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Battery Energy Storage Systems in Korea and Germany

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Current Status and Prospects

Content

List of Abbreviations

B.KWK	German Federal Association Combined Heat and Power
BDEW	German Association of the Energy and Water Industries
BEE	German Association for Renewable Energy
BESS	Battery Energy Storage System
BKZ	Grid Construction Cost
BMWK	German Federal Ministry for Economic Affairs and Climate Action
BNetzA	German Federal Network Agency
BVES	German Federal Association for Energy Storage Systems
BWS Solar	German Federal Association Solar Industry
CAES	Compressed Air Energy Storage
CFE	Carbon Free Energy
CHP	Combined Heat and Power
DFG	German Research Foundation
DoD	Depth of Discharge
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
DSR	Demand Side Response
EBA	European Battery Alliance
EEG	Renewable Energy Sources Act
ERDF	European Regional Development Fund
ESS	Energy Storage System
EV	Electric Vehicle
FCR	Frequency Containment Reserve
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IPP	Independent Power Producer
KEPCO	Korea Electric Power Corporation
KfW	German National Development Bank
KPX	Korean Power Exchange
LDES	Long-Duration Energy Storage
LFP	Lithium Iron Phosphate
LMP	Locational Marginal Pricing
MOTIE	Korean Ministry of Trade, Industry and Energy
MVDC	Medium Voltage Direct Current
NDC	Nationally Determined Contribution (to the Paris Agreement)
NMC	Nickel Manganese Cobalt
NREL	National Renewable Energy Laboratory
PHS	Pumped Hydro Storage
PPA	Power Purchasing Agreement
PV	Photovoltaics
RE	Renewable Energy
REC	Renewable Energy Certificate
RPS	Renewable Portfolio Standard
SI	System Integrators
TCTF	Temporary Crisis and Transition Framework
TRL	Technology Readiness Level
TSO	Transmission System Operator
VRE	Variable Renewable Energy
VRFB	Vanadium Redox Flow Battery

Executive Summary

Electricity storage can play a significant role in modern decarbonized energy systems by enabling a time-delayed use of electricity. Especially for the integration of intermittent energy sources such as wind and solar energy into the power grid, this function is important to ensure grid stability. In particular, large-scale battery energy storage systems (BESSs) are gaining prominence due to their high efficiency and flexibility. Unlike pumped hydro storage, which is geographically constrained, BESSs allow for installation at strategic locations (e.g. on industrial sites). Moreover, they enable a wide field of applications and have a higher round-trip efficiency in comparison to other storage options.

Germany and Korea target climate neutrality by 2045 and 2050, respectively. To reach their targets, the countries plan to significantly increase the share of renewable energies in their electricity systems. Both countries recognise the important role of BESSs in the transition of their electricity systems and are committed to promoting their deployment. This study examines the current status and future potential of large-scale BESSs in Korea and Germany. It provides an overview of the status of this technology in both countries and identifies challenges impeding a swift roll-out. It also provides recommendations for German-Korean cooperation to further promote the deployment of BESSs.

Germany and Korea are united in their need for BESSs to reaching their climate neutrality targets and plan for a similar sized BESS capacity of 24.4 GW short- and medium-duration capacity by 2036 in Korea and 24 GW by 2037 in Germany. Currently, Korea has a more advanced deployment status of BESSs than Germany and was able to establish itself as a global leader of battery cell production. However, Germany has experienced a surge in demand for large-scale BESSs in recent years for several reasons, including a profitable market environment for arbitrage trading as well as an energy transition away from fossil fuels. In contrast, Korea has faced a decline of demand following a series of fire incidents and related safety concerns since 2017. Both countries actively target the scale up of both BESSs deployment as well as domestic production and thus have published specific strategies and policies, including research programmes, demand measures and financial incentives.

The analysis shows that various technical, regulatory and market challenges are hindering the deployment of BESSs in both countries. Both Korea and Germany face supply chain vulnerabilities and share technical challenges such as limited lifespan of batteries or high up-front investment costs. They also experience investment vulnerabilities, although the nature of these challenges varies because of the different electricity market structures. In addition, the deployment of BESSs in both countries is constrained by existing regulatory and policy frameworks albeit with specifics to each country's electricity markets and participation opportunities for BESSs. Addressing these challenges is essential for the transition to a decarbonized energy system based on renewable and clean energy.

Collaboration between Germany and Korea can support this endeavour and is recommended on the following topics:

- Integration of BESSs into the electricity grid
- Safe operation and standardization of BESSs
- Resilience of BESS supply chains and domestic production

By focusing on these measures, both countries can enhance their energy transition, ensuring a more cost-effective and sustainable integration of renewable energies.

1 Introduction

Electricity storage already plays a significant role in modern energy systems today. Storage systems allow for a time-delayed use of electricity, which is crucial for the integration of intermittent energy sources such as wind and solar energy into the power grid. They are thus important for achieving the globally agreed greenhouse gas emission reductions. Especially large-scale battery energy storage systems (BESSs) are well suited to balance out power supply and demand in the short term, providing the power grid with necessary stability.

The transition to a net-zero emissions economy necessitates increased reliance on renewable energy sources for power generation. Germany has set a target for 80% renewable energy consumption by 2030 and has a long-term vision to achieve net-zero emissions by 2045. In the electricity sector, Germany aims to be almost climate-neutral by 2035. The Republic of Korea, hereafter Korea, is planning to achieve 21.9% renewable energy generation by 2030 (currently 9%) and has set a net-zero target for its economy by 2050 (Ministry of Trade, Industry and Energy 2025).

In order to achieve their net-zero goals, both countries have to decarbonize not only the electricity system but also other sectors of the economy, such as industry, transport and buildings. This will lead to the electrification of many processes and, in turn, to an expected increased demand for green electricity. Estimations show that with this decarbonization pathway, around 600 terawatt hours (TWh) of green electricity will be required in 2030 in Germany compared with 254.9 TWh today (2024) (Federal Ministry for Economic Affairs and Climate Action 2023b; Bundesnetzagentur 2025a). To compare: In Korea, the amount of renewable electricity generated today is 56.7 TWh. The expected total demand for electricity in 2030 would be at 612.4 TWh, if Korea adheres to its 2030 nationally determined contribution (NDC) targets and its 2050 carbon neutrality goal (Berkeley Lab 2023).

With intermittent renewable electricity sources like onshore and offshore wind as well as solar PV, energy systems must enhance their flexibility to integrate increasing shares of these sources. Following Cebulla et al. flexibility is the "ability to balance the residual load (electricity load minus viable renewable energy)"(2018, 449). This necessity for adaptability is crucial for both Germany and Korea as they strive to incorporate more renewable energy into their grids (U.S. Energy Information Administration 2023).

With the help of Energy Storage Systems (ESS), some of the challenges that are created by high shares of intermittent energy sources in the power grid can be addressed. ESS allow for the time-delayed use of electricity. They support balancing grid supply and demand by storing energy when demand is low and releasing it during peak periods. ESS can therefore level out demand fluctuations and reduce the need for costly backup power generation (Frey et al. 2021). This stabilizes not only electricity prices but also the system itself while supporting its economic efficiency. Fast-response ESS (e.g. Lithium-ion batteries) also help maintaining electric grid frequency, by quickly compensating for fluctuations in supply and demand, thus preventing disruptions like spikes, surges or outages that could harm electric equipment and contributing to power quality, meaning voltage stability, frequency stability among others. Moreover, they enable solar and wind plants to meet grid operators' dispatch calls even when direct generation is unavailable, thus minimizing curtailment and maximizing renewable energy utilization. Additionally, placing ESS on strategic locations on the grid can help utilities in answering to growing electricity demand at lower cost than expanding the grid itself (U.S. Energy Information Administration 2023). Thus, energy storage allows for the energy transition to evolve smoothly and efficiently by reducing pressure on grid expansion. This is particularly important in regions where grid expansion is met with opposition from society (Fraunhofer ISI 2020).

As of today, electricity storage systems are ideally suited for managing short-term delays between power generation and consumption. For long-term storage, which is necessary to balance supply and demand over extended periods and across different seasons, the current advanced solution involves converting electricity into other forms of energy, like hydrogen, and then converting it back (Federal Ministry for Economic Affairs and Climate Action 2023b).

Despite their many benefits, the roll-out of ESSs faces challenges in both Germany and Korea. Among these challenges is the factor of high up-front investment costs with varying amortisation periods depending on the market environment. The economic viability of ESS often hinges on the price differences between charging and discharging periods, meaning that ESSs are only profitable if the peak demand periods and the low demand periods have a large price contrast. Another factor is that of existing technological limitations, such as limited storage capacity and duration, and thermal management (Deguenon et al. 2023; Hannan et al. 2020). The development of utility-scale ESS technology is still in an early stage. Although the first grid-scale ESS, in form of pumped hydro storage was installed in the late 19th century in Switzerland, the bulk of global storage capacity has been installed since 2016 in form of BESSs, more specifically lithium-ion batteries (Mul 2025). This demonstrates how little time has passed in terms of technology development, in particular with regard to ESS´s, and how much potential there still is (Thimet and Mavromatidis 2023). This factor is tightly connected to the issue of investment costs. Only if investors deem battery technology for energy storage economically viable and a sound investment opportunity, the ESS market will be able to grow appropriately. This in turn, is hinged on existing regulatory hurdles. A favourable regulatory framework is recommended that reduces investment risks and decreases economic burdens, such as taxes, if feasible, (Federal Ministry for Economic Affairs and Climate Action 2023b; Deguenon et al. 2023).

In Germany, a large amount of the total installed electricity storage capacity is provided by pumped-hydro storage (24 GWh/ 6 GW) while battery storage contributes a capacity of 18 GWh (as of January 2025). This capacity is provided by 15 GWh household battery storage systems, 2.2 GWh large-scale systems and approx. 750 MWh industrial battery storage systems (Figgener et al. 2025; Federal Ministry for Economic Affairs and Climate Action 2023b). This showcases the current predominance of pumped storage and home appliance systems in Germany. However, the potential for additional pumped storage capacity in Germany is limited due to geographical constraints. Therefore, the focus of this study is on the deployment of BESSs.

In Korea, the situation is slightly different: Korea has installed and operated energy storage systems totalling 9.1 GW/48 GWh as of the end of 2023. Among these, lithium-ion battery ESSs account for 4.4 GW/10.4 GWh, primarily used for frequency regulation, renewable energy integration, and demand management for large consumers (Ministry of Trade, Industry and Energy and Korean Energy Economics Institute 2023). The household ESS deployment is currently being conducted as part of a pilot project. The remaining storage capacity is provided by pumped hydro storage (PHS) with 4.7 GW/37.6 GWh of storage capacity (Statista 2023b).

Large-scale BESSs are gaining prominence due to their high efficiency and flexibility. Unlike pumped hydro storage, which is geographically constrained, BESSs can be deployed widely, often near strategic locations such as transformer stations (Gür 2018). Moreover, new fields of application continue to emerge: better market integration of electricity from large PV facilities and wind farms, ‘grid boosters’ which support grid operations management (transmission system operators and distribution system operators), and efforts to optimise energy management at large industrial sites (Federal Ministry for Economic Affairs and Climate Action 2023b). Furthermore, BESSs exhibit higher round-trip efficiency compared to pumped hydro storage (PHS) and compressed air energy storage (Deguenon et al. 2023).

To ensure system stability and flexibility in the power grid, which is essential for transitioning to a net-zero economy, large-scale battery storage of electricity will play a crucial role and has significant potential in both Korea and Germany. However, many questions remain unanswered, such as the determination of optimal locations for battery energy storage systems to best serve the grid in each country. Therefore, this study will analyse the status, potentials and challenges of large-scale battery storage systems in Korea and Germany. The study will proceed as follows: First, a brief overview on battery storage systems, the existing technology and use-cases will be given. Subsequently, the study will dive into the status quo, potentials, policies, challenges and stakeholders of the BESS roll-out in both Korea and Germany. It will also display one case study of a large-scale BESS for each country respectively. Finally, a comparative analysis of both countries will be drawn and recommendations for future cooperation between Germany and Korea will be given.

2 Battery Energy Storage Systems Overview

Battery Energy Storage Systems have several advantages over other types of large-scale energy storage systems such as high power capacity; a rapid response time to grid signals and their capacity for modular building, leading to great scalability. There are four common types of battery technology which are used for BESS: lithium-ion; lead-acid, sodium-nickel-chloride and redox-flow batteries. All of them can be applied for different use-cases both in transmission grids and in distribution grids. Among them are ancillary services, peaking capacity and industrial energy supply.

2.1 Definition and types of BESS

2.1.1 Definition

While the definition can vary depending on context, the specific grid requirements, and the purpose of the system, the term 'large-scale battery storage systems' typically refers to battery energy storage systems of at least 1 MW of power capacity up to over 100 MW, depending on the specific system (U.S. Energy Information Administration 2023; Kyon Energy 2025). Large-scale battery storage systems can serve the purpose of balancing supply and demand, stabilizing the grid, integrating renewable energy sources, and providing backup power. They offer the following advantages over other types of ESS: rapid response time, meaning they can respond to grid signals within milliseconds, making them suitable as fast-response service; scalability, as they are often arranged in a modular fashion; high power capacity, allowing them to provide power for several hours (e.g. up to 4 hours for lithium-ion batteries), up to a day (e.g. redox flow batteries); and high round-trip efficiency, meaning high efficiency in storing and discharging energy (Prakash et al. 2022; Figgener et al. 2023). Additionally, they can be used flexibly and decentral, especially compared to pumped hydro storage, which necessitates certain geographical preconditions (Bundesverband Energiespeicher Systeme 2023).

2.1.2 Types of large-scale BESS

There are different types of batteries, which can be used in a large-scale battery storage facility.

When comparing different types of battery technologies, there are several characteristics that should be considered. Among them are: its *storage capacity*, which defines the quantity of electricity which is accessible in a battery; its *power attribute*, which specifies how much power a battery can deliver; its *round-trip efficiency*, which, as explained in the introduction, describes the ratio of energy delivered by a battery during discharge to the energy given during a charge cycle. Other characteristics are *the depth-of-discharge (DoD)*, indicating the percentage of energy discharged from a battery relative to its total capacity and *the battery lifetime*, which is defined as the number of charge and discharge cycles a battery can supply during its lifetime (Prakash et al. 2022). In addition, aspects such *as safety and environmental considerations*, which might arise with the production of the batteries; the *range of temperatures* the battery can be operated in, and their aggregate *investment costs* might be considered.

