[58] See to the UCIe Consortium website for official statements from each company: https://www.uciexpress.org/_files/ugd/0c1418_74c8a7bba0714b489dd54ef658c1c968.pdf

[59] From the release of the GP100 graphics processor incorporating a GPU for VR and AI applications in 2016, to the Blackwell GPU, announced in March 2024 and specialized for generative AI, Nvidia has adopted TSMC's chip on wafer on substrate (CoWoS) technology, which connects GPU and memory (HBM) via a silicon interposer. AMD's Instinct MI300 series, a GPU released in December 2023, also utilizes CoWoS. Intel's Gaudi 3, a chip announced in April 2024 for AI training, employs embedded multi-die integrated bridge (EMIB) technology, where two dies are connected via a silicon bridge, allowing them to function as a single chip.

[60] Intel's Ponte Vecchio GPU, announced in September 2022 for high-performance computing, is considered a benchmark ghiplet product, integrating 47 dies within a single package using EMIB and 3D interconnects. This approach is based on a balance between efficient utilization of 7nm EUV lithography and the costs associated with die scaling and miniaturization.

[61] Established on December 1, 2023, the organization currently comprises Subaru (Japan), Toyota (Japan), Nissan (Japan), Honda (Japan), Mazda (Japan), Denso (Japan), Panasonic Automotive Systems (Japan), Socionext Inc. (Japan), Cadence Design Systems, Japan (Japan), Nihon Synopsys (Japan), Mirise Technologies (Japan), and Renesas Electronics (Japan).

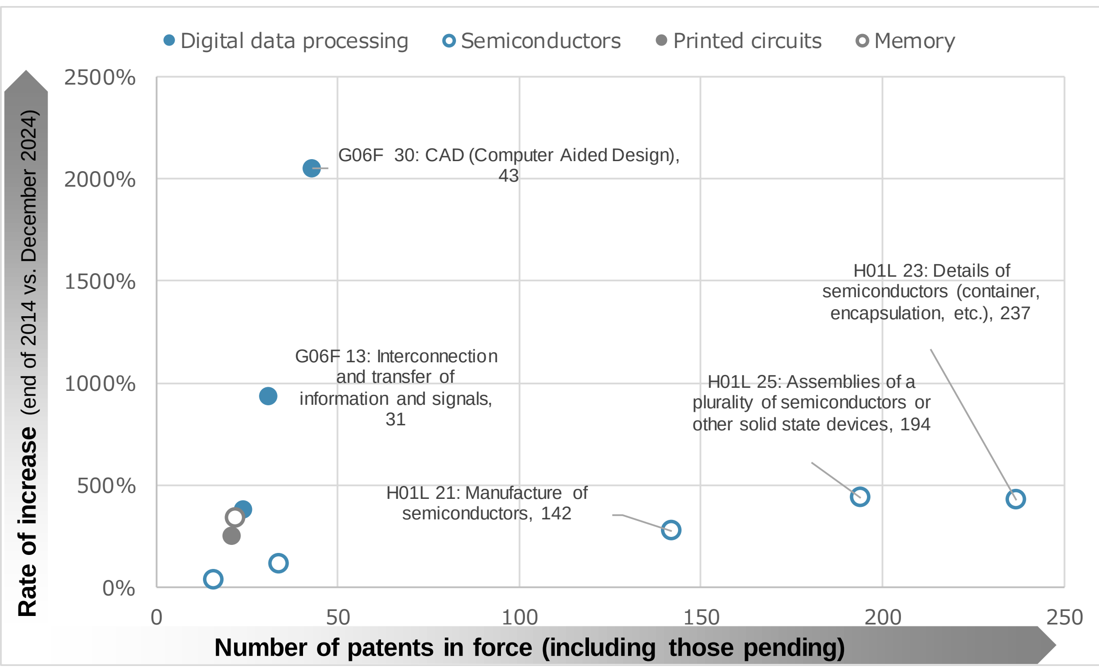
for installation in mass-produced vehicles from 2030. Chiplet technology is also anticipated to play an important role in the advancement of CASE vehicles.

IP Analysis of Chiplets

Keywords such as “chiplet” that are closely related to this technology and International Patent Classification (IPC) codes associated with semiconductors and computer aided design (CAD) were identified (289 in force as of December 2024, including pending applications[62]) and an analysis was conducted based on technology classifications and top players.

Figure 6 compares the number of patents in force chiplets and their growth rates. The horizontal axis represents the number of patents in force, while the vertical axis shows the growth rate by comparing the number of patents in force as of December 2024 with those at the end of 2014. These results indicate a growing focus on details of semiconductors (H01L30) and module-related technologies (H01L25). In recent years, there has also been a significant increase in the number of patents related to design tools (electronic design automation: EDA) classified under CAD (G06F30).

Figure 6: Number of patents in force and growth rate (by technology category)

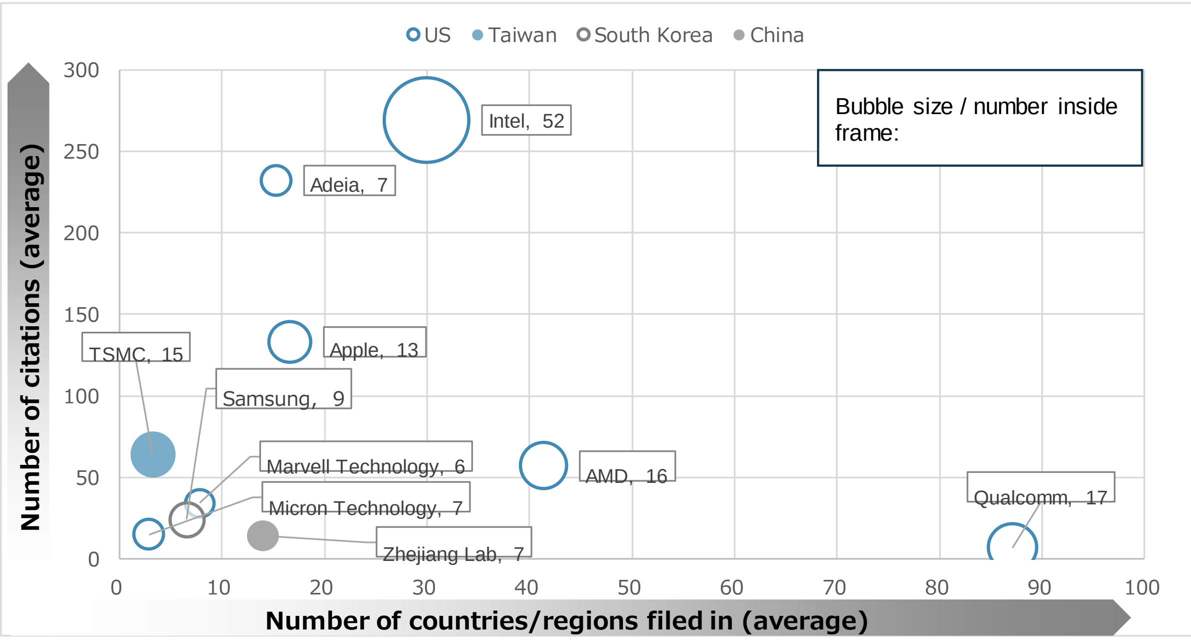


Source: Compiled by MGSSI based on data from LexisNexis PatentSight

[62] The total number of patents includes both filed patents and granted patents that have completed the examination process and are enforceable as intellectual property rights.

