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Digitalization Options Handbook for the Energy Sector

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FOREWORD

As the world grapples with the severe impacts of climate change on society and the environment, it is clear that innovative approaches are needed to integrate policy, investment, and technology solutions for sustainable climate actions and infrastructure.

Digitalization offers a promising pathway for economic development and structural transformation, aligning with the global agenda for sustainable development. Utilizing digital tools, particularly in developing countries and Small Island Developing States, has the potential to significantly enhance their capacity to address technology challenges and opportunities for climate adaptation and mitigation.

Despite the numerous benefits of digitalization, there is a considerable need to understand the digital readiness of developing countries. This includes evaluating existing policy frameworks to bridge digital divides, improving climate technology literacy, raising public awareness, and understanding available finance and investment mechanisms.

The project named “Developing a National Digitalization Readiness Index for Developing Countries” aims to establish a comprehensive understanding of the digital capacity (or readiness) of developing countries, with a particular focus on energy infrastructure. The National Digital Readiness Index (NDRI) has been developed to assess key facets of a country's digital readiness, including social, economic, regulatory, and technological aspects. This Index serves as a foundational tool for evaluating and enhancing a country's potential to adopt digital tools and technologies to strengthen its energy technology capacity.

This handbook aims to provide additional information for digitalizing the energy sector that has not been included in the main report on developing the NDRI. Even though it is obvious that these technologies require close investigation and analysis to check their applicability with consideration for each country’s unique conditions and characteristics, we hope that these technology options and corresponding information may help those who are interested in digitalizing their country’s energy sector which may help in starting to establish their own plan for digitalizing the energy sector.

This project was funded by the United Nations Environment Programme and the United Nations Climate Technology Centre and Network.

May 31, 2024

UN CTCN Digitalization Implementation Partners

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Background

This handbook is a supplement to the project named “Developing a National Digitalization Readiness Index for Developing Countries.” The project aims to strengthen developing countries' capacity to address technology challenges and opportunities for climate adaptation and mitigation by developing a “National Digitalization Readiness Index (NDRI)” to evaluate each country’s potential for applying digital tools to transform its economic, social, and technology systems. In this regard, this handbook provides details that are summarized in the report to provide additional information for starting in digitalizing the country’s energy sector.

To digitalize the Energy sector, countries worldwide are developing policies to promote digitalization, and various technologies are being introduced worldwide; some technologies may be in the early stages, such as research and development, while others are practically applied. In this report, we have (1) investigated policy options, including strategies and plans, of Korea and Thailand to promote digitalization in the energy sector and (2) investigated rising and promising technology options for digitalization in the energy sector that are currently being applied in Korea.

The major purpose of this introduction is to show what kind of options may be applicable after identifying the current condition of digitalization in each country’s energy sector. Korea has been a leading country in terms of digitalization, resulting in the application of various digital options in various fields. However, these technology options should be carefully reviewed and analyzed before being applied to other countries because the major characteristics, conditions, or surrounding environment differ from those of Korea. Nonetheless, this introduction is expected to help stakeholders in developing countries develop their own options considering the unique characteristics and surrounding environment of their country’s Energy sector.

Team

This project was conducted by a multidisciplinary team of scientists and experts representing non-Annex I and Annex I countries, as well as the private sector.

(1) National Institute of Green Technology (Republic of Korea)

The National Institute of Green Technology is a government-affiliated research institute under the Ministry of Science & ICT (MSIT) that provides national green technology R&D policies and coordinates related domestic/international organizations to support the sustainable development of other countries based on green/climate change technologies.

(2) The George Washington University Environmental and Energy Management Institute (United States)

The GW Environmental and Energy Management Institute conducts state-of-the-art, relevant research to promote graduate and professional education. It undertakes service activities that are pertinent to the application and implementation of national and international standards for the management of environmental, energy, and sustainability challenges facing organizations and communities throughout the Nation and the world.

(3) Chatmine Technologies (United States)

Chatmine Technologies is a science-based, woman-led social enterprise that utilizes Big Data Analytics and AI to translate science and policy into pragmatic solutions for sustainable development and investment challenges.

Part 1. Policy and Strategy Options

Republic of Korea

In Korea, the digitalization of the energy sector is promoted through various policies and strategies. Representatively, "The Fourth Basic Plan for Sustainable Development," "The New Government's Energy Policy Direction," and "The Third Basic Plan for Intelligent Power Grid" include major plans to promote digital transformation in the energy sector. Especially, expansion of renewable energy, promotion of energy efficiency, and the application of digital technologies to achieve carbon neutrality are identified in these plans. In particular, developing an intelligent power grid using ICT technologies is being promoted as an important project to optimize electricity supply and demand, improve energy efficiency, and support sustainable electricity production and consumption. Intelligent microgrids, power storage systems, and smart electricity metering systems are being introduced to support the integration of renewable energy into the power grid and enhance energy efficiency in buildings, systematically supporting the establishment of an overall decentralized energy system. (More details for each policy and strategy are shown in Appendix F).

The Fourth Basic Plan for Sustainable Development (2021-2040): Since 2006, Korea has been developing a 20-year plan to implement international agreements on low-carbon sustainable development and promote national sustainability. The latest version of this plan, the 4th iteration, covers the period from 2021 to 2040. Within this plan, the energy sector is specially addressed under Goal 7, which focuses on producing and consuming energy in an eco-friendly manner. Additionally, the plan includes detailed targets for using digitalization to support sustainable development in the energy sector.

The Third Basic Plan for Intelligent Power Grid (2023): The Korean government has been establishing basic plans to promote intelligent power grids every 5 years. This plan aims to optimize the supply and demand of electricity by monitoring real-time data using ICT, promoting the development, demonstration, use, and diffusion of related technologies, promoting the industry, and enhancing the efficiency of electricity production and consumption.

The 1st National Carbon-Neutral Green Growth Plan (2023-2042): This plan is the highest-level statutory plan for achieving carbon neutrality and green growth in Korea. It contains sector and annual emission reduction targets and mid- to long-term policy directions. The plan covers the next 20 years and will be established and implemented every 5 years. Due to the large portion of carbon emissions, this plan also mentions targets and policies to reduce carbon emissions in the energy sector through innovative technologies, including digitalization.

Thailand

Thailand's energy sector policy is overseen by the Ministry of Energy and the National Energy Policy Committee (NEPC). The NEPC's main tasks are to recommend national energy policy, management, and development schemes to the government and set Thailand's energy tariff structure. The majority of Thailand's electricity generation and transmission network is owned and operated by the Electricity Generating Authority of Thailand (EGAT). This state-owned company sells its power to the Metropolitan Electricity Authority (MEA) and Provincial Electricity Authority (PEA), which are also state-owned companies. The private sector is also involved in renewable energy generation. Thailand is utilizing digital technologies in its energy transition plan for a low-carbon society. In particular, efforts are being made to utilize digital technologies to keep the energy system stable and efficient, to expand the number of electric vehicles, and to create a smart grid that integrates electric vehicle infrastructure with the existing power grid.

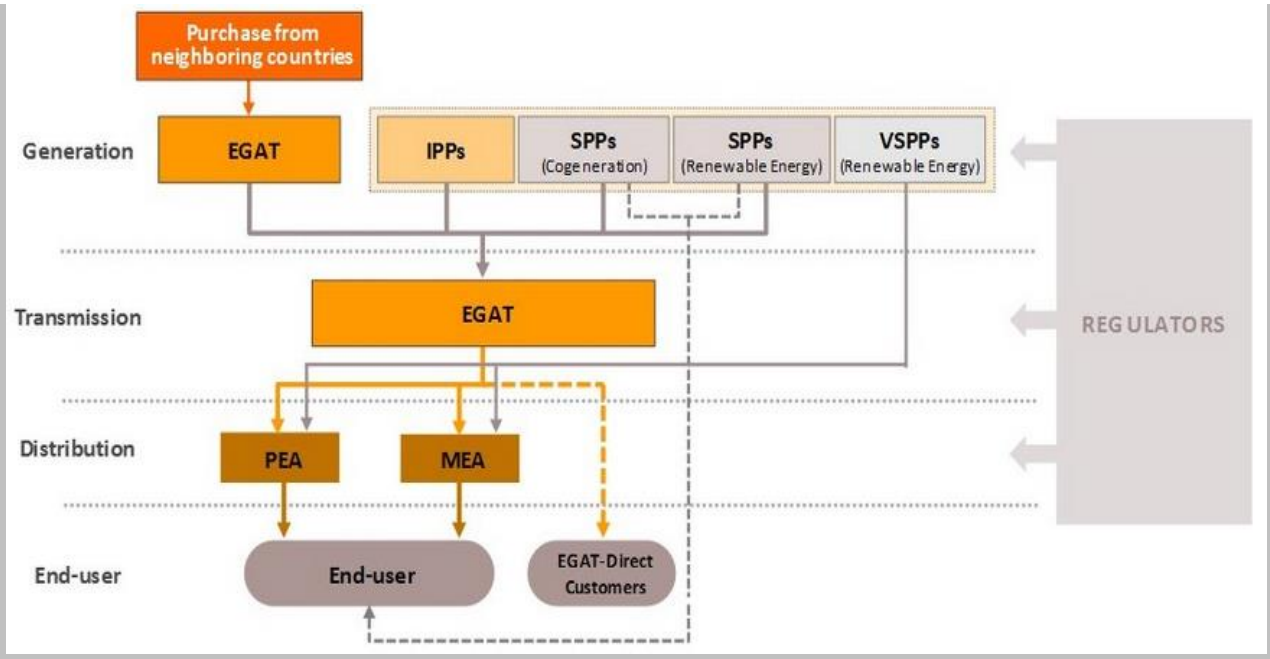

FIGURE 17: THAILAND'S ELECTRICITY SUPPLY CHAIN (SOURCE: TUNPAIBOON, 2021).

National Economic and Social Development Plan (NESDP): The NESDP is a comprehensive 5-year national development plan covering all sectors. First set in 1961, the plan serves as the basic guideline for economic and social development to improve the quality of life in Thailand. The most recently released NESDP is the 13th plan and covers the period from 2023 to 2027. The goal of the 13th NESDP is to transform Thailand into a progressive society with a sustainable value-creating economy, and a total of 13 targets have been set to achieve this goal. One of the NESDP's 13 targets, the goal of

establishing a manufacturing base for electric vehicles (EVs), is one of the strategies that can be realized through the digitalization of the energy sector. The plan also includes plans for smart grid technologies to integrate the connection and management of EV charging, including an integrated platform to connect public charging stations and EV data.

Power Development Plan (PDP): Thailand's Power Development Plan (PDP) and Alternative Energy Development Plan (AEDP) are developed by Thailand's Ministry of Energy and are the centerpiece of the country's energy plan. Thailand's Power Development Plan 2018 covers the period of 2018 to 2037, and its main directions are as follows: (1) Regional balance and reliable supply of power generation, transmission, and distribution systems, (2) Ensuring power system flexibility to respond to energy crises (grid flexibility), (3) Encourage low-cost power generation to reduce consumer burden, (4) Preparing a competitive power generation system that takes into account power generation efficiency, (5) Minimize environmental impact, (6) Promote electricity generation from renewable energy sources, and (7) Expand smart grid development.

Thailand Smart Grid Master Plan (2015): This is a comprehensive plan established by the Ministry of Energy in 2015, covering the period of 2015 to 2036. This plan includes 3 focus areas: (1) establishment of ICT integration to the energy and communication sector for system modernization, (2) strategies and regulations for electricity pricing and monitoring for customer-centric reform or smart life, and (3) initiatives to develop renewable energy forecasting to promote and increase the use of renewable energy.

Energy 4.0 – The Smart Grid Project: Thailand's Provincial Electricity Authority (PEA) is partnering with a private company to implement a smart grid to transform the energy infrastructure of Pattaya. The PEA aims to lead the energy transition in Thailand, meeting with the national energy 4.0 plan to contribute to the country's economic success and ensure its competitiveness within the ASEAN society. One of the key parts of the energy transition is the digital upgrade, including power supply improvement and expanding renewable energy sources in Thailand. Pattaya will be a pilot city to showcase a new paradigm through the digital transformation of smart substations.

Electricity Generating Authority of Thailand (EGAT): The EGAT aims to promote innovation through research into the integration of digital technologies to accelerate value creation and business transformation in issues such as renewable energy, energy storage, grid modernization, and carbon capture and storage (CCS). To promote sustainable development, EGAT's operations will be modernized with digital procedures and systems that integrate technology, automation, and AI expertise into management functions, including the power plant's internal systems, carbon emission analysis, and environmental impact assessment. EGAT's infrastructure will be strengthened to support the digital transformation, including digital documents, leveraging the cloud and other innovative technologies to analyze data and modernize operational processes.

Part 2. Technology Options

The investigated technology options consider various energy system components, such as power plants, distribution systems, and monitoring systems. Moreover, this report has also reviewed education programs to introduce slightly how to enhance capacity-building for digitalization in the energy sector. A shortlist of technology options that are introduced in this report is provided as follows:

1. Digital Twin power plant
2. Intelligent Digital Power Plant (IDPP)
3. Virtual Power Plant (VPP)
4. Energy Management System (EMS)
5. Microgrid EMS
6. Advanced Metering Infrastructure (AMI) for buildings and apartments
7. AI-enabled prediction and diagnosis
8. Advanced Distribution Management System (ADMS)
9. Digital transformation education program

The major contents to introduce each option are as follows: First, (1) the concept and purpose of each technology option are introduced, and (2) technical features such as basic structure or core functionality are introduced for a clearer understanding of the technology, and at last (3) some application examples or case studies are introduced to see how these technology options are used for digitalizing the Energy sector (details of the case studies are also shown in Appendix D).

1 Digital Twin Power Plant

Concept and purpose

Digital twins have emerged in response to the simultaneous and prolific development of technologies such as sensors, the Internet of Things (IoT), big data, artificial intelligence, and cyber-physical systems (CPS), and the need to utilize these technologies to increase productivity, economy, and safety in various industries. A digital twin is a digital representation of a physical object (asset, process, system, etc.) that is a digital copy of a physical object (asset, process, system, etc.) that is used to simulate tests that are difficult to perform in the real world (Lee, 2021).

Unlike static digital models, digital twins are dynamic models where one piece of data creates N pieces of knowledge and solutions that feedback in real-time to optimize physical assets. It acts as a virtual model that reflects the properties and state of an object in real-time throughout its lifecycle and dynamically models how it behaves. Digital twins can be applied in various sectors such as disaster safety, agriculture and fisheries, healthcare, manufacturing, security, smart cities, etc. In the energy sector, digital twin refers to a convergence technology of digital energy intelligence that builds a virtual energy supply and demand system synchronized with the real-world power supply and demand system through digital modeling and provides customized energy supply and demand optimization technology through data collection/analysis and simulation (Kim, 2019).

A digital twin power plant is a technology that creates a virtual replica of a real-world power plant and leverages real-time data, Internet of Things (IoT) technology, artificial intelligence (AI), and big data analytics to reflect the operational status, performance, fault prediction, maintenance requirements, and more of a real-world power plant. Using digital twins, power plant operators can maximize the efficiency of their plants, proactively prevent unexpected issues, and reduce maintenance costs. It also contributes to improving safety and minimizing environmental impact (Jung et al., 2021).

Technical features (structure and core functionality)

The core technologies that make up a digital twin vary, as shown in Figure below, but are broadly classified into seven categories (Jung et al.,2021): 1) visualization and operations, 2) analytics, 3) multidimensional modeling and simulation, 4) connectivity, 5) data and security, 6) synchronization, and 7) federation between individual digital twins.

Visualization and operational capabilities essentially provide a digital reflection of a physical object or system in visual form, allowing users to monitor real-time data and intuitively understand operational status. Analytics capabilities leverage collected data to perform in-depth analysis, which can be used for a variety of intriguing applications, including predictive maintenance, performance optimization, and failure analysis. Multidimensional modeling and simulation provide the ability to predict the response of an object or system by mimicking its real-world environment. This plays an essential role in design

validation and operational optimization. Connectivity capabilities, such as through IoT technologies, enable real-time data collection and information exchange between digital twins, ensuring real-time synchronization and seamless data flow.

Data and security are essential for managing large amounts of data safely and ensuring security factors such as confidentiality, integrity, and access control. The synchronization process is based on real-time data to continuously maintain state matching between physical objects and digital twins, contributing to adaptation to change and predictive analytics. Finally, federation technologies enable multiple digital twins to interact with each other and function as an integrated system, increasing the efficiency of operational optimization and resource management in complex systems or environments. These technologies make digital twins powerful and flexible tools that enable applications in various fields (Jung et al., 2021).

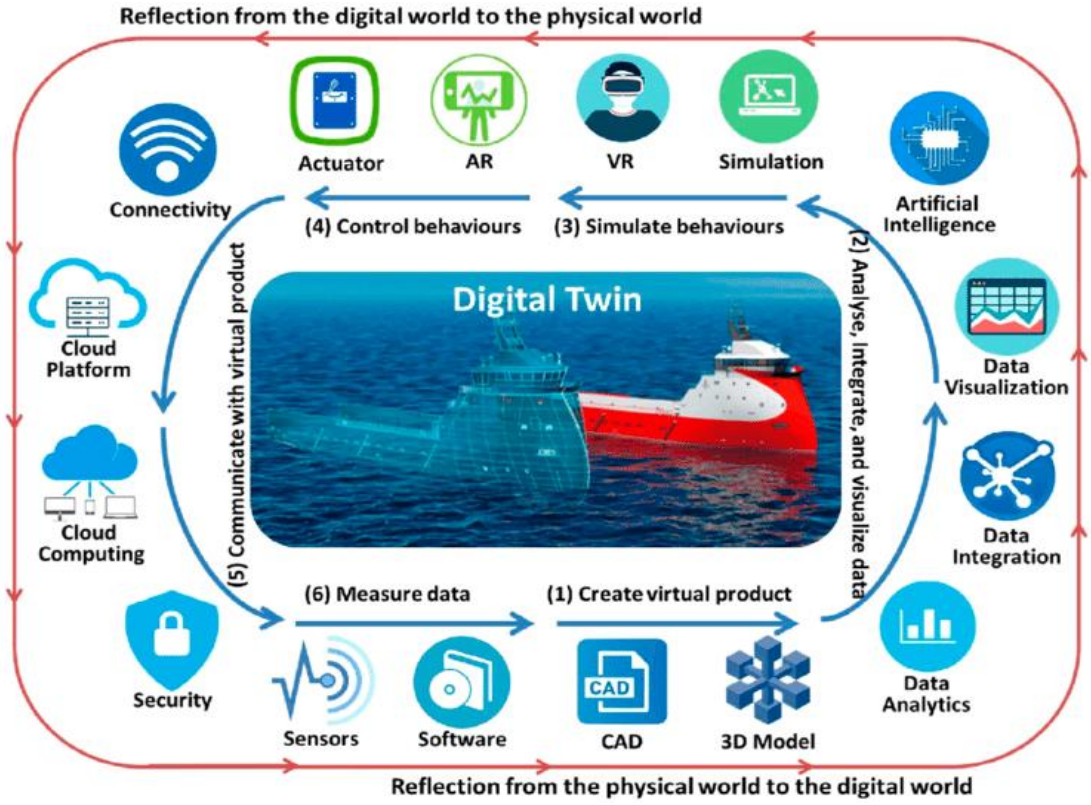

FIGURE E3: ENABLING TECHNOLOGY OF DIGITAL TWIN (SOURCE: TAO ET AL., 2019).