The most common types of batteries, their advantages and disadvantages are described below:

Lithium-ion battery: The most common type of battery technologies used in large-scale BESSs is the lithium-ion (Li-ion) battery (Mongrid et al. 2019). Lithium-ion batteries were first invented in the late 1970s and are also commonly applied in household battery energy storage systems as well as electric vehicle (EV) batteries and appliance-size batteries such as smartphones and laptops (Liu 2019). The lithium-ion battery is characterized by a wide range of beneficial qualities such as high-power attributes; a high depth-of-discharge; high round-trip efficiency and a long lifecycle. Moreover, the lithium-ion battery displays a wide range of operating temperatures; recyclable lithium oxides; and generally, a good performance (Prakash et al. 2022). At the same time, the technology has its drawbacks, including: environmental and safety issues due to toxic materials such as lithium, cobalt and nickel which can cause water and soil contamination and pose risks to human and wildlife health and often involve unsustainable mining practices. While the technology has been characterized by relatively high costs in the past, the average price for lithium-ion battery cells has dropped rapidly from 166 US dollar per kilowatt hour in 2022 to 115 dollar in December 2024. (Zheng 2023; Clark 2025; Statista 2025). Moreover, a main safety risk of the lithium-ion battery is thermal runaway, which refers to a process of overheating and a resulting fire or explosion (Dai and Panahi 2025). At the same time, while the solutions for recovery and recycling of materials used inside a Li-ion battery are fewand not yet widely applied, (Prakash et al. 2022; Ritchie 2024), recycling capacities in Europe are currently increasing with several expansion projects of existing facilities as well as announcements for new recycling plants (Stephan 2024).

Lead-acid battery: The lead-acid battery is known for being a well-developed technology with good storage capacity and a fast response time. It has a low self-discharge rate and rather low investment costs compared to the Li-ion battery. However, it also displays some disadvantages such as environmental and safety issues, due to the sulfuric acid in the batteries being highly corrosive and potentially causing burns or injuries upon contact. The contained lead can equally cause serious health issues, including neurological damage. Improper disposal or recycling can release acid and lead into the environment, causing pollution and increasing the risk of health hazards. Further disadvantages are a low depth-of-discharge; bulkiness and a low cycling capacity, meaning its ability to undergo repeated charge and discharge cycles while maintaining its performance and capacity (Prakash et al. 2022; May et al. 2018).

Sodium-nickel-chloride battery: The sodium nickel chloride battery has a high energy density, meaning it can store more energy in less space than other types of battery, and a long lifecycle. It is also known for a long discharge time, a fast response and low investment costs compared to the Li-ion battery. Moreover, sodium is an abundant resource, making it an optimal material for battery production. On the other hand, it has high operation and maintenance cost and a high self-discharge rate and is still undergoing research and development for improved energy density, cycle life, and safety (Prakash et al. 2022; Lan et al. 2023).

Vanadium-redox-flow battery: A promising type of battery especially for large-scale energy storage is the redox-flow battery. It is highly scalable; has a long cycle life and improved safety features since the energy is stored in liquid form outside of the cell stack. Moreover, it has a rapid response ability and minimized environmental risks. However, the redox-flow battery has a lower energy density and lower round-trip efficiency than other types of battery. Additionally, due to relatively high technological complexity, it has high investment costs (WattLogic 2021; Olabi et al. 2023).

Solid State battery: Solid state batteries are advanced energy storage devices that replace the liquid electrolytes in traditional lithium-ion batteries with solid electrolytes, addressing key challenges such as thermal instability, limited energy density, and safety concerns. The battery operates by transferring lithium ions through a solid electrolyte during charging and discharging. The solid electrolyte acts as a stable ion conductor and mechanical separator, preventing short circuits and enabling tighter cell packing. Materials like ceramics, sulfides, or polymers are used for the solid electrolyte, offering trade-offs in conductivity and durability (Lozanova 2025).

Further types of batteries which can be used for large-scale ESS but are either still undergoing research or are not yet widely applied for other reasons are: nickel-cadmium; sodium-sulfur; zinc-bromine flow; and natrium-ion.(WattLogic 2021; Sino Voltaics 2025).

2.2 Use Cases for large-scale BESS

Large-scale BESSs can be applied for a range of purposes with different kinds of batteries more or less suitable for different applications/ services (Eichhammer et al. 2020). Generally, BESSs can be used both in transmission grids and in distribution grids for one or more of the following services: grid support to provide power quality and uninterrupted power supply; meeting peak energy demand; enhancing the benefits of integrating renewable and distributed energy sources; and reducing the costs associated with expanding or reconfiguring distribution networks (Prakash et al. 2022). Moreover, large-scale BESSs can be installed both in front of the meter in combination with renewable energies and conventional power plants, where electricity is directly stored after generation, in transmission/ distribution grid, and behind the meter for industrial and residential applications to shift energy demand (PWC 2024).

In the following, the most important use-cases for large-scale battery storage facilities are described to give a comprehensive overview.
First, large-scale BESSs can be used for **ancillary services** in both distribution and transmission grids. Ancillary services refer to services that support the transmission of electric power from generators to consumers while maintaining a reliable gird. This includes short bursts of electricity, which are provided or absorbed to maintain a balance between supply and demand; but also ensuring voltage stability, which directly translates to grid security; as well as frequency regulation and the provision of reserves.
Moreover, large-scale BESSs can help with **peaking capacity**, meaning the provision of sufficient capacity to satisfy the system's peak demand.
Further, BESSs should be able to allow for **energy shifting**, which means that energy storage is charged during low costs and released when demand exceeds supply. Batteries may be charged using excess renewable energy or assets that become dispatchable when combined with the battery.
By **optimizing the existing grid infrastructure** through large-scale BESSs, utilities can defer or even avoid investments in traditional grid expansion.
Lastly, large battery systems can be used for **industrial energy supply**, making industries more flexible in their electricity consumption. Similar to grid applications, industries can fall back on BESSs for backup power or simply managing costs by using stored power during peak hours, therefore avoiding high electricity prices. This practice is known as peak-shaving. Additionally, industries sometimes build renewable energy parks for their power supply. In this case, large-scale BESSs can provide the same advantages in levelling intermittent electricity generation as in grid applications (Prakash et al. 2022; Figgener et al. 2023; DIN et al. 2021).

For large-scale batteries a business case exists mainly for the use cases ancillary services, participating in capacity markets, and shifting energy volumes, i.e. storing electricity in periods with lower market prices and releasing it in periods with higher prices – also known as arbitrage trading. Unlike other flexibility options, such as hydrogen electrolysers or traditional power plants, where the focus lies on marginal prices and the absolute market price level, the key factor for BESSs is the expected price differential between the market prices at time of purchase and sale. Moreover, economic viability of BESSs is contingent on the number charge-discharge cycles. The more frequently a BESS can complete cycles, the more economic it becomes (Tennet 2024).

3 Status and Prospects of BESS in Germany

Germany is rapidly advancing its large-scale battery energy storage systems deployment as a crucial component of its energy transition strategy. While the current installed capacity stands at approximately 1.7 GW, projections from the Federal Network Agency indicate a needed increase to between 43 and 54 GW by 2045. Despite the absence of specific government roll-out targets, these systems are increasingly recognized as vital for achieving Germany's 2045 net-zero ambitions. The current market dynamics and growing renewable energy integration needs are creating favourable conditions for significant BESS expansion, even as the sector navigates various regulatory and technical challenges.

3.1 Current status of BESS in Germany

As of January 2025, Germany's large-scale battery storage capacity has reached 2.2 GWh with a combined power of 1.7 GW. In comparison to December 2022 with a total installed storage capacity of 863 MWh/ 787 MW, the capacity in Germany has doubled in only two years showcasing the rising interest in BESSs (Figgener et al. 2025). The five largest BESS projects currently in operation in Germany are listed in Table 1. The table shows that the projects are all used for ancillary services and more specifically frequency containment reserve (FCR). Generally, large-scale battery storage systems in Germany are primarily used for ancillary services, renewable energy integration, industrial energy supply and multi-use operation such as arbitrage trading or grid booster projects. Because large-scale storage systems have been primarily built for the provision of FCR until 2019, BESSs for ancillary services are dominating the German market. This is followed by grid booster purposes, renewable energy integration, multi-purpose operation and industrial energy supply (Figgener et al. 2023).

The demand for large-scale BESSs in Germany is expected to grow significantly, driven by increasing electrification and renewable energy integration, which necessitate enhanced grid security and stability. Batteries have already established their dominance in the German storage market, accounting for 75.3% of large-scale storage technology revenue in 2023 (Bundesverband Energiespeicher Systeme 2024). Until 2027, Figgener et al. (2023) project an increase in large-scale battery storage capacity of up to 3.9 GWh . The Bundesverband Solarwirtschaft (BWS Solar, eng. Federal Association Solar Industry) even expects an increase of up to 8.6 GWh until 2026 (Bundesverband Solarwirtschaft e.V. 2024). This growth trajectory is corroborated by the German transmission system operators (TSOs) Amprion, TransnetBW, and 50Hertz, who report a surge in grid connection requests for BESSs since 2022, particularly intensifying through 2023-2024 (Johannsen 2024c). Looking further ahead, the German Federal Network Agency (BNetzA) projects a need for approx. 24 GW large-scale electricity storage by 2037 and 43.3. to 54.5 GW until 2045 (Bundesnetzagentur 2024a).

The location of the planned and existing large-scale BESSs is depicted in Figure 1. It shows clearly that the lithium-ion batteries will and currently are largely dominating the BESS-market in Germany (Thimet and Mavromatidis 2023; Bundesverband Energiespeicher Systeme 2024). A market review by Figgener et al. (2023) finds that between 2016 and 2019 more technologically versatile installations took place in the

Table 1: Top 5 installed BESS projects in Germany according to the total capacity (based on Bundesnetzagentur (2025))

Project name	Power/ Capacity (MW/ MWh)	Location	Operator	Use Case	Type of battery	Date of connection
Battery storage Werne 2	140/ 150	Hamm, NRW	RWE Generation SE	Frequency Containment Reserve (FCR), arbitrage trading	Lithium-Battery	28.12.2024
Battery storage Neurath	80/ 84	Grevenbroich, NRW	RWE Generation SE	FCR, arbitrage trading	Lithium-Battery	06.01.2025
Battery storage Werne	72/ 72	Werne, NRW	RWE Supply &Trading GmbH	FCR, arbitrage trading	Lithium-Battery	15.12.2022
SMAREG4 Wartburg Speicher Eisenach	60/ 67	Eisenach, Thüringen	SMAREG4 GmbH & Co. KG	FCR, arbitrage trading	Lithium-Battery	30.11.2022
Big Battery Lausitz	53/ 50	Spremberg, Brandenburg	Lausitz Energie Kraftwerke AG	FCR, arbitrage trading	Lithium-Battery	19.11.2020

large-scale battery sector but after 2019 lithium-ion batteries were installed “almost exclusively” for three years in a row. On second and third place were redox-flow batteries, followed by different kinds of Solid State batteries (Fraunhofer ISI 2020). While these other technologies exist and seem to have been installed in Germany and elsewhere, recent research seems to agree, that they are “less mature and will most likely be outperformed by lithium-ion batteries in the near future” (Thimet and Mavromatidis 2023).

Some examples for large-scale BESS projects which are currently under construction in Germany are 3 GW worth of battery storage power in planning by RWE by 2030. In addition, the Austrian energy firm VERBUND is working on large-scale battery storage facilities with a combined power of 1 GW by 2030, with part of this capacity already operational in Bavaria since early 2023. Meanwhile, LEAG is developing a large-scale storage facility with an anticipated power of approximately 750 MW in the Lausitz region, in one of the old coal-fired power plant sites (Federal Ministry for Economic Affairs and Climate Action 2023b). E.ON, Amprion and LWE Verteilnetz are currently planning a decentralized “Netzbooster” in Bavaria with a total power capacity of 250 MW. In contrast to other centralized projects that are directly connected to the transmission grid, the grid booster is planned to be divided between five locations of already existing substations in the LEW distribution grid in the Swabia region. This modular approach reduces the connection costs, increases the availability of the grid booster and reduces the impact on the landscape at the individual locations (Amprion 2024; Tennet 2024).

Among the reasons for the current surge in BESS projects in Germany is the exit from nuclear power production, which was completed in 2023 and the ongoing phase-out of coal-fired power generation, completed latest by 2030 in the western German coal region (Rheinisches Revier) and 2038 in the eastern German coal region (Lausitz) (Federal Ministry for Economic Affairs and Climate Action 2023b). With the decline in fossil fuel and nuclear power generation and the rise of renewable energy sources, the demand for energy storage solutions has reached an unprecedented level. At the same time, closed-down nuclear and coal power plant sites present excellent opportunities for large-scale battery installations, as they already have the necessary grid connections in place and repurposing pre-existing industrial sites is associated with less bureaucratic overhead in comparison to creating new industrial sites (Fraunhofer ISE 2022).