Figure 7 compares the top players in terms of the number of patents related to chiplets. The bubble size represents the number of patents in force, the horizontal axis indicates the average number of countries or regions where applications were filed, and the vertical axis represents the average number of citations, reflecting the technological impact. The results show that US companies dominate the top ranks, highlighting their significant influence in chiplet technology. Leading the field by a considerable margin, Intel has filed seven patents since 2022 that are highly relevant to the UCIe standard, as they explicitly mention “Universal Chiplet Interconnect Express” or “UCIe” in their documentation. Although all these patents are still under review, they reflect Intel’s strong commitment to this technology.

Figure 7: Number of patents in force, number of countries/regions filed in, and number of citations (by top players)



Source: Compiled by MGSSI based on data from LexisNexis PatentSight

Recycling Technology Based on Biomanufacturing
—Plastic Recycling with Enzymes Utilized by Smart Cells—

Kazuko Sato
Industry Innovation Dept.
Yui Matsuura (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

Toward the goal of achieving carbon neutrality by 2050, the Ministry of Economy, Trade and Industry (METI) established the Green Innovation Fund in 2021. This fund aims to increase annual public and private investment to JPY 3 trillion by 2030. Additionally, initiatives such as the Bio Manufacturing Revolution Promotion Fund, with a budget of JPY 300 billion, are being promoted, reflecting the growing momentum for public-private research and development efforts. Meanwhile, in Europe and the United States, proactive policies are being formulated against the backdrop of decarbonization and the promotion of a circular economy. In particular, plastic recycling technology based on bio-manufacturing is attracting increasing attention, with companies intensifying efforts toward commercialization.

Summary

- Utilizing enzymes produced by genetically modified microorganisms (smart cells) based on biomanufacturing has enabled plastic recycling with lower environmental impact while maintaining a certain level of quality.
- Despite the challenge of mass production of enzymes, technologies are being established to resolve this through the use of AI.

1. What is Biomanufacturing?

1-1. Biomanufacturing

Biomanufacturing is an emerging field that aims to address social issues such as global warming by using genetic engineering to alter the quantity and properties of substances produced by microorganisms. This approach has been officially incorporated into the Japanese government's Grand Design for a New Form of Capitalism[63]. Internationally, this field is also a key focus. In the EU, a policy document aimed at strengthening biotechnology and biomanufacturing within the region was published in March 2024[64]. In the United States, a presidential executive order was issued in September 2022 to promote the domestic bio industry, signaling a national effort to enhance competitiveness in this sector.[65]

Biomanufacturing refers to the creation of genetically modified microorganisms (smart cells) that enable the efficient production of useful substances and the execution of conventional chemical reactions under conditions that are less harmful to the environment. These smart cells are utilized for material production.

The development of smart cells involves an iterative process that includes the following steps.

[63] Grand Design and Action Plan for a New Form of Capitalism 2024 Revised Version
[64] The European Commission Releases Policy Document on Strengthening the Bioindustry Within the Region (EU) | Business News – JETRO Overseas News
[65] President Biden Signs Executive Order to Promote the Domestic Bioindustry (US) | Business News – JETRO Overseas News

Design: Create a blueprint for genetic modifications and metabolic pathway alterations.

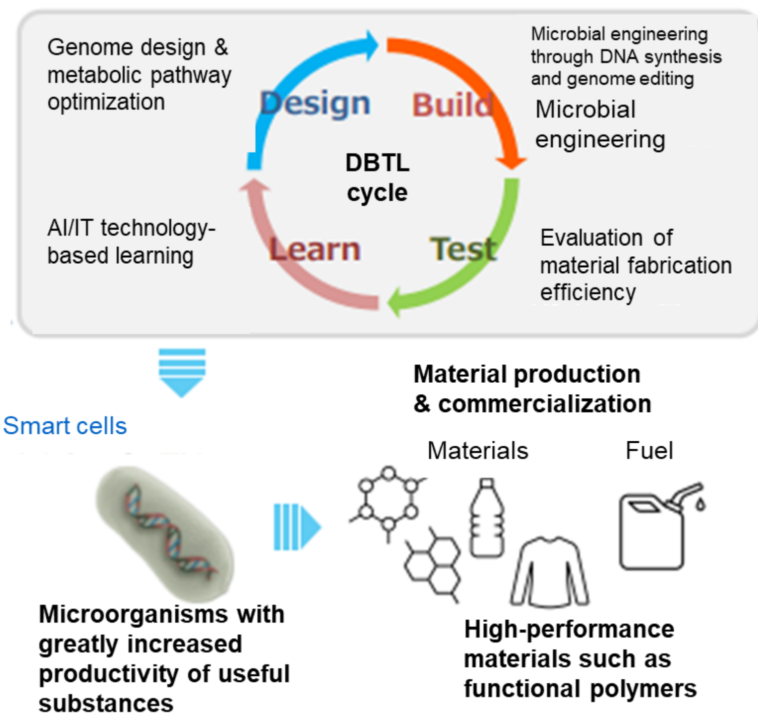
Build: Modify the genes based on the design to produce smart cells.

Test: Evaluate the functionality of the created smart cells.

Learn: Analyze evaluation data to identify areas for improvement and design more optimized smart cells.

This series of processes is known as the DBTL cycle (Design, Build, Test, Learn). By continuously iterating through this cycle, it becomes possible to develop microorganisms capable of efficiently producing valuable substances (see Figure 1).

