KAST 한국과학기술한림원
The Korean Academy of Science and Technology

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KAST-Leopoldina Perspectives

Navigating the Energy Transition in Korea and Germany

The 8th bilateral KAST-Leopoldina Symposium, held in Seoul on 14-15 January 2025, and a series of virtual expert workshops throughout 2024, brought together leading scientists from Korea and Germany in the fields of solar technologies, hydrogen, batteries, grid management, and future energy sources. The goal was to foster collaboration and promote progress towards a sustainable and resilient energy future in both countries. This joint paper summarizes the outcomes of the workshops and the symposium, highlighting scientific challenges, identifying priorities for bilateral research, and offering recommendations for policymakers in Korea and Germany.

Solar Technologies

Photovoltaics (PV) offer the lowest cost of electricity generation among renewable energy technologies, with the highest potential for large-scale adoption. Both Korea and Germany have set ambitious goals for the energy transition and PV plays a key role. Technological know-how and world-leading research in both countries position Korea and Germany as key players in advancing solar technologies globally.

Challenges

- **Efficiency limits:** Crystalline silicon solar cells, which dominate the global PV market, are a fully mature technology which approaches the single junction efficiency limit.
- **High R&D costs:** Advancing PV technologies requires extensive research, significant financial investment, and long development timelines.
- **Environmental impacts:** Increased global production of PV modules generates waste. Land-use conflicts complicate large-scale adoption.

Recommendations

1. **Foster innovation in next-generation PV technologies:** Advance perovskite-silicon tandem and silicon-free multi-junction solar cells, which promise higher efficiency, and other next-generation PV, like organic cells with an extremely low CO_2 footprint.
2. **Invest in artificial intelligence and discovery strategies:** Machine learning integration in PV research labs can significantly reduce costs and accelerate development time by discovering novel optimized materials tailored for direct transfer into industry.
3. **Promote a closed-loop approach:** Start from material sourcing to end-of-life recycling, for example by focusing on organic solar cells. Strengthen the integration of multi-benefit PV into buildings, agricultural areas, vehicles, and floating structures to reduce land-use conflicts.

Priorities for Bilateral Research

Engage in strategic, coordinated projects by creation of joint research grants and industrial partnerships to foster cooperation and knowledge transfer, shared R&D infrastructure, and joint production facilities for next generation solar cells such as tandem PV.

Hydrogen Technologies

Hydrogen plays a crucial role in decarbonizing hard-to-electrify sectors, supporting grid stability, and enabling large-scale energy storage. Both Korea and Germany are advancing hydrogen technologies, with a focus on electrolysis, catalyst innovations and fuel-cells, recognizing hydrogen as essential for the energy transition. In addition to production, both countries face the need for infrastructure to support the import, transportation and storage of hydrogen and its derivatives.

Challenges

- **Dependency on imports:** High energy demand and limited domestic green hydrogen production capacities create the need for new international energy partnerships.
- **Expensive and complex infrastructure:** The geographical distance between producers and consumers of green hydrogen requires significant investment in ships, pipelines and ports which must be built and adapted for hydrogen and its derivatives.
- **Slow adoption:** High production costs and limited supply of green hydrogen hinder rapid implementation and challenge the efforts to meet climate goals.

Recommendations

1. **Enhance hydrogen production efficiency:** Accelerate optimization and large-scale production of electro-catalysts and thermo-catalysts relevant to the hydrogen economy.
2. **Advance efficient hydrogen carriers:** Strengthen liquid organic hydrogen carriers such as LOHC and dimethyl ether (DME) for efficient, long-distance transport, leveraging existing fuel infrastructure including repurposed gas-pipelines.
3. **Scale-up existing and demonstrate new green hydrogen technologies:** Showcase the viability and prioritize hydrogen in heavy industries like steel and cement production and in long-range transportation, including ships and trains, to drive wider adoption. Invest in renewable-powered hydrogen production and high-temperature electrolysis to lower costs and increase availability.

Priorities for Bilateral Research

Strengthen collaboration on fundamental research and applications of catalytic and electro-catalytic materials and hydrogen carrier cycles at both low and high technological readiness levels (TRLs) by joint strategic, coordinated projects. This approach can accelerate innovation across the hydrogen supply chain.