Moreover, demand for large-scale BESSs has been high due to fluctuating prices on the electricity spot market. With an increasing share of renewable energies – and especially photovoltaics – in the Germany electricity

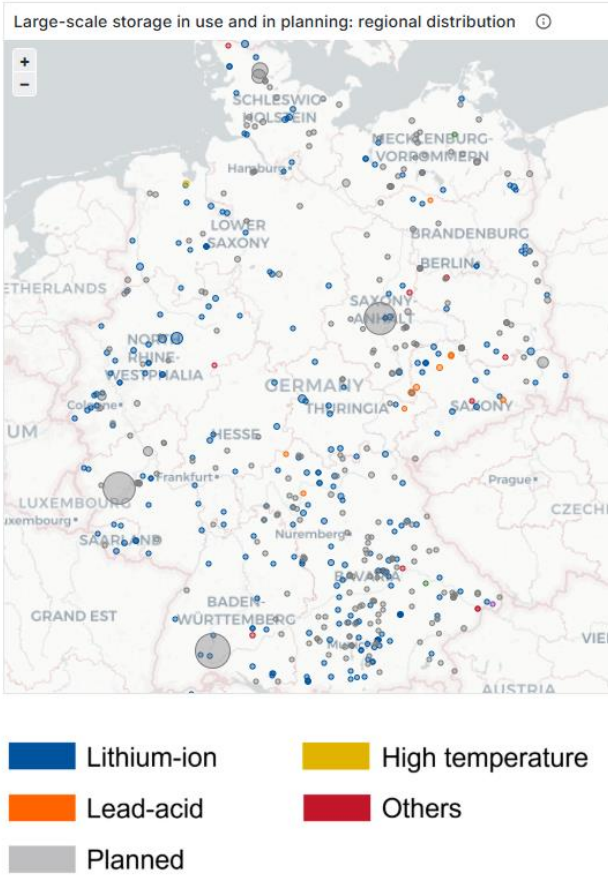

Figure 1: Regional Distribution of planned and existing large-Scale BSS in Germany (Source: Figgener et al. (2025))

system, prices have become more volatile. Oversupply of renewable energies have at times even lead to negative prices on the day-ahead electricity market. Especially, volatility of prices on spot market, allows for arbitrage trading of electricity with BESSs for immediate or near-term delivery (day-ahead market or intraday market). According to industry experts, the current market environment for battery storage systems is highly attractive with possible return margins of 15 to 20% depending on the type of installed system and purpose (Johannsen 2024b).

The German Federal Ministry for Education and Research aims to establish a technologically sovereign, competitive and sustainable battery value chain in Germany (Federal Ministry of Education and Research 2023). Therefore, substantive research funding initiatives have been in place since 2007 to foster the creation of a national value chain (see also Section 3.2.1.). Total private and public investments in battery production capacities in Germany until 2030 are EUR

18.5 billion (approx. KRW 27.8 trillion)[1] (Deutscher Bundestag 2024).

Production capacity[2] for the entire battery value chain for all types of battery cells is being expanded in Germany along with the increase in large-scale BESSs installations. For instance, BASF opened a new site for battery material production and recycling in mid-2023, and Tesvolt is expanding its capacity to potentially build up to 80,000 battery storage systems per year, with a new site opening in 2025 (dpa 2024; BASF 2023; MDR 2024).

In 2023, the German battery industry had a turnover of EUR 9.4 billion (approx. KRW 14.1 trillion), of which 76% was generated domestically and 24% abroad. In the same year, Germany imported lithium-ion batteries worth a total of EUR 20.3 billion in 2023 (approx. KRW 30.5 trillion) with 42% from China (EUR 8.5 billion or KRW 12.8 trillion), 3% from Korea (EUR 0.6 billion or approx. KRW 902.2 million) and the remaining 52% from European neighbours and other Asian countries (Verband der Elektro- und Digitalindustrie 2024; Statistisches Bundesamt 2024; Statistisches Bundesamt and ZVEI 2024). Measured in GWh, Germany was the top battery producing country in the European Union with 354 GWh in 2024. Moreover, the greatest addition of cell production capacities is also expected in Germany with a planned increase of 462 GWh – more than doubling the current energy capacity. According to the Battery Atlas 2024, a publication focused on the status quo of the battery industry in Europe, Germany is the centre of concentration for many companies along the whole battery value chain and thus plays a pioneering role in the development of battery production systems (RWTH Aachen University 2024).

3.2 Overview of BESS policy instruments and strategies

3.2.1 Objectives

In 2021, Germany has amended its Climate Change Act to include a target of greenhouse gas neutrality by 2045. For the electricity sector, at least 80% of gross electricity in 2030 is to be supplied by renewable energy, equal to about 600 TWh. To achieve this, the power capacity of offshore wind energy is to be increased to 30 GW, onshore wind energy to 115 GW and PV to 215 GW by 2030 (Federal Ministry for Economic Affairs and Climate Action 2023b). The energy transition from fossil fuels to renewable energy sources will affect the demand and constraints on the electricity sector. By replacing fossil energy sources with renewable ones, electricity generation is being decentralised in Germany. Moreover, new structures, tasks and issues will occur as other energy sources, providers and users will enter the market (e.g. local production of solar PV in private homes). While energy efficiency and energy saving measures are employed, electricity consumption might also increase due to electrification of hard-to-abate industry processes or mobility. These changes will affect the availability of electricity. With the power sector based on renewable energies, power can now be generated anywhere but not anytime due to fluctuation in the availability of renewable energy (Schulz and Bundesverband Energiespeicher Systeme 2025).

This temporary availability and lack of flexibility can be addressed with energy storage options, such as battery storage. In order to achieve the desired level of grid flexibility and integrate the necessary quantity of renewable energies to reach Germany's emission reduction targets, the government wants to facilitate the roll-out of battery energy storage. The German Federal Government has not defined specific roll-out targets for the power capacity of large-scale BESS in Germany but emphasizes the general need for the technology in its Electricity Storage Strategy from 2023 and thus shows commitment to the scale up of the technology. To facilitate this roll-out, the Federal Ministry for Economic Affairs and Climate Action (BMWK) has identified strategic objectives in its 2024 Electricity Storage Strategy to be implemented as soon as possible. Among these are: Supporting grid construction and fostering the integration of BESSs, addressing grid use fees, assessing the potential of electricity storage within the energy system as flexibility options and addressing issues related to licensing, bureaucratic processes or the integration into the grid. For the full list of objectives please consult the Electricity Storage Strategy (here).

3.2.2 Policy instruments

To foster the roll-out of battery energy storage systems in Germany, the following policies have been implemented. These can be categorised into three main areas of support: research on batteries; building up production capacities; and supporting the roll-out of battery storage systems. Together these policy instruments contribute to a favourable environment for the development of utility-scale battery storage projects.

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[1] All currencies have been converted at an exchange rate of 1 EUR = 1503.8 KRW (as of 05/02/2025).

[2] Please note that the following numbers refer to the battery industry generally as data on the value chain of BESSs are not yet available. They thus also include data on the rising industry of batteries for electric vehicles.

Battery research

Since 2007, the Federal Ministry of Education and Research (BMBF) has provided funding for research on batteries. In 2018, the BMBF has pooled funding measures and research programmes for battery research under the umbrella concept 'Forschungsfabrik Batterie' (eng. Battery Research Factory). It aims to enable battery research, support the development of a competitive, large-scale battery cell production in Germany and accelerate the transfer of research results into applications. The umbrella concept combines measures with mission-orientated and open-topic approaches. All parts of the battery research factory umbrella concept should work together and bring research results to the next stage of value creation (Federal Ministry of Education and Research 2022, 2025). To realize these goals, investments in battery research by the BMBF have risen from EUR 79 million Euros in 2018 (approx. KRW 118.8 million) to EUR 145 million (approx. KRW 218 million) in 2023 (Deutscher Bundestag 2024).

Moreover, the BMBF provides additional funding for battery research as part of its institutional research funding programme. This involves supporting research institutions and organisations that are funded by the BMBF independently, together with the federal states or with other partners. The Fraunhofer-Gesellschaft and the Leibniz and Helmholtz Associations are particularly relevant to the field of battery research. Moreover, the German Research Foundation (DFG) and Max Planck Institutes are also contributing to research on electrochemical energy storage (Batterie 2020 2025a).

The targeted development of large-scale (battery) energy systems was first supported by the BMBF and the BMWK in 2011 as part of the 'Energy Storage Initiative' under the 6th Energy Research Program of the Federal Government (Batterie 2020 2025b). It is also included in the 8th Energy Research Programme which came into effect in June 2024. Here, a special focus on stationary energy storage systems for the electricity system is included (Federal Ministry for Economic Affairs and Climate Action 2023a).

Battery storage roll-out

The German federal government has implemented various policy measures to incentivise stakeholders to invest and engage in large-scale battery storage projects. Most notable are the legal provisions that support the installation of BESSs and reduce costs for their operation. They are the following:

First of all, in March 2023, a legally 'overriding public interest in the establishment of electricity storage facilities' was stipulated by amending the *Regional Planning Act* and other provisions. This amendment was designed to grant privileges to electricity storage projects, such as fast processing of approval procedures, which essentially gives them the same relevance as renewable energies (Federal Ministry for Economic Affairs and Climate Action 2023b).

Second, the regulatory framework Section 118(6) in the *Energiewirtschaftsgesetz (EnWG, eng. Energy Industry Act)* and section 19(2) and (4) in the *Grid Fee Ordinance* governing large-scale energy storage facilities in Germany entails significant provisions for BESSs. These largely or entirely exempt storage facilities from grid use fees, including the fees for electricity volumes lost during the storage process. This regulatory approach aims to encourage the deployment and integration of large-scale storage solutions by reducing operational costs. In this context it is important to note that the future regulation of grid use fees for these storage facilities will be under the exclusive jurisdiction of the Bundesnetzagentur (BNetzA, eng. German Federal Network Agency), as mandated by the European Court of Justice's ruling on the independence of regulatory authorities. Moreover, stationary battery storage facilities (including BESSs) are exempt from electricity duty where they feed the electricity released from storage into the grid. This is stipulated in the *Electricity Duty Act*, section 5(4) (Federal Ministry for Economic Affairs and Climate Action 2023b). However, this exemption from grid charges is currently only valid until 2029. Therefore, diverse associations call for the permanent abolition of taxes on BESSs. They argue that a discontinuation of this exemption could lead to existing BESSs no longer operating economically (see (Bundesverband Kraft-Wärme-Kopplung e.V. 2024; Bundesverband der Energie- und Wasserwirtschaft 2024)

Third, ESSs are classified as renewable energy installations if they exclusively consume renewable energy during charging under Section 3, Number 1 of *Erneuerbare Energien Gesetz (EEG, eng. Renewable Energy Sources Act)*. In such cases, the financial support provided for renewable energies extends to electricity generated by the storage system. This includes scenarios where, in a photovoltaic (PV) and storage combination, the renewable energy does not flow directly from the PV installation to the grid but rather through the storage system.

Since 2021, ESSs in combination with renewable energy sources (e.g. solar or wind energy) may also participate in the so-called bi-annual 'innovation tenders' that are stipulated in § 39 of the EEG. According to the EEG, the innovation auctions are intended to 'promote technical solutions that are particularly useful to the grid or system and that prove to be efficient in a technology-neutral competitive process'. In practice, this primarily refers to the use of storage systems in combination with renewable energies in order to better utilise the grid infrastructure, absorb peak loads from photovoltaics and wind and stabilise the electricity grid. To participate in the auction, projects must have a combined energy capacity of at least 1 MWh and the subsidised system must draw electricity from the subsidised RE source and not the grid (EEG). When the innovation auctions were first introduced in 2021, winning bids received a fixed market premium. However, since December 2022 a floating market premium is tendered. This premium will now only be granted if the market value of the electricity falls below a specific value set in the auction, that is in reference to the monthly average value of the EPEX electricity exchange (NEXT Kraftwerke 2025). In the most recent tender in September 2024, 50 renewable energies-plus-storage projects with a total volume of 587 MW were awarded. The volume put out to tender amounted to 583 MW. A total of 154 bids were received, totalling 1,856 MW and the auction thus oversubscribed. The German Federal Network Agency reported that the tariffs ranged from €0.0674 /kWh to €0.0745 /kWh, with an average price of €0.0709 /kWh. The maximum bid value for the tender was set at €0.0918/kWh (Bundesnetzagentur 2024b).

Other types of public financial support by the federal government for the installation or operation of large-scale BESSs are currently not provided. In the past, initiatives have successfully targeted smaller battery setups for home purposes. For instance, the national development bank Kreditanstalt für Wiederaufbau (KfW), in collaboration with the Federal Ministry of Economic Affairs and Energy (now BMWK), introduced a low-interest subsidy scheme for small-scale energy storage system buyers, facilitating early investments in storage technologies in 2016. This initiative contributed to the growth of approximately 14 GWh of home storage capacity in Germany by 2024 (Prakash et al. 2022; Stöcker 2024). Similar initiatives for large-scale systems are not planned, as lithium-ion battery costs decreased significantly since 2022 and are expected to stay stable (Fraunhofer ISI 2020). Goldman Sachs Research even estimates an annual decrease of 11% on average between 2023 and 2030 for battery packs (Federal Ministry for Economic Affairs and Climate Action 2023b).

In the absence of federal funding, banks and investors are developing credit schemes for storage projects (PV Magazin 2024c). Furthermore, certain federal states offer financial support for stationary battery energy storage systems. For instance, Saxony-Anhalt has announced a funding programme with a total volume of EUR 22 million (approx. KRW 33.1 million), financed by the European Regional Development Fund (ERDF). The funding is available for investments by companies in stationary, electrochemical storage systems with an energy capacity of more than 30 kilowatt hours (kWh) for electricity generated from renewable sources, including the necessary battery management system and storage inverters (Ministry of Science, Energy, Climate Protection and Environment of the State of Saxony-Anhalt 2024). Industry associations also call for the financial support of not only BESSs coupled with renewable energy production sites – as done in the innovation auctions -but general funding of electricity storage systems in consumer regions or installed directly with the end consumer (Bundesverband Kraft-Wärme-Kopplung e.V. 2024).

National production capacities

Since 2020, BMWK has been actively supporting the expansion of production capacities in battery cell manufacturing and the entire battery value chain with the aim of establishing industrial scale production of battery cells in Germany by mid 2020s. The federal government has therefore contributed around 1.5 billion euro for supporting innovative endeavours along the whole battery value chain to strengthen the German industry location (Federal Ministry for Economic Affairs and Climate Action 2025).

This initiative is significantly driven by two Important Projects of Common European Interest (IPCEI) on batteries: the "European Battery Innovation" (EuBatIn) and the "European Battery Alliance" (EBA). These projects aim to enhance the competitiveness and sustainability of the European battery industry. The efforts are complemented by training and reskilling programs for workers in the battery sector, focusing on regions undergoing structural transformation and initial vocational training across Germany's states.

Additionally, BMWK is advancing digitization and sustainability in battery cell manufacturing through initiatives like the Battery Pass project, which lays the groundwork for the digital battery passport to be implemented under the new Battery Regulation (Federal Ministry for Economic Affairs and Climate Action 2023b).