Figure 1: Conceptual diagram of biomanufacturing



Source: Compiled by MGSSI based on Realization of the Biomanufacturing Revolution, Ministry of Economy, Trade and Industry, April 19, 2023
Compiled by MGSSI based on
https://www.meti.go.jp/shingikai/sankoshin/shin_kijiku/pdf/014_05_00.pdf

1-2. Application of Biomanufacturing to the Recycling Sector

Conventional biomanufacturing typically utilizes biomass for material production. However, in recent years, there has been a growing number of research reports on plastic recycling technologies using enzymes produced by smart cells developed through this technology. Being biological molecules, enzymes react only with specific molecular structures and chemical bonds. Compared to mechanical and chemical recycling, this characteristic gives enzyme-based recycling higher selectivity. As such, enzymes basically do not react with impurities, enabling more efficient recycling. Unlike traditional chemical recycling, which requires high temperatures, high pressures, and chemical agents, enzyme-based recycling can proceed under ambient temperature and pressure, thereby reducing energy consumption. Furthermore, while mechanical recycling often leads to physical degradation of material properties, enzyme-based recycling can yield recycled materials with quality close to the original.

1-3. Challenges in Applying Biomanufacturing to the Recycling Sector

Since enzymes are biologically derived, their reaction speed is slower compared to conventional technologies, precise temperature and pH control is required, and the production cost is high because mass production methods for enzymes have not been established. Although the DBTL cycle is being utilized to develop higher-performance enzymes to address these issues, further technological advancements are expected to enhance efficiency and reduce costs.

2. Notable Trends

2-1. Examples of Plastic Recycling Using Biomanufacturing

A leading example is Carbios (France), which is developing an enzyme-based technology to break down PET into ethylene glycol and terephthalic acid (TPA). The company plans to launch a commercial plant in 2026. Kirin Holdings Company (Japan) has announced the development of a highly efficient PET-degrading enzyme in collaboration with Shizuoka University, the National Institutes of Natural Sciences, and Osaka University[66].

Beyond PET recycling, the Samsara Eco (Australia) has developed nylon recycling technology and successfully produced recycled nylon 6/6 in partnership with the sportswear brand Lululemon (US), resulting in prototype sportswear made from recycled materials. Additionally, the Kanematsu (Japan) has invested in Samsara Eco, aiming to establish a recycling supply chain[67].

Figure 2: Status of plastics recycling research and development

Name of company / research institute	Recycled material	Overview
Carbios (France)	PET	Actively forming partnerships with multiple enterprises as a pioneer in enzyme-based PET depolymerization. Working towards the 2025 launch of a factory through a joint venture with Indorama Ventures.
Samsara Eco (Australia)	Nylon, PET	Developing enzyme technologies utilizing research from Australian National University (ANU). Also exploring the scale-up of enzyme-based nylon recycling, despite many companies focusing on PET degradation.
Enzymity (Latvia)	PET, polyester, polyurethane, polystyrene	Possesses an optimized platform that leverages machine learning capabilities. Successfully reduced degradation times, cutting PET depolymerization from 100 hours to 15 hours, and polyethylene degradation from 50 days to 20 days.
Epoch BioDesing (UK)	Nylon, polyester	Uses generative AI to design promising enzyme candidates for plastic depolymerization by leveraging both public and proprietary datasets. Implemented physical modeling to evaluate the ability of enzymes to degrade polymers under mild conditions.
Kirin Holdings Company (Japan), Shizuoka University, National Institutes of Natural Sciences, Osaka University	PET	Succeeded in developing a highly thermostable enzyme. Demonstrated that these enzymes can selectively degrade PET in blended fibers such as PET and polyurethane, as well as PET and cotton, and achieved a world-record PET degradation rate of 90% in PET-cotton blends.

Source: Compiled by MGSSI

2-2. The Rise of AI in Smart Cell Creation

The advancement of AI is reducing the time needed to design smart cells to obtain ever more efficient enzymes. Effective AI utilization relies on leveraging both proprietary and publicly available datasets. Until now, companies that possessed extensive proprietary datasets had a competitive advantage. However, the emergence of generative AI platforms is now enabling companies without their own large datasets to design smart cells as well. For example, Ginkgo Bioworks (US), which has previously focused on producing substances such as flavors, announced a partnership with Google Cloud in September 2023. This collaboration is to develop a generative AI platform for smart cell design by third parties using Ginkgo Bioworks' datasets and Google Cloud's AI technologies.

66 Kirin Holdings Company Develops Chemical Recycling Technology Using Highly Efficient PET Decomposition Enzyme – The Chemical Daily (Electronic Edition)

67 Kanematsu Invests in Australian Environmental Tech Startup Samsara Eco – Proprietary Enzyme Recycling Technology Converts Plastics into Monomers, Reducing CO_2 Emissions and Enabling Infinite Recycling

The platform has been available to third parties since September 2024[68,69]. These new services are expected to expand participation in enzyme development using smart cells, stimulate further research and development, and accelerate product launches to the market.

2-3. Advancement of Mass Production Technology

Mass production technology for smart cells is still in its infancy, but Chitose Laboratory (Japan) is aiming for stable mass production leveraging AI technology. Conventional culture techniques have relied not only on easily measurable data such as temperature, pH, and dissolved oxygen concentration but also on subjective factors such as color and smell, which depend on the experience and intuition of skilled workers. Chitose Laboratory is addressing this by continuously and cost-effectively collecting multidimensional data (electrical potential data, odor data, image data, etc.) that AI can easily learn from in addition to conventional data, and using this "convolutional data" to determine optimal cultivation conditions. These technologies are expected to be widely used in the design of new microorganisms in the future and become an important foundation for the stable production of smart cells.

3. Future Prospects

Enzyme-based recycling technologies are expected to contribute to energy savings and reductions in greenhouse gas (GHG) emissions. For example, it has been reported that enzyme-based methods can reduce energy consumption in PET recycling by 69% to 83% compared to fossil fuel-based conventional processes, and GHG emissions by 17% to 43% per kilogram of terephthalic acid (TPA), the raw material for PET throughout the supply chain[70]. Given that PET contains ester bonds, which make it relatively easy to hydrolyze using enzymes, and certain recycling methods have been established, many companies and research institutions are working on developing even more efficient enzyme-based recycling solutions. However, as mentioned above, AI-driven enzyme development is expected to expand beyond PET to materials like nylon and polyester, enabling high-efficiency enzymatic recycling for a broader range of common plastics.

IP Analysis of Biomanufacturing

For the IP analysis of biomanufacturing, patent data related to enzyme-based recycling technologies was extracted and analyzed to assess the technological landscape. The analysis covered 311 patent families filed between 2015 and 2024, identified using the global patent search tool PatSnap.