Real-world phenomena are too organic and complex to be optimized with a single digital twin, so we have expanded the traditional three-stage digital twin technology evolution to five stages, as shown in Table and Figure below. In steps 1-3, the real world is replicated, controlled, and optimized in the digital world as before, i.e., one real world is converted into one digital world and optimized. In step 4, the single optimized digital twins are interconnected to optimize the complex real world. In step 5, the organically connected digital twins autonomously recognize problems in the real world and perform

optimizations. This evolution of digital twin technology keeps you informed about its progress and potential.

TABLE E2- THE STAGE OF DIGITAL TWIN TECHNOLOGY EVOLUTION. HIGHER-LEVEL DTW INCLUDES LOWER-LEVEL DTW TECHNOLOGY

Technical steps	Definition	Description.
Step 5	Autonomous DTW's (Autonomous)	Autonomously recognize and resolve issues in individual and composite digital twins to optimize physical targets
Step 4	Federated DTW's (Federated)	Reconstruct a composite digital twin of interconnected individual physical targets and optimize physical target interoperation.
Step 3	Mock DTw (Monitoring)	Digital twin-based physical target monitoring and control with correlation analysis
Step 2	Control DTw (Monitoring)	Digital twin-based physical target monitoring and control with correlation analysis
Step 1	MockDTw (Mirroring)	Replicate a physical object as a digital twin

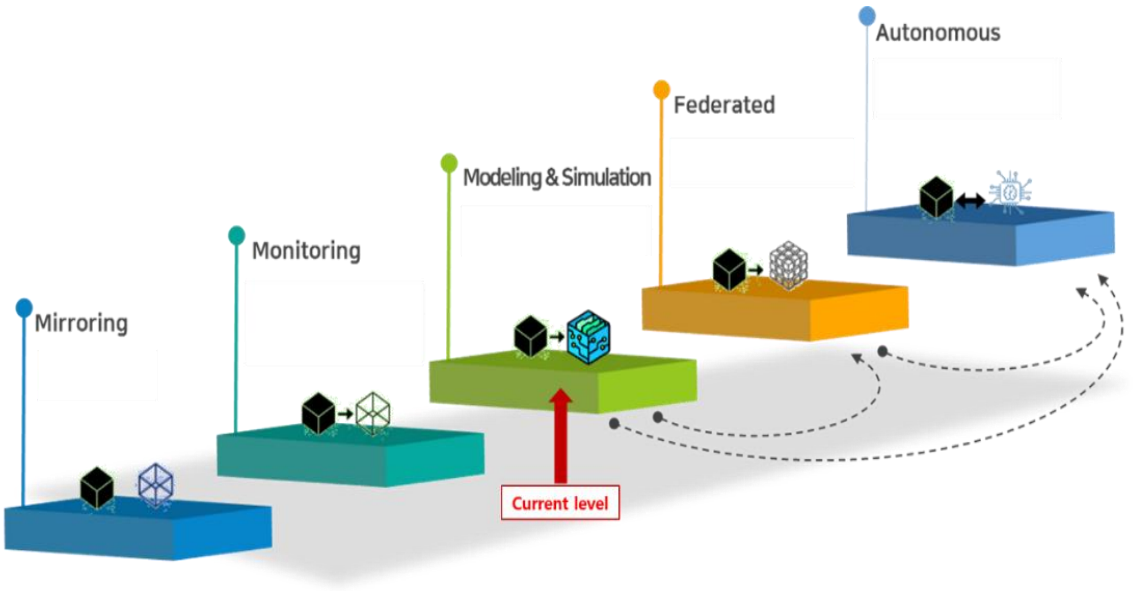

FIGURE E4: STAGES OF DIGITAL TWIN TECHNOLOGY DEVELOPMENT (SOURCE: SON, 2021).

Application examples

Korea Hydro & Nuclear Power Co., Ltd (KEPCO)

Digital twin technology is recognized as an innovative approach to improving the safety and efficiency of nuclear power plants. In these facilities, events such as compressor failures can lead to reactor

shutdowns, which are costly to bring back online. To address these issues, digital twin technology employs deep learning algorithms that can predict potential compressor failures 30 to 60 days in advance. This capability allows power plant operators to take preventive measures, reduce costs, and ensure reliable operations.

Korea Hydro & Nuclear Power Co. recently adopted digital twin technology to enhance the operational safety and efficiency of its nuclear power plants. These plants must monitor various variables, including temperature, humidity, radiation levels, turbine rotation, and over 1,200 other variables. Given the vast amount of data accumulated in real-time from various sensors, the total increases further when including duplicate data from each generating unit. Previously, this data was merely recorded and stored. However, today, KEPCO is utilizing digital twins to monitor the status of critical devices and systems in real-time, detect performance degradation in advance, and take proactive measures, thereby laying the foundation for safe nuclear power plant operations (Kim, 2020).

Pohang Iron and Steel Co., Ltd (POSCO)

Since 2016, digital twin projects in various fields, such as digital furnace smart solutions, have been competitively promoted. These projects are particularly expected to significantly improve productivity, including energy savings and product quality, when introduced to upstream processes that are often black boxes due to high-temperature and high-pressure environments. AI was applied to the second blast furnace at Posco Pohang. The 'AI blast furnace' monitors the condition of the blast furnace in real time based on five variables that determine its status (air permeability, combustibility, etc.) and predicts the outcome of operations in advance (Posco Newsroom, 2020). It then proactively and automatically adjusts the operating conditions to produce the best quality steel with the least deviation.

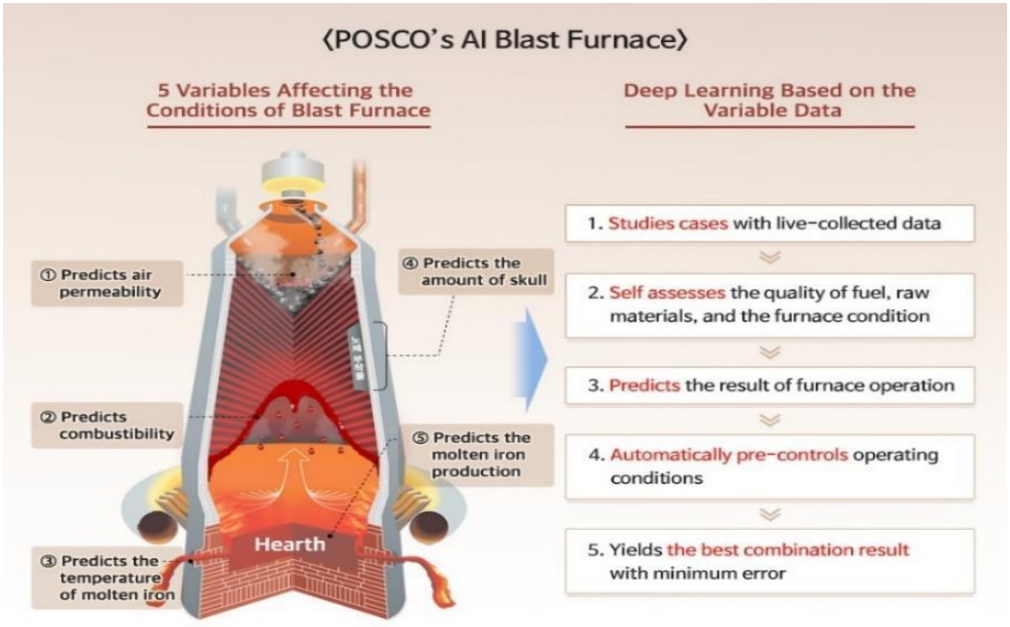

FIGURE E5: POSCO'S AI BLAST FURNACE (SOURCE: POSCO NEWSROOM, 2020).

Korea South-East Power Co. Ltd.

Korea South-East Power Co. Ltd. (KOEN) has established the KOEN Digital Transformation Promotion Strategy based on AICBM (AI, IoT, Cloud, Big data, Mobile) technology to prevent on-site safety accidents, efficiently manage power generation facilities, and become a leading energy company in digital transformation. KOEN built a pilot digital twin power plant for units 5 and 6 of Yeongheung Thermal Power Plant, the first case in Korea to apply digital twin technology to a large-scale thermal power plant in actual operation. There are four main aspects of building a digital power plant: data standardization for integration and hyper-connection of existing systems, intuitive operation through visualization, AI-based optimal decision support, and platform-based standardization. As shown in the Figure below, KOEN's employees can check the site's status in real-time by connecting various alarm sensors, including CCTV, to the digital twin platform (Kang, 2024).

FIGURE E6: KOEN'S DIGITAL TWIN POWER PLANT (SOURCE: KANG, 2024).

Future outlook or direction

Digital twin technology is projected to generate $3.9 trillion in economic value by 2025, with manufacturing and factories expected to be the primary beneficiaries. This trend is likely to expand to full-scale adoption across all industries, including automotive and healthcare. The manufacturing sector is poised for rapid adoption due to its high acceptance of digital and software-assisted situational judgment and relatively lenient regulations. The decline in the production workforce could lead to reduced resistance to digitizing skilled know-how and developing decision-support systems for unskilled workers.

In 2020, the digital twin market in South Korea was relatively small, valued at around KRW 690 billion, but is expected to grow at an annual rate of 70%. Although the manufacturing and factory sectors are most representative of digital twins, significant savings are also anticipated in the aviation and power generation sectors. For instance, a 1% increase in fuel efficiency could save between 6 trillion to 8 trillion won annually, and a 1% increase in energy facility uptime could save between 5 trillion to 7 trillion won annually (E-Daily, 2021).

In Korea, initiatives are underway to develop a virtual nuclear power plant (NPP) instrumentation and control system and a digital twin of the NPP safety system. Plans include developing virtual nuclear power plant research based on a physical model simulator, which will enhance the efficiency of training and maintenance by developing a digital twin of the instrumentation and control system, including a subject language room. Additionally, developers will create digital twins for nuclear power plant safety systems, developing digital twin technology for real-time residual life prediction and diagnosis of safety-grade digital protection systems critical to nuclear power plant safety.

Specifically, the digital twin of the safety system aims to reduce the causes of unplanned shutdowns due to malfunctions in the instrumentation control system and parts replacements, thereby increasing safety by preventing significant accidents. Furthermore, by monitoring the operating environment of the nuclear power plant in real-time, developers can predict and diagnose the remaining life of the digital protection system, thus enhancing operability and maintainability (Kim, 2020).

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2 Intelligent Digital Power Plant (IDPP)

Concept and purpose

The power industry is realizing digital transformation by introducing Intelligent Digital Power Plants (IDPPs). An intelligent digital power plant is a power plant that aims to realize high productivity and efficiency by utilizing the latest technology and artificial intelligence to monitor and predict the performance of power generation facilities in real-time through data analysis, artificial intelligence, and machine learning, enabling failure prevention, energy efficiency improvement, and operation optimization. By applying digitalization and intelligentization[1] technologies using collected data, IDPP aims to optimize facility operation and maintenance, improve management efficiency, and reduce power generation costs (Park, 2023).

In particular, the power generation sector is highly dependent on fossil fuels such as coal and oil, which results in high greenhouse gas emissions. Hence, introducing IDPP is essential. The ultimate goal of digital transformation in the power generation industry is to optimize power generation costs by reducing potential operation and maintenance costs and to create a new revenue structure by creating value in a new power generation digital marketplace based on a platform (Lee, 2020).

Technical features (structure and core functionality)

Intelligent Digital Power Plants (IDPPs) function as smart power plants, utilizing a network that leverages operation and maintenance data from the facilities. This technology employs AI and big data analysis to predict facility conditions in advance, thereby minimizing operational expenditures (OPEX) in power generation, preventing failures, and enhancing asset operation efficiency. IDPPs monitor various micro-signals to detect equipment failures or abnormal operations effectively. Each facility installs vibration, pressure, temperature, and more sensors, which collect real-time information. Technicians then process this data through intelligent digitalization, optimizing the operation and maintenance of power generation facilities.

Based on collected and analyzed data, IDPPs can identify optimal operating conditions and the best timing for maintenance. This capability ensures optimized preventive maintenance, reduces breakdowns, and supports the remote implementation of technology when necessary. IDPPs drive industrial innovation by enhancing power generation efficiency, preventing accidents, and improving environmental conditions. Optimizing the operation and maintenance of power generation facilities reduces the emission of pollutants, such as fine dust, carbon dioxide, and nitrogen oxides, but also

[1] Intelligentization refers to the process of incorporating advanced technologies, such as artificial intelligence (AI), machine learning, and automation, into systems, processes, or devices to enhance their functionality, efficiency, and decision-making capabilities. This concept is often applied in various fields, including industry, healthcare, transportation, and everyday consumer products, aiming to create smarter and more responsive environments.

decreases inspection times for field workers and actively prevents safety accidents (Korea Electric Power Research Institute, 2022).

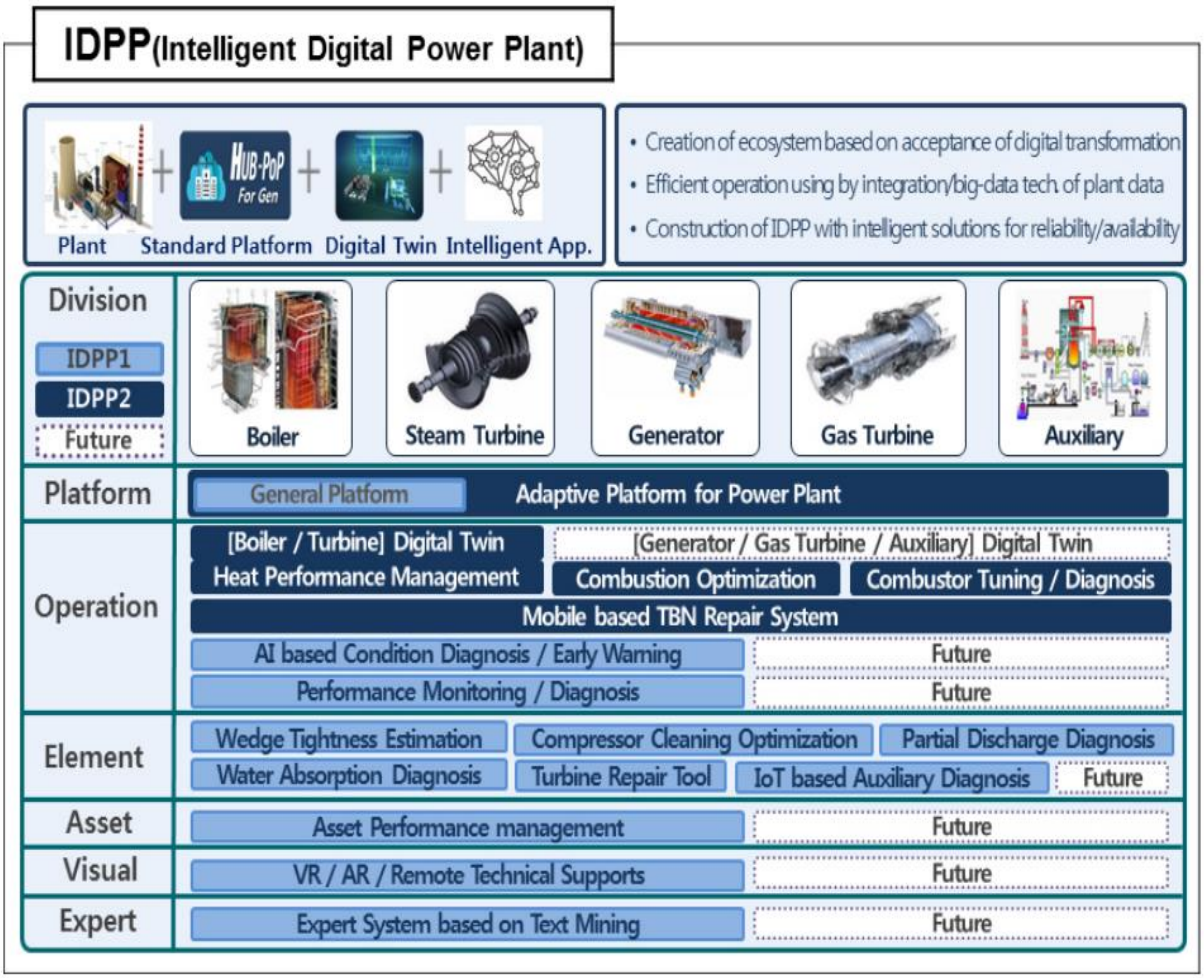

FIGURE E7: IDPP TECHNOLOGY DEVELOPMENT ORGANIZATION AND STEPS (SOURCE: LEE, 2020).

Application examples

Korea Hydro & Nuclear Power Co., Ltd (KEPCO)

KEPCO has developed 16 intelligent apps that utilize technologies such as machine learning to monitor and predict the status of key facilities in power plants and apply them to actual sites. The representative app, Siren-X, is an early warning system that prevents unplanned shutdowns by selecting key signals from power plants and building a learning model tailored to operating conditions to detect abnormal conditions in advance. The system can reduce model learning time by more than ten times compared to early warning systems.

KEPCO also built a data center based on a digital platform called "KEPCO Big Data Place" with government support. The platform is an integrated IT infrastructure that supports big data and cloud

capabilities, enabling the connection and secure sharing of 100,000 operational data from five power companies and 16 power plants. The "Cloud Platform" enables private developers to develop and validate app services utilizing the data. The "power generation digital twin" technology implements the same functions as an actual power plant in a virtual space, allowing users to simulate operations. It enables power plant operators to derive optimal operating conditions based on future operating scenarios (KEPCO, 2023).

Currently, KEPCO is actively marketing IDPP to overseas power generation sectors. KEPCO has conducted digital power generation technology workshops for Taiwan Electric Power Company and Daewan Nuclear Power Research Institute and is in talks to conduct a pilot project at Taiwan Electric Power Company's power plants. GENCO3, a power generation subsidiary of Vietnam Electric Power Corporation, focuses on achieving management optimization through operation and maintenance efficiency by promoting digitalization of power generation with KEPCO (Cho, 2023).

Korea Midland Power Company (KOMIPO)

Korea Midland Power Company (KOMIPO) is building smart power plants based on big data and AI-based predictive diagnostic systems and has established a platform called 'KOMIPO-MIRI.' The overall composition of the first phase of the MIRI platform consists of a Power Generation Operation Information System (Smart-PIS), an Early Warning System (Smart-EWS), and an Efficiency Monitoring System (Smart-EMS). The Smart-PIS collects 400,000 data, such as temperature, pressure, vibration, flow, etc., from sensors and instruments in the power plant process every second. Smart-EWS is a system that prevents power plant equipment failures by using machine learning-based prediction models to recognize and address abnormalities in advance. Smart-EMS is a system that uses data and simulation techniques to manage the efficiency of the entire process periodically.

The deepened Phase 2 MIRI platform applies various AI techniques based on big data to address areas of safety, environment, and profit improvement with high field needs. The components of the second phase of the MIRI platform include the following: Power Plant Startup Support System (Smart-RTS), Doctor Vibration Engine (Smart-VIB), Automatic Detection of Hazardous Behavior (Smart-Vision), Operating Margin Visualization (Smart-TMI), Gas Turbine Power Optimization (Smart-WAS), Power Consumption Monitoring (Smart-OSP), and Environmental Facility Monitoring (Smart-ECO) (Kang, 2021).

Future outlook or direction

KEPCO and the Korea Electric Power Research Institute (KEPRI) estimate that intelligent digital power plants can reduce greenhouse gas emissions by about 1% (approximately 1.5 million tons) (Korea Economic Daily, 2022). Currently, KEPCO has successfully conducted a digital power generation technology workshop for Taiwan Electric Power Company and the Taiwan Nuclear Power Research Institute, and discussions are underway to conduct a pilot project for Taiwan Electric Power Company's power plants. KEPCO also held a technical seminar at the request of GENCO3, the power generation subsidiary of Vietnam Electricity Corporation, and will expand the application of IDPP technology in the

Vietnamese power generation market with a customized technology proposal that meets GENCO3's specific requirements (Lee, 2020).