3.3 Overview of stakeholders

The following stakeholder map (Figure 2) provides an overview of German institutions and businesses active across the BESS value chain. As is shown in the map, the BESS market in Germany is highly diversified and a broad range of actors are involved in the development, production, regulation and operation of battery energy storage systems. A summary of them is found below.

Please note that the map does not represent a complete depiction of actors and that these were selected based on desk research independently by the authors. Please also note that on the production side, actors often contribute not only to the production and assembly of large-scale battery energy storage systems but also produce for instance small-scale BESSs for home application, battery cells for home appliances or focus on battery cell packs for electric vehicles. A differentiation between these products is often difficult – especially since the focus often lies on batteries for EVs.

Governmental actors involved are the Federal Network Agency, responsible for the regulation of the power grids, the Federal Ministry for Economic Affairs and Climate Action, the leading ministry for the roll-out of electricity storage systems, and the Federal Ministry of Education and Research providing direction and funding for research projects on BESSs.

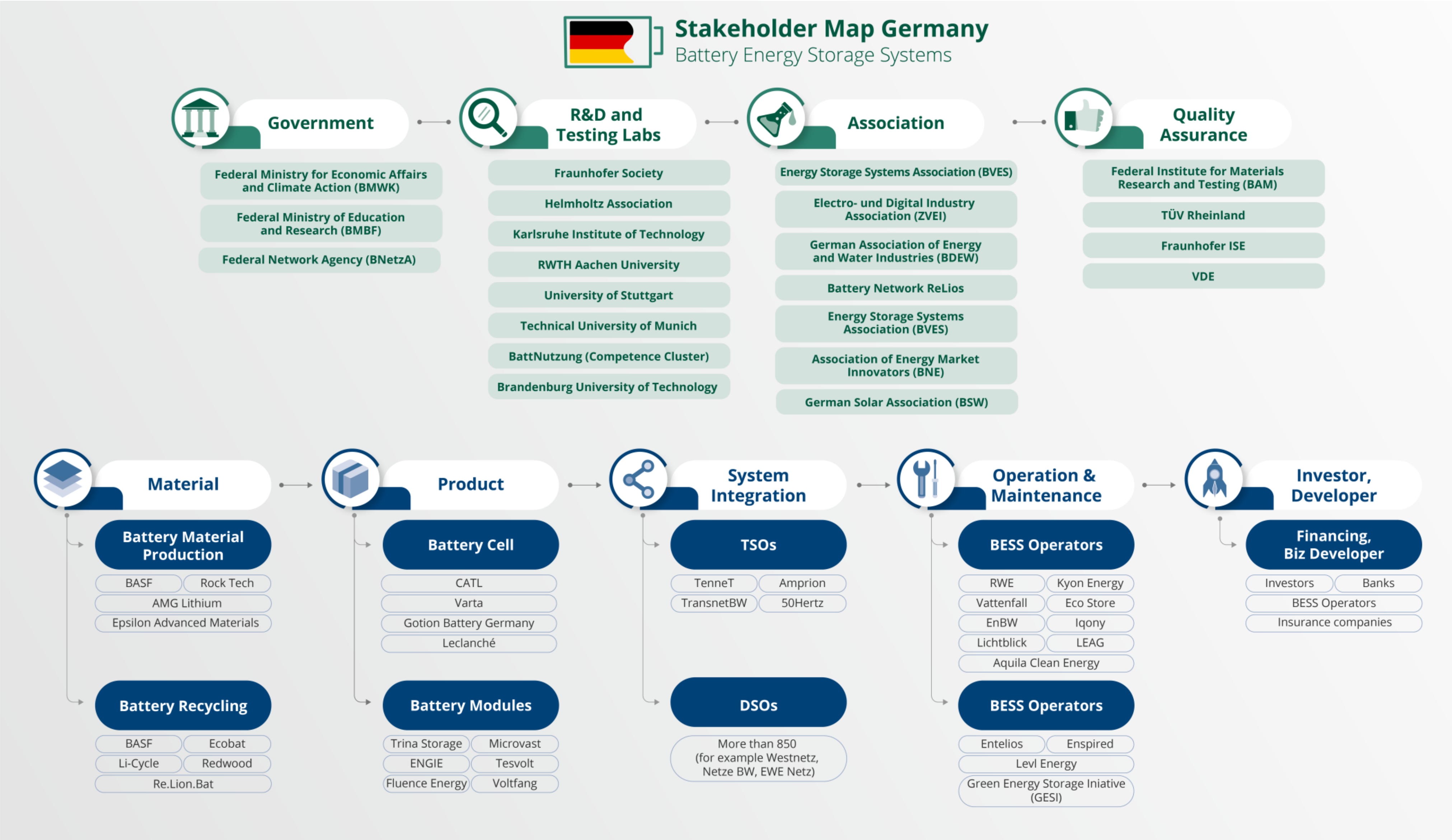

Figure 2: Stakeholder map for the German BESS ecosystem (Source: Own illustration)

Research institutes and universities such as the Fraunhofer ISE or the KIT Batterietechnikum have specialized research groups on battery technology for many years and have contributed to technology development in Germany.

Industry Associations: Battery and industry associations such as the Bundesverband Energiespeichersysteme (BVES, eng. Federal Association for Energy Storage Systems) pool the interests of their members, facilitate the exchange of knowledge and advocate on their behalf vis-a-vis governmental and regulatory actors. Because storage technologies can be utilized by many industries, there are not only new associations, but all types of different pre-existing/ established associations involved such as the Bundesverband Energie- und Wasserwirtschaft (BDEW, eng. Federal Association of Energy and Water Industries).

Producers of BESS: This includes actors along the whole value chain from raw material sourcing, material production, battery cell manufacturing, system assembly and management to recycling of used batteries. As the value chain for the battery market in Germany is still under development and currently scaling up, the actor landscape is very diverse. These range from small companies and startups such as Voltfang or VoltStorage, to larger and well-established companies such as the chinese company CATL or the US-american company FLUENCE. Moreover, companies from other sectors such the automotive sector (e.g. Volkswagen) are also entering the battery production market albeit often with the aim of producing batteries suited for their specific product needs.

BESS Quality Assurance: Standardization and testing bodies like TÜV Rheinland and Fraunhofer ISE ensure the quality and safety of BESSs, which is crucial given the risks associated with lithium-ion batteries.

BESS Operators: There is a broad range of actors involved in operating large-scale battery energy storage systems in Germany. Depending on its designated use-case these actors vary from distribution system operators (e.g. LWE or Westnetz GmbH), private project developer (e.g. Energisto) or energy providers (e.g. RWE or Lichtblick). While not involved with the direct operation of BESSs, the four TSOs TenneT, Amprion, 50hertz and TransnetBW enable their use in the electricity grid.

Others: Additional stakeholders include financial institutions like the KfW and the European Union, which finance BESS projects, as well as entities responsible for creating the necessary grid infrastructure.

A more comprehensive overview of the diverse actors involved in the German and European Lithium-Ion Battery Industry can be found in the Battery Atlas 2024, a publication by the RWTH Achen. However, please note that other types of batteries such as redox flow batteries are not included, and not all of the listed actors are relevant for the value chain of the battery energy storage systems. The Battery Atlas 2024 can be accessed here.

3.4 Potential of BESS in Germany

Estimates of the power capacity needed for large-scale BESSs in Germany vary. The research institute Fraunhofer ISE came to the conclusion that approximately 100 GWhel and 180 GWhel battery storage (all sizes) is needed by 2030 and 2045 respectively to provide dynamic grid stability (Fraunhofer ISE 2022). Researchers from the ETH Zürich investigated the role of energy storage systems for the German electricity system transition. Following their estimation, up to 140 GWh are needed in Germany in 2050 and they emphasize that energy storage systems will play a critical role in enabling the energy transition, especially after 2030 (Thimet and Mavromatidis 2023). The BNetzA's grid development plan, based on data from transmission system operators, takes a medium stance and forecasts a power capacity of 91 GW by 2037 and 168 GW by 2045, with stationary large-scale BESSs contributing 24 GW by 2037 and 45-55 GW by 2045 (Bundesnetzagentur 2024a).

Although the German energy storage association BVES does not provide specific numbers, it anticipates a strong growth of large-scale battery storage in Germany in the coming years due to strong demand based on widely fluctuating electricity spot market prices and expected increases in revenue margins. The BVES also sees substantial potential for 'behind-the-meter' storage solutions, which leverage existing grid connections, enjoy greater local acceptance, and bypass lengthy licensing processes (National Renewable Energy Laboratory 2019; Bundesverband Energiespeicher Systeme 2024). Additionally, rising CO_2 prices in combination with a restructuring of grid tariffs in Germany could provide the necessary incentives for the industry to install large-scale battery systems for on-site energy management purposes (Schulz and Bundesverband Energiespeicher Systeme 2025).

The deployment of large-scale BESSs in Germany in line with the prior estimations has the potential to significantly accelerate the transition to a 100% renewable electricity system and achieve net-zero emissions by 2045 for several reasons:

First and foremost, BESSs can provide greater flexibility to the German electricity grid by offering a broad range of ancillary and transmission-related services (e.g. provision of reactive power and cold-start ability). Unlike conventional thermal power plants, BESSs can charge or discharge rapidly, providing both negative and positive stimuli to the grid. This makes them particularly suitable for short-term reliability services like Primary Frequency Response and regulation options

(National Renewable Energy Laboratory 2019). While currently mainly employed for primary balancing power, BESSs could also be used for secondary balancing power in Germany, currently mostly provided by pumped storage facilities[3]. As the potential for pumped storage is limited due to geographic restrictions, this can help to provide greater flexibility if needed in the future (Federal Ministry for Economic Affairs and Climate Action 2023b). When replacing conventional flexibility options, BESSs can reduce dependence on foreign fossil fuel imports, aligning with Germany's energy policy objectives.

Second, BESSs can enable the integration of higher shares of renewable energies (> 80-90%), thus addressing the volatility of renewable energy production (Thimet and Mavromatidis 2023; Fraunhofer IWES et al. 2014). Especially for photovoltaics, market simulations have shown that large-scale BESSs can effectively address daily fluctuations, potentially increasing the market value of photovoltaics by 4 to 11% and incentivising further capacity expansion (Tennet 2024; Johannsen 2024b). Moreover, BESSs can relieve the grid of local or regional grid bottlenecks, such as those caused by offshore wind farms in northern Germany. By storing excess electricity, they prevent the curtailment of renewable energies, increase local grid stability and enable the integration of high shares of renewable energies. However, proper geographic allocation of BESSs is needed for this (Fraunhofer IWES et al. 2014).

Third, in contrast to other flexibility options, BESSs can provide multiple system services simultaneously, although some services are mutually exclusive. For instance, BESSs can help to balance peak demand by feeding electricity into the grid and thus defer new transmission during selected hours in the year. In times of low demand, BESSs can then also provide reserve services. This "value-stacking" approach, when supported by regulation, enhances grid stability and profitability for developers, especially for rarely needed services like black start capacities (National Renewable Energy Laboratory 2019). However, current regulations do not fully enable this approach (Bundesverband Erneuerbare Energien 2024), and careful drafting of appropriate regulation is required to avoid double compensation to BESS projects for the provided services.

Fourth, BESSs can help to achieve the transition of the energy system faster and more cost-efficiently. Following Thimet and Mavromatidis (2023), the installation of BESSs can defer investments in grid expansion by providing flexibility to the system. As grid investments often face public resistance and experience construction delays, BESSs may provide a timely and cost-efficient alternative, especially in the short term. However, the Fraunhofer IWES argues that these effects only apply when the grid expansion is delayed (Fraunhofer IWES et al. 2014). Moreover, as decentralized grid boosters, BESSs can also reduce the need for costly redispatch measures, saving billions of euros annually (Amprion 2024).

Despite these advantages, increased adoption of other flexibility options like Demand Side Management (DSM) and Combined Heat and Power (CHP) solutions may lessen the demand for large-scale BESSs in Germany's electricity grid. It is therefore imperative that ongoing assessments are conducted to take into account the current status of the grid.

3.5 Challenges

The expansion of large-scale BESSs in Germany faces several significant challenges, which can be categorized into technical, market, regulatory, and external challenges. This division of existing challenges is meant to aid the clustering and comprehension of the different obstacles. It is not meant to suggest that only regulatory challenges can be alleviated with regulations. Quite contrary – many of the listed challenges below can be met with regulatory adjustments.

3.5.1 Regulatory challenges

Regulatory challenges significantly impact the deployment of large-scale BESSs in Germany. The most pressing challenges can be found below:

Legal definition of energy storage: The *Energiewirtschaftsgesetz (EnWG, eng. Energy Industry Act) §3 No. 15d* classifies energy storage systems as both final consumers of electricity when storing and producers when discharging electricity. This aims to ensure a level playing field among producers, consumers, and flexibility providers (Federal Ministry for Economic Affairs and Climate Action 2023b; Bundesnetzagentur 2021). However, industry associations criticize this

[3] *Primary balancing power* is utilized to maintain grid frequency stability on very short notice. It needs to be available within seconds and sustain for a minimum of 15 minutes. *Secondary balancing power* takes over from primary balancing power and is used to restore the frequency to its nominal level. It must be supplied within 5 minutes and last for 15 minutes (Federal Ministry for Economic Affairs and Climate Action 2023b).

definition and argue that the *process* of electricity storage should be legally defined as well. In their opinion, this would ensure a non-discriminatory application of energy storage similar to other flexibility options because a financial double burden would be avoided (see (Bundesverband Kraft-Wärme-Kopplung e.V. 2024; Bundesverband der Energie- und Wasserwirtschaft 2024)).

Exclusivity principle in the EEG Act: The *Erneuerbare Energien Gesetz (EEG, eng. Renewable Energy Sources Act)* stipulates that BESSs can only be renumerated for providing green electricity when they take in 100% green electricity from renewable energy sources. However, if BESSs use additional electricity from the grid, currently categorized as grey, they lose out on funding for the temporarily stored green electricity. This practice limits the optimal use of storage capacity for flexibility purposes (Federal Ministry for Economic Affairs and Climate Action 2023b).