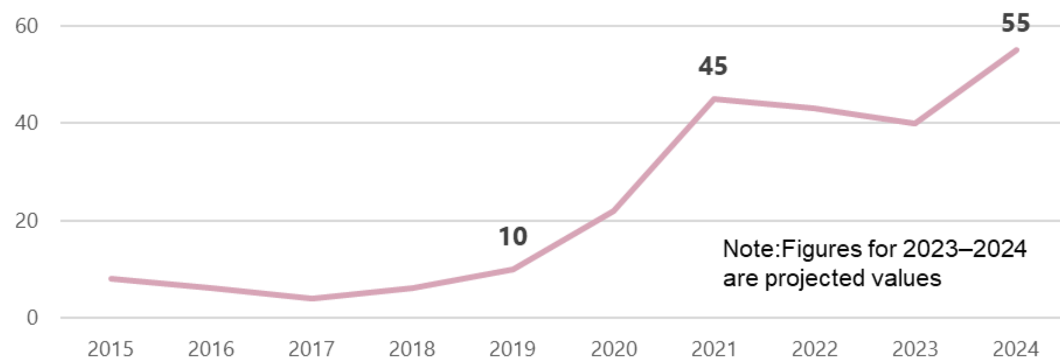
As shown in Figure 3, the number of patent filings increased significantly between 2019 and 2021, reflecting both technological maturation and growing market demand. Forecasts for 2024 indicate that patent filings are expected to rise further, underscoring the increasing importance of enzyme-based recycling technologies and the expansion of the market. As illustrated in Figure 4, major patent applicants include both research institutions, such as Jiangnan University, and companies, such as Carbios.

An analysis of the patent data reveals there to be many enzyme technologies specialized in PET degradation, with ongoing research and development aimed at commercialization. Carbios is particularly focused on PET degradation technologies and holds patents that emphasize unique process designs aimed at industrial-scale implementation. Jiangnan University is conducting research on the degradation of multiple plastic materials, including polyester and polystyrene, with a focus on unique genetic engineering modifications to improve enzyme performance.

68 Google and Ginkgo: Foundry-Scale Data Meets AI - Ginkgo Bioworks
69 Introducing Ginkgo's Model API: A Programmable Interface for Ginkgo's AI Research - Ginkgo Bioworks
70 Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate): Joule

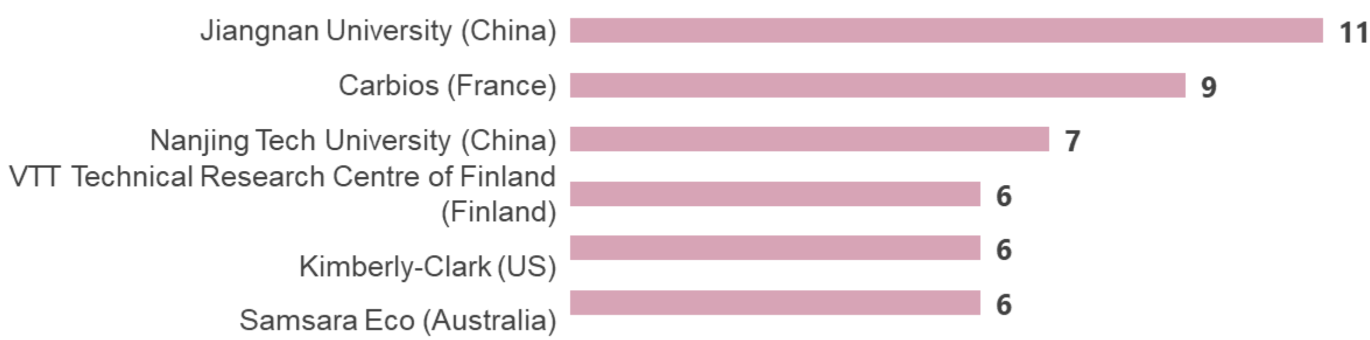
The current body of patents mainly represents laboratory-scale achievements, proving that enzyme recycling is technically feasible. However, commercialization remains a barrier to actual implementation. While Carbios' patents highlight near-term industrial applications, foundational research from Jiangnan University and other institutions is valuable for exploring new materials and opening up markets in the long term.

Figure 3: Annual patent filings related to enzyme recycling technology



Source: Compiled by MGSSI

Figure 4: Top ranking of patent applicants by number of filings (2015–2024)



Source: Compiled by MGSSI

Humanoid Robots

—Technological Advancements Driven by Generative AI and the Launch of Pilot Programs—

Rieko Tsuji
Consumer Innovation Dept.
Yui Matsuura (IP Analysis)
Intellectual Property Dept.
Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Biz Tech Focus 2025

Why This Technology?

Advances in AI have greatly improved control precision, enabling delicate operations that were previously difficult. Manufacturing costs have also decreased substantially, making mass production a realistic possibility. As a result, Amazon(US) and BMW(Germany) have launched pilot programs at their logistic warehouse and automobile factory in the United States, accelerating the movement toward real-world implementation. At this stage, it is unclear whether humanoid robots will become widely integrated into society but this will be an opportunity to take a broad view of the situation and consider how it may impact your business domain.

Summary

- In 2024, a large amount of capital flowed into humanoid robot startups, with the amount of investment in humanoid robot startups reaching a record high. Large companies are also working to develop the technology, and there is a growing trend toward collaborations.
- Although challenges remain, such as safety concerns and cost issues, the economic impact of general-purpose humanoid robots could be immense. Their adoption is expected in industries facing future labor shortages and fields involving hazardous tasks.

1. What is a Humanoid Robot?

1-1. Definition of Humanoid Robot

While there is no strict definition of humanoid robot (hereafter "humanoid;"), the term typically refers to a general-purpose, bipedal robot modeled after human form and capabilities. Most humanoids are designed to handle a wide range of tasks. These include industrial applications, such as grasping objects, moving containers, and positioning parts, as well as household services, such as folding laundry and engaging in conversation with humans (Figure 1).

Having a human-like form makes humanoids more socially acceptable and easier to integrate into human-centric system. In the future, they are expected to assist or replace human labor.

