energy storage and applications

Review

Advancing Energy Storage Technologies and Governance in the Asia-Pacific Region: A Review of International Frameworks, Research Insights, and Regional Case Studies

Chung-Han Yang [1,2,*] and Jack Huang [3]

1 Centre for Environment, Energy and Natural Resource Governance (C-EENRG), University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, UK
2 Department of Environmental and Cultural Resources, National Tsing Hua University, 101, Section 2, Kuang-Fu Road, Hsinchu 300044, Taiwan
3 United Nations Office of Information and Communications Technology, The United Nations Building Phra Nakhon, Bangkok 10200, Thailand; huangj@un.org
* Correspondence: chyang@cantab.net; Tel.: +44-07450678652

Abstract

This review explores the development of energy storage technologies and governance frameworks in the Asia-Pacific region, where rapid economic growth and urbanisation drive the demand for sustainable energy solutions. Energy storage systems (ESS) are integral to balancing renewable energy fluctuations, improving grid resilience, and reducing greenhouse gas emissions. This paper examines the role of international organisations, including the United Nations, International Energy Agency (IEA), and International Renewable Energy Agency (IRENA), in promoting energy storage advancements through strategic initiatives, policy frameworks, and funding mechanisms. Regionally, the Asia-Pacific Economic Cooperation (APEC), the Association of Southeast Asian Nations (ASEAN), and the Asian Development Bank (ADB) have launched programs fostering collaboration, technical support, and knowledge sharing. Detailed case studies of Japan, Thailand, and China highlight the diverse policy approaches, technological innovations, and international collaborations shaping energy storage advancements. While Japan emphasises cutting-edge innovation, Thailand focuses on regional integration, and China leads in large-scale deployment and manufacturing. This analysis identifies key lessons from these frameworks and case studies, providing insights into governance strategies, policy implications, and the challenges of scaling energy storage technologies. It offers a roadmap for advancing regional and global efforts toward achieving low-carbon, resilient energy systems aligned with sustainability and climate goals.

Keywords: Asia-Pacific; Association of Southeast Asian Nations (ASEAN); Asia-Pacific Economic Cooperation (APEC); Asian Development Bank (ADB); International Energy Agency (IEA); International Renewable Energy Agency (IRENA); United Nations (UN)

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Received: 27 January 2025
Revised: 28 May 2025
Accepted: 13 June 2025
Published: 23 June 2025

Citation: Yang, C.-H.; Huang, J. Advancing Energy Storage Technologies and Governance in the Asia-Pacific Region: A Review of International Frameworks, Research Insights, and Regional Case Studies. *Energy Storage Appl.* **2025**, 2, 8. https://doi.org/10.3390/esa2030008

1. Introduction

The Asia-Pacific region, which is home to over 60% of the world's population, is experiencing rapid economic growth and urbanisation. This growth has led to an increasing demand for energy, which, in turn, has highlighted the critical need for sustainable and efficient energy storage solutions. Energy storage technologies are central to balancing the fluctuations in renewable energy sources, thereby improving grid stability and ensuring a reliable energy supply. As countries in the Asia-Pacific region strive to meet their energy needs while committing to reducing greenhouse gas emissions, the advancement of energy storage technologies has become a key focus area [1].

Energy storage systems (ESS) play a crucial role in the transition to a low-carbon energy future. They enable the integration of renewable energy sources, such as solar and wind power, into the electricity grid by storing surplus energy generated during periods of high production and releasing it during periods of high demand. This capability not only helps to balance supply and demand but also reduces dependence on fossil fuels, helping to reduce carbon emissions [2]. In addition, energy storage technologies can increase the resilience of energy infrastructure and make it more adaptable to disruptions caused by natural disasters or other unforeseen events [3].

In recent years, global efforts to develop and deploy advanced energy storage technologies have increased significantly. International organisations such as the United Nations (UN) [4], the International Energy Agency (IEA) [5], and the International Renewable Energy Agency (IRENA) [6] have been at the forefront of advocating for policies and initiatives that support the growth of energy storage. These organisations have recognised the potential of energy storage to transform the energy landscape and are working to create an enabling environment for its development through research, funding, and policy advocacy [7].

At the regional level, initiatives by the Asia-Pacific Economic Cooperation (APEC) [8], the Association of Southeast Asian Nations (ASEAN) [9], and the Asian Development Bank (ADB) [10] have been instrumental in promoting energy storage technologies. These organisations have launched various programmes and projects aimed at promoting cooperation between member countries, sharing best practises and providing financial and technical support for energy storage initiatives. Such regional co-operation is essential to address the unique challenges of the Asia-Pacific region, including different energy needs, different levels of technological development and different regulatory frameworks.

In terms of the existing literature, the transition to sustainable energy systems has been increasingly recognised as a critical global priority, driven by the urgent need to mitigate climate change and reduce greenhouse gas emissions (Intergovernmental Panel on Climate Change [IPCC], 2023) [11]. Energy storage systems (ESS) play a pivotal role in this transition by enabling the integration of renewable energy sources, enhancing grid reliability, and providing flexibility to energy markets (Chen et al., 2021) [12]. As highlighted by Liu et al. (2022) [13], energy storage technologies not only support the variability of renewable generation but also contribute to energy security and sustainability.