Complex licensing process: The licensing process for large-scale battery storage systems in Germany is complex and lengthy. Currently, each of the more than 850 Distribution System Operators (DSOs) have different criteria for which requirements apply for the integration of ESS into the electricity grid; which documents are required; and which regulatory requirements apply. The lack of digital access to necessary information means that during the certification process, planners might discover restrictions on component use or missing documentation, leading to project delays or cancellations. To streamline project development, these licencing procedures need to be reviewed and made more efficient at both federal and state level in Germany (Federal Ministry for Economic Affairs and Climate Action 2023b).

Undifferentiated grid construction costs: The *Baukostenzuschuss (BKZ, eng. grid construction cost)* is a one-off payment by grid connection applicants to cover their share of the costs for the expansion of grid capacity. Unlike the annual grid fees, which are calculated based on actual energy consumption, the BKZ is determined by the maximum agreed connected load and the required grid capacity. This model aims to ensure that costs are distributed in line with the costs incurred and to incentivise the efficient utilisation of grid resources. Although grid operators can charge the BKZ on a differentiated basis if electricity is both consumed from and fed into, this differentiated treatment is not extended to grid-connected BESSs as they are treated as final consumers of energy (Shelestova et al. 2024). The battery storage industry criticizes this, arguing that it fails to accurately represent the operational realities of BESSs and places significant financial burdens on projects (Bundesverband Energiespeicher Systeme 2024).

Non-uniform contribution requirements: BNetzA is considering the introduction of formal procedures to establish and standardize binding requirements for financial contributions from developers and operators of electricity storage systems. These contributions would cover BKZ and grid connection costs. The proposed framework aims to ensure these contributions are guided by principles of transparency, causation, and regional harmonisation. This initiative responds to industry concerns about regional discrepancies in contribution requirements, which currently hinder the ability to accurately forecast costs and impede the swift deployment of large-scale battery storage projects (Federal Ministry for Economic Affairs and Climate Action 2023b).

3.5.2 Technical challenges

Lack of grid connection: One major technical challenge for scaling up large-scale BESSs is securing grid connections. TSOs and DSOs face an increasing number of connection requests for planned large-scale storage projects. The process of granting grid access is inherently lengthy and complex, involving multiple stakeholders. While regulatory adjustments can alleviate some issues, a complete resolution is not expected in the next 2-3 years (Cook 2023; Johannsen 2024c).

Limited lifespan of BESS: Although BESS prices are decreasing, industry representatives put forward that high upfront investment costs and the limited lifespan of batteries undermine the business case for private investors. The current regulatory environment, which offers only limited exemptions from grid fees, fails to create a favourable long-term investment climate (Bundesverband der Energie- und Wasserwirtschaft 2024). Additionally, the previously mentioned innovation auctions often require a 20-year installation commitment, which contrasts with the typical battery lifespan of 10-15 years (Eco Affect 2024; Tennet 2024).

3.5.3 Market challenges

The optimal use of BESSs and provision of storage capacities for the stabilization of the German electricity market is hindered by several market challenges.

Uniform price signals: BESSs in Germany operate based on price signals from the central electricity exchange in Leipzig, that are uniform across the German electricity market. In arbitrage trading, batteries are charged when market prices are low and discharged when prices are high. However, the uniform prices available in Germany do not reflect the conditions of *local* grids. For example, an abundant supply of offshore wind energy in northern Germany can lower wholesale electricity prices on the intraday market, impacting BESS operations nationwide. This uniformity can exacerbate grid congestion issues, particularly if electricity cannot be efficiently transported from north to south, leading to potential grid strain in southern Germany. The TSO Tennet reports that the current orientation towards market signals can even intensify grid congestion and lead to regional cluster formation (Tennet 2024). The business optimized loading and unloading of batteries can thus make redispatch necessary and result in increased grid management costs (Johannsen 2024a). To mitigate these negative effects on the electricity grid and enhance the use of BESSs for ancillary services a more differentiated price signal that reflects the regional status of the electricity grid is necessary.

Lack of incentives for system-beneficial use: Industry associations point out that there are insufficient incentives for operators to deploy BESSs in a manner that supports grid stability in Germany. The current market design primarily rewards the feed-in of electricity, encouraging BESSs to operate based on market prices rather than grid needs. This can exacerbate grid stability issues, as electricity is not necessarily stored and released at optimal times for the grid. To address this, industry associations advocate for legal and regulatory incentives that promote grid-relieving operations for BESSs (Bundesverband der Energie- und Wasserwirtschaft 2024).

Location and timing: To fully harness the potential of BESSs to stabilize the electricity system, a strategic distribution of these systems is necessary. Large-scale BESSs can be strategically deployed in various locations, such as: 1) within the transmission network; 2) within the distribution network near load centres; or 3) co-located with variable renewable energy (VRE) generators. The location of BESSs significantly affects the type of services they can optimally provide. For instance, when BESSs are located near load, this can reduce transmission and distribution losses as well as provide local power quality services and improve resilience (National Renewable Energy Laboratory 2019). The TSO Tennet emphasizes that crucial factors for BESS location planning include the current status of grid expansion, proximity to regional renewable energy centres, and the presence of existing BESS installations to prevent grid congestion and avoid regional cluster formation (Tennet 2024). However, industry experts point out that the current market dynamics do not reflect the needs of the grid. For example, many installation requests are concentrated in northern regions, which could strain the electricity grid if realized (Bundesverband der Energie- und Wasserwirtschaft 2024; Johannsen 2024a). In November 2024, the BNetzA announced plans to introduce a regional differentiation for the grid construction costs (BKZ). Under this scheme, grid operators can adjust the BKZ based on how advantageous a location is for the overall system. New BESS installations in high-demand areas could increase charges up to 100%, while those in regions with unused capacity might see costs reduced to as low as 20% of the BKZ. The aim is to encourage the economical use of grid capacities by introducing price signals and motivating connectees to plan capacities efficiently (Bundesnetzagentur 2024c). However, the battery association BVES argues that this mechanism would lead to 'the locations where energy storage is most urgently needed having to bear the highest costs' because the BNetzA's calculations diverge from those of the grid operators (Bundesverband Energiespeicher Systeme 2025; PV Magazin 2024a).

External challenges

Lack of trained personnel: A significant external challenge is the shortage of skilled personnel needed for the construction of BESSs. According to a survey conducted by the BVES in 2024 more than a third of companies in the battery sector have voiced a lack of skilled personnel as an obstacle to the field. Over 50% of survey participants were not able to staff their teams adequately and over 90% were looking to hire in 2024 (Bundesverband Energiespeicher Systeme 2024). This issue is prevailing in the entire renewable energy sector in Germany and has to do with Germany's changing demographic: an aging population and lower birth rate coupled with a growing economy (although trending towards a stagnating economy in 2024) and an increasing demand in power. At the same time the education of installation and maintenance skills for new technology lags behind the development of said technology. Given that large-scale battery storage is a relatively new technology, this challenge is somewhat expected. Addressing it requires expanding training programs and launching comprehensive marketing campaigns to attract talent, similar to initiatives in the solar PV industry (PV Magazin 2024b).

Supply chain vulnerabilities: Another external challenge is presented in the supply chain for raw materials as well as components for batteries. Supply chains for both are very concentrated on very few suppliers and from few countries, making them volatile for disruptions. Factors such as resource shortages and supply-demand imbalances can lead the domestic production to slow or halt (Miao et al. 2023). It is therefore important to diversify supply chains and increase domestic production of components. Moreover, with the prevalence of lithium-ion batteries there is an inherent need for large quantities of lithium. While lithium is not a rare material, it does constitute a critical mineral for the energy transition and global demand for lithium will likely rise in the future. Additionally, the price for battery-grade lithium has multiplied since 2015 (Talan and Huang 2022). It is therefore crucial to invest in recycling technologies to recover this valuable resource, as these are not yet widely available, presenting another challenge. Expanding recycling facilities for lithium and other critical materials needed for battery production is necessary (Tembo et al. 2024).

3.6. Case study: Megabattery117+ project

Figure 3: Battery storage system in Lingen and Werne, Germany (Source: RWE, reproduced with permission)

RWE's battery storage system MEGABATTERY 117+ in Lingen and Werne is in operation since January 2023. The system has a storage capacity of 128 MWh (117 MW) and was built over a period of 14 months. A total of 420 lithium-ion battery modules were installed at pre-existing power plant sites to make use of the available grid infrastructure.

The two facilities, with capacities of 49 MWh (45 MW) in Lingen and 79 MWh (72 MW) in Werne, are virtually integrated with RWE's hydroelectric power plants along the Moselle River. This virtual integration allows for improved coordination and optimization of grid stabilization by selectively regulating the flow rate of these plants. RWE has invested around €50 million in this battery storage system.

The BESS units in Werne and Lingen contribute to frequency regulation in the grid, mitigating fluctuations. It also reduces price volatility during peak and off-peak periods, thereby stabilizing the energy market. By 2025, RWE plans to bring two more battery storage systems online in the same region, with a combined capacity of 235 MWh (220 MW).

Key Facts about the BESSs in Lingen and Werne

Operator	RWE Generation SE
Energy Capacity	128 MWh (49MWh at Lingen and 79 MWh at Werne)
Construction Time	14 months
Operational since	January 2023
Investment	€50 million

Sources:

RWE (2023): RWE completes megabattery in Lingen and Werne. Available online at https://www.rwe.com/en/press/rwe-generation/2023-01-09-rwe-completes-megabattery-in-lingen-and-werne/

En:former (2023): RWE stellt Megabatterie in Lingen und Werne fertig. Available online at https://www.en-former.com/rwe-stellt-megabatterie-in-lingen-und-werne-fertig/

4 Status and Prospects of BESS in Korea

As of late 2023, Korea has emerged as a key player in the global energy storage sector, boasting a cumulative capacity of 10 GWh in operational energy storage systems. The sector is advancing swiftly, driven by a strong emphasis on renewable energy integration and demand management. Predominantly relying on lithium-ion batteries, these systems are vital for Korea's energy transition, particularly given its isolated grid. Despite previous challenges, Korea is making significant strides to enhance deployment and sustain its competitiveness in the global market.

4.1 Current status of BESS in Korea

In Korea, electricity storage is mainly provided by BESSs (4.4 GW/ 10.4 GWh) and pumped storage (4.7 GW/ 37.6 GWh). The following subsections will provide an overview on the deployment status of both types, how they are used and the recent status of technology for different battery types.

4.1.1 Deployment status

Battery Energy Storage System

As of the end of 2023, a cumulative BESS capacity of 10 GWh is installed and operational in Korea. The main applications are for renewable energy integration (55.8%), demand management (42.4%), and frequency regulation, with other uses accounting for the remainder. More than 99% of the deployed capacity is based on lithium-ion batteries, while technologies like vanadium redox flow batteries (VRFB) and sodium-sulfur (NaS) batteries are limited to pilot research and early demonstration projects (Ministry of Trade, Industry and Energy and Korean Energy Economics Institute 2023).

A series of fire incidents since 2017 and the expiration of support programs have led to a significant contraction in the BESS market. To maintain the BESS market, the government has enacted a law requiring the installation of BESSs in public buildings (see Section 4.2.2.). The current market is therefore limited to public institutions under a mandatory deployment scheme (e.g., public institutions with over 2,000 KW of contract capacity must install BESSs equivalent to 5% of their capacity (Korea Energy Agency 2024a).

Meanwhile, the Korea Power Exchange (KPX) launched a pilot project in Jeju for a central contract market for BESS (65 MW/260 MWh), aimed at addressing power curtailment issues in Jeju's grid. Installation of the BESS is planned to be finished in 2025, with additional deployments under consideration. Jeju's grid, powered by high voltage direct current (HVDC), thermal, and renewable sources, has faced increasing curtailment of wind and solar power since 2015 due to overcapacity.

Info Box 1:

Renewable Energy Certificates (RECs) are issued based on the amount of electricity supplied from eligible renewable energy facilities, multiplied by a weighting factor, and measured in MWh units. These certificates serve as proof that power producers have generated and supplied electricity using renewable energy facilities. Obligated suppliers can fulfil their supply obligations by purchasing these Renewable Energy Certificates.

In this context, obligated suppliers refer to Independent Power Producers (IPPs) that supply electricity. These are existing power generation companies under the Renewable Portfolio Standard (RPS) system, which mandates that they supply a certain government-designated amount of electricity from renewable sources.

In Korea, large-scale electricity storage systems are mainly employed for the following purposes:

Renewable Energy Integration: Battery energy storage systems linked with renewable energy sources such as solar PV and wind energy were incentivized with increased REC weightings as a temporary measure by the government, ensuring profitability. This led to a significant deployment of BESSs between 2018 and 2020 (Korea Energy Agency 2024c).

Demand Management: Industrial and commercial consumers with high electricity usage install BESSs to reduce electricity bills. Korea's electricity tariff structure for these consumers consists of demand charges based on peak demand and energy consumption charges, with time-of-use rates applied for large-scale consumers. BESS deployment enables reducing peak demand to lower basic charges or discharging during peak-rate hours to save energy costs. Furthermore, a temporary policy allowed for a 50% discount on nighttime charging rates for BESSs, significantly enhancing the economic feasibility and leading to widespread deployment (Korea Energy Agency 2024b).

Frequency Regulation: Between 2015 and 2017, the Korea Electric Power Corporation (KEPCO) installed 376 MW (30-minute capacity) of frequency regulation BESSs. The operation of these BESSs enhances power quality, improves grid operation efficiency, and reduces power procurement costs. BESS utilization for frequency regulation allows conventional power generators to maximize electricity output, enhancing energy efficiency (Lee 2018).

Grid Stabilization: From 2023 to September 2024, KEPCO installed grid stabilization BESSs with a total capacity of 978 MW/889 MWh across six substations, including a 336 MW system at the Yeongcheon Substation. Grid stabilization BESSs address constraints arising from delays in grid infrastructure development, easing power generation curtailments by up to 1 GW. These systems also enhance grid reliability by accommodating high variability in renewable energy output, thus contributing to frequency stability (Han-gyo Jeong 2024a).

Pumped Storage

Korea operates 4.7 GW of pumped storage as backup capacity. Pumped storage provides frequency regulation, reserve capacity, and black start services, functioning as long-duration ESS. New projects will employ variable-speed pumped storage hydropower to better absorb renewable energy variability (Statista 2023b).