1-2. Advances in Technologies Supporting Humanoid Robots

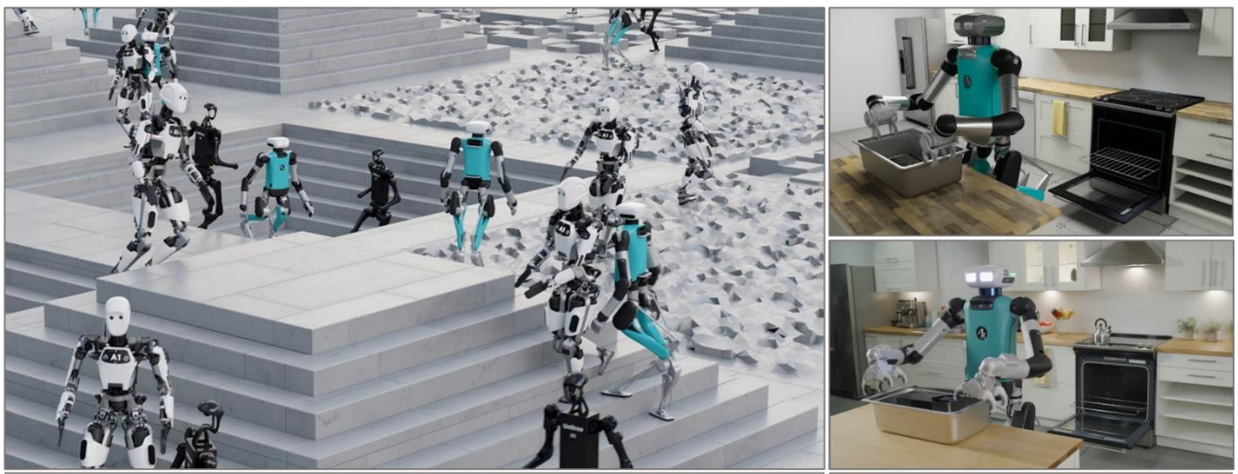
Humanoid technology encompasses a wide range of software and hardware, requiring comprehensive technological capabilities. Among these, AI technology has advanced significantly in recent years. Previously, training AI models with real-world data required substantial costs and time. However, with the ability to concurrently simulate multiple humanoids in virtual environments, AI can now efficiently learn various actions such as walking, falling, and object manipulation, leading to major improvements in motion control (Figure 2). Despite these

Figure 1: Characteristics of humanoid robots

Element	Characteristics	Illustration
Form	Many humanoid robots have a head, torso, arms, and legs similar to those of a human, and are often close to human height and build in size. Some have structural differences, such as joints that bend in the opposite direction from human joints.	
Movement	Can walk on two legs with smooth and natural movement. Ideally, they should be capable of grasping objects with their hands and performing other fine motor tasks, although some models lack individual fingers.	
Function	Expected to make decisions and perform actions autonomously similar to humans. Designed to work in various roles, including factory work, nursing, security, and reception tasks.	

Source: Compiled by MGSSI based on various company materials (Illustration: Los Angeles Times https://www.latimes.com/business/story/2024-10-15/tesla-optimus-bots-were-remotely-operated-at-cybercab-event (Accessed December 28, 2024))

Figure 2: Learning in a virtual space



Humanoids learning to walk on steps and over obstacles in a virtual space	Reproducing movements learned in the virtual space (upper) in the real world (lower)

Source: Compiled by MGSSI based on various company materials
(Illustration: left: NVIDIA Isaac https://developer.nvidia.com/isaac, right (both upper and lower): NVIDIA's Youtube https://youtu.be/kr7FaZPFp6M?feature=shared

advancements, fully replicating the real world in a virtual environment remains challenging. When applying virtual training results to real-world scenarios, discrepancies can occur, necessitating adjustments. Therefore, real-world data continues to be important. Nvidia (US) offers the "Isaac," a development platform that enables robot AI training in virtual environments. Just as the CUDA software for GPUs established Nvidia's dominance in AI development and attracted many researchers, the company appears to be positioning itself as a leader in robot AI technology.

Recent advancements have also introduced learning methods such as end-to-end learning and methods where AI autonomously learns from human behavioral data such as large-scale behavior models, and further progress in these areas is expected in the future. Beyond AI, improvements in actuators and the maturation of sensing technologies have also contributed to improving robot precision (Figure 3).

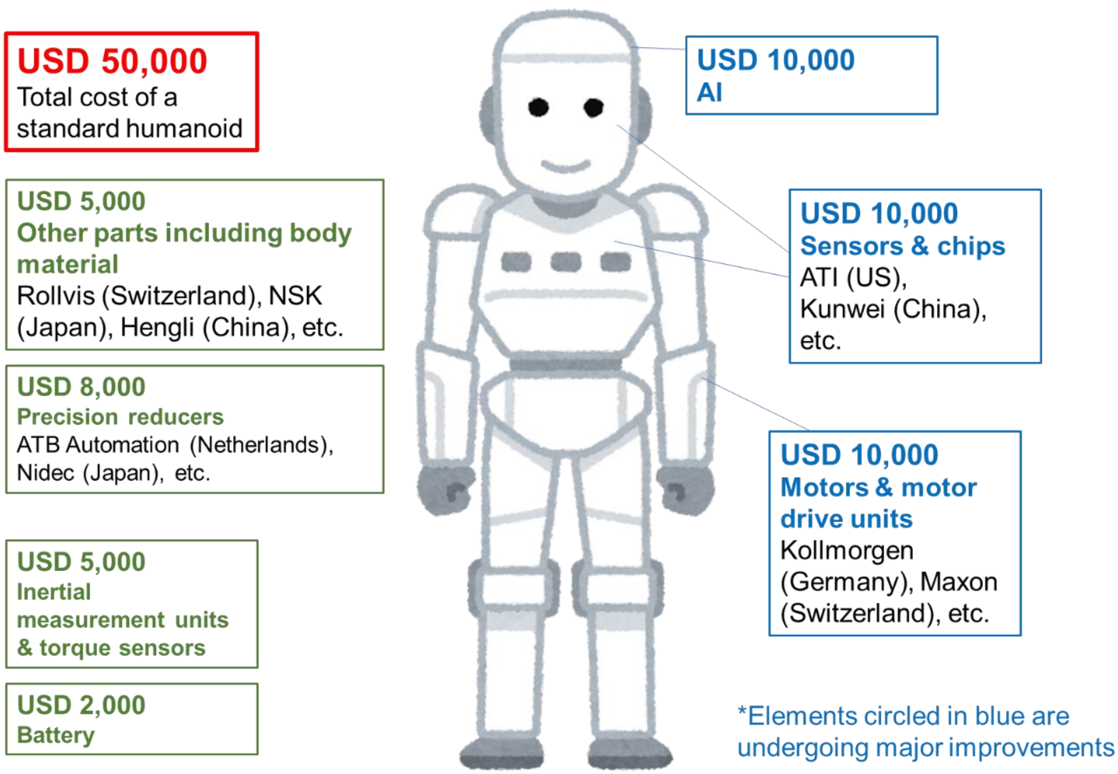
Figure 3: Technologies contributing to improved control precision in humanoids