In April 2017, KEPCO's Electric Power Research Institute started the Intelligent Digital Power Plant (IDPP1) research project, and in May 2019, it started the Power Plant Customized Platform and App Development (IDPP2) research project. In this process, a structure was established to integrally utilize databases, including various operating data, experiences, and facility knowledge of power generation facilities centered on a single platform called 'HUB-PoP' (Figure below). IDPP research mainly focuses on developing a platform that can store and analyze operating data of boilers, turbines, generators, and auxiliary equipment, which are the core facilities of power plants in digital form. The platform will enable the development and market distribution of related apps, allowing users to utilize the data in real-time.

IDPP is a technology development project conducted by KEPCO itself to build a foundation for intelligent digital power plants using big data, AI, and IoT, and aims to (1) develop expert systems, elementary and operation, and asset performance management technologies based on expert experience and knowledge to diagnose and early warn the operating status of core facilities of power plants, (2) provide information for decision-making on maintenance cycles and plans through evaluation of the health of assets such as operating status monitoring/diagnosis/prediction, maintenance history, and financial information to optimize power generation costs, and (3) provide on-site training and remote technical support services using AR/VR technology at the visual center.

The IDPP Phase 1 research project aims to lay the foundation for an intelligent digital power plant through technology development led by KEPCO. This phase will utilize big data, AI, and IoT technologies to develop a diagnostic and early warning system for the operating status of core facilities in power plants and provide decision-making information for maintenance cycles and planning through monitoring, diagnosis, prediction, and asset health assessment of operating status. Phase 2 of the IDPP is a joint development and demonstration application with power group companies to develop and utilize a standard platform (Hub-PoP for Gen) specialized for power generation and to develop new applications related to power plant thermal performance management systems, optimal combustion expert systems, digital twin and cyber-physical systems, etc. It also aims to apply them to power plants and the existing applications developed in Phase 1 of the IDPP (Lee, 2020).

A key technology for the digital transformation of power generation technology is a power generation-specific platform and app development technology that works in conjunction with it. Doosan Heavy Industries & Construction operates a Prevision-based remote management service program for power plants in South Korea. Still, it is mainly limited to local power plant cases and has yet to be ready for widespread use. Korean utilities are in the early operational stages of adopting digital technologies, such as early warning and performance monitoring, on individual platforms centered on collecting and storing operation and maintenance data. This situation suggests the need for advanced technologies to optimally manage power generation facilities, such as lifetime prediction, based on a typical big data utilization platform (Kang, 2021).

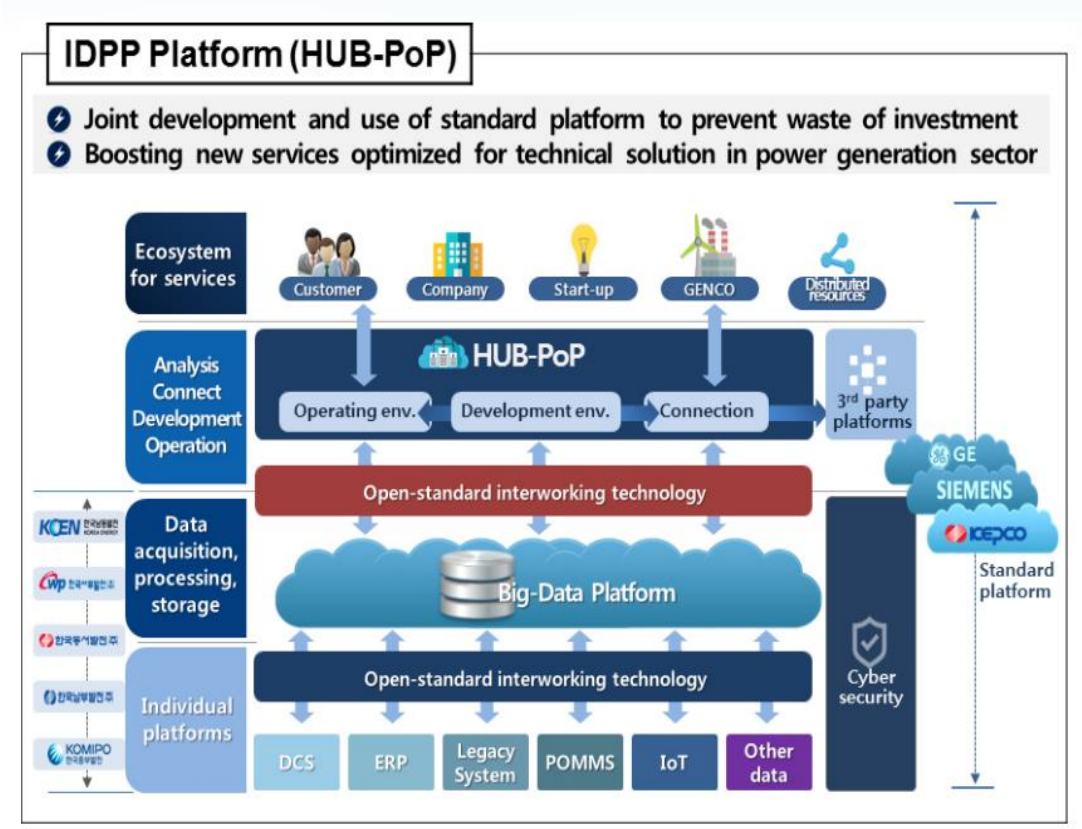

FIGURE E8: IDPP PLATFORM, HUB-POP (HYPER-CONNECTED UBIQUITOUS BRIDGE-PLATFORM OF PLATFORMS) (SOURCE: LEE, 2020).

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3 Virtual Power Plant (VPP)

Concept and purpose

In response to climate change, energy sources are gradually shifting from coal-fired power generation to renewable energy, and the energy system is changing to a 'distributed energy resource' (DER) that includes various small-sized power generation sources such as solar power and fuel cells. A system that gathers, integrates, and manages power generation sources distributed throughout the country using information and communication technology (ICT) and optimizes energy production and distribution is called a virtual power plant (VPP).

Distributed energy resources (DER), which is the background of VPP, refers to a system that produces and consumes energy near the demand area, including distributed generation (DG) such as fuel cells, solar power, and wind power, energy storage systems (ESS), and demand response (DR). Distributed energy resources are often powered by renewable energy sources, making them not only environmentally friendly but also economical, as they do not require large-scale power plants and long-distance transmission networks, reducing construction and operation costs and power losses during transmission. However, there is one drawback to distributed energy resources: the variable nature of renewable energy, such as sunlight and wind, makes it difficult to generate as much power as needed at the desired time (SK Ecoplant, 2023).

Instead of physically owning power plants, VPPs use information and communication technology and artificial intelligence to collect, predict, control, and manage scattered renewable energy resources. By connecting small renewable energy power plants on a platform and operating them as a single power plant, VPPs can predict the power generation and demand of distributed energy resources and strategically produce, store, distribute, and trade energy accordingly. Increasing the accuracy of renewable energy generation forecasting through VPPs makes it possible to minimize the problem of renewable energy output limitation caused by surplus electricity at certain times. Alternatives can be found, such as curtailing fossil-fueled power plants during periods of low demand or proactively identifying other uses for surplus electricity, such as charging electric vehicles (Setiawan et al., 2024).

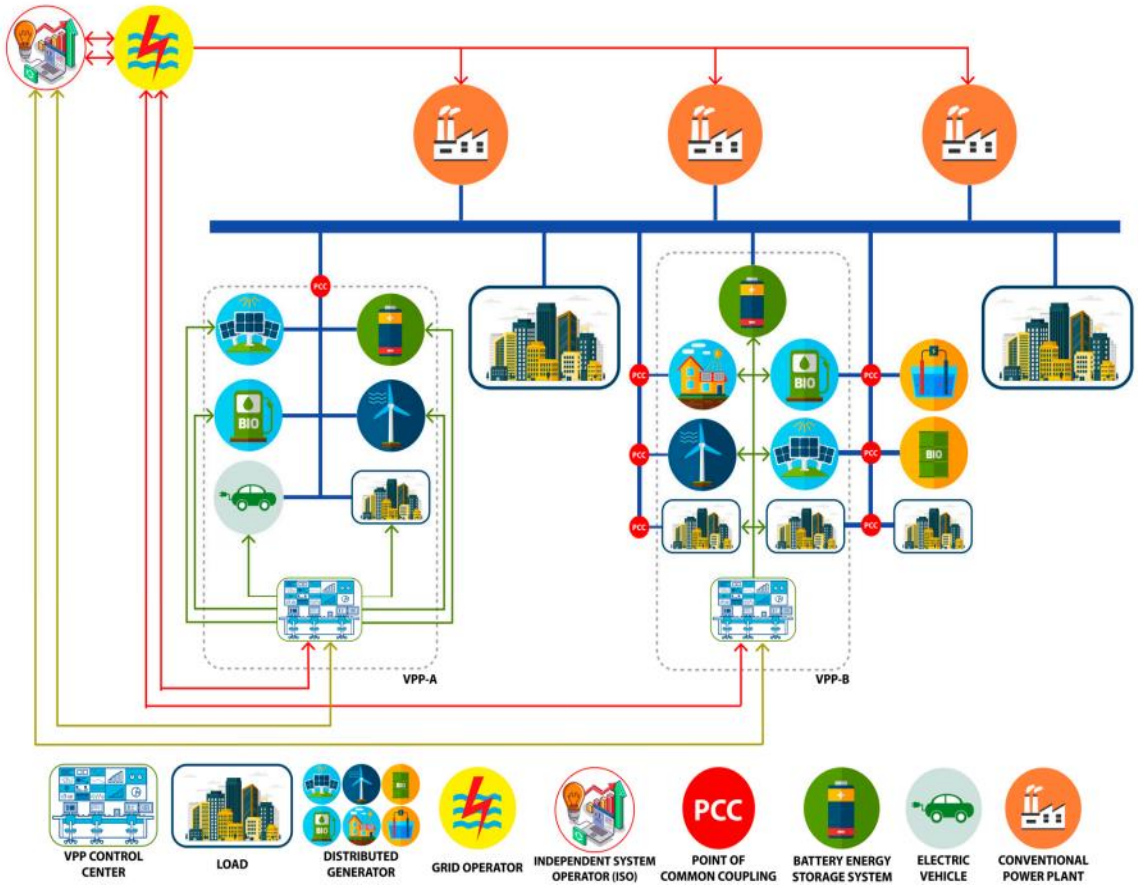

FIGURE E9: ILLUSTRATION OF VPP DEFINITION (SOURCE: SETIAWAN ET AL., 2024). THE RED LINE INDICATES COMMUNICATION BETWEEN THE VPP AND THE UTILITY OPERATOR, THE YELLOW LINE INDICATES COMMUNICATION BETWEEN THE VPP AND THE SYSTEM OPERATOR, AND THE GREEN LINE INDICATES COMMUNICATION WITHIN THE INTERNAL VPP.

Technical features (structure and core functionality)

VPPs monitor power consumption and supply in real time, transmitting the measurement results to the electricity provider's control system. This system uses AI to analyze the data and sets the appropriate power generation and supply routes for power plant operation. For instance, if an industrial park powered by wind energy experiences reduced power output due to environmental factors, a large thermal power plant usually needs to operate to prevent a power outage. However, VPP technology can transfer excess power from neighboring areas to the industrial park, maintaining grid stability without additional power generation (Ahn & Kim, 2019).

There are three types of VPPs: supply, demand, and converged (Frost & Sullivan, 2017). A supply-type VPP uses information and communication technology to integrate distributed energy resources (DER), such as small-scale renewable energy generation and storage devices. It manages these resources as a single power plant, controlling the output of the DERs to contribute to the stability of the power system. Conversely, demand-type VPPs reduce power consumption from centralized sources during peak times by utilizing energy efficiency systems and software. These are particularly suitable for countries with

advanced demand response (DR) systems, as they help reduce electricity bills and the cost of wholesale power purchases during peak hours. Converged VPPs combine the features of supply and demand VPPs, supplying electricity to the grid through distributed energy resources and efficiently operating demand resources. In addition to the benefits of supply and demand VPPs, converged VPPs contribute to power system stabilization by providing power supply and demand balance services.

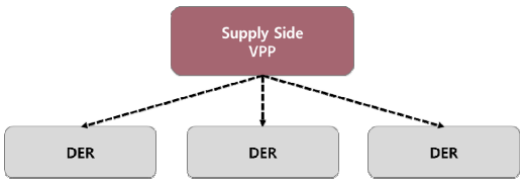

FIGURE E10: SUPPLIED VPP (SOURCE: FROST & SULLIVAN, 2017)

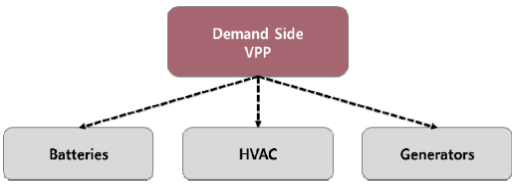

FIGURE E11: DEMANDED VPP (SOURCE: FROST & SULLIVAN, 2017)

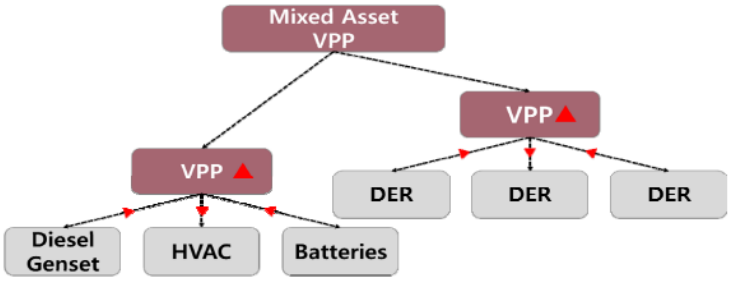

FIGURE E12: CONVERGED VPP (SOURCE: FROST & SULLIVAN, 2017)

Another criterion for categorizing VPPs is that they are classified into technical VPPs (TVPPs) and commercial VPPs (CVPPs). The primary purpose of a technical virtual power plant (TVPP) is to comprehensively define system calculations, technical applications, storage, and optimization. TVPP ensures that the VPP operates effectively and safely while considering physical constraints and services. On the other hand, the purpose of a commercial virtual power plant (CVPP) is economic optimization. It includes managing financial risks such as costs, maximizing revenue from electric energy exchange, linking economic paradigms with intelligent grid services, and regulating transactions in the VPP (Setiawan et al., 2024).

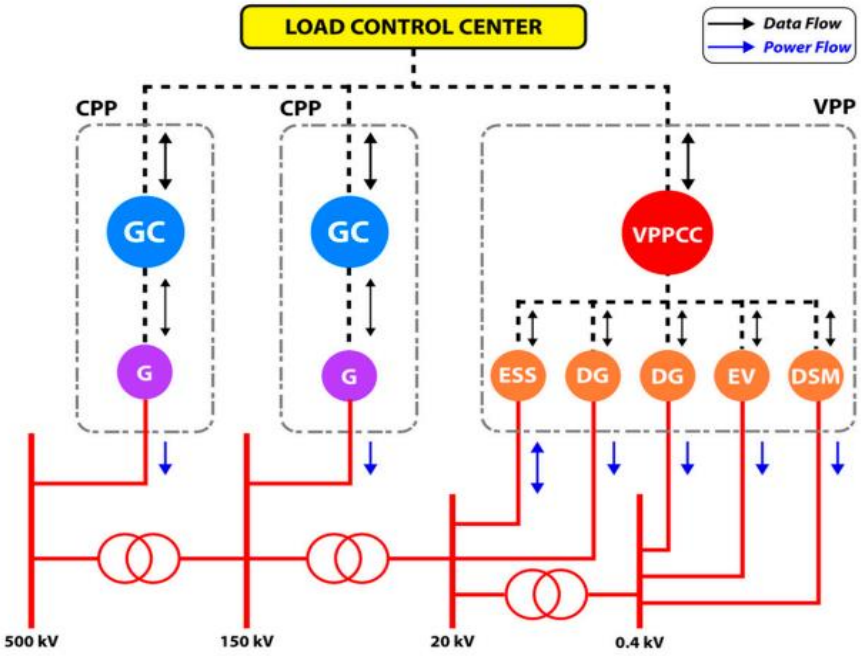

FIGURE E13: VPP POSITION IN THE ELECTRICITY SYSTEM (SOURCE: SETIAWAN ET AL., 2024).

Application examples

SK EcoPlant Co., Ltd.

SK EcoPlant, a leading Korean environmental and energy company, has entered the VPP-based power brokerage business. The company signed an agreement with 91 renewable energy plants in Jeju Island and started a 50MW power brokerage business by collecting their power. The power brokerage business is a business in which individual power generation facilities of 20 MW or less, including renewable energy and energy storage systems (ESS), are collected and organized into a single resource and traded in the power market by an intermediary. SK ecoPlant launched Power ZEN, a bidding platform based on renewable energy generation forecasts. Power ZEN provides data on the status of the power system, including power generation forecasts and power transmission. It is characterized by its ability to determine the actual power supply capacity (Choi, 2024). Through this platform, renewable energy intermediaries will receive incentives from the power exchange, which operates the power market based on high renewable energy generation forecasts (SK Ecoplant Newsroom, 2023).

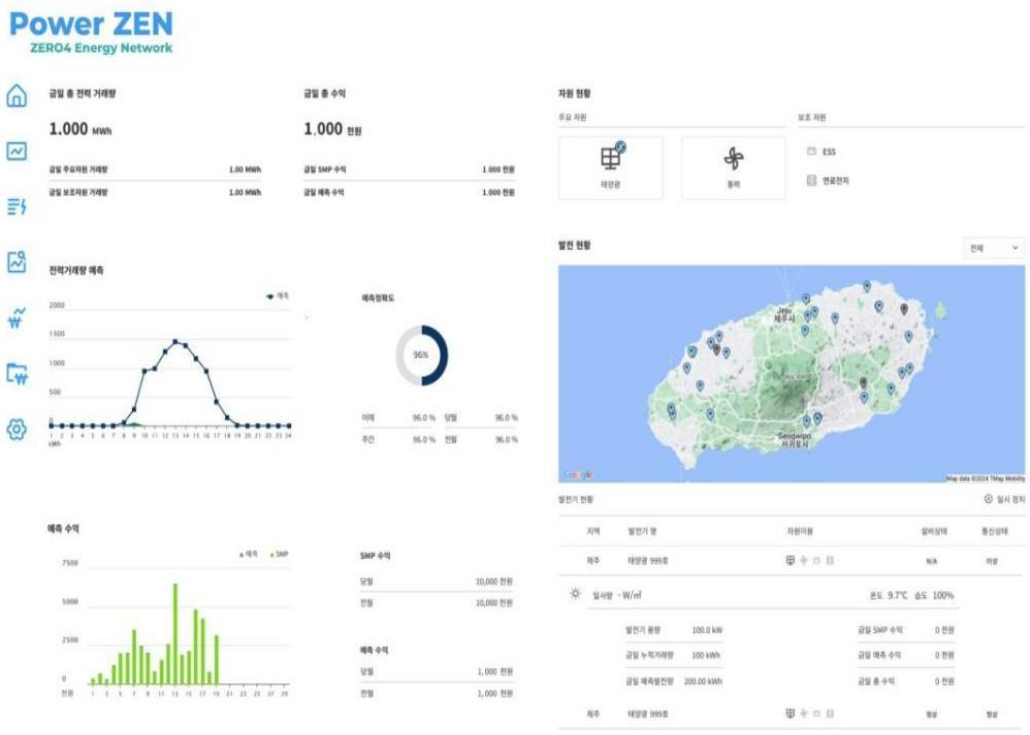

FIGURE E14: SK ECOPLANT'S POWER ZEN (SOURCE: CHOI, 2024).

Korean government (K-VPP) and small power intermediaries

The Korean government is promoting the expansion of distributed resources to improve the problems caused by the centralized power system and has introduced the K-VPP. As of 2022, Chungnam's power generation accounted for 18% of the country's total power generation, the highest in the country, but only 47% was utilized, and the rest was transmitted to other regions. According to Chungcheongnam-do, the cost of power losses due to using distant transmission networks was 2.7 trillion won in 2021. The expansion of decentralized power sources centered on renewable energy enables short-distance transmission, reducing the cost of transmission and distribution facilities, and is considered suitable for responding to the climate crisis by increasing the utilization of renewable energy.

Since February 2019, the Small Power Brokerage Business System has been in effect in South Korea, enabling electricity generated or stored from small-scale power resources to be aggregated and traded on the electricity market. The main operators of the small power open market are KT, SK E&S, KEPCO, H Energy, Solar Connect, KEPCO, KEPCO South East, KEPCO East West, and KEPCO Seoul. Intermediaries can aggregate small-scale generation resources such as renewable energy, energy storage, and electric vehicles of 1 MWh or less on the network without physical connection and sell power and renewable energy certificates (RECs). However, so far, sellers prefer direct power purchase agreements (PPAs13) with KEPCO, which have simple procedures, and the revenue model for intermediaries is limited to brokerage fees and predicted settlement payments for generation, so activation has been slow (KB Financial Holdings Research Institute, 2023).

Hanwha Solutions Co. (Hanwha Q Cells)

Hanwha Solutions holds the No. 1 market share in the U.S. residential and commercial solar modules market and is trying to enter the virtual power plant market, starting with Australia, through M&A and investment. The company acquired Grewing Energy Labs (GELI). This U.S. software company sells systems that control solar power generation facilities and ESS through data analysis technology. It announced investing KRW 1.5 trillion in next-generation solar and hydrogen technologies and virtual power plants. In addition, Hanwha Solutions announced that it will launch Q.Home Core, a residential energy solution, in Australia and target the virtual power plant market in earnest. The company has been selected to participate in a virtual power plant pilot project in Victoria, Australia. It will provide a platform, and the state government will provide a subsidy of $4,174 to residents who participate in the virtual power plant project (QCELLS, 2023).

Future outlook or direction

Large-scale capital flows are happening in Europe and the United States due to the growth of the virtual power plant market. Mergers and acquisitions, investments, and the emergence of new business models highlight the increasing profitability of virtual power plant-related business models. Virtual power plants that interact with renewable energy, energy storage, and electric vehicles are likely to develop alongside the growth of related industries. Compared to other major countries, South Korea's virtual power plant market is still in its infancy, primarily due to the low share of renewable energy generation, the centralized power system led by KEPCO, and the absence of a legal framework for vitalization. However, legal and institutional improvements are in progress to support the distributed energy and virtual power plant industries, and these improvements are expected to revitalize the market in the future.

In particular, South Korea is promoting the expansion of decentralized resources. It plans to prepare laws and systems for introducing the Korean VPP (K-VPP) within the year (KB Financial Holding Management Institute, 2023). The country has already introduced and operates a small-scale power brokerage business system, a model for collecting and trading power generated or stored from small-scale resources such as renewable energy, ESS, and electric vehicles. In December 2018, the Korean government completed the revision of the Electricity Business Act and Enforcement Decree, and the small-scale power brokerage business has been in operation since February 2019. Small-scale power resources consist of renewable energy, energy storage systems (ESS), and electric vehicles (no size limit) of 1 MW or less, and intermediaries collect and trade electricity generated or stored from recruited small-scale resources, and provide services such as trading of renewable energy certificates (RECs) and facility maintenance. Five intermediaries are in operation, with a registered capacity of 24.4 MW, of which 11.1 MW is currently traded (Ahn et al., 2019).

In addition, in February 2023, the Ministry of Trade, Industry, and Energy released the 3rd Intelligent Power Grid Master Plan, which outlines plans to invest KRW 3.7 trillion in intelligent power grids between 2023 and 2027 and to introduce Korean integrated power plants to manage and resource renewable energy efficiently. The plan includes enacting and amending relevant laws and regulations to register VPP projects, setting minimum capacity for market bidding, and calculating appropriate capacity fees. From the end of 2023, it will also provide market activation measures such as differentiated

compensation to encourage small and medium-sized distributed resources to participate in VPPs (KB Financial Holding Institute, 2023).

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4 Energy Management System (EMS) & Microgrid EMS

Concept and purpose

An energy management system is a comprehensive framework and set of practices designed to optimize the utilization, monitoring, and control of energy resources within an organization or facility. The system aims to visualize and optimize energy flows and use for commercial buildings, factories, homes, and social infrastructure (power grids, transportation networks, etc.) by leveraging information and communication technology (ICT) and control technologies. An EMS collects energy consumption data from various sources, such as sensors, meters, and utility bills, and analyzes it to identify trends and efficiency information. Based on these analyses, organizations can take energy-saving measures. Implementing an EMS is pivotal in increasing energy efficiency, promoting sustainability, and reducing costs. The system also allows organizations to monitor power usage and production and control equipment and appliances for rational energy use. It also enables efficient management and control of renewable energy sources such as solar power or energy storage systems (ESS) (NECPL, n.d.).

Looking at the detailed areas of EMS, there are mainly building energy management systems (BEMS), factory energy management systems (FEMS), and home energy management systems (HEMS). BEMS is a system that integrates measurement, control, management, and operation to provide optimized building energy management plans by monitoring energy usage to maintain a comfortable indoor environment and efficient energy management. FEMS is an energy management system that optimizes the energy supplied and consumed in the factory through monitoring, analysis, planning, and control from energy measurement of facilities. FEMS can be considered similar to BEMS in concept, as the target of application changes from buildings to factories. Still, the difference is that, unlike buildings, it is essential to manage various production facilities according to the characteristics of factories, so understanding and experience of facilities are essential, and real-time is vital for the control of production facilities. HEMS is a system that provides energy management services for monitoring, controlling, and optimizing the use of energy, such as electricity and gas, from the recipient's perspective. HEMS aims to maximize energy savings and efficiency improvement by providing usage meter reading and information collection functions of energy devices through energy service interfaces, energy MMI devices, etc., and providing a service environment such as automatic control and measurement of the recipient (KEMSIA, n.d.).

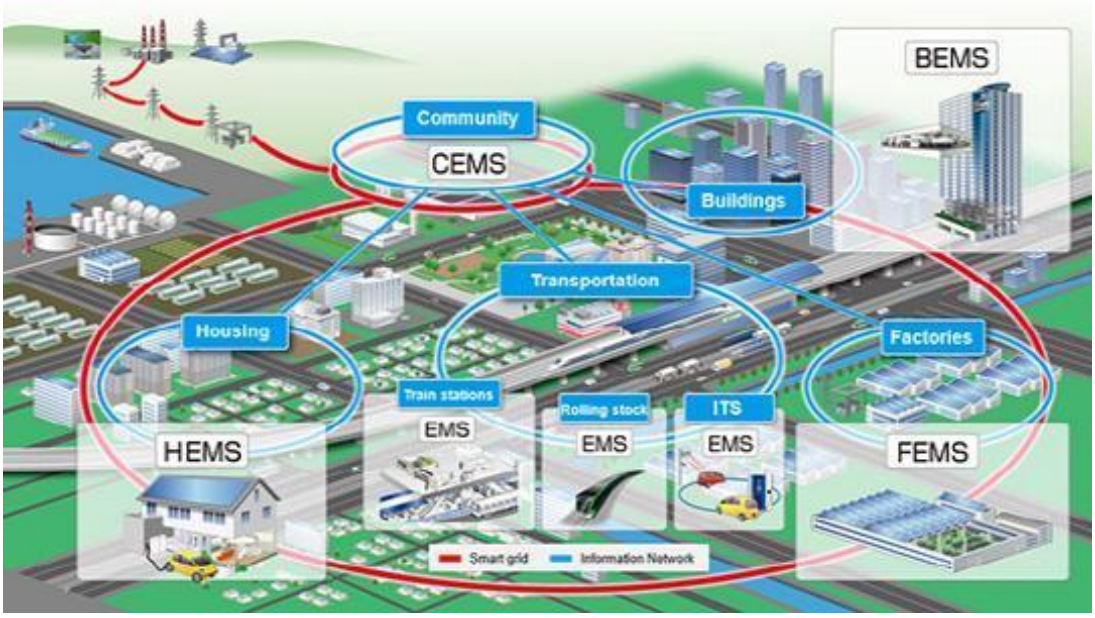

FIGURE E15: TYPES OF EMS (SOURCE: ENERGY ECONOMIC NEWS, 2015).

Technical features (structure and core functionality)

An energy management system, with its ability to measure and collect energy and environmental information, is a powerful tool in reducing environmental impact. It not only monitors energy consumption but also statistically processes the collected data and predicts future energy consumption. This system, accessible to external users and operators, enables clear energy consumption analysis. It identifies waste and suggests reduction measures, leading to increased energy efficiency. It contributes to direct cost savings and improved sustainability by significantly reducing environmental impact through reduced carbon emissions. The system also supports compliance with energy-related regulations and standards, such as ISO 50001. It includes features that support energy management by monitoring energy consumption and using forecasting results to identify inefficiently operating facilities and savings measures. Currently, energy management systems offer different technologies depending on the manufacturer and application, and standards for reference models and functional requirements are being developed to standardize them. An EMS typically consists of three main subsystems: an energy information system, an energy control system, and an energy management joint base system (KEMSIA, n.d.). Each of these systems may have different applications, but they all share the ability to monitor energy flows and control equipment and devices.

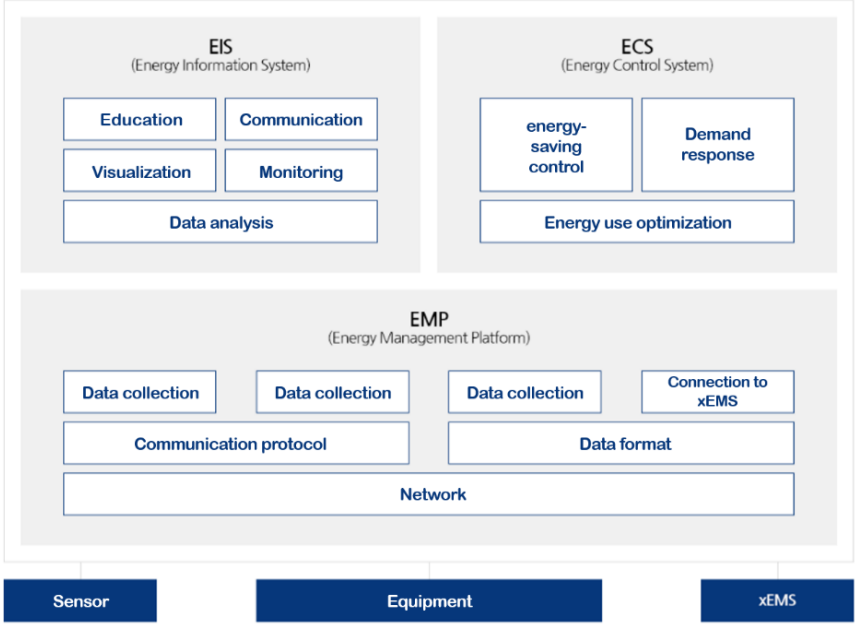

FIGURE E16: EMS SUBSYSTEMS AND FUNCTIONS (SOURCE: KEMSIA, N.D.).

Looking at the entire process of EMS, first, energy consumption and environmental data are collected through sensors and meters in real-time or periodically, which may vary depending on the collection format, collection frequency, and communication method, and then the collected data is delivered to the energy management system through a gateway. Since data omissions or errors may occur during the collection process, the EMS performs preprocessing to identify and correct omissions and errors before storing the collected data (Choi, 2023). A database that can efficiently and quickly process the vast amount of data collected in real-time is required, and the server platform serves as a central hub for data processing and analysis. Data visualization helps users monitor and manage energy information comprehensively, displaying energy consumption patterns and trends in the form of tables and graphs as dashboards (Mariano-Hernández et al., 2021; Mahapatra & Nayyar, 2022).

Application examples

POSCO DX, POSCO E&C

POSCO DX (formerly POSCO ICT) is a South Korean company that provides engineering, automation, system integration, and IT outsourcing services. It has expanded its business around smart technology and digital transformation solutions, including smart factories, smart cities, and energy efficiency projects. In 2013, POSCO ICT launched Smart EMS, an energy efficiency solution. Smart EMS consists of an industrial energy management system (FEMS) and a building energy management system (BEMS). FEMS is a solution that reflects easy-to-apply and effective practices by analyzing more than 10,000 energy-saving cases at domestic and overseas industrial sites, including POSCO, and its strength is data collection and analysis for energy efficiency. By analyzing the energy usage of facilities, it also detects

performance degradation and problems and notifies the time for maintenance. In addition, based on the different electricity tariff systems applied to industrial companies during daytime and nighttime hours allow facilities to be operated at night when electricity costs are lower (Kim, 2013).

In 2023, POSCO Eco & Challenge (POSCO E&C) declared carbon neutrality by 2050 and established a strategy and roadmap to respond to climate change, introducing and continuously improving its energy management system. The company fostered specialized personnel who can independently operate and improve energy management, redefined energy planning and review methodologies specialized for the construction industry, upgraded its GHG management computer system, PGMS, and developed and applied guidelines for GHG reduction at construction sites. In 2023, POSCO E&C obtained ISO50001 energy management system certification, an international standard that enables organizations to build a sustainable management strategy by systematically integrating energy efficiency activities. It enables POSCO E&C to achieve energy reduction and efficiency improvement through developing energy management indicators in the production sector and developing and commercializing green technologies (POSCO Newsroom, 2023).

KT (Korea Telecom)

KT is the first company in Korea to develop and provide a cloud-based BEMS system. By installing the BEMS in the KT Cloud, it is possible to save up to 47% in construction costs and 67% in operating costs compared to the existing BEMS method. KT's smart building BEMS reduces operating costs by providing energy management services remotely from KT estate's integrated control platform for five years. KT estate's integrated control platform is an intelligent control platform that monitors major facilities in buildings and controls them remotely through algorithmic analysis, and building management professionals using the intelligent control platform can check building conditions in real-time from the integrated control center and respond to situations remotely (Lee, 2021).

The control platform has a feature called "predicted peak hours," which analyzes power usage by building to predict and control when power usage will peak. In addition, the GIS (Geographic Information System) based map allows for the location of itinerant technicians so that when an incident occurs, the nearest itinerant technician can be dispatched to the site, ensuring a professional and fast response without missing any prime time, even during the vulnerable early morning and weekend hours when field technicians are scarce. The integrated control platform's human-machine interface (HMI) can also monitor and control on-site mechanical equipment, as the building's significant facilities are digitally twinned (Lee, 2021). KT's application of the unified control platform at the Jeongdong Building in Seoul helped reduce cooling energy by 30% by optimizing chiller costs, controlling chilled water temperature, and adjusting heating supply schedules. Previously, the Jeongdong Building experienced many cooling complaints from tenants. However, after implementing the platform, the number of complaints from tenants about the cooling and heating in their office space decreased significantly (Cho, 2020).

LS Industrial Systems Co., Ltd. (LS Electric)

Through the BEMS, LS Electric controls the energy usage of laboratory equipment and computers in real time and learns consumption patterns to help employees optimize energy consumption. Sensors that act as 'human eyes' are installed in all places where electricity is supplied to identify human movements in real-time, which automatically controls the air conditioning, heating, and lighting in spaces such as empty offices and conference rooms. In large spaces, lights are turned on only where people are active. LS Electric also installed a factory energy management system (FEMS) at Cheongju Plant 2 in Chungcheongbuk-do, and Cheongju Plant 2 manages the entire factory's energy usage from a central control center built on the FEMS station, saving more than KRW 110 million in electricity costs annually (KT Enterprise, n.d.).

Pulmuwon Co., Ltd.

Pulmuwon implemented a BEMS system during the design and construction phases. The BEMS system analyzes energy usage patterns to ensure efficient operation of the heating and cooling system and to save energy. The BEMS system reduces energy waste by predicting the cooling load (the amount of heat that needs to be reduced when cooling) in the building and then operating the cooling and heating system efficiently based on this information. In addition, the indoor environment information of the office space is collected by sensors, and clean air is circulated inside through an air conditioning system that removes fine dust. The BEMS system has enabled Pulmuwon's technicians to reduce greenhouse gas emissions by 10% in one year (KT Enterprise, n.d.).

Seoul National University of Science and Technology

Seoul National University of Science and Technology (SNUST) is creating smart buildings that can reduce energy consumption by 30 percent, developing autonomous shuttle buses that run 24/7 and high-reliability energy storage systems (ESS). The university's research center will develop smart buildings, autonomous electric vehicles, high-reliability ESS, smart energy town intelligent platforms, and electric vehicle charging robots in three phases over nine years until 2028. As part of the first phase, SNUST has converted some buildings into smart buildings since 2019. Once the smart energy management system and Internet of Things (IoT) sensors are installed, energy losses can be reduced by up to 30 percent by remotely monitoring and shutting off lights, air conditioners, and hot and cold water-heaters in empty classrooms, laboratories, and labs after lectures, contributing to global warming prevention. In particular, the costs saved through the development model can be used for more than 50 buildings on campus and external activities, enabling follow-up business support for participating companies, enhancing their technological competitiveness, and promoting local greening projects (Lee, 2019).

Future outlook or direction

The global energy management system (EMS) market will grow from approximately $19.96 billion in 2019 to $41.97 billion by 2027, with a compound annual growth rate of 9.9%. South Korea's EMS market is also expanding rapidly, projected to increase from KRW 1.534 trillion in 2019 to KRW 3.236 trillion by 2025. In South Korea, EMS technology is already quite advanced, with a wide range of technologies and solutions under development and application, particularly for enhancing energy efficiency. This growth stems from the country's high demand for energy efficiency and the increasing application of EMS through technological advancements.

South Korea's next-generation EMS technology aims to optimize energy production, distribution, storage, and usage and to construct a green and sustainable energy management system. These advancements include integrating smart grid systems, efficient management of distributed energy resources, control of peak hours through energy storage technologies, and applying AI and big data technologies to identify optimal ways to produce and use energy. Integrating digital twin technology will enable more advanced energy management, and experts believe these technological advancements will significantly contribute to steering South Korea's EMS industry toward an efficient and eco-friendly direction (Kharn, 2023).

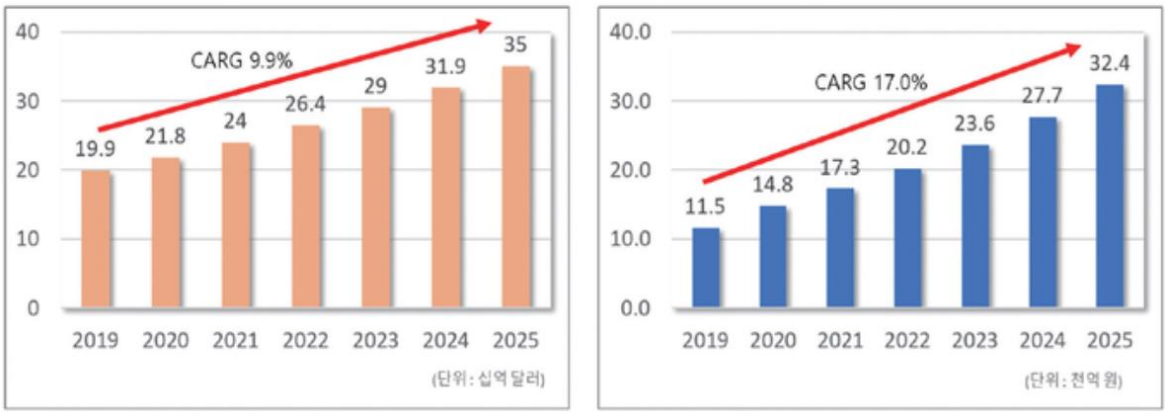

FIGURE E17: GLOBAL (LEFT, BILLION DOLLARS) AND KOREAN (RIGHT, ONE HUNDRED BILLION WON) EMS MARKET SIZE AND OUTLOOK (SOURCE: KHARN, 2023).

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5 Advanced Metering Infrastructure (AMI) for buildings and apartments

Concept and purpose

Advanced Metering Infrastructure (AMI) is an intelligent electricity metering system that employs a two-way communication network to provide customers with detailed electricity usage and hourly rate information, promoting voluntary electricity conservation. For instance, AMI allows real-time monitoring of home appliance usage, building lighting, and heating and cooling systems. By analyzing and predicting electricity consumption patterns, AMI can offer efficient energy consumption strategies for each household, potentially reducing electricity bills

AMI systems are installed across various buildings, including apartments, factories, retail centers, universities, and campuses, offering numerous social, economic, and energy efficiency benefits (Ryu et al., 2022). Socially, AMI helps manage homes with no significant change in electricity use over long periods, providing social safety services such as preventing lonely deaths among the elderly. For example, a sensor on a power pole could notify a caregiver if a person with dementia wearing a wearable device wanders beyond a set distance, or it could alert a caregiver or social service agency if an older person living alone does not turn off the lights unusually late or shows no morning increase in electricity usage. From an energy efficiency standpoint, AMI provides real-time power usage data to electricity recipients, encouraging them to adjust their power consumption. It also supports efficient distribution operations by offering detailed power consumption data to help prevent over-investment in distribution grid capacity (KPX, 2019).

A smart meter combines an electronic meter and a meter reading modem in a single device, installed individually in each household. Deploying smart meters provides several advantages, such as reminders of progressive tax dues, real-time electricity usage monitoring, and the opportunity to save on electricity bills by choosing appropriate electricity plans. Unlike the progressive system, a flat rate applies to each season and time of day, allowing users to benefit from lower rates during off-peak times and higher rates during peak times. Additionally, smart meters enable access to various information such as electricity usage, price information, comparisons among neighbors, and efficient electricity usage strategies based on usage patterns, all available on smartphones (Nuri Flex, n.d.).

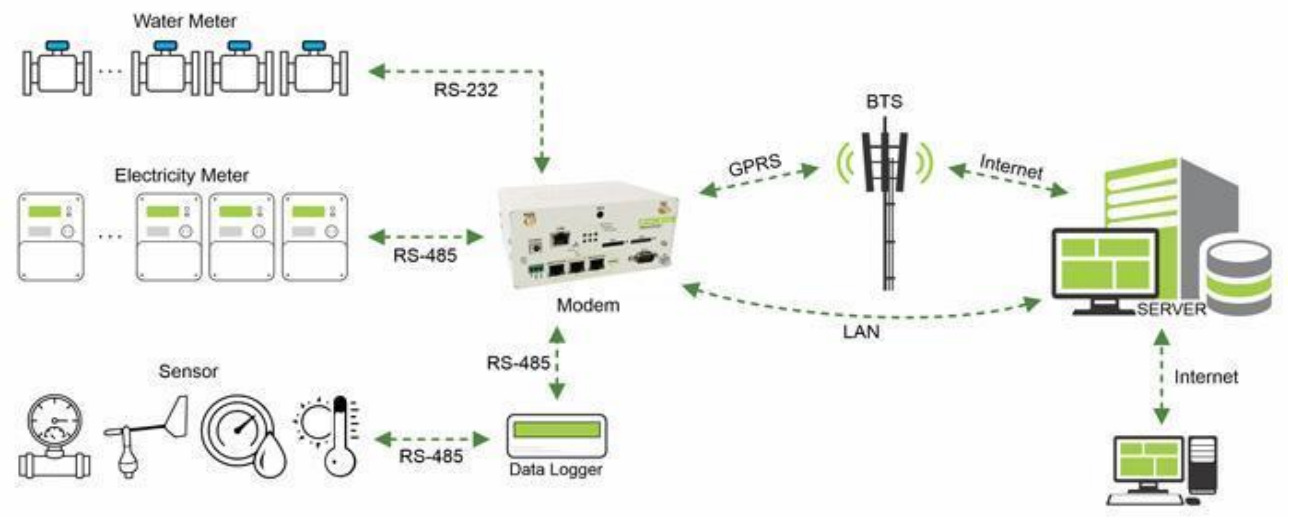

FIGURE E18: ADVANCED METERING INFRASTRUCTURE (SOURCE: GERMAN METERING, N.D.).

Technical features (structure and core functionality)

Advanced metering infrastructure includes smart meters, networks, and data management systems (Bian et al., 2014). Since early 2019, Korea has implemented AMI in various buildings (Lee, 2015). AMI collects real-time data on energy consumption, such as electricity, gas, and water, in buildings, providing information necessary to understand building energy characteristics, including usage patterns by households and peak hours (Niyato & Wang, 2012). Recently, as a core component of the smart grid, it has developed into an energy management technology by integrating with control management systems such as home appliances, air conditioners, and heating devices in general households to conserve energy (Myoung, 2010).

The technology structure of AMI comprises three main components: smart meters, communication infrastructure, and data management and analytics systems. Smart meters installed in high-voltage and low-voltage networks measure and record power usage in real time. These meters periodically collect electricity usage data to help understand and predict power consumption patterns. The communication infrastructure facilitates data transmission between smart meters and the utility's control center using wireless technology, ensuring secure data transfer, real-time monitoring, and remote control. Data management and analytics systems store, process, and analyze the collected data to monitor and optimize the power network's health, enabling utilities to forecast power demand, diagnose faults, and enhance service (Myoung, 2010).

AMI operates based on smart meters that communicate with metering devices to measure, collect, and analyze energy usage periodically. This system integrates hardware, software, communications, and consumer energy display and control, using a two-way communication network known as the AMI network for information exchange between metering devices and business systems. AMI networks generally consist of Home Area Networks (HAN), Neighborhood Area Networks (NAN), and Wide Area Networks (WAN) extending from the consumer side to the operation center. A Home Area Network (HAN) is a digital communication network between devices, displaying control and application services for information appliances. Notable technologies in this domain include LC technology and ZigBee in the

wireless personal area network (WLAN) area, along with WiFi for wireless local networks. A Neighborhood Area Network (NAN) connects all components within a distribution network field area, linking smart meters and data aggregation devices using technologies like WiFi Mesh, PLC, ZigBee, and the new standard, Smart Utility Network (SUN) wireless mesh network technology. A Wide Area Network (WAN) consists of a core/metro network and a backhaul network, transmitting data from the meter data collection units to the operation center. This network may use wired Ethernet-based networks or wireless and mobile network technologies like WIBRO, CDMA, and 3GPP LTE technology (LG Display&IT PLAY, 2019).

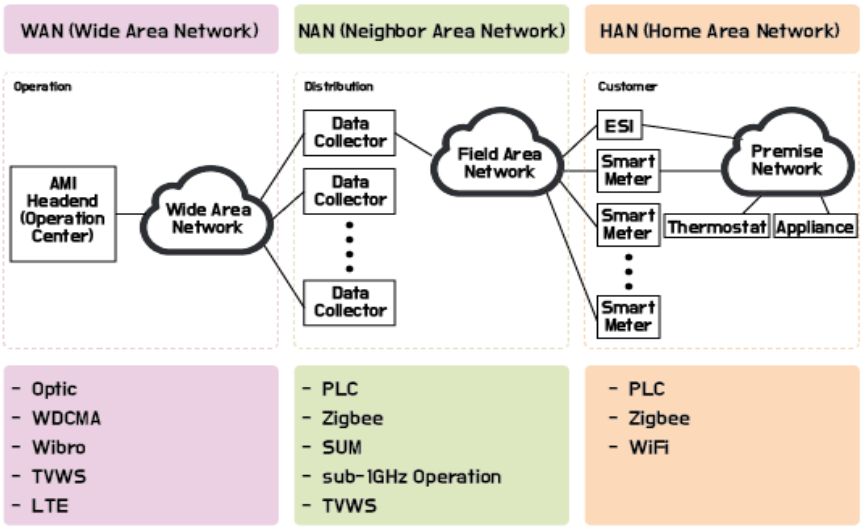

FIGURE E19: TYPES AND SUBSYSTEMS OF AMI NETWORKS (SOURCE: MYOUNG, 2010).

Application examples

Korea Hydro & Nuclear Power Co., Ltd (KEPCO)

KEPCO began deploying AMI in approximately 22.5 million homes in 2010. By the end of August 2022, it had deployed AMI in 10.86 million homes, or about 48%, and aims to complete the deployment by 2024. The project initially faced delays due to patent disputes over power line communication (PLC) and the application of security technologies. However, with established technical standards and security technologies, KEPCO can now accelerate the project. KEPCO has encountered both benefits and challenges with AMI adoption.

Regarding security, KEPCO suffered a cyberattack in March 2021, during which malicious code infected over 12,000 AMI modems on its communication network. Despite this, the power supply remained uninterrupted, and the internal network was secure. Following this incident, KEPCO enhanced its security by implementing an AMI-specific LTE network for the modems. Economically, the widespread adoption of AMI has led to a decrease in meter reading fees. For instance, while the total meter reading fee for the entire workforce decreased by KRW 16.9 billion, the main reason for the increase in meter reading fees in 2021 compared to 2019 was due to the near doubling of meters with

expired validity periods, necessitating replacements as mandated by law. Adopting AMI systems is crucial for enhancing electricity use efficiency and modernizing energy management. KEPCO is committed to building a more reliable and efficient power management system by fully deploying AMI by 2024 (Song, 2022).

POSTECH Campus

The Pohang University of Science and Technology (POSTECH) campus features buildings with varying characteristics, including different sizes, purposes of use, and types of users. These differences lead to variations in power consumption and patterns, prompting the deployment of Advanced Metering Infrastructure (AMI) on a building-by-building basis. Researchers installed three types of smart meters to establish AMI in seven buildings. Three-channel smart meters collect power usage data from large areas, such as entire buildings or floors; 24-channel smart meters gather data from smaller areas, like specific rooms or sections within buildings; and high-speed sampling sensors capture power usage data from specialized appliances or equipment that consume significant amounts of power.

The insights gained from our data collection and analysis have practical implications for managing energy consumption at POSTECH. For instance, as demonstrated in the research paper, the library's electricity usage typically increases from March to May and decreases in June, reflecting the academic schedule from the start to the end of the semester, including midterm and final exams. In April and May, we observe significant fluctuations in power usage. The fluctuations in April likely result from the changing power use during and after the midterm exams, and in May, from the preparations for final exams and the activation of cooling devices as temperatures rise. In June, we attribute the decrease in power usage to the reduced number of users following the semester's end (Ryu et al., 2022).

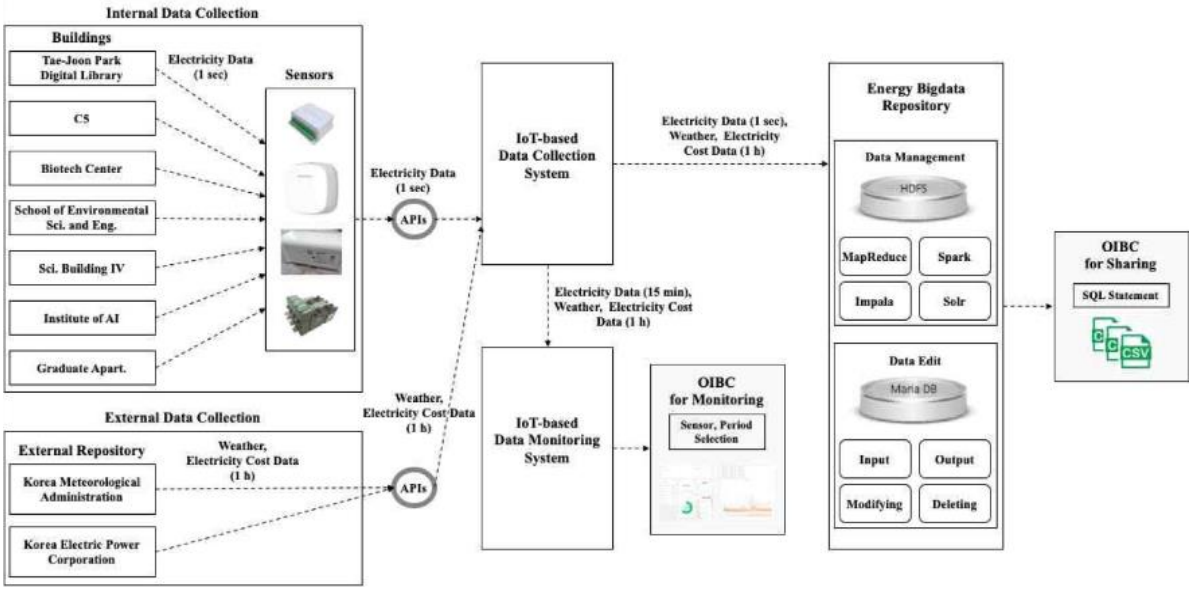

FIGURE E20: POSTECH AMI (SOURCE: RYU ET AL., 2022).

Electric Power Big Data Convergence Center, KEPCO

Electric Power Big Data Convergence Center operates 216 power systems, which generates over 3 trillion pieces of power data every year. In particular, electricity metering data is closely related to people's lives and is the basis for creating high-value-added industries when fused with data held by companies, so in October 2019, KEPCO opened the 'Power Big Data Convergence Center' to revitalize the domestic data industry. The Data Science Research Institute, an organization specializing in big data analysis, researches and develops analysis models specific to the energy sector, and the Power Data Sharing Center provides KEPCO's power data to operators to help them develop data business models. The 'Energy Marketplace' is a platform that brokers transactions for energy business models created using power data provided by KEPCO and connects suppliers and consumers of various services such as energy efficiency improvement and power demand management.

The Electricity Data Sharing Center provides Open APIs for electricity consumption by contract type, electricity consumption by industry classification, average household electricity consumption, increase and decrease of electricity customers by industry classification, changes in billing methods, electric vehicle charging station installation status, renewable energy status, welfare discount targets, and common code information, and the source data that is meaningful for actual big data analysis is available in four sharing centers located nationwide (Seoul, Daejeon, Naju, and Daegu) (Lee, 2021).

KSGI's Smart Grid Big Data Center

The Korea Smart Grid Institute (KSGI) is a foundation corporation that develops, spreads, and manages smart grid technologies and systems and is currently developing and distributing ten kinds of data products by processing and analyzing AMI data of 150,000 individual apartment units recruited through the smart grid expansion project. The Smart Grid Business Unit has established the 'Integrated Management Center (IMC) for the Smart Grid Expansion Project' to collect real-time metering and operation information, support comprehensive monitoring and joint utilization, and verify operational performance by business model.

Regarding AMI, the project is collecting data on house type code, legal building code, electricity usage, tariff plan, voltage classification of tariff plan, and tariff plan selection classification, and based on this, it is providing energy statistics information, providing energy usage pattern analysis, and predicting and analyzing energy and demand. Based on the IMC, the project team built a smart Grid Big Data Center for sharing and opening AMI data, implementing functions such as internal routing and real-time preprocessing of collected data, DB storage and distribution, analysis, processing, and relocation of data, data collection, and distribution flow management through NiFi console application, and metadata definition and management through CKAN user console. The Smart Grid Big Data Center can self-monitor and diagnose each hardware and software comprising the system to ensure data quality. It is equipped to monitor, simulate, and test the IoT data delivery process for sensor values and the data loading, processing, and big data generation process and to apply automated data quality diagnosis solutions (Lee, 2021).

Future outlook or direction

KEPCO is advancing efforts to streamline electricity consumption by aiming to install intelligent energy metering systems (AMI) in a total of 22.5 million households in Korea by 2025. This plan is designed to reduce electricity usage by 2 million MWh annually, equivalent to the consumption of about 55,000 four-person households. It also anticipates reducing greenhouse gas emissions by approximately 1.09 million tCO_2eq annually upon completion of the AMI installations. These efforts are poised to contribute to developing a next-generation power grid market centered around AMIs, enhancing energy utilization efficiency by enabling power demand distribution and real-time control through smart grid implementation (Kim, 2023).

The smart grid market in South Korea is projected to grow at an average annual rate of 28%, from about KRW 400 billion in 2012 to KRW 2.5 trillion by 2020. Among the five sectors of AMI—consumer, service, transportation, and regeneration—the sector promoted by government policies represents the largest segment. The global smart meter market is projected to reach USD 14.1 billion (KRW 16.39 trillion) by 2022, expanding at a CAGR of 9.5% from USD 8.9 billion in 2017. China held the largest market share at 46.1% in 2015, followed by Asia-Pacific, North America, Europe, South America, Russia-CIS, the Middle East, and Africa. However, Africa is expected to experience the highest growth rate from 2015 to 2025 at 42.1%, followed by Russia-CIS, South America, the Middle East, and Europe (Lee, 2020).

In 2024, KEPCO is planning various initiatives to build and strengthen AMI. Under this initiative, KEPCO and its regional headquarters will execute 19 AMI-related projects. These projects aim to efficiently measure, collect, and analyze energy usage through the AMI system, including operations within KEPCO's smart metering rooms. It indicates a nationwide expansion of the AMI system in South Korea, leading to a more systematic and efficient energy management system (Kim, 2024).

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6 AI-enabled prediction and diagnosis

Concept and purpose

AI is particularly well-suited to maintaining the reliability of the power grid. It excels in analyzing large data volumes and responding to complex scenarios, which is crucial for predicting and diagnosing potential issues in energy systems. As the complexity and diversity of distributed energy systems grow, the role of AI in ensuring safety and reliability becomes increasingly vital.

AI-driven technologies utilize real-time data from sensors and smart meters to quickly identify potential faults or abnormal conditions within the energy system. This data includes critical information such as energy usage, voltage levels, and current fluctuations. By processing this data in real-time, AI systems can detect unusual patterns early on, predict potential machine failures, overloads, and other issues. This predictive capability not only helps in taking preventive measures before failures occur but also significantly reduces costs and downtime (Kim, 2023).

Moreover, AI leverages big data and IoT devices to enable more precise analytics. For example, it can detect energy flow anomalies in the grid or predict variability in renewable energy sources that are not programmable. Such analysis helps optimize grid operations, manage demand, and enhance fault detection, thereby improving the efficiency of the entire energy system. Figure below illustrates the AI taxonomy for applications in the energy sector, providing a comprehensive overview of how these technologies are implemented to address various challenges. Overall, AI-enabled safety and reliability prediction and diagnostics are essential for tackling the complex challenges of modern energy systems and ensuring the continued availability of safe and reliable energy supplies (Quest et al., 2022).

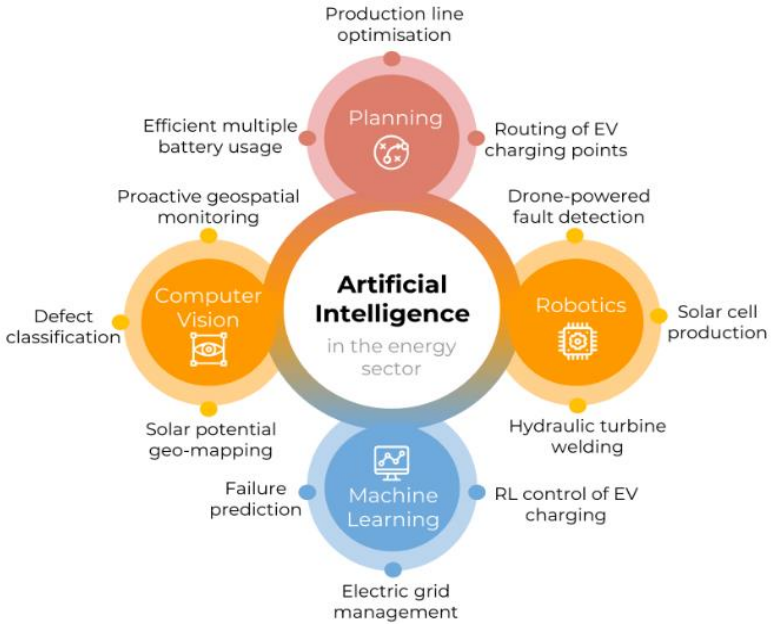

FIGURE E21: AI TAXONOMY FOR APPLICATIONS IN THE ENERGY SECTOR (SOURCE: QUEST ET AL., 2022).

Technical features (structure and core functionality)

AI-enabled prediction and diagnosis technology, leveraging machine learning and deep learning, meticulously process vast amounts of data to discern intricate patterns. This precision enables real-time monitoring of equipment and infrastructure within energy facilities, integrates historical data to forecast failures, and strategizes maintenance and accident prevention. It also considers weather conditions, geographical factors, and other environmental elements to anticipate potential risks.

Computer vision technology, a proactive measure to avert industrial accidents, analyzes and processes images to identify objects such as people, vehicles, and items in video footage. It assesses these images for abnormalities based on learned algorithms. Local governments use this technology to alert air traffic controllers to emergencies, such as a person falling in public spaces. Similarly, in industrial settings, the technology alerts when a person is too close to dangerous equipment like forklifts or if safety gear like hard hats or harnesses are not being used through alerts on CCTV systems (Kim, 2021).

AI is also pivotal in evaluating battery performance. In automotive battery safety diagnostics, the process involves five main steps: 1) Generating input data through experiments, including cycle tests under standard conditions; 2) Labeling the output after cycle tests; 3) Decomposing cells and analyzing failures to match observations with specific conditions; 4) Deriving relationships between inputs and outputs, which involves training models to recognize normal versus abnormal conditions using big data analytics; and 5) Developing a MLOps (Machine Learning Operations System) to standardize and automate these tasks for commercial application (Battery Inside, 2023).

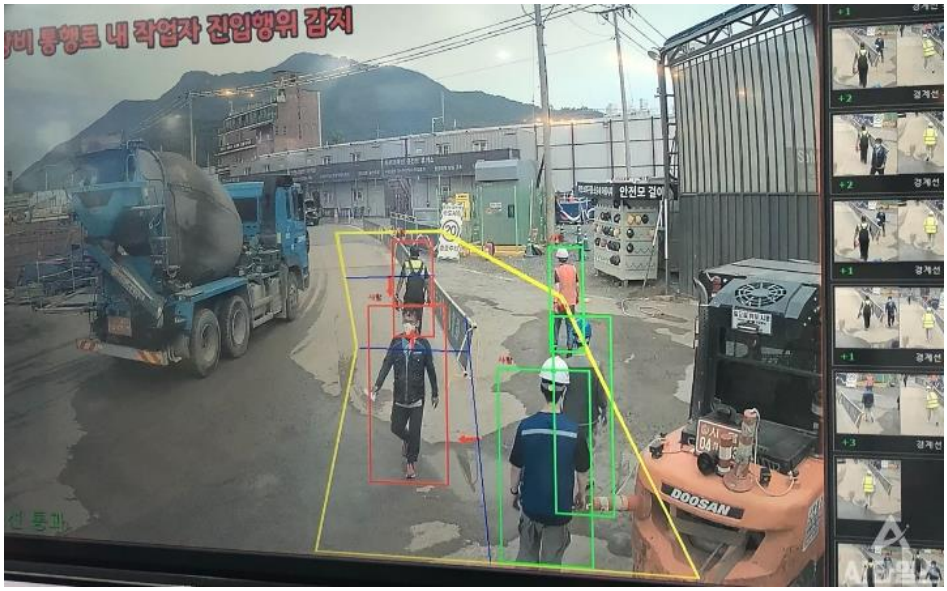

FIGURE E22: AI VISION TECHNOLOGY IN INDUSTRY (SOURCE: KIM, 2021). SUPPOSE A PERSON WITHOUT A HARD HAT ENTERS A HAZARDOUS AREA. THE AI WILL THEN MARK IT WITH A RED SQUARE IN THE VIDEO TO ALERT MANAGERS, AND AN AUDIBLE ALERT WILL NOTIFY BOTH MANAGERS AND WORKERS OF THE HAZARDOUS SITUATION.

Application examples

LG Energy Solution Co., Ltd. (LGES)

LGES collaborates with various universities to strengthen its AI expertise. With Harvard University, we are working on organizing battery charge-discharge degradation data into images, and with KAIST, we are developing a 2D CNN model to develop a network that can predict the point at which battery capacity will rapidly decline earlier and with higher accuracy. Recently, LGES tested the accuracy of human experts and AI in diagnosing defects in batteries for safety diagnosis, and based on the data of about 3,000 batteries, the accuracy rate of human experts was 81%, and the accuracy rate of AI was 71%, which did not reach the level of human experts with limited data. However, when we expanded the data to 8,000 cells and allowed for more complex patterns, the AI could diagnose 78% of the cells. At the same time, the human expert could only diagnose 52%, suggesting that AI can reach higher performance.

LGES is expanding the scope of safety diagnostics to the cloud based on AI technology. Previously, safety diagnosis relied on installation within the vehicle's Battery Management System (BMS), but computing power and memory limitations restricted its effectiveness. Therefore, developers considered implementing a cloud-based BMS, which offers the advantage of enabling more immediate and effective measures without requiring customers to visit the service center in person. Currently, LGES focuses on securing technology in three areas: AI, cloud BMS, and instant updates at service centers (Battery Inside, 2023).

Hyundai Engineering & Construction Co., Ltd. (Hyundai E&C)

Hyundai E&C started full-scale AI-based construction site safety management by launching 'Disaster Prediction AI.' Disaster Prediction AI is a system developed by Hyundai E&C to provide information on expected disaster risks on the day of work to all domestic construction sites currently under construction to enable preemptive safety management. The system was developed based on more than 39 million big data collected from all projects Hyundai E&C has carried out over the past ten years, including civil engineering, architecture, and plants. It contains a wide range of data, from actual safety accidents that had occurred in the past to preliminary accidents that did not lead to human damage, such as when a construction vehicle slipped and almost fell in an icy section or when construction materials fell in an unattended area, to more accurately identify and prevent potential disaster risks at construction sites.

Disaster prediction AI analyzes scheduled construction information entered by field personnel in a separate site management system to derive the probability of occurrence of safety accidents and safety management guidelines by type and delivers them to field personnel via email and text message on the day of work. Each site can utilize this to carry out preemptive safety management, such as itemized pre-inspections. In addition, the technology learns construction information updated daily from sites across the country in real-time to maintain up-to-date data and predict disaster risks more accurately. When a

site manager enters information such as the process rate and equipment used into the site management system after completing the construction schedule for the day, the AI predicts the contents of the upcoming construction and analyzes the probability of disasters occurring. In addition, Hyundai E&C is continuously collecting and digitizing various information related to safety at each site to improve the performance of disaster prediction AI (Hyundai E&C Newsroom, 2020).

Hyundai E&C's AI Image Recognition Equipment Jamming Prevention System is a state-of-the-art system that improves the shortcomings of the existing ultrasonic method. The system uses AI to distinguish between objects and people through image analysis of cameras installed at the side and rear, which are blind spots of heavy equipment and provides an alarm only when a person approaches the heavy equipment. Depending on the nature of the construction sites, it may be challenging to detect workers, even with AI image recognition and equipment collision prevention systems. For example, when working lower than the equipment, such as burying pipes in the ground, there are still blind spots that cannot be detected by cameras alone. Hyundai E&C will continue to upgrade the system to enable all-round detection of image recognition to eliminate blind spots in the camera. In addition, Hyundai E&C is promoting the development of an equipment collision prevention system that can minimize the distance error between workers and heavy equipment by using a UWB (ultra-wideband wireless technology) based communication method, which has improved accuracy compared to BLE (low-power Bluetooth) communication method, an existing wireless communication-based distance recognition technology (Park, 2023).

FIGURE E23: AI IMAGE RECOGNITION EQUIPMENT STENOSIS PREVENTION SYSTEM (SOURCE: PARK, 2023).

Korea Institute of Machinery & Materials (KIMM)

The Mechanical System Safety Division of the Korea Institute of Machinery & Materials (KIMM), under Korea's Ministry of Science and ICT, is developing an AI and IoT sensor-based facility disaster safety management system. This system utilizes AI to proactively identify and manage risk factors, thereby ensuring the safety of SOC (Social Overhead Capital) such as construction sites, aging facilities, and power generation plants. The system aims to measure, store, and analyze complex data, including wind

speed, temperature, and seismic activity, to monitor facility safety and predict risks using the gathered data.

KIMM also uses AI to predict future risk levels from accumulated IoT sensor data and recommend countermeasures based on these predictions. To achieve this, KIMM promotes the full-cycle digitalization of its facility disaster safety management system by integrating ICT, IoT sensors, and big data technologies. The system enhances existing IoT sensor modules with edge computing technology, transmitting various measurement data—from facility tilts to seismic acceleration and temperature—to the management server and cloud via wired and wireless communication. The central management system uses this data for real-time analysis and risk prediction, automatically sending danger signals to stakeholders when necessary.

Another research team at KIMM, the System Dynamics Laboratory, is developing AI-based predictive diagnosis and accident response technologies for mechanical systems in various plant facilities like power generation, ships, and offshore platforms. This technology helps prevent accidents and economic losses due to equipment failure. It minimizes recovery time during incidents by predicting the status of critical mechanical systems such as high-temperature and high-pressure pumps. The team has built a test bed replicating a high-temperature/high-pressure pump used in the field and is collecting data on various failure modes. Using AI, researchers are developing technologies to accurately diagnose current conditions and early-stage failures and control multiple smart valves to ensure safe accident response even during controller failures (KIMM, 2020).

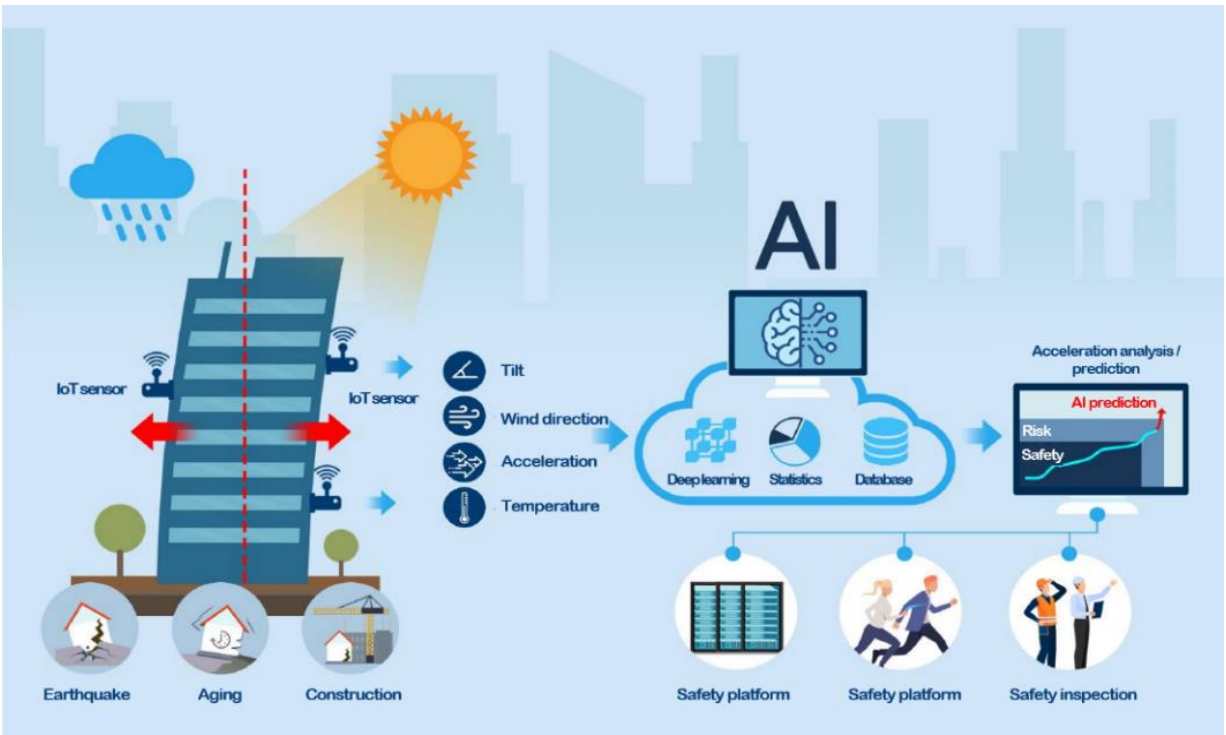

FIGURE E24: CONCEPTUAL DIAGRAM OF FACILITY DISASTER SAFETY MANAGEMENT SYSTEM USING AI AND IOT SENSORS (SOURCE: KIMM, 2020).

Intellivix Co., Ltd.

Intellivix develops and supplies vision AI technology for industrial applications. Through AI video surveillance technology, we have developed intelligent video surveillance software that can automatically detect and track moving objects (people, vehicles, etc.) in the video and then perform predetermined event detection. It simultaneously provides motion-based and deep learning-based object detection and tracking to enhance analysis and real-time analysis of recognized pedestrian attributes and vehicle types. For example, AI vision technology is applied to industrial sites to instruct workers who are not wearing hard hats to wear hard hats, to inform workers in dangerous places that they are in a dangerous area and request them to move, to inform heavy equipment operators of the danger when workers approach the radius of heavy equipment operations, to stop operations, and to notify them in real-time when a fire is detected. In addition, Intellivix has commercialized a technology that can detect fires by analyzing images of cameras mounted on drones in real time using AI (Intellivix, n.d.).

KT Enterprise

KT Enterprise has developed an AI Virtual Fence based on LiDAR technology to prevent entrapment accidents, the leading cause of fatalities in the manufacturing industry. It is not uncommon for workers to get caught in or hit by equipment while entering a hazardous area, and there is also the possibility of being crushed when entering a space where lifts are moving up and down. AI Virtual Fence analyzes when a worker approaches a three-dimensional area set as a danger zone and notifies them with an alarm or provides a contact signal that can be linked to the customer's equipment so that the customer can use it to stop the equipment urgently. KT developed 3D LiDAR (a device that uses lasers to detect nearby objects), which is the core of the solution, for cost-effective AI Virtual Fence. To identify objects approaching the danger zone, it is essential to have a device that can analyze space rather than the existing one- or two-dimensional detection device, and 3D LiDAR fulfills this role. In particular, KT's LiDAR is designed for industrial-specific use to dramatically reduce the price and secure a wide field of view at close range. KT launched the 'AI Virtual Fence' solution by combining 3D LiDAR hardware and AI software optimized for industrial sites (KT Enterprise, 2022).

Future outlook or direction

AI can help predict and detect unpredictable disaster situations. The role of AI in the safety industry is expected to grow in the future. As the number of large-scale disasters increases due to climate change and urban structural changes, the need for various measures for safety has increased, and safety solutions utilizing science and technology, such as AI, are gaining attention. Since the disaster safety field deals with human lives, it is vital to reduce threats and accidents through thorough on-site management. AI can help predict and detect unpredictable disaster situations. AI can actively predict

and detect unpredictable disaster situations. Experts anticipate significant growth in AI's role within the safety industry.

In particular, the adoption of AI by companies to reduce safety accidents is expected to increase as the Act on the Punishment of Serious Accidents has been in effect since January 2022. Vision AI is currently the most popular AI technology used to prevent industrial accidents. Vision AI technology is already widely used in industrial sites in Korea. One of the leading vision AI technology companies in Korea is Intellivix. Intellivix currently provides AI vision solutions to industrial sites of various companies such as LG Chem, SK Reco Plant, Samsung C&T, Hanwha Solutions, Kolon Global, and LG Display. In addition to AI specialists, Korean conglomerates are also developing AI technology for industrial safety. Hyundai E&C has developed its AI CCTV video analysis system based on the company's data to develop more construction-specific safety solutions. Lotte E&C applied AI to its risk assessment, which relied on humans and had problems with missing hazards. Other large Korean companies, including Hyundai E&C, Lotte E&C, and KT, are also utilizing AI and big data within their organizations to expand the development of AI technology in the construction sector further.

The role of AI in disaster safety is also expected to grow. This year, the South Korean government announced that it would increase the budget for the '2023 Disaster Safety R&D for Field Response Ministries,' a development project to research AI and robots needed for disaster prevention and response, by 3.6 percent from last year to a total of KRW 254.8 billion. In announcing the 'National Forest Fire Prevention Comprehensive Plan' in 2023, the Korea Forest Service announced that it would upgrade forest fire monitoring and decision-making support processes using ICT, including automatic monitoring of forest fires through AI CCTV. It will expand the number of 'forest fire prevention information and communication technology platforms' linked to AI CCTV, which were six as of last year. It will automatically monitor forest fires and incineration activities adjacent to forests. The Ministry of Environment announced the introduction of a flood forecasting system utilizing AI. It will minimize flooding and other damages caused by localized heavy rains that have occurred in the past. With the AI flood forecasting system, the forecasting time will be three hours earlier than the current one (three hours in advance), and it will also be possible to predict how high the water level will rise, making it easier to prepare countermeasures (Kwak, 2023).

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7 Advanced Distribution Management System (ADMS)

Concept and purpose

The Advanced Distribution Management System (ADMS) refers to a software platform that manages and optimizes power distribution (Gartner, 2022). Through the ADMS, automated recovery systems can be established in the event of power outages. It enables real-time identification of potential faults within the power grid and safely isolates them from other grids for a more reliable recovery process. Additionally, it optimizes voltage and voltage-ampere response to achieve energy savings through voltage reduction. Monitoring and managing energy peak demands are also facilitated, leading to enhanced performance of the distribution network. Moreover, ADMS can be integrated with microgrids and electric vehicle charging systems to further enhance its utility and effectiveness.

Technical features (structure and core functionality)

The traditional DMS is a system designed to control switches, protective devices, and other equipment installed in the power grid to manage the quality of electricity supplied from substations to end consumers (Shim, 2020). In the event of an outage on a distribution line, the DMS plays a critical role in swiftly controlling switches remotely from the distribution center to isolate the affected section and restore service to healthy sections, thereby minimizing the outage area and duration. However, the existing technology of power grid management systems faces new challenges due to the emergence of paradigm shifts such as the liberalization of electricity markets, strengthened environmental regulations, and the economic viability of renewable energy sources and distributed generation. The development of new technologies and changes in the conditions of the power industry demand new relationships between traditional power companies and consumers, as well as new functions and roles for the power grid.

The ADMS improves upon traditional DMS to monitor, control, and operate distribution networks suitable for future distribution environments (Shim, 2020). According to the figure below, this system incorporates new field devices such as distributed energy resources (DERs), energy storage systems (ESS), electric vehicles (EVs), smart meters, and Internet of Things (IoT) devices, along with related systems like New Distribution Information System (NDIS), Supervisory Control and Data Acquisition (SCADA), and Meter Data Management System (MDMS). ADMS integrates data from these field devices and other systems to effectively manage and utilize various information, thus enhancing the capabilities of the power grid for the future. The ADMS ensures technical reliability by integrating control over the power grid, thereby supporting real-time management of power distribution and demand prediction (NREL, 2020). The control mechanism of ADMS combines centralized and decentralized control methods, forming an integrated management system. Leveraging this system, optimal power flow can be

monitored in real-time, enhancing the performance of the distribution network. Furthermore, the utilization of data-driven predictive models allows for the evaluation of the effectiveness of distribution network control algorithms and rapid identification of problem areas in real-time, enabling efficient response and recovery measures. Thanks to these technical features, shortcomings such as slow response times and inefficiencies in energy management systems, previously criticized in traditional power grid management systems, have been significantly improved. ADMS reduces downtime in the event of risks, leading to cost savings through effective response management. By establishing a stable and reliable real-time energy management system, it enhances the efficiency, stability, reliability, and operational ease of the power grid.

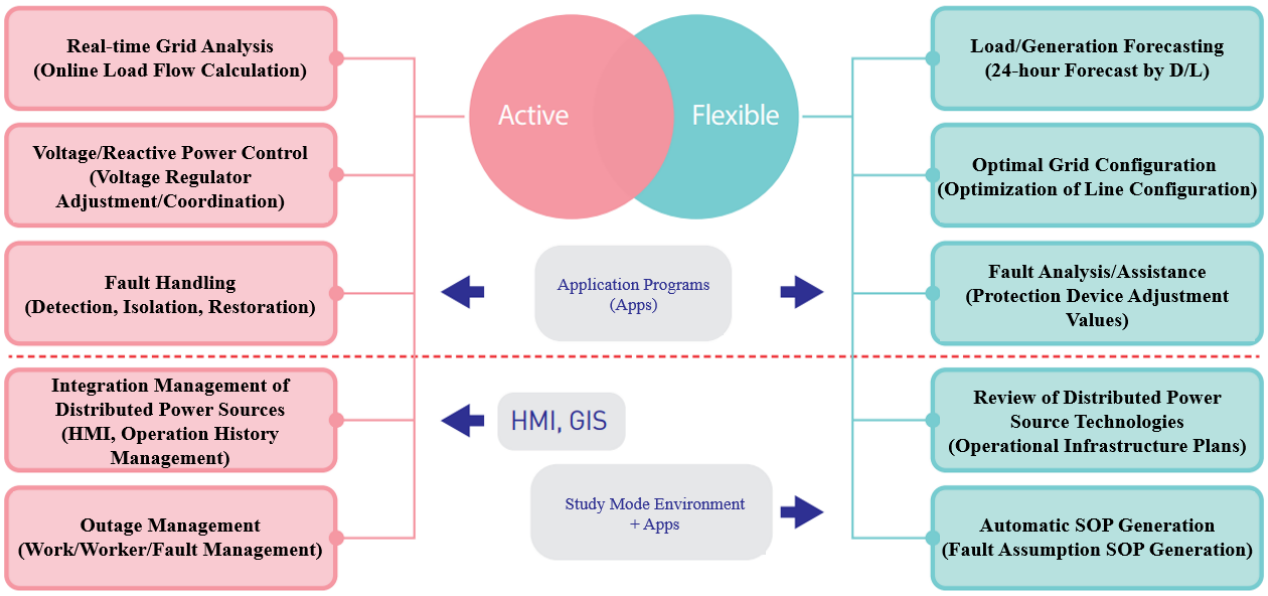

FIGURE E25: ADMS'S TECHNICAL PROCESS FEATURING SIMULTANEOUS AND REAL-TIME MONITORING (SOURCE: SHIM, 2020).

Application examples

ADMS Worldwide

Countries worldwide are actively promoting the adoption of ADMS to enhance the efficient utilization of energy resources. India, for instance, is pursuing a national policy initiative known as the Smart Grid Vision and Roadmap. As part of this policy, India has introduced a distribution management system based on the Electrical Transient Analyzer Program (ETAP) model (ETAP, n.d.). This system aims to improve the performance and efficiency of power networks, shorten system recovery times in the event of outages, maintain real-time status and performance of substation equipment, and reduce training time for control system operators. Through these measures, India seeks to achieve more efficient energy management and a more reliable and stable power transmission and distribution system. In Australia, SA Power Networks, along with companies such as Enel in Italy and SICAE France in France, have adopted Schneider Electric's EcoStruxure ADMS. This system enables comprehensive monitoring and

management of power network networks, enhances the performance of energy management systems, and improves the stability and reliability of clean energy production and supply systems. Moreover, it facilitates the optimization of grid systems and integrated management of distributed energy resources (Schneider Electric, n.d.).

ADMS in South Korea, KEPCO

According to the figure below, the development of power grid management systems in South Korea began in 1983 with research on intelligent operation of distribution lines. Subsequently, in 1990, research on the development of a Korean-style power grid management system was initiated. In 1997, the Korean Distribution Automation System (KODAS) was developed and underwent trial operation, leading to full-scale operation from 1998 onwards. The Total Distribution Automation System (TDAS) was developed in 2001, and by 2008, the system achieved full integration, transitioning to centralized operation through distribution centers from 2010 onwards. While South Korea has effectively operated its power distribution system based on these developments, there have been limitations in the utilization of applications compared to advanced utilities abroad, as the focus has been primarily on remote monitoring and control of distribution facilities (Shim, 2020). Additionally, the design of the power grid management system's line configuration and protection coordination system has been based on one-way power flow, posing challenges such as reliability issues and electrical quality concerns when numerous distributed power sources generating reverse power are connected to the grid.

In response to the South Korean government's policy for expanding distributed power sources, exemplified by the Renewable 3020 initiative (achieving 20% renewable energy production ratio by 2030), and to accommodate new technologies such as power IoT and artificial intelligence, there is a need for suitable new systems. Furthermore, the distribution grid, as a critical national infrastructure, must ensure uninterrupted operation for stable power supply and maintain high security to address external risks such as disasters, accidents, and hacking effectively. Therefore, addressing external environmental risks comprehensively is imperative.

The primary objective of developing and operating the ADMS in South Korea is to establish a distribution grid monitoring, control, and operation system suitable for future distribution environments (Shim, 2020). The development scope is classified into several categories, including high-capacity high-speed processing and uninterrupted operation for a common platform, application programs for optimal operation of the distribution grid, security/communication networks for ensuring communication reliability and establishing security systems, and verification systems to enhance the reliability of system development. In particular, the selection of application programs reflects the urgency and importance of transitioning distribution grid operation to an "Active & Flexible" mode, considering input from headquarters and business units (Shim, 2020). To provide a user-centered, convenient, and accurate distribution grid estimation and operation solution, functionalities such as real-time segment load estimation/distributed power generation estimation, highly reliable fault automatic processing, distributed power technology review, and SOP creation have been developed.

Additionally, synchronization with the NDIS allows for real-time calculation and communication of blackout areas, affected power amounts, and other relevant information to operators.

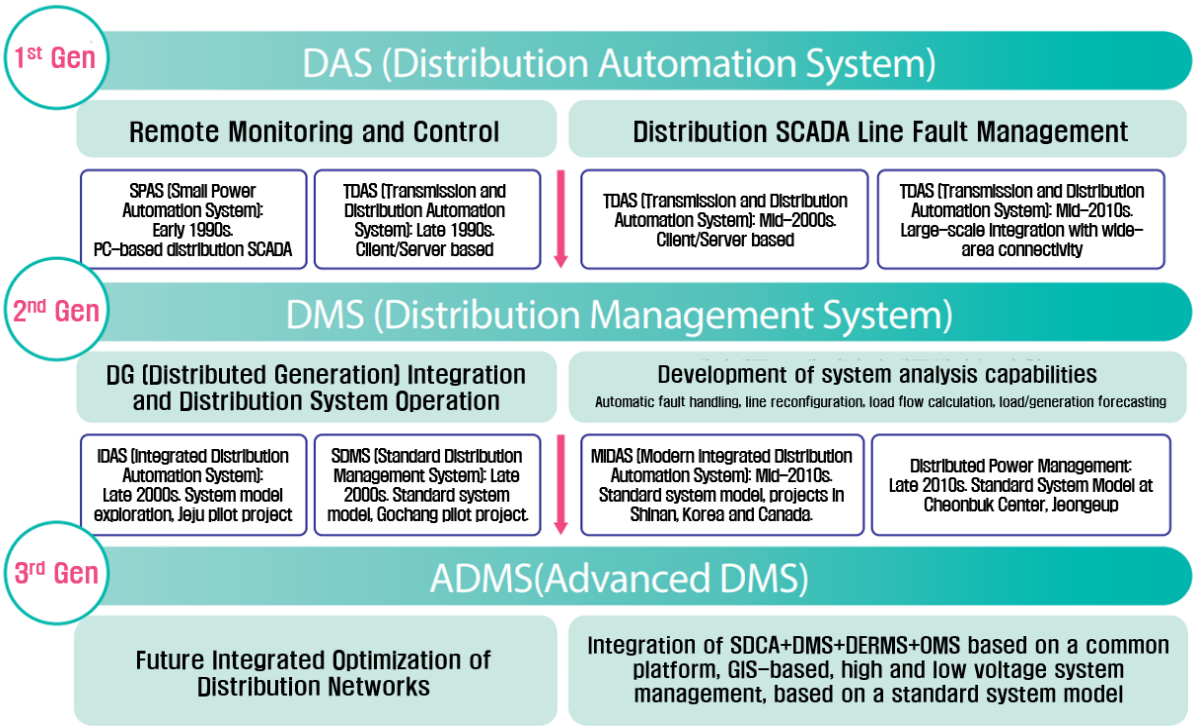

FIGURE E26: THE HISTORICAL DEVELOPMENT OF DMS IN SOUTH KOREA (SOURCE: SHIM, 2020).

Korea Electric Power Corporation (KEPCO) has announced the successful development of its next-generation ADMS based on domestic technology and its installation at its Chungbuk Branch since 2021, where it has completed validation in actual grid systems (Oh, 2022). With a total budget of 300 billion won allocated over a four-year period from 2017 to 2020, KEPCO collaborated with industry, academia, and research institutions to develop the ADMS. The system has been successfully operating on all distribution lines in the Chungbuk region. Starting with regions heavily reliant on renewable energy such as Jeju, Jeonbuk, and Gwangju/Jeonnam, KEPCO plans to expand ADMS to all 15 regional branches nationwide by 2024, thereby establishing an integrated management system for the national distribution network. Upon completion of the nationwide deployment of ADMS, an additional capacity of 2341 MW for renewable energy integration will be secured, leading to a budget savings of 309.2 billion won by reducing the need for additional distribution network construction. It is anticipated that the application of advanced ICT technologies for equipment optimization will result in an annual maintenance cost savings of 5.1 billion won. In addition, in line with the evolving trend of the digital transformation era, the development and updating of the ADMS platform software have been completed by 2024 (Lee, 2023). This enables the establishment of a system that can respond more swiftly and effectively to the rapidly changing distribution network operational environment.

Future outlook or direction

It is predicted that ADMS will play a crucial role in addressing the complexity of national power grids and the dynamic changes in energy efficiency. Therefore, it can be argued that there is a need for national policy support to achieve the convergence and innovation of operational technology (OT) and information technology (IT) through the advancement of smart grid technologies, aiming to achieve higher efficiency and reliable performance in power grid management. Additionally, given the significant variability in the efficiency of renewable and eco-friendly energy sources over time, building analytical models that accurately predict the real-time utilization of energy resources is essential for efficient and reliable utilization of power networks. Consequently, ADMS is forecasted to facilitate the maximization of the benefits brought by distributed generation by providing effective tools for power prediction and modeling.

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8 Digital Transformation Education Program

Definition and Purpose (Role)

Digital Transformation (DT) refers to the process whereby businesses utilize digital technologies not only in engineering but across various functions to adapt to changing environments and capitalize on innovative growth opportunities (Codestates, 2023). Through the adoption of digital technologies and tools, companies can innovate their business models and processes, leading to increased efficiency and automation through the utilization of AI-driven data analysis and cloud computing. Consequently, DT has emerged as a critical strategy for enhancing the competitiveness and ensuring the long-term growth of South Korean businesses (Baek, 2024; Lee, 2020). In today's rapidly changing competitive landscape, companies can effectively respond to evolving customer expectations and demands by actively embracing digital technologies. Furthermore, DT enables the establishment of data analysis systems and predictive models through AI and Machine Learning, facilitating automated decision-making. As a result, DT enables the construction of faster and more accurate decision-making processes, strengthening connectivity with customers, and significantly enhancing productivity within companies.

The comprehensive meaning of digital transformation extends beyond industrial-level digital innovation to encompass the digitization of personal and societal lifestyles (Lee, 2020). Achieving such digital transformation requires not only integrating digital technologies but also engaging in digital innovation across all aspects of societal value chains, redesigning existing digital experiences, and creating new business values and opportunities. Major global IT companies are introducing AI platforms based on big data and cloud technologies, thereby extending the influence of digital transformation across various industrial sectors. This situation is led by top companies in market capitalization worldwide, such as Apple, Google, Amazon, Facebook, and Microsoft, which are pioneering technologies and platforms in AI, cloud computing, and big data algorithms (Bloomberg, 2020). As digital transformation technologies emerge as core values in business operations, the significance of having a workforce equipped with leading knowledge and capabilities in this field has become a critical factor influencing national competitiveness.

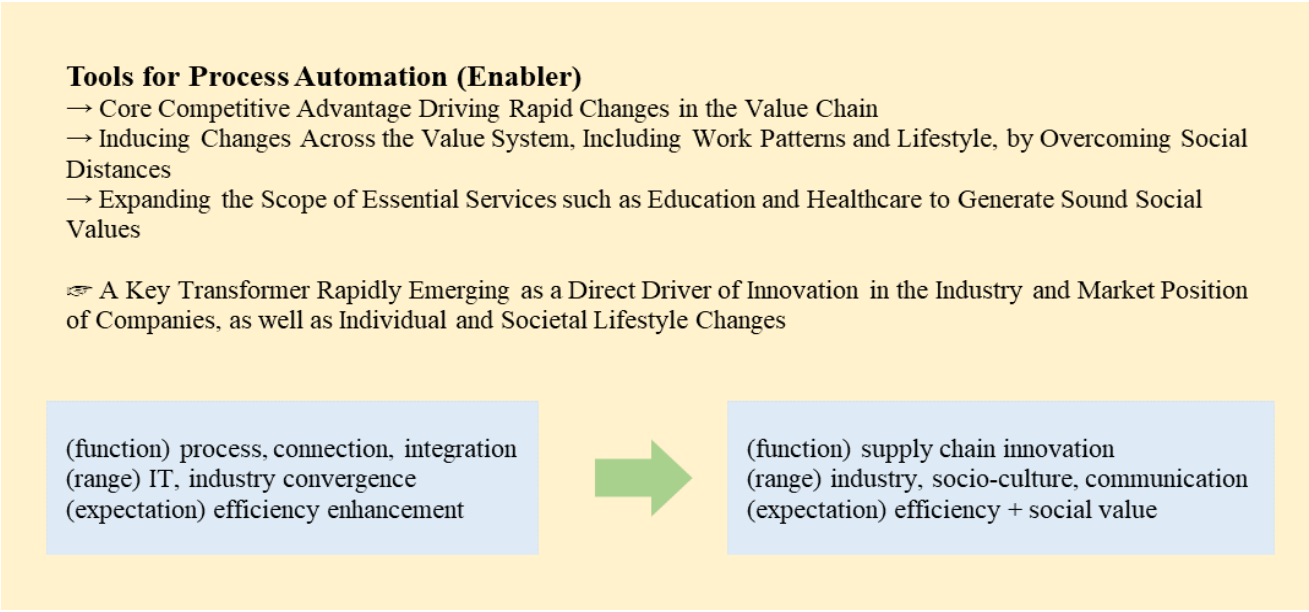


FIGURE E27: THE EVOLUTION OF SOFTWARE ROLES IN DIGITAL TRANSFORMATION (SOURCE: LEE, 2020).

As the concept of digital transformation and the importance of the technical skills and infrastructure required for digital transformation have gained increasing attention, there is a global trend towards the development of various education programs termed Digital Transformation Education Programs (DTEP). These programs can be broadly categorized into those conducted at the public sector and national levels, and those conducted at universities and educational institutions.

Public sector and national-level education programs for digital transformation aim to equip professionals with the necessary skills and knowledge to lead digital initiatives within government organizations and across various industries. These programs often focus on policy development, regulatory frameworks, and the implementation of digital strategies to enhance public services and drive economic growth. For instance, the United States Department of Education recently proposed revisions to the National Educational Technology Plan (NETP) in 2024, focusing on enhancing student learning experiences through the utilization of digital technology (Office of Educational Technology, 2024). Concurrently, the plan aims to support educators in expanding and designing learning experiences through digital technology. Particularly, the updated plan for 2024 emphasizes three key policies: digital access, digital design, and digital use, aiming to provide equal accessibility to digital technology for both students and educators. Furthermore, the Netherlands is investing in digital transformation policies based on the Digital Regulation Platform to expand digital infrastructure, innovate technological scalability, and promote ethical use of data (Digital Regulation, 2023). These strategies encourage collaboration within and outside government agencies through national governance, establishing clearer communication processes, roles, and responsibilities to facilitate digital transformation. Saudi Arabia has introduced the National Transformation Program (NTP) to support Vision 2030, aiming to diversify the national economic structure and promote the development and dissemination of digital infrastructure for achieving the visible outcomes outlined in Vision 2030 (Vision 2030, n.d.). Lastly, Vietnam is raising awareness of the necessity of digital transformation across society through digital transformation education programs (Giang, 2021). The country is focusing on developing

infrastructure and platform-building projects for digital transformation, promoting changes in perception through national promotion efforts, and prioritizing the development of national digital infrastructure through policies such as developing high-speed broadband infrastructure, expanding and upgrading 5G networks, and promoting smartphone adoption. Vietnam is also actively engaged in building digital identification and authentication systems and developing cloud computing technologies at the national level.

On the other hand, education programs offered by universities and educational institutions concentrate on preparing students and professionals for roles in the private sector, where digital transformation is driving significant changes in business operations and strategies. These programs typically cover a wide range of topics, including digital technologies, data analytics, cybersecurity, and business innovation, to ensure graduates are well-equipped to navigate the complexities of the digital age. MIT has established the Professional Certificate Program in Digital Transformation (MIT Professional Education, n.d.), aimed at comprehensively addressing key concepts in the digital revolution such as blockchain, cloud computing, AI, IoT, and cybersecurity. The curriculum is designed to enable participants to understand the conceptual definitions of these technologies, adopt and disseminate digital technologies, and cultivate emotional intelligence and leadership skills necessary for achieving effective digital transformation. Through this program, participants are educated to develop competencies that lead global digital transformation and innovation. Similarly, Stanford University has assembled a diverse faculty from fields including business, computer science, and engineering to develop the curriculum for its digital transformation program (Stanford Online, n.d.). Emphasizing the convergence of digital technologies and industrial sectors, the program focuses on research aimed at formulating effective corporate strategies to gain a competitive edge in the rapidly changing and uncertain digital technology society. It also places importance on developing digital-friendly organizational cultures. Furthermore, Harvard's Wharton School offers a digital transformation program addressing various topics such as challenges and uncertainties arising from digitalization, discerning opportunities for digital transformation, industrial transition to digital platforms, organizational characteristics and networks necessary for digitalization (Wharton Executive Education, n.d.). Through a two-month webinar series, participants share experiences on applying digital transformation in actual business management, discussing difficulties and expected outcomes. Lastly, UC Berkeley's digital transformation program covers modules on the overview of digital transformation, capturing opportunities for digital transformation in corporate management, the role of data analysis, processes for digital transformation, business models for disseminating digital transformation, effective organizational management for digital transformation, and digital transformation technologies and policies (Berkeley EM-Executive, n.d.). This program offers opportunities to explore various topics such as understanding the growth of subscription models, improving customer-centric processes, exploring regulations and ethical questions regarding data collection and usage, and learning about the utilization of digital technologies in various industries such as healthcare, banking, advertising, retail, and transportation.