- The *9th Basic Plan for Electricity Supply and Demand* (2020–2034) includes 1.8 GW of new pumped storage with a target completion date of 2030.
- The *10th Basic Plan* (2022–2036) identifies 1.75 GW of new projects for completion by 2035.
- The upcoming *11th Basic Plan* (2024–2038) aims to incorporate an additional 1.15 GW of preliminary projects, replacing coal-fired power plants with pumped storage where feasible, with completion planned for 2035–2038.

4.1.2 Current status of technology

Lithium-ion Battery ESS: Korea is home to three of the world's top 10 lithium-ion battery manufacturers. These companies operate production facilities not only in Korea but also in China, the United States, and Europe, producing batteries for EVs and ESSs. Currently, the market is dominated by nickel manganese cobalt (NMC) lithium-ion batteries, but production of lithium iron phosphate (LFP) batteries is under preparation. In addition, research and mass production plans for next-generation technologies such as solid-state batteries are underway. More than 99% of BESSs installed in Korea use domestically manufactured NMC lithium-ion batteries (SNE Research 2023).

Non-Lithium Battery ESS: Among non-lithium secondary batteries, Vanadium Redox Flow Batteries (VRFB) are the only commercially viable option for energy storage applications in Korea. A Korean venture company has established production facilities capable of manufacturing 300 MWh annually and is currently conducting a 20 MWh VRFB demonstration project in California, USA. VRFB technology, in its early commercialization stage, is emerging as an alternative to lithium-ion batteries for long-duration energy storage systems (LDES) (Murray 2024).

LDES: For long-duration energy storage outside the battery category, technologies such as thermal and mechanical large-scale storage systems are being considered. Research on high-temperature thermal storage systems, utilizing decommissioned coal-fired power plants, is scheduled to begin in 2025. Additionally, research and development efforts are planned for compressed air energy storage (CAES), leveraging Korea's expertise in power plant equipment, engineering capabilities, and civil engineering technologies (Han-gyo Jeong 2024b).

4.2 Overview of BESS policy instruments and strategies

4.2.1 Objectives

The Korean government acknowledges the importance of energy storage and has thus formulated two main objectives supporting the deployment of BESSs.

Flexibility for the electricity grid with rising shares of renewables

As of 2022, over 30% of Korea's carbon emissions originate from the power sector (Carbon Neutrality and Green Growth Commission 2025). The key pillars of Korea's energy transition policy are the phased decommissioning of coal-fired power plants, increased utilization of nuclear power, and expanded deployment of renewable energy. According to the *11th Basic Plan for Electricity Supply and Demand*, by the late 2030s, nuclear and renewable energy will account for more than 70% of Korea's power supply (Ministry of Trade, Industry and Energy 2025). Currently, nuclear power provides about one-third of South Korea's electricity with government plans to increase the share to 32.4% by 2030 and 34.6% by 2036 (World Nuclear Association 2025; International Trade Administration 2023).

Renewable energy, being a variable power source, present a challenge for supply-demand balancing in Korea's standalone grid, which lacks interconnection with neighbouring countries. Stable power supply is thus a critical concern and ESSs are crucial for integrating variable renewable energy sources in the Korean power systems. This is particularly important for expanding the hosting capacity of the power grid, minimizing output curtailment, and maximizing the utilization of renewable energy. Additionally, Korea's manufacturing sector has a high proportion of electricity-intensive industries, such as semiconductors, where power reliability and cost directly impact industrial competitiveness.

In this context, securing flexibility resources and expanding the power grid are critical issues in the energy transition. As a national strategic industry, secondary batteries represent a high-growth market not only for electric vehicles but also for energy storage. They play a vital role in addressing grid challenges and enhancing Korea's competitiveness in the global battery market.

Supporting ESS as strategic Korean industry

As a manufacturing powerhouse, Korea possesses significant industrial capabilities in the energy sector, including petrochemicals, power generation equipment, and transmission and distribution systems. In response to carbon neutrality goals, Korea's energy transition policy identifies new energy industries such as smart grids, demand response systems, MVDC/HVDC technology, and electric vehicle charging infrastructure as future growth engines.

Energy storage holds crucial technological and industrial value in the 3D trends driving the energy transition: **Decarbonization** (reduction of carbon emissions), **Decentralization** (distributed energy resources), and **Digitalization** (application of AI).

Beyond secondary batteries, industries like power conversion, control software, and AI technology also have significant ripple effects. Moreover, these sectors demonstrate substantial potential for global growth, further emphasizing their importance as strategic industries for Korea's future.

4.2.2 Policy instruments

To support the previously mentioned objectives, the Korean government has employed the following policies and strategies.

Government support

The Korean government has designated secondary batteries as one of the 12 national strategic technologies. It leads the development of strategies and provides continuous support across all areas from technology development to industrialization and export.

- *'Secondary Battery Industry Development Strategy'* (2008, Ministry of Knowledge Economy)
- *'2030 Secondary Battery Industry (K-Battery) Development Strategy'* (2021, Joint Ministries)

These development strategies present a mid-to-long-term technology vision and include implementation strategies such as technology development roadmaps, creation of industrial ecosystems, and generation of market demand.

The fields of technology development include core components and materials, battery manufacturing technologies, and also supports the establishment of business foundations such as human resource development and construction of testing infrastructure. Furthermore, through the designation of advanced technologies, tax credit benefits are provided for investments in production facilities.

Quantitative targets linked to the Basic Plan for Electricity Supply and Demand

Korea formulates its *Basic Plan for Electricity Supply and Demand* every two years, which outlines the required capacities for power generation and backup facilities based on demand forecasts. The plan specifies the necessary energy storage capacity to support the increasing deployment of renewable energy. Long lead-time solutions, such as pumped storage, are included as separate allocations within the plan.

Backup capacity requirements are calculated for both short-duration storage (less than one hour) and long-duration storage (greater than one hour). These calculations consider the regional distribution of renewable energy deployment and transmission and distribution network expansion plans, with the goal of limiting annual renewable energy curtailment to 3% or less. All backup capacity, excluding pumped storage, is assumed to be provided by battery-based ESSs.

For pumped storage, the process involves collaboration between five public power generation companies and local governments to identify suitable sites. Once the site is confirmed, the necessary capacity is reflected in the Basic Plan and finalized. Investments in pumped storage are determined competitively by public power generation companies.

Other recent policy advances:

As of March 2025, Korean lawmakers are working on a legislative measure to enhance its domestic battery sector. The proposed legislation, spearheaded by a bipartisan group of 11 lawmakers, aims to introduce direct subsidies for domestic battery producers. This initiative parallels the US Advanced Manufacturing Production Credit (AMPC) and represents a strategic effort to counter growing competition from Chinese manufacturers and a global decline in electric vehicle (EV) demand. The so-called Battery Industry Special Act seeks to provide targeted financial support to the battery industry. This marks South Korea's second significant attempt at industry-specific legislation, following the Semiconductor Industry Promotion Act of 2024. The initiative underscores the nation's commitment to bolstering its position in the global battery market amidst shifting economic and competitive dynamics.

Past policies: Early deployment policies supported by government initiatives (~2020)

To promote the deployment of BESSs and the growth of the lithium-ion battery market, the Korean government introduced a temporary support program in 2016. This program provided REC weightings of 4.0–5.0 for BESSs linked to renewable energy. This policy was offering additional income to ESS operators as REC weightings were applied to electricity charged from renewable sources between 10 a.m. and 2 p.m. and discharged outside of these hours. As a result, by 2018, 3.7 GWh of ESSs—accounting for one-third of the global ESS market—were deployed. However, while small-scale, standalone ESS projects linked to solar PV initially expanded the industry base, they primarily operated independently of the grid and focused on generating REC revenue through simple charge-discharge cycles. This limited their contribution to grid stability. Excessive REC issuance due to high REC weightings (4.0–5.0) also disrupted the REC market supply-demand balance (Korea Energy Agency 2024c). Consequently, the policy was phased out by the end of 2020. As a results, REC weightings were discontinued, and government recommendations on charge/discharge rates significantly cooled the market.

For demand-side ESS, the government implemented a 50% discount on nighttime charging rates, encouraging large-scale electricity consumers to adopt ESSs.

Following a series of fire incidents starting in 2017 and the expiration of REC and charging discount policies after 2020, the market entered a downturn.

Current policies: Deployment policies through electricity market reforms (2020–Present)

Current Situation: Korea's electricity market currently operates as a single day-ahead spot market, making it challenging to deploy ESSs through market mechanisms. This is due to the low revenue structure relative to the required investment in ESS. Additionally, the retail market is monopolized by KEPCO, restricting peer-to-peer energy trading.

Plans: To enhance the electricity market, the government and the KPX are discussing reforms, including the introduction of a 15-minute real-time balancing market and long-term/short-term contract markets. Furthermore, the *Dispersed Energy Promotion Special Act*, passed in 2023, came into force in June 2024 following the revision of its enforcement decree. This act designates Distributed Energy Zones where pilot programs, such as peer-to-peer energy trading and locational marginal pricing (LMP), are implemented allowing for direct electricity supply between users and generation facilities without involving the electricity market.

Ongoing Efforts: Ahead of full-scale market reforms, the KPX has been conducting pilot projects in Jeju. Examples include the BESS Central Contract Market, Renewable Energy Bidding Market, and Stored Energy Sales Market initiated in 2023. The BESS Central Contract Market, specifically aimed at addressing power curtailment issues in Jeju, secures long-term (15-year) bids for 4-hour long-duration BESS. Based on the outcomes of these projects, plans are in place to expand such programs in Jeju and eventually nationwide.

In the first round of bidding on the Jeju BESS Central Contract Market, that was opened in November, a bidding volume for a capacity of 65MW/260MWh was offered. The bidding was divided into two regions, with competition ratios of 3.6:1 and 2.7:1 respectively. Successful bidders have been selected for 35MW/140MWh in the eastern region, and 10MW/40MWh and 23MW/92MWh in the western region. The winning power generators will construct and operate long-duration ESS facilities capable of running for more than 4 hours and will be compensated at the winning bid price for 15 years. The facilities are expected to be completed by early 2025. They will be composed of 100% domestically produced lithium batteries, and operational results have not yet been obtained.

Technology development: Strategies for securing a storage mix

The Ministry of Trade, Industry, and Energy (MOTIE) announced the "*Energy Storage Industry Development Strategy*" in October 2023. This strategy focuses on ensuring stable grid operations, fostering the energy storage industry as an export-oriented sector, activating the ecosystem, promoting deployment, and securing advanced technologies.

Short-term: The short-term strategy aims to maintain Korea's competitive edge in the global ESS market, which is currently centred on lithium-ion batteries. Key objectives include:

- Enhancing fire safety through the adoption of water-cooling systems.
- Advancing high-performance and high-density LFP battery technology to expand their use in global ESS markets.

As of 2023, LFP batteries accounted for 80% of the global ESS market due to their low cost, fire safety, and long lifespan, despite lower energy density. These characteristics make LFP batteries particularly suitable for stationary ESS applications (BloombergNEF 2023).

Mid-term: The mid-term strategy focuses on developing high-TRL (Technology Readiness Level) technologies that can be commercialized within five years, tailored to ESS applications for enhanced performance and cost-effectiveness. By around 2030, these technologies will enable widespread deployment in Korea's grid to accommodate increasing renewable energy penetration. Additionally, efforts to reduce global reliance on lithium-based ESS technologies will create export opportunities for long-duration energy storage (LDES) systems designed for grid flexibility.

Promising mid-term technologies include flow batteries, sodium-sulfur (NaS) batteries, and mid-scale (sub-100 MW) variable-speed pumped storage systems, all of which are in the early stages of commercialization.

Long-term: The long-term strategy targets the ESS market beyond 2030, when renewable energy deployment will mature. The focus is on developing low-cost, eco-friendly, durable, and large-capacity long-duration ESS technologies. Non-battery-based LDES technologies, currently in research or pilot stages in advanced economies, will leverage Korea's industrial and research capabilities for commercialization, domestic application, and export.

Representative technologies include Compressed Air Energy Storage (CAES): Existing since the 1970s and 1990s in Germany and the U.S., CAES is being advanced to overcome site constraints using artificial tunnel technology. Development goals include adiabatic CAES (A-CAES), which eliminates the need for fossil fuels. Carnot Batteries: These systems utilize decommissioned coal-fired power plants to create large-scale, low-cost long-duration ESS solutions.

The goal is to repurpose infrastructure for high-capacity thermal storage systems that support grid stability. This comprehensive strategy aims to position Korea as a leader in global ESS technology and innovation while ensuring domestic energy security and sustainable growth.

4.3 Overview of stakeholders

The Korean large-scale battery energy storage system market is comprised of an array of diverse actors. A stakeholder map for the Korean BESS ecosystem can be found in Figure 5. Please find below the description of the most important actors/ group of actors.

Korea Electric Power Corporation (KEPCO): Acts as both the DSO and TSO, responsible for the construction, operation, and maintenance of transmission and distribution networks. It is also the sole wholesale and retail electricity provider. All installed BESSs, that perform frequency regulations, are owned and operated by KEPCO.

Power Generation Companies and Private Independent Power Producers (IPPs): Includes five major public power generation companies (e.g., Korea East-West Power) and multiple private IPPs, serving as investors and operators in the ESS sector. The BESSs used for renewable energy integration and demand management are primarily owned and operated by private ESS operators or renewable energy companies. The five major power generation companies also own and operate BESSs, which are linked to their own renewable energy sources.

Korea Power Exchange (KPX): Manages grid operations and electricity market operations.

Battery Manufacturers, System Integrators (SI), and Equipment Manufacturers: Involved in component production, software development, and system integration for ESSs.

Associations, Research Institutes, and Testing Organizations: Responsible for standardization, technology development, and testing and certification.

Government in particular Ministry of Trade, Industry, and Energy (MOTIE): Oversees policies for distributed energy and ESS deployment, technology development, and medium- to long-term planning

4.4 Potential of BESS in Korea

4.4.1 Background

The importance of BESSs in Korea is highlighted by the following reasons:

Long-term Power Mix Policy Centred on Nuclear and Renewable Energy
Korea maintains a power mix strategy that focuses on nuclear power and renewable energy. Korea is highly dependent on energy imports and has a well-established nuclear industry ecosystem. Therefore, Korea plans with nuclear power as a critical component of its energy mix for energy security and industrial policy reasons, despite continuing debates on nuclear energy. Korea advocates for a Carbon-Free Energy (CFE) mix that includes nuclear power, renewable energy, and hydrogen.