Element	Characteristics
AI	● Sim2Real: A method for applying learning from virtual environments to real-world scenarios ● End-to-End Learning (E2E learning): An AI learning approach that processes the entire learning pipeline in a single step, rather than dividing it into separate stages such as recognition and movement ● Robot Foundation Model: A base model for robots trained on large datasets, including language, images, and behavioral data ● Large Behavior Model (LBM): A model trained by observing and learning from human behavioral data
Hardware	● Actuators: In general, the transition from hydraulic to electric drive systems has reduced costs. Tesla's Optimus reportedly uses linear actuators such as ball screws and planetary rollers to enable high-precision control ● Sensor: Different types of sensing data such as LiDAR and cameras can now be integrated and handled

Source: Compiled by MGSSI based on various company materials

On the cost front, the manufacturing cost per unit, which had long remained in the range of tens to hundreds of millions of JPY, has significantly decreased. As of 2023 estimates, the cost has dropped to around USD 50,000, and is approaching a realistic price for mass production (Figure 4).

Figure 4: Humanoid robot components/costs (2023 estimates) and major suppliers



Source: Compiled by MGSSI based on materials of Global X and others

2. Notable Trends

Companies developing humanoids are securing massive funding. In the period of January to March, 2024, funding for humanoid-related projects reached USD 775 million, already surpassing all previous full-year funding records[71]. The majority of this funding was raised by Figure AI (US), which secured USD 675 million from a number

[71] Based on the CB Insights report "Humanoid Robotics in 5 Charts: AI drives funding to record levels" (published March 7, 2024, last accessed on December 28, 2024).

of well-known organizations, including OpenAI (US), Nvidia, Microsoft (US) and Jeff Bezos' investment firm in February 2024. Although Figure AI dominates in terms of funding volume, 2024 has seen numerous other startups securing investments, including Agility Robotics (US), Unitree Robotics (China), 1X Technologies (Norway), Sanctuary AI (Canada), Fourier Intelligence (China), and Apptronik (US) (Figure 5). The number of startups that have raised over USD 100 million cumulatively is also increasing, highlighting the growing interest in this sector.

Figure 5: Startups developing humanoids and their funding status

Company name	Series (Most recent month of funding)	Estimated cumulative funding	Estimated company value	Major investors
Figure AI	Series B (Feb 2024)	USD 845 million	USD 2.7 billion (as of Feb 2024)	● OpenAI Startup Fund ● NVIDIA ● Microsoft ● Bezos Expeditions ● Intel ● Libera Gaming Operations (Japan)
Agility Robotics	Series B (Jul 2024)	USD 178 million	USD 1 billion (as of Oct 2024)	● Amazon ● Sony Innovation Fund ● TDK Corporation
Unitree Robotics	Series C (Sept 2024)	USD 150 million	USD 1.1 billion (as of Sept 2024)	● Beijing Robot Industry Fund ● Zhongguancun Science City Science
1X Technologies	Series B (Jan 2024)	USD 140 million	USD 400 to 600 million (as of Jan 2024)	● OpenAI ● Samsung Next
Sanctuary AI	Series A (Jun 2024)	USD 140 million	—	● Accenture Ventures ● BDC Capital
Fourier Intelligence	Series D (Jan 2024)	USD 94.5 million	—	● Softbank Investment Advisors
Apptronik	Seed (May 2024)	USD 65.3 million	USD 250 million (as of Aug 2024)	● Assembly Ventures ● BlueLake Ventures

Source: Compiled by MGSSI based on Crunchbase, PitchBook and others

Companies other than startups are also working on humanoid development. Examples of companies working on their own humanoid projects include Tesla (US), UBTECH (China), and Toyota (Japan). Another key player is Boston Dynamics (US), which has long been a leader in humanoid development and became a subsidiary of Hyundai (South Korea) in 2020. Among the Big Tech companies, Google (US), Meta (US), and Nvidia (US) are actively working on AI technologies for humanoids, development of robotic arms, and the like. Collaborations between companies are also progressing. Figure AI and OpenAI share capital ties. In October 2024, Boston Dynamics announced a partnership with Toyota Research Institute for humanoid development. In December 2024, Apptronik announced a partnership with Google (Figure 6). Regarding current technical capabilities, Western companies are considered strong in advanced control technologies, such as delicate hand and finger manipulation, while Chinese companies are making significant progress toward mass production.

Figure 6: Major development partnerships among humanoid development companies

Humanoid development company	Partner(s)	Initiatives
Figure AI	Open AI	Open AI builds AI models for Figure AI's humanoids.
Boston Dynamics	Toyota Research Institute (TRI)	Implementing TRI's AI technology on Boston Dynamics hardware.
Apptronik	Google Deep Mind	Combining Apptronik's robotics platform with Google Deep Mind's AI expertise.

Source: Compiled by MGSSI

Humanoids are being increasingly tested across various industries, including in automobile manufacturing plants, fulfillment centers, commercial facilities, and iPhone production factories. While Tesla, which operates its own facilities, is conducting independent trials, most other humanoid development companies are partnering with facility operators to conduct tests (Figure 7).

Among humanoid developers, three companies stand out as key players.

1. Figure AI's Figure 02

   BMW has introduced Figure AI's humanoid robot, Figure 02, into its automobile production line for chassis assembly and parts transportation. As of November 2024, a few months after its deployment, Figure 02 has undergone functional upgrades, resulting in a 400% increase in movement speed compared to its initial introduction. This enhancement allows the robot to place up to 1,000 automotive components per day.

2. Agility Robotics' Digit

   Agility Robotics' Digit is a humanoid robot with reverse-jointed legs. It has been trialed in Amazon's fulfillment centers and GXO Logistics' (US) factories, where it is responsible for box transportation and other repetitive tasks.

3. Tesla's Optimus

   Optimus is expected to be deployed in Tesla's automobile manufacturing plants. The robot is scheduled for commercial release by 2026, with an estimated price of USD 20,000 to USD 30,000. Designed as a general-purpose robot, Optimus is intended to perform a wide range of tasks, including shopping, lawn mowing, and even babysitting.