Batteries

Batteries are essential for the transition to electric mobility, ensuring grid stability and providing short- and medium-term (from minutes to a few hours) energy storage solutions. With strong research environments and industrial capacities, Korea and Germany are important players in the development of advanced battery technologies.

Challenges

- **Supply chain constraints:** The rising demand of raw materials for batteries increases economic pressure. High energy density, extended lifespan and performance in extreme conditions, particularly for electric vehicles (EV), need to be addressed.
- **Risks and public concerns:** The large-scale adoption of batteries in EV and buildings comes along with new challenges such as thermal runaway or fire hazards.
- **Seasonal variability in renewable energy:** Seasonal and annual storage of renewable energy remains a major challenge but is crucial for the goal of carbon neutrality.

Recommendations

1. **Implement closed-loop battery manufacturing:** Improve battery recycling processes as well as battery resilience and finding other battery chemistries (Na, K) to reduce environmental impact including the use of per- and polyfluoroalkyl substances (PFAS). Repurpose EV batteries in smart buildings for grid storage.
2. **Increase battery safety:** Invest in research on fire-resistant materials and solid-state batteries
3. **Advance seasonal and annual storage solutions:** Leverage research on long-term, scalable energy storage solutions such as primary large-scale seawater and Al-air batteries, where the energetic reactive metals can be stored outside the batteries themselves.

Priorities for Bilateral Research

Strengthen collaboration on large-scale coordinated joint research initiatives with a focus on liquid and solid-state batteries and post-lithium technologies. Capitalize on Germany's strength in basic research and Korea's original equipment manufacturers by building partnerships, accelerating the path from experimental breakthroughs to market-ready products.

Grid Management

Smart grids are essential for integrating renewable energy, reducing grid congestions and improving stability. Korea cannot rely on neighboring countries to balance grid impacts – unlike Germany, which is embedded in the European energy system. These differing framework conditions pose complementary requirements for smart grid solutions. Addressing these requirements simultaneously, from concepts to demonstrators, will accelerate research and development efforts. While Germany has experience in renewable energy integration, Korea's pioneering efforts in AI-driven grid optimization present promising tools for enhancing grid stability.

Challenges

- **Grid congestion and instability:** The change in generation structure causes congestion. Missing conventional power plants lead to a "weaker" grid with voltage instability and volatile infeed from renewables to frequency challenges.
- **Delayed network expansion:** Wind energy is often generated far away from where it is consumed, which requires new transmission lines that can lead to social conflicts. At the same time, household PV, heat pumps and EV charging points strain existing infrastructure, making the role of the distribution network more relevant.
- **Transitioning fossil electricity markets:** Variability of wind- and PV-based generation requires flexible back-up capacities and/or distributed storage capacities. Differences in the timing and location of supply and demand complicate electricity markets further.

Recommendations

1. **Increase system flexibility:** Control residual load through demand-side-management using power-to-gas, electric vehicle's batteries integration, sector-coupling (heat, gas/hydrogen), and smart household and industry consumption.
2. **Combine central and local energy systems:** Distributed Energy Resources (DER) help to localize energy systems, by expanding Virtual Power Plants (VPPs), energy cloud systems and fractal, micro- and modular grids. Embedded High-Voltage-Direct-Current (HVDC) transmission systems enable power transmission of distant renewable sources. The resulting hybrid, alternating-current/direct-current transmission network enables stable operation with higher utilization and controlled power transmission.
3. **Promote competitive energy markets and a coherent and cohesive plan of digitalization of the energy infrastructure:** Digitalization is key for a more efficient use of the available infrastructure. Flexibilization of the system is only possible if adequate digitalization is in place at every level of the grid. Apply AI tools to enhance grid management and stability. Introduce flexible, market-based mechanisms for real-time energy adjustments, supporting both investments in renewables and in the provision of back-up power plants. International coordination is key to make sure that solutions working in one country are also interoperable in another country.

Priorities for Bilateral Research

Foster joint research on organizing resilient grids, focusing on new operational principles and integrated planning of networks. Collaborative studies on microgrid applications and system-stability offer promising avenues to enhance grid flexibility and stability in both Korea and Germany. Invest in the development and translation of joint platforms for grid design and management.