However, both nuclear power and renewables are inflexible power sources, complicating the balance of electricity supply and demand. While research on enhancing nuclear power's load-following capability is ongoing, deploying BESSs as flexibility resources is essential during the interim.

No Interconnection with Neighbouring Countries
Grid interconnection with neighbouring countries is one of the most effective means of ensuring supply-demand balance and securing flexibility. However, due to national security concerns, Korea currently does not have grid interconnections with neighbouring countries. As a result, Korea must independently maintain a stable electricity supply without importing or exporting power. This makes sufficient deployment of BESSs critical for supply-demand balance and backup power needs.

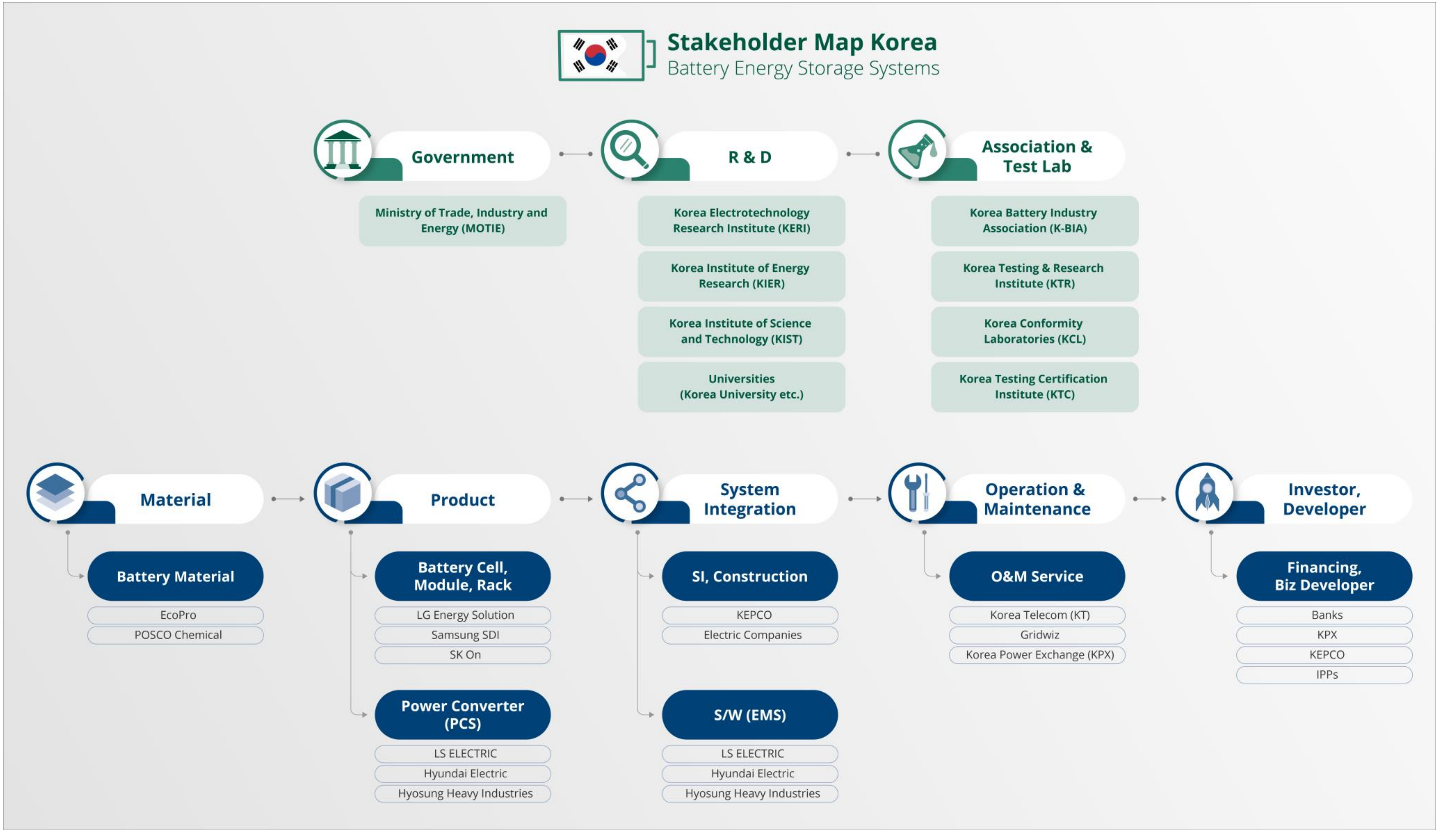

Figure 4: Stakeholder map for the Korean BESS ecosystem (Source: Own illustration)

4.4.2 Market

According to the *10th Basic Plan for Electricity Supply and Demand* (2022–2036), storage capacity requirements to support renewable energy expansion are as follows:

- **Ultra-Short Duration Storage:** Systems like synchronous condensers for maintaining grid inertia and voltage stability.
- **Short-Duration ESS:** Storage systems with a duration of less than 1 hour for frequency regulation and real-time supply-demand balancing. A cumulative capacity of 3.66 GW/2.29 GWh is required by 2036.
- **Long-Duration ESS:** Storage systems with a duration of more than 1 hour for mitigating curtailment, load levelling, and addressing oversupply. A cumulative capacity of 20.85 GW/124.97 GWh is required by 2036, along with an additional 1.75 GW of pumped storage.

An estimated investment of KRW 45 trillion (approx. EUR 29.9 billion) is projected for storage systems, primarily battery-based ESS. Depending on technological advancements, alternative storage technologies may also be considered.

4.4.3 Technology

Except for ultra-short duration solutions like synchronous condensers and pumped storage as part of long-duration solutions, most of the backup capacity for short- and long-duration storage is assumed to rely on lithium-ion batteries. VRFB, sodium-sulfur (NaS) batteries, and thermal or mechanical long-duration storage technologies are currently less competitive in terms of cost and performance. However, with early commercialization and successful demonstrations, these technologies could become viable options for backup systems during this period.

4.5 Challenges

4.5.1 Policy challenges

For effective power supply-demand balance and stable grid operation, flexibility resources and backup facilities like ESSs and other measures, such as demand response and sector coupling, are needed. While the backup capacity requirements outlined in the *10th Basic Plan for Electricity Supply and Demand* consider ESSs, they do not account for flexibility measures such as Demand Response (DR) and Sector Coupling. These requirements assume that renewable energy curtailment will be maintained at a level of 3%. Further policies and technical plans are needed to introduce diverse flexibility resources, that considers their performance, costs, and availability. Designing an optimal mix of flexibility resources presents a significant policy challenge. Additionally, while renewable energy curtailment is currently uncompensated, if it cannot be adequately managed, corresponding compensation policies may become necessary.

4.5.2 Technical challenges

At present, most backup systems are expected to rely on lithium-ion batteries, which face numerous risks including the need for large-scale investments, installation site constraints, community acceptance, safety concerns, and material supply chain instability. In Korea, specific local constraints include insufficient space for BESS installation near urban substations and high land costs. Moreover, BESSs are classified as power generation facilities in Korea, necessitating compensation to local communities, which further increases investment costs. Like transmission and distribution facilities, BESS installations also require local residents' consent. However, community acceptance is often low, primarily due to fire risks associated with lithium-ion battery ESSs, fuelling “not in my backyard”-arguments. This conflict increases permitting times and investment costs further.

Pumped storage systems also face challenges such as site limitations, community acceptance, environmental impacts, high investment costs, and long construction periods. Developing an energy storage technology mix to mitigate these risks represents a significant challenge. Emerging storage technologies, while promising, require time for performance improvements, cost reductions, and large-scale demonstrations to validate their applicability (Denholm et al. 2021).

4.5.3 Deployment and market challenges

The deployment of ESSs requires substantial investment and determining the optimal approach to deployment poses another challenge. The optimal strategy to ESS deployment includes optimizing the timing and capacity of ESS installations based on changes in the power mix, grid congestion, and instability. This approach requires identifying an economically viable and efficient combination of ESS types, such as short-term lithium-ion batteries and long-term storage solutions. It also includes evaluating alternatives to lithium-ion batteries, like non-lithium battery ESSs, and large-scale storage technologies such as Carnot batteries and compressed air storage. Optimized ESS placement necessitates an assessment of the distribution of renewable energy sources, the current state of the power grid, and changes in the locations of major energy consumers.

Moreover, decisions need to be made regarding whether to rely on public investments by the government or utilities, or to encourage private capital investment through market mechanisms.

Furthermore, the social and industrial impacts necessitate careful and thorough analysis. For instance, a potential increase in electricity prices could accelerate the BESSs deployment. Currently, Korea has fixed electricity tariffs that are very low in comparison to other OECD countries. If electricity prices would rise to OECD levels, the deployment of household and utility-scale BESSs may accelerate because of cost savings for households and increased investment returns for utilities.

4.6. Case studies

The following two case studies on noteworthy BESS projects in Korea exemplify the diverse use cases that electricity storage systems can be used for in Korea.

4.6.1. Frequency Regulation ESS

Project Overview: KEPCO decided to invest approx. KRW 620 billion (approx. EUR 412.6 million) to install and operate 500 MW of frequency regulation ESSs as part of its comprehensive ESS deployment plan. The project duration was from January 2014 to December 2017. The objective of this project was to reduce power procurement costs, create new power industry markets, and support domestic companies' entry into global markets.

Frequency regulation ESSs replace the traditional practice of maintaining 5% output reserve from generators for frequency regulation by using ESSs. For instance, operating 52 MW of ESSs can increase coal-fired power plant output from 95% to 100%, securing approximately 500 MW of reserve capacity (equivalent to the capacity of one coal-fired plant) and generating an estimated annual national benefit of KRW 350 billion (approx. EUR 232.9 million), including KRW 320 billion (approx. EUR 213 million) in power procurement savings.

Progress: In October 2014, KEPCO launched the first pilot project by investing KRW 52 billion (approx. EUR 34.6 million) to install 52 MW of ESSs at Seoanseong (28 MW) and Sinyongin (24 MW) substations, the largest scale globally at the time. By 2017, KEPCO had installed 376 MW of 30-minute ESSs across 13 substations, with individual capacities ranging from 16 MW to 48 MW.

Impact: KEPCO expects the operation of 376 MW of frequency regulation ESSs to improve power quality, enhance grid operation efficiency, and save approximately KRW 62 billion (approx. EUR 42.3 million) annually in power procurement costs. Over four years, companies involved in the frequency regulation ESS project advanced battery charge/discharge speeds by up to 1.6 times, enabling exports worth KRW 1.2 trillion (approx. EUR 798.5 billion) to the U.S., Europe, and Asia by 2017. KEPCO plans to expand the use of ESSs for renewable energy stabilization and peak reduction while fostering the ESS industry ecosystem. Additionally, KEPCO aims to leverage its domestic experience to support the global export of frequency regulation ESS technology (Lee 2018).

4.6.2. Grid Stabilization ESS

Project Overview: In response to growing renewable energy adoption and aging power infrastructure, KEPCO initiated a grid stabilization ESS project in 2021. Grid stabilization ESSs are multifunctional, supporting frequency regulation while alleviating generation constraints.

Progress: In 2022, the project passed a preliminary feasibility study and was included in the *9th Basic Plan for Electricity Supply and Demand*. By July 2024, KEPCO completed the construction of ESSs with a total capacity of 978 MW/889 MWh across six substations (Yeongju, Hamyang, Yesan, Yeongcheon, Sinnanwon, and Bubuk). The largest installation, with a capacity of 336 MW, was at Bubuk Substation, with a total investment of KRW 830 billion (approx. EUR 552.4 million).

Impact: The grid stabilization ESS project is expected to contribute to carbon neutrality by facilitating the integration of zero-carbon power sources. Additionally, it is anticipated to alleviate up to 1 GW of generation constraints, addressing power supply instability and ensuring reliable electricity supply (Han-gyo Jeong 2024c).

5 Comparative Analysis

This subsequent chapter provides a comparison of the current status quo of the BESS roll-out, its potential and related policies in Korea and Germany as described in Chapters 3 and 4. The chapter identifies the main similarities and differences between both countries.

5.1 General context and electricity system

Before delving into the specifics of BESS deployment in Korea and Germany, it is important to understand the overarching context that influences the deployment. The comparison of the two countries should be viewed in light of these similarities and differences.

The Republic of Korea and Germany have both set themselves ambitious net-zero targets and aim to become climate neutral by 2050 and 2045, respectively. Both countries are classified as high-income, their economies are diversified, and they are characterised by a highly developed industrial manufacturing sector that contributes significantly to their national wealth. Both countries often rank among the global leaders in the manufacturing sector, and they are keen to maintain this position. However, both countries are confronted with the challenge of limited raw materials and resources, necessitating imports of these materials from third countries. Despite Germany’s larger size, economy, and population, Korea consumes more electricity than Germany (compare 463 TWh in Germany and 557 TWh in Korea in 2023 (Statista 2023a)). At the same time, both countries are resource poor as well as highly dependent on energy imports and have thus suffered under recent global energy price volatilities.

Relevant differences concerning the deployment of BESSs in Germany and Korea arise from their geographical realities. Germany is both geographically and politically well integrated into the European landmass and the European Union. South Korea, on the other hand, is geographically relatively isolated, being a peninsula whose only land border with the Democratic People’s Republic of Korea poses an acute and long-standing security threat. This disparity is also evident in the power market. Germany's integration into the European central power market is well-established, whereas Korea's power system is insular. Consequently, Korea faces distinct challenges in terms of energy security and must ensure sufficient electricity production. In contrast, Germany's integration into the power infrastructure of its neighbouring countries enables it to balance its.