Figure 7: Key features of major humanoids and pilot program examples

Development company (Robot name)	Figure AI (Figure 02)	Agility Robotics (Digit)	Tesla (Optimus)
Example pilot program (Time of launch)	BMW's US automobile manufacturing plant (Aug 2024)	Amazon's US fulfillment centers (Oct 2023)	Own automobile manufacturing plants (scheduled)
Work	● Assembly of chassis and transportation of parts ● 1,000 parts placed per day (as of November 2024)	● Transportation and shelving of boxes	● Demonstration video shows installation and transportation of parts
Characteristics (including plans)	● 168cm, 70kg ● Degrees of freedom: 41 ● Payload: 20 kg ➢ Conversation possible	● 175cm, 65kg ● Degrees of freedom: 32 ● Payload: 16 kg ➢ No fingers	● 173cm, 57kg ● Degrees of freedom: 42 ● Payload: 20 kg ➢ Utilizing autonomous driving technology for environmental recognition
Photo	 Figure 02 **assembling** a chassis	 Digit **transporting** boxes	 **Optimus Gen2** handling eggs without breaking them

Development company (Robot name)	Apptronik (Apollo)	Sanctuary AI (Phenix)	UBTECH (Walker S1)
Example pilot program (Time of launch)	Amplifier's US fulfillment centers (Dec 2024)	Canadian Tire's Canadian apparel stores (Mar 2023)	Foxconn's iPhone manufacturing plants (scheduled)
Work	● Sort goods by shipping container for multiple carriers	● 110 tasks such as picking, packing, cleaning, tagging, labeling, and folding merchandise	● Work that could cause worker health problems in the iPhone assembly process
Characteristics (including plans)	● 173cm, 73kg ● Degrees of freedom: – ● Payload: 25 kg ➢ Communication possible via monitor on chest, etc.	● 170cm, 70kg ● Degrees of freedom: 21 for hand only ● Payload: 25 kg ➢ Housing made of carbon	● 172cm, 76kg ● Degrees of freedom: 41 ● Payload: 15 kg ➢ Emergency stop button on chest
Photo	 **Apollo** sorting goods	 Phenix (5th generation) **displaying** goods	 **Walker S1** transporting a box

*Degrees of freedom refers to the number of joints or axes in a robot's movable parts

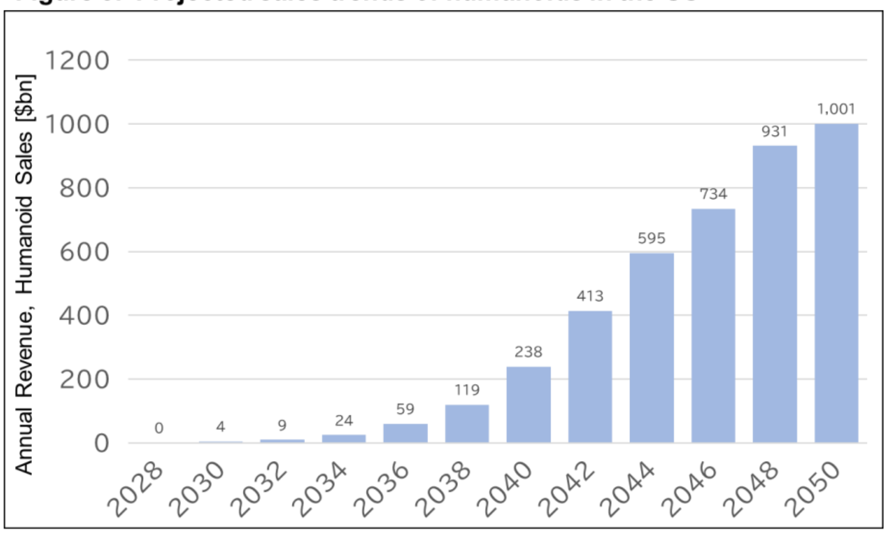
Source: Compiled by MGSSI based on various company materials (Illustration: upper left: BMW's website https://www.press.bmwgroup.com/global/article/detail/T0444265EN/successful-test-of-humanoid- robots-at-bmw-group-plant-spartanburg?language=en, upper center: Agility Robotics' website https://agilityrobotics.com/products, upper right: Tesla's Youtube https://youtu.be/cpraXaw7dyc?feature=shared, lower left: Apptronik's X https://x.com/Apptronik/status/1872326657979421153/photo/1, lower center: Sanctuary AI's website https://sanctuaryai.substack.com/p/sanctuary-ai-deploys-first-humanoid, lower right: UBTECH's Youtube https://youtu.be/UBbk18oZbTc?feature=shared (Accessed December 28, 2024))

3. Future Prospects

One of the key challenges regarding humanoids is improving the interpretability[72] of AI models. AI technologies based on deep learning are difficult for humans to understand in terms of how they arrive at their decisions. As a result, identifying the cause of problems is challenging, making AI difficult to use in safety-critical environments. Ensuring physical safety is another major issue. Humanoids weigh roughly as much as an adult and are designed to collaborate in close proximity with humans. If they make unexpected movements, they could cause significant physical harm. Other challenges include enhancing precision, achieving mass production, and reducing costs. Overcoming these obstacles will likely accelerate wider industrial adoption.

Currently, humanoids are still in the trial deployment phase, where their usefulness is being evaluated. In the near term, they will likely be outperformed by specialized task-specific robots in both performance and cost. However, given the rapid pace of technological advancements and increasing investment, humanoids could surpass specialized robots within the next decade or so. If this happens, general-purpose humanoids could see widespread adoption across various fields. In addition to logistics, manufacturing, retail, healthcare, and household applications, as discussed in Section 2, humanoids could play a crucial role in industries facing labor shortages due to population decline, such as food service and construction. They could also be deployed in areas where minimizing human presence is desirable, such as defense and disaster response. In the United States, the number of humanoids is projected to grow from 40,000 units in 2030 to 8 million in 2040 and 63 million in 2050, with total revenue expected to reach USD 1 trillion[73]. Given these projections, humanoids may integrate into society more rapidly and extensively than anticipated (Figure 8).