Recent studies emphasise the importance of robust policy frameworks and international cooperation in advancing energy storage technologies (IRENA, 2023) [14]. According to a report by the International Energy Agency (IEA, 2023) [15], global energy storage capacity is projected to grow significantly, driven by innovations in battery technologies and supportive regulatory environments. This growth is essential for achieving climate goals outlined in international agreements such as the Paris Agreement and the United Nations Sustainable Development Goals (UN SDGs) (United Nations, 2015) [16].

Various international organisations, including the United Nations (UN), the IEA, and the International Renewable Energy Agency (IRENA), have developed strategic frameworks and initiatives aimed at promoting the deployment of energy storage systems. For instance, the UN's COP29 Pledge aims to increase global energy storage capacity to 1500 GW by 2030, reflecting a commitment to sustainable energy practices (United Nations, 2024) [17]. Similarly, IRENA's reports on electricity storage highlight the economic benefits and market opportunities associated with energy storage technologies (IRENA, 2022) [18].

This review paper aims to provide a comprehensive overview of the current state of energy storage technologies and governance in the Asia-Pacific region. It examines the international frameworks and policy initiatives that are driving the progress of energy storage, as well as the regional efforts of APEC, ASEAN and ADB. Detailed case studies of Japan, Thailand and China will be used to highlight the progress these countries have made in developing and implementing energy storage solutions. It also draws out key lessons from the frameworks, initiatives and case studies analysed and provides an original discussion on the implications for future research and policy development.

The importance of energy storage cannot be overemphasised in the context of the energy transition in the Asia-Pacific region. As countries in the region continue to urbanise and industrialise, the demand for reliable and sustainable energy will continue to grow. Energy storage technologies offer a viable solution to meet this demand while supporting the region's climate goals. By reviewing existing frameworks and initiatives, this paper aims to contribute to the ongoing discourse on energy storage and provide valuable insights for policymakers, researchers, and industry representatives.

To summarise, the advancement of energy storage technologies is critical to the sustainable energy future of the Asia-Pacific region. International and regional frameworks play an important role in promoting the development and deployment of these technologies. Through collaborative efforts and continuous innovation, the region can achieve a more resilient, efficient, and low-carbon energy system. This overview paper will explore these issues in detail and provide a comprehensive analysis of the current landscape and future prospects of energy storage in the Asia-Pacific region.

2. Reviewing International Frameworks, Policy Initiatives, and Relevant Research

The advancement of energy storage technologies is underpinned by a robust framework of international policies and initiatives. Key global organisations, including the United Nations, the International Energy Agency, and the International Renewable Energy Agency, have been instrumental in promoting the development and deployment of energy storage solutions. These organisations provide critical guidance, funding, and advocacy to support the integration of energy storage into national and regional energy strategies. This section will explore the contributions of these international bodies, highlighting their efforts to create a conducive environment for energy storage innovation and implementation.

2.1. United Nations (UN)

The United Nations has been actively promoting the development and deployment of energy storage technologies through various initiatives and resolutions. UN SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy for all. As part of this goal, the UN emphasises the importance of energy storage in achieving universal energy access and integrating renewable energy sources [19]. The UN's policy briefs and reports highlight the role of energy storage in enhancing energy efficiency and supporting the transition to sustainable energy systems. These efforts are aimed at enhancing global energy security, supporting the integration of renewable energy sources, and contributing to climate change mitigation.

1. COP29 Global Energy Storage and Grids Pledge: During the COP29 summit, the UN launched a significant initiative to boost global energy storage capacity. The pledge aims to increase global energy storage capacity by six-fold, reaching 1500 gigawatts (GW) by 2030 [20]. This initiative is part of a broader effort to triple renewable energy capacity by 2030 while maintaining energy security. The pledge also includes commitments to add or refurbish more than 80 million kilometers of electricity grids by 2040 [21]. This ambitious

target underscores the critical role of energy storage in achieving global renewable energy goals and ensuring a stable and reliable energy supply. As of May 2025, global energy storage capacity has reached approximately 800 GW. The pledge aims for 1500 GW by 2030, indicating significant progress but highlighting challenges such as regulatory barriers and the need for international collaboration.

2. United Nations Framework Convention on Climate Change (UNFCCC): The UNFCCC has been instrumental in driving global climate action, including the promotion of energy storage technologies. The Marrakech Partnership for Global Climate Action, launched at COP22, has been a key platform for enhancing collaboration between parties and non-party stakeholders (NPS) in the fight against climate change. At COP29, the Marrakech Partnership showcased various initiatives and best practices related to energy storage, highlighting the importance of these technologies in achieving climate goals [22]. The Marrakech Partnership continues to facilitate initiatives for energy storage, with several countries reporting advancements in integrating energy storage into their climate action plans. However, precise metrics on energy storage deployment linked to UNFCCC commitments are still being developed.

3. United Nations Environment Programme (UNEP): The UNEP has been working to create a favorable enabling environment for renewable energy and energy