Future Energy Sources

Small Modular Reactors (SMRs) and fusion energy are technologies with the potential to support global efforts to achieve low-carbon, resilient energy systems. Fusion energy might provide a source of clean power in the future. Recent advancements in stellarator and tokamak designs, along with international initiatives like ITER, are paving new pathways to achieve viable fusion energy by mid-century or beyond. SMRs potentially offer a flexible solution for reliable power and heat generation, well-suited to phase out fossil energy systems and to offer stable energy supply to the grid. While both technologies still face scientific, technological and commercial challenges, they hold potential for a strong complementary contribution to a low-carbon energy future.

Challenges

- **Technological complexities:** Fusion energy requires, among others, stable, steady-state plasma confinement and integrated engineering solutions. SMRs need engineering solutions to demonstrate enhanced safety which can minimize emergency planning zones for nuclear power plants.
- **Investment risks:** High investment costs, long project cycles, and the need for international cooperation complicate sustained funding and commercialization for fusion. SMRs are expected to be demonstrated within the next decade, but the uncertainties in the construction cost and learning curve of serial production (n-th of-a-kind devices) are yet to be addressed.
- **Public acceptance:** Both technologies must effectively navigate risks involving safety and security. Public concerns and acceptance must be addressed regarding environmental impact for successful commercialization.

Recommendations

1. **Advance plasma and reactor designs:** Expand research on plasma confinement and stability, 3D magnetic configurations and material development for both stellarators and tokamaks. Continue and demonstrate innovative technologies in SMR design and safety, optimize configurations for different target applications, and include the reuse of infrastructure from retiring fossil power plants.
2. **Enhance grid integration and storage solutions:** Research on advanced confinement concepts and new materials has the potential to accelerate progress to a cost-effective fusion solution. For SMRs, explore innovative applications such as zero carbon hydrogen production and utilizing energy storage systems for improved flexibility in operation.
3. **Strengthen transparency and safety measures:** Develop safety and licensing concepts, both for fusion and SMRs, which can practically exclude any requirement of emergency measures. Enhance reactor resilience possibilities for nuclear waste management. Employ high precision simulation platforms and AI-aided approach to provide real-time emergency response capabilities. Proactively foster a dialogue on safety issues and communicate possible long-term environmental benefits to build public trust.

Priorities for Bilateral Research

Key areas of research collaboration could include advancing 3D physics in reactor design, developing materials resilient to high-heat and neutron-rich environments, and implementing real-time simulation systems for emergency response. There is a strong potential for collaboration in safety research for both fusion and SMR systems, as well as in nuclear waste management – each critical to long-term public acceptance and environmental sustainability.

Overarching Recommendations

To further support the specific recommendations in the five areas central to the energy transition in Korea and Germany above, the following overarching measures should be implemented:

1. **Establish long-term funding cycles (10-15 years)** to develop and scale-up innovative, sustainable, efficient and safe technologies for the global energy transition in Korean-German R&D collaborations. Tailored funding schemes should be jointly developed by Korean and German governments and funding agencies.
2. **Facilitate the exchange of young researchers** to foster collaboration and knowledge sharing between Korea and Germany from the early stages of their careers.
3. **Enhance training programs** to support the development of a skilled workforce in the energy industry, preparing efficient implementation of the energy transition in Korea and Germany.

Conclusions

As Korea and Germany navigate the transition from fossil fuels to sustainable energy sources, the need for innovative scientific solutions has never been more urgent. Despite distinct challenges, both countries share the goal of achieving carbon neutrality and advancing green energy technologies. By leveraging complementary strengths, Korea and Germany can accelerate progress through deepened scientific collaboration across key areas identified in this joint paper that promise high potential. Through their partnership, KAST and Leopoldina will continue to promote interdisciplinary dialogue, from basic research to large-scale demonstration of cutting-edge technologies, driving meaningful change towards a sustainable energy future.

This joint paper builds on the proceedings of the 8th bilateral KAST-Leopoldina Symposium "Energy Transition", and a series of virtual expert workshops that were held throughout 2024. It was compiled by the scientific coordinators of the symposium, Leopoldina Member Prof. Dr. Wolfgang Marquardt, former Chairman of Forschungszentrum Jülich, and KAST Fellow Prof. Dr. Nam-Gyu Park, Sungkyunkwan University, with assistance from the international departments at KAST and Leopoldina. More information on the symposium can be found here: https://www.leopoldina.org/veranstaltungen/veranstaltung/event/3219/

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