Figure 8: Projected sales trends of humanoids in the US



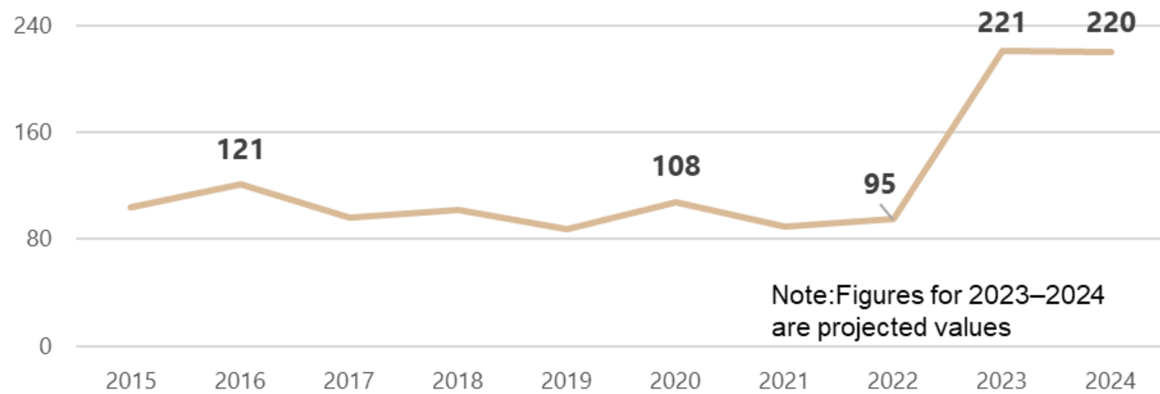
Source: Compiled by MGSSI based on Morgan Stanley

[72] Whether humans can interpret the processes and reasoning behind the predictions or inferences made by AI models based on deep learning.
[73] Based on the Morgan Stanley report "Could AI Robots Help Fill the Labor Gap?" (published on August 13, 2024, last accessed on December 28, 2024).

IP Analysis of Humanoid Robots

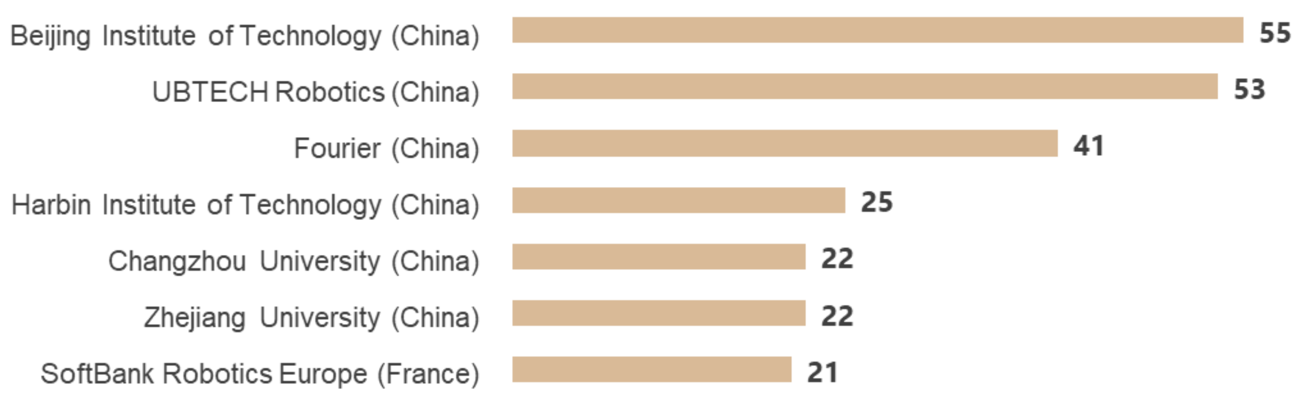
For the IP analysis of humanoid robots, patent data tagged with "Humanoid Robot" was extracted from documents using AI, and analyzed to assess the technological landscape. The analysis covered 1,121 patent families filed between 2015 and 2024, identified using the global patent search tool PatSnap.

Figure 9: Annual patent filings related to humanoid robots



Source: Compiled by MGSSI

Figure 10: Top ranking of patent applicants by number of filings (2015–2024)



Source: Compiled by MGSSI

As shown in Figure 9, while the number of patent applications surged in 2023, there was a steady flow of filings from 2015 to 2022, indicating that research and development in this field have been ongoing for many years. As illustrated by Figure 10, the majority of top patent filers are Chinese companies and universities. The only European company on the list is SoftBank Robotics Europe, known for developing the humanoid robot "Pepper." However, most of its 21 patent filings were made in 2015, and no further patent activity has been observed in recent years.

Meanwhile, companies outside of China are also advancing their own humanoid robot technologies. For example, Agility Robotics, mentioned above, has filed patents for robotic grippers and systems to enhance robot mobility, which serve as fundamental technologies in robotics. While these technologies are not exclusive to humanoid robots and therefore fall outside the scope of this search, they represent important patents demonstrating the company's technological capabilities. Although not ranked among the top filers, Kawasaki Heavy Industries (Japan), which developed the humanoid robot "Friends," has filed 15 patent applications that suggest potential applications in industrial and service sectors. While Chinese entities lead in patent filings, companies and research institutions worldwide are pursuing diverse approaches to humanoid robot development. As a result, future market competition and the emergence of new technologies in this field will be closely watched.

Figure 11: Technical topic classification

Technical topic	Rate of increase since 2020	Changes in filing trends
Sensing technology	68%	**Integration of multiple sensors** is advancing, with increasing emphasis on environmental recognition technologies that combine visual, tactile, and audio data.
Robot bodies	62%	Focus shifting from durability and stability; acceleration of **modular and lightweight designs** Pursuit of manufacturing cost reductions and improved maintainability
Artificial intelligence & learning algorithms	56%	Increased development of **environment-adaptive algorithms** and self-learning functions using machine learning and reinforcement learning
Control systems	50%	In addition to improved motion precision, advancements are being made in **cooperative control and real-time control**. Focus on cooperation between multiple robots
Drive & actuation	41%	Shift from conventional drive systems (pneumatics/hydraulics) toward **electric actuators and flexible drive mechanisms**

Source: Compiled by MGSSI

Figure 11 shows the patent data on humanoid robots classified by technology topic. Since 2020, the fastest-growing technology topic in terms of patent filings has been sensing technology. Notable inventions in this category include vision sensors focused on high-precision 3D image processing and environmental recognition algorithms, tactile sensors designed to enhance real-time processing of touch, and sensor integration technologies that enable real-time processing of multimodal data. The competitive advantages provided by advancements in sensing technology include improved real-time responsiveness (allowing robots to instantly recognize their environment and select optimal actions), high-precision operation (precise detection of force and touch to enable delicate tasks), natural human-robot interaction (integrated vision and tactile technologies enabling recognition of human facial expressions and movements and appropriate response).

Patent data suggests that humanoid robot development is primarily driven by efforts to address three major societal challenges: (1) labor shortages, (2) safety, and (3) social acceptance. These advancements are expected to accelerate humanoid adoption across industrial, healthcare/nursing, and household/service sectors.