Technology Properties (Structure and Core Functions)

There is a growing trend towards the development and implementation of industry-led digital transformation education programs aimed at enhancing societal responses and technological competitiveness in various fields (Baek, 2024; Lee, 2020). These initiatives receive significant support at the national policy level. However, given the potential challenges associated with adopting digital transformation, it is imperative for companies to effectively implement and utilize digital transformation education programs (Codestates, 2023). The difficulties encountered in the process of digital transformation include: Firstly, digital transformation is a technically complex process. It involves the adoption of various technologies and the swift adaptation to technological advancements, necessitating continuous learning among company members through well-designed education programs led by competent experts. Secondly, digital transformation demands changes in organizational culture. Given the familiarity of company members with conventional work practices, resistance to change, lack of collaboration, and cultural differences may arise during the digital transformation process. Effective education programs are required to adjust the mindset and capabilities of members to ensure successful digital transformation. Thirdly, digital transformation entails significant costs and time. Investments in updating systems, transferring data, and adopting relevant technologies require substantial resources. Effective management of the resources and planned transitions in operations and communication necessitate the introduction of effective digital transformation education programs.

The current pace of digital transformation is accelerating rapidly, extending digital competency beyond the realm of engineering into areas such as marketing, data analysis, and across all business functions within companies (Codestates, 2023). Domains that were previously achievable solely through human effort are increasingly being replaced by AI, showcasing superior accuracy and delivering more sophisticated results in a shorter time frame through advancing digital technologies, including instances of generative AI. In this context, it is essential to recognize that humans remain the creators and users of technology, emphasizing the notion that technological advancements are ultimately made for the betterment of humanity. Consequently, the ability of creative individuals to leverage digital technology, based on an understanding of various skills, and to connect and utilize these skills in diverse ways, is becoming increasingly emphasized as a vital aspect of competence. Individuals possessing the capability to connect various skills, as depicted in Table X, are defined as convergence talents (Codestates, 2023). As businesses transcend geographical boundaries due to digital transformation, they actively seek such convergence talents on a global scale to enhance their competitiveness in the global market. In the rapidly evolving landscape, the future leaders who will guide nations and businesses are envisioned as convergence talents equipped with digital literacy, from digital competence development to innovative mindsets and collaborative abilities.

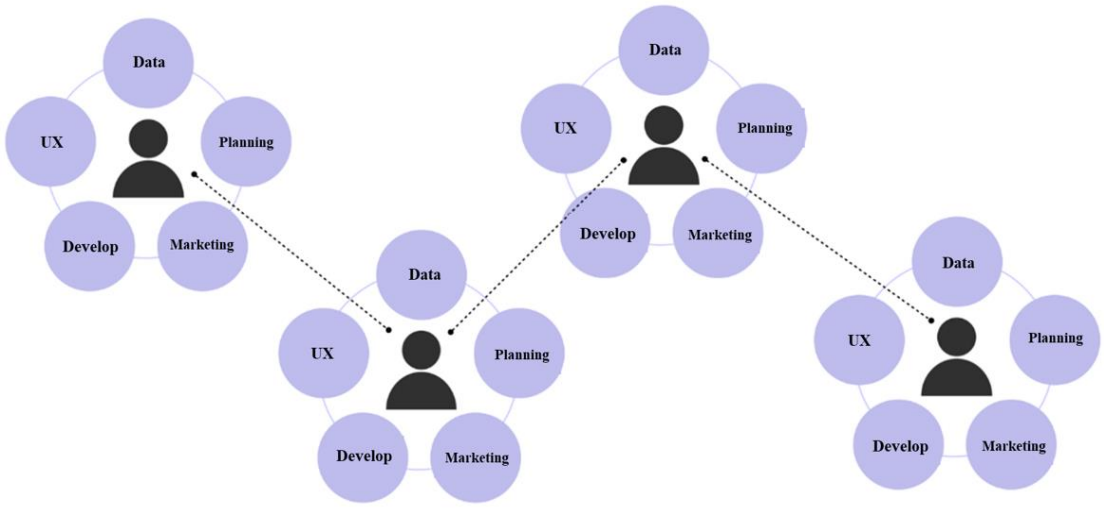


FIGURE E28: CREATIVE UTILIZATION OF CONVERGENCE SKILL SETS (SOURCE: CODESTATES, 2023).

The introduction of digital transformation education programs aims to mitigate risks associated with digital transformation and enhance its effectiveness (Baek, 2024; Codestates, 2023). To ensure the successful implementation of such programs: Firstly, strategic planning and approaches are necessary. Clear establishment of the company's vision and goals for digital transformation, along with exploratory research on the required technologies, are essential. Specialized digital transformation education programs tailored to these needs should be designed. For instance, digital transformation (DT) competency diagnostic assessments measure specific aspects of a company's and its members' digital transformation readiness, willingness to participate, and practical strengths and weaknesses in each stage (Codestates, 2023). Based on these assessments, tailored education programs can be designed. Secondly, active participation of company members should be encouraged. Clear communication of educational backgrounds, objectives, and expected outcomes of digital transformation programs tailored to the company's situation is essential. Project-Based Learning (PBL) curriculum, which is integrated with practical work, can be established to effectively encourage participation in digital transformation education programs and establish more effective linkage with practical work.

Cases in Korea

The digital transformation education programs in South Korea are structured with the following curriculum components to effectively address digital innovation.

KAIST DT Education Curriculum

According to the digital transformation education program offered by Korea Advanced Institute of Science and Technology (KAIST) (refer to Table X), the curriculum is structured into three phases. In the first phase, which is tailored for non-IT professionals, the focus is on practical education and training. This phase covers topics related to the utilization of AI-based technologies, emphasizing the acquisition

and enhancement of foundational skills such as utilizing big data, classification, discrimination, prediction, and automation.

Moving to the second phase, the emphasis shifts towards the development of AI technology applications and services. This phase provides task-oriented educational programs suitable for IT development and operational roles. Participants engage in projects aimed at applying AI technologies to real-world scenarios, fostering hands-on experience and practical skills development.

Finally, in the third phase, the program concentrates on fostering collaboration between academia and industry in the field of AI. It aims to uncover and support research projects relevant to AI in the context of the Fourth Industrial Revolution. Through project-based R&D curricula, participants are equipped to identify and address challenges and opportunities in AI, ensuring alignment with industry needs and trends.

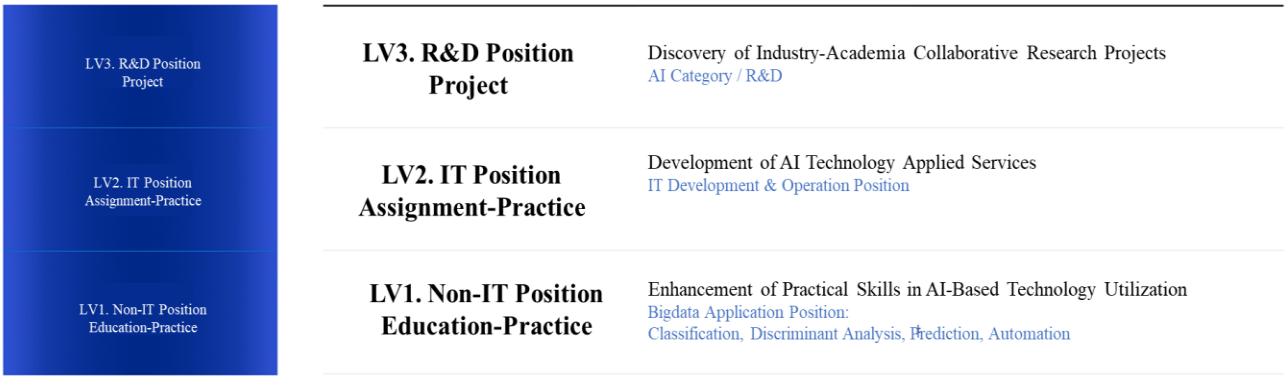


FIGURE E29: THE STEP-BY-STEP PROCESS OF DIGITAL TRANSFORMATION EDUCATION PROGRAMS (SOURCE: KAIST IT ACADEMY).

The education process at each stage is structured as outlined in Table X. In the second stage, learners' requirements for designing digital transformation education are analyzed through face-to-face consultations, and these are then reflected in the development of learning modules. Moving to the third stage, consulting and instructor matching take place to design customized educational courses considering individual characteristics and proficiency levels of learners. This facilitates the proposal of optimized education curricula tailored to learners. In the fourth stage, the details of the education program are finalized, leading to agreements and the commencement of education in line with these specifications. Finally, in the fifth stage, survey evaluations and feedback sessions regarding the education process are conducted, fostering discussions on how to design subsequent educational courses based on this feedback.

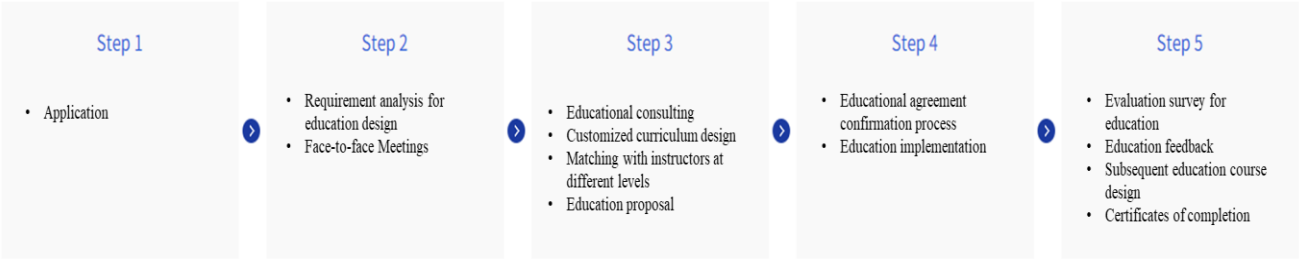
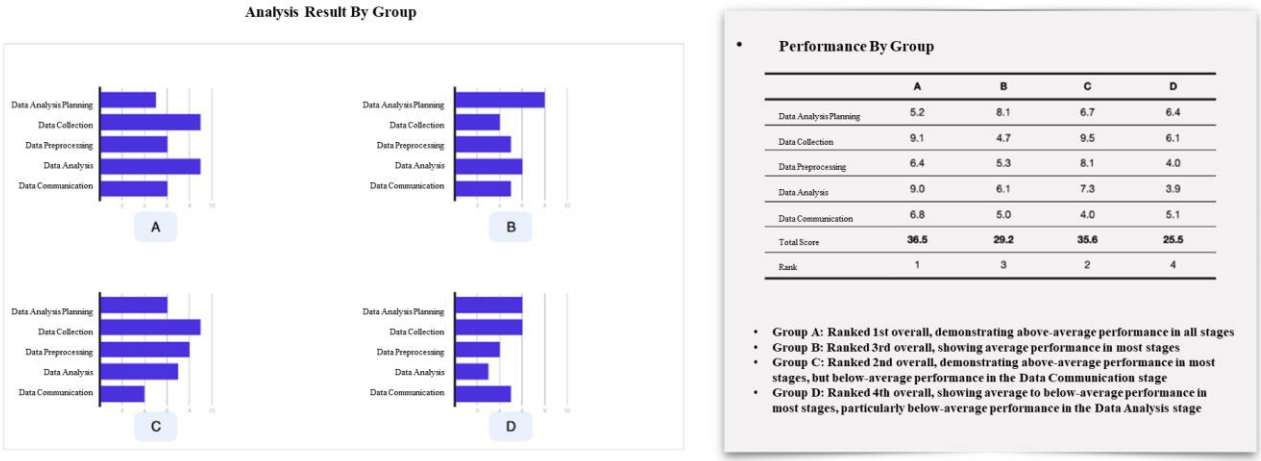


FIGURE E30: DIGITAL TRANSFORMATION EDUCATION PROCESS (SOURCE: KAIST IT ACADEMY).

Codestates's DT Capacity Assessment

Codestates, a digital transformation education institution, specializes in generating ideas regarding the relationship between AI and digital transformation, as well as designing digital transformation education programs to enhance core competencies in the current landscape (Codestates, 2023). Offering a variety of customized digital transformation education programs, ranging from onboarding to recruitment-linked training, Codestates operates with a focus on preparing talents equipped with practical skills that can be immediately deployed in real-world scenarios, often proposing regulations for formal hiring after completing these programs. To effectively assess and improve the design of such education programs, Codestates has introduced the DT Capacity Assessment to reduce the failure rate of digital transformation initiatives and guide companies towards successful outcomes. By conducting DT capacity assessments, Codestates objectively evaluates companies' current DT capabilities, enabling the design of tailored education curricula beyond standardized ones, thus providing customized digital transformation education. Leveraging the diagnostic results for both organizations and individuals, Codestates offers curricula of appropriate difficulty levels, fostering increased participation among employees.



	A	B	C	D
Data Analysis Planning	5.2	8.1	6.7	6.4
Data Collection	9.1	4.7	9.5	6.1
Data Preprocessing	6.4	5.3	8.1	4.0
Data Analysis	9.0	6.1	7.3	3.9
Data Communication	6.8	5.0	4.0	5.1
Total Score	**36.5**	**29.2**	**35.6**	**25.5**
Rank	1	3	2	4

FIGURE E31: EXAMPLE OF DT CAPACITY ASSESSMENT (SOURCE: CODESTATES, 2023).

According to the table above, Codestates conducts efficient diagnostic assessments based on an online diagnostic system. These assessments focus on three key factors: awareness of digital transformation, fundamental competencies required for Citizen Data Scientists (CDS), and the performance competencies of CDS. Following the diagnostic assessments, detailed reports are provided approximately two weeks later. Companies can use these diagnostic results to objectively evaluate their organization's current capabilities, enabling them to design systematic DT education programs effectively.

Future outlook or direction

South Korea is actively exploring ways to enhance the digital capabilities of successful businesses and government organizations through digital transformation education programs. To achieve these goals in the future, the government is focusing on key concepts such as task manager-oriented education, personalization, Project-Based Learning (PBL), nurturing Digital Transformation (DT) evangelists, and leveraging generative AI (Baek, 2024; Codestates, 2023). Firstly, it is essential to cultivate integrated problem-solving skills beyond mere task execution through task manager-oriented education. Rather than standardized programs, there is a need for educational courses that support comprehensive digital transformation capabilities among members, enabling them to perform effectively in their roles. Secondly, adapting to the era of personalization requires diversification of educational content. As the competency levels of individuals vary in response to the accelerating digital transformation, designing personalized curricula and educational programs based on advanced competency assessments can effectively enhance both individual and organizational DT capabilities. Thirdly, providing expanded educational experiences based on Project-Based Learning (PBL) is crucial. This involves mentoring, coaching, and feedback from experts or peers, fostering learner skill enhancement and flexibility to immediately engage in real-world tasks. Fourthly, achieving digital transformation at the organizational level requires strategic development of educational programs aimed at nurturing DT evangelists. These individuals actively embrace digital transformation technologies and lead change, guiding others to adopt and adapt to digital advancements. Lastly, encouraging the proactive utilization of generative AI can effectively combine fragmented data and computations, leading to explosive improvements in organizational capabilities and productivity.

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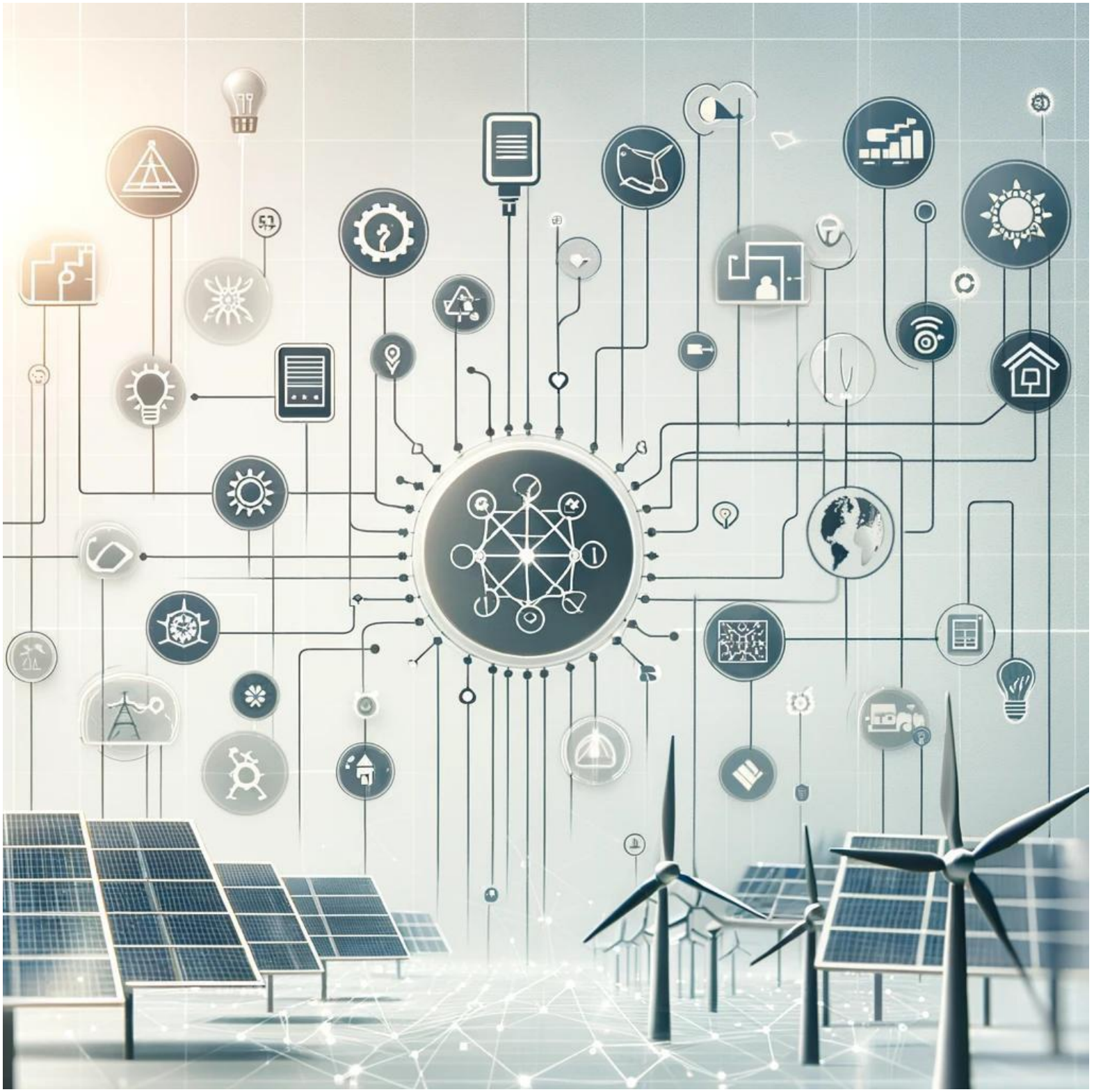

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