Moreover, while both countries have signed and ratified the Paris Climate Agreement and aim to achieve climate neutrality in accordance with it, their respective approaches diverge. Germany has phased out nuclear energy in 2024 and puts its focus for decarbonization on renewables, with a target of 80% of renewables in the power mix by 2030. In contrast, Korea has adopted a different strategy, relying on nuclear power (with a projected share of 35% in 2038 according to the 11th Basic Plan) next to renewables to decarbonise its electricity system (Ministry of Trade, Industry and Energy 2025). Even though both countries aim to largely increase carbon neutral energies (renewable and nuclear) in their power mix, they will be faced with different challenges to ensure grid stability and security. In contrast to a nuclear-dependent power mix, Germany's power mix will be more affected by the seasonal variability of renewables. Furthermore, Germany has started its energy transition earlier and has placed more emphasis on a fast roll-out of renewable energies. As a result, it already has a much higher share of renewables in its power mix (compare 52% in Germany versus 9% in Korea in 2023) (Umweltbundesamt 2024; International Energy Agency 2025). This suggests that Germany is further along the transition pathway. Therefore, it might encounter different obstacles than Korea today but which can also be relevant for Korea in the future.

Last, it is important to note the differences in the design of the electricity market and related regulatory frameworks that affect the reality of operating BESSs in both countries, as will be seen in the following sections. In Korea, part of the electricity market - the transmission, distribution and retail segments - are under the sole control of the Korea Electric Power Corporation (KEPCO). This contrasts with the liberalized German market. One example of these differences is the number of market participants. In Korea, only few market participants operate in the electricity market, while in Germany a large number of participants with diverse characteristics, tasks and interests are involved. For example, there are currently more than 800 distribution system operators in Germany, while in Korea KEPCO is the sole operator of the distribution system.

5.2 BESS deployment status and potential

5.2.1 Current status

In comparison to Germany, Korea has a more advanced deployment status of BESSs. Korea's cumulative energy storage capacity at the end of 2023 was almost 5 times higher than Germany's (compare 10 GWh versus 1.5 GWh) (Figgener et al. 2025; Ministry of Trade, Industry and Energy and Korean Energy Economics Institute 2023). However, Germany has seen a dramatic increase in demand for large-scale BESSs in recent years for several reasons, including a profitable market environment for arbitrage trading as well as an energy transition away from fossil fuels, while Korea has experienced a decline of demand following a series of fire incidents and related safety concerns since 2017. The expiration of the aforementioned support policies has also been a factor in market contraction.

When comparing how BESSs are deployed in the two countries, distinct patterns emerge. In Korea, BESSs are predominantly utilised for renewable energy integration, i.e., BESS installed with direct connection to renewable energy production sites and store excess renewable energy, followed by grid demand management. Conversely, in Germany, BESSs are primarily used for ancillary services with renewable energy integration as a secondary purpose. The stronger focus on renewable energy integration in Korea can be attributed to the successful support programme under the REC scheme from 2016 to 2020, which promoted the deployment of BESSs alongside renewable energy sources. Although Germany has also supported the co-development of BESSs with renewables through the innovation auction, this has only been introduced more recently (after 2020) and its design does not incentivize the operation of BESSs in a grid-oriented way (see Figgener et al. 2023). The prevalence of BESSs for ancillary services in Germany can be explained by several factors. Prior to 2019, BESS installations were almost exclusively built for ancillary services due to the absence of incentives for other applications, such as those provided by the innovation auction. Furthermore, Germany's liberalised electricity market offers a conducive environment for BESSs, encouraging (unrestricted) participation from a diverse range of actors who can profit from BESS operations in the electricity market. In contrast, Korea's centralized and cost-based electricity market, which operates with limited ancillary services and real-time markets, is not favourable for BESS market entry. Until 2020, BESS deployment was largely driven by support policies such as charging fee discounts and additional REC for renewable energy-integrated BESSs, attracting public and private investment.

It is important to recognise that these insights also reflect the current situation. Germany is expected to see a significant increase in battery storage installations in the coming years, potentially altering the prevalent use cases. For example, high-capacity 'grid boosters' are anticipated to contribute substantially to this growth. Meanwhile, the Korean market has faced setbacks in recent years. A series of fire incidents post-2017, required the strengthening of safety measures, which lead to increases in costs for BESSs. Moreover, the expiration of support policies led to a market downturn, from which it has not fully recovered. Plans are underway to revitalize BESS deployment through electricity market reforms, with pilot projects preceding these reforms. For example, Jeju Island has a central BESS contract market that compensates for BESS power supply costs through bidding prices over 15 years.

When examining the actors involved in the BESS market in Korea and Germany, a significant difference lies in the organisation of their electricity markets. Korea operates a centralized electricity market managed by the Korea Power Exchange (KPX) and Korea Electric Power Corporation (KEPCO), which construct and manage transmission and distribution facilities and operate the retail market. The ownership and operation of BESSs are also in a transitional phase, with KEPCO owning and operating frequency regulation and grid stabilization ESSs, while renewable energy and demand management BESSs are operated by individual owners under predefined rules and tariff systems. The central BESS contract market is owned by private or public investors and operated by KPX for purposes such as resolving output limitations. In contrast, Germany's market involves a diverse array of participants, reflecting its liberalised and decentralised approach. BESSs cannot only be operated by the over 800 DSOs but also other actors such as energy companies or private investors.

Korea has established itself as a global leader of battery cell production and hosts three of the world's top 10 lithium-ion battery manufacturers, that have factories not only in Korea but also worldwide. More than 99% of ESSs installed in Korea use domestically manufactured NMC lithium-ion batteries. The Korean government is targeting to revive its currently slowed down domestic ESS industry and to further strengthen its position as a global manufacturing leader (see Chapter 3). In Germany, the majority of battery cells are imported. However, Germany is currently expanding production capacities along the entire battery value chain to address national demand and mitigate supply chain risks. Despite the recent failure or delay of production capacity projects of 243GWh, Germany is expected to remain one of the leading countries for battery cell production in Europe. While the scale of domestic battery production differs in the two countries, both share a commitment to scaling up domestic production, albeit with distinct goals.

5.2.2 Potential for BESSs

The potential for large-scale battery storage systems in Korea and Germany is similar in absolute terms. According to current estimations, Korea will need a combined electricity storage capacity of 24.4. GW short- and medium-duration capacity by 2036, while Germany will need 24 GW by 2037 (compare to estimated energy consumption of approx. 630 TWh by 2037 in Germany and 700 TWh by 2038 in Korea) (Bundesnetzagentur 2024a; Ministry of Trade, Industry and Energy 2025). Compared to the respective targets for the share of renewables (90% in Germany and around 30% in Korea), Korea appears to have a relatively higher need for flexibilization via BESSs, despite the lower share of renewables in the electricity mix. The fact that Korea's electricity grid is an island grid with no connection to neighbouring countries probably factors into this.

5.3 BESS policy targets and support

Korea and Germany have both announced special public interest in electricity storage and have recognized the technology as important for their respective energy transitions. To facilitate the roll-out, both countries have recently published specific strategies. However, while Korea has concrete roll-out targets for the coming years, for Germany no official targets but only estimates based on differing scenarios exist.

To fulfil its targets, Korea focuses on reviving domestic demand and production of BESSs through diverse measures put forward in comprehensive mid- and long-term strategies. Notably, the introduction of the renewable energy certificates (REC) for renewable energy sources linked to ESSs in 2016 led to a strong demand until 2020 when the REC system was phased out. However, because the demand for BESSs has declined in recent years due to several incidents and related safety concerns, and more crucially, the sunset of the REC regime, the Korean government must adapt its current strategy. In this regard, it plans to reform the electricity market mechanism and has introduced a central bidding market for BESSs for long-duration capacities in Jeju Island.

Similar to Korea, Germany is committed to fostering domestic battery production. The development of batteries and battery systems has been supported in Germany for many years through research programmes, establishing a strong foundation in this field. Recently, the political focus has shifted towards enhancing domestic battery production capabilities. While deployment is also encouraged, demand-side measures have been more limited in comparison. Similarly to Korea, Germany has also introduced incentives to install renewable energy sources in combination with electricity storage and has lowered the operation costs of ESSs by reducing grid fees. However, the financial support for BESSs is not as comprehensive in light of the more favourable market environment in Germany which makes investments more interesting. Moreover, the German government aims to create a 'level playing field' for all flexibilization options. Nevertheless, the implementation of the measures and fields of actions outlined in the Electricity Storage Strategy, published in December 2023, is anticipated to affect the market and investment environment for electricity storage in Germany.

5.4 Challenges

The deployment of BESSs in Germany and Korea is hindered by several challenges. To unfold the full potential of storage options for the energy transition these need to be addressed. Both countries face challenges in regard to their existing regulatory and policy frameworks. While for Korea the integration of flexibility measures in the electricity supply planning and the management of renewable energy curtailment is insufficient, for Germany BESS installation and operation is directly hindered by, for instance, complex licensing procedures, non-uniform installation requirements, and restricting laws and regulations.

In addition to regulatory hurdles, both countries share common technical challenges related to the technology itself such as limited lifespan of batteries or high up-front investment costs. Moreover, they are both faced with supply chain vulnerabilities and issues with installation sites. In contrast, safety concerns and community acceptance are more pronounced in Korea due to past fire incidents, whereas in Germany, the integration with existing grid infrastructure presents significant challenges.

Market challenges also pose substantial barriers. Both Korea and Germany experience investment vulnerabilities, though the nature of these challenges differ. Korea's previous strong incentive schemes (RECs) have attracted private and public investment, but it has been clear that they are not financially sustainable. Therefore, it is focusing on restructuring the electricity market, which is more favourable to BESS investments. In Germany, although the market appears more favourable for BESS investments, uncertainties about grid fee exemptions post-2029 and mandatory long operational horizons for publicly funded projects—despite shorter BESS lifespans—restrict investments. Market challenges also stem from differing electricity market designs. Germany's decentralized system lacks incentives for system-beneficial use of BESSs and fails to encourage optimal location and timing for BESS deployment. Korea is also facing these problems but also needs to consider the social and industrial impacts, such as the possibility of an increase in electricity prices due to the construction of BESSs.

6 Conclusions and Recommendations for Korean-German Cooperation

6.1 Conclusions

This study examines the deployment and potential of Energy Storage Systems in Korea and Germany, focusing on Battery Energy Storage Systems as pivotal components of their energy transitions. Both countries recognize the critical role of large-scale battery storage in stabilizing their power grids, integrating renewable energy, and achieving carbon neutrality. Korea, leveraging its advanced battery manufacturing industry, aims to enhance grid stability amidst its nuclear and renewable energy-centric power mix. Germany is expanding its battery production and implementing policies to support renewable integration and grid flexibility.

The study identifies several challenges, including the uniform market pricing in Germany, which impacts BESS operations by not reflecting local grid conditions, and the shortage of skilled personnel in both countries' energy sectors. This underscores the importance of strategic BESS placement to optimize grid services and the necessity for differentiated pricing signals to address regional grid needs effectively. Additionally, the low deployment of BESSs in Korea following the abolition of support programs in times of increasing prices for BESSs showcase the need for carefully designed policy support measures that consider external (market) signals.

It is recommended that the expansion of renewable energy should go hand in hand with the expansion of flexibility options such as BESSs. Addressing the here presented challenges in each country will therefore be crucial for fostering a targeted and system-compatible deployment and integration of BESSs. For instance, simplifying or adapting regulatory frameworks governing storage ownership and operation, thus allowing TSOs to optimally utilize storage options, can help to unlock the full potential of storage systems. Given the short time frame of reaching the respective net-zero targets, measures should be taken in a timely manner.

6.2 Recommendations for Korean-German cooperation

While most of the challenges need to be addressed individually, cooperation on certain aspects is advisable. Recommendations for Korean-German cooperation include harmonising regulatory standards and fostering technological collaboration to overcome these hurdles. In the following, recommendations for cooperation on BESS deployment, operation and manufacturing are provided. A vehicle for this bilateral cooperation is the Korean-German Energy Partnership, a high-level cooperation format established in 2019 between the German Ministry of Economic Affairs and Climate Action (BMWK) and the Korean Ministry of Trade, Economics and Industrie (MOTIE) for advancing the energy transition in both countries.

Enabling BESS integration into the electricity grid

Crucial for the optimal operation and utilization of BESSs is the right and in-time integration into the electricity grid. The challenges identified in earlier chapters show that the different electricity systems in Germany and Korea lead to diverse challenges. Conducting policy- and expert exchanges can lead to mutual learning and inspire positive developments. Therefore, it is recommended to:

- Hold an expert exchange on the integration of large-scale BESSs in the electricity system in Korea and Germany.
- Exchange among TSOs/DSOs on the integration of BESSs for flexibilization of the electricity system.

Moreover, to support the integration of BESSs, we recommend the bilateral exchange on neighbouring topics such as grid security and stability, and the flexibilization of power supply.

Technology development and standards for BESS

Korea and Germany both aim to establish themselves as global/ regional leaders in the BESS manufacturing sector. The Energy Partnership could support this ambition through several cooperation formats:

First, to ensure a safe operation of and enable the global trade with BESSs, collaboration on (safety) standards and regulations is advisable. A report by the European Commission on battery safety tests in standards from 2024 comes to the conclusion that there are significant differences among existing safety standards (Hildebrand et al. 2024). This lack of standardisation creates technical barriers to trade and discourages market entry (Fraunhofer ISI 2020). Moreover, as seen in Korea, safety concerns among the public due to for instance fire incidents can lead to a halt in BESS operation. The Energy Partnership could support the development of (global) standards by supporting a coordination between Germany and Korea on this issue through:

- Organising expert workshops focused on the standardisation and certification of BESSs.
- Facilitating exchanges between standardisation bodies to harmonise standards and certification processes.

Second, to foster the development of more efficient, safe and renewable battery types, especially in light of fire incidents related to BESS installations, the following formats are recommended:

- Conducting expert exchanges on current research trends, including new battery technologies, battery recycling, and the creation of more sustainable batteries.
- Organising expert workshops on safe operation of BESS systems and battery safety standards.

Resilience of BESS supply chains and domestic production

Both countries emphasise the importance of local production and the resilience of BESS supply chains. To support and enable mutual learning among small and medium businesses involved in the battery economy, the Energy Partnership could support this by holding the following formats:

- Hosting B2B meetings and exchanges among businesses across the entire battery value chain.
- Supporting mutual visits by enterprise delegations to facilitate networking and collaboration.
- Exchanges on the resilience of supply chains and raw material procurement for BESSs.

By implementing these recommendations, the Korean-German Energy Partnership can support the deployment and integration of BESSs in the Korean and German electricity sector and advance both countries' strategic position in the BESS manufacturing sector. This collaboration can help both countries align with global sustainability goals while enhancing domestic energy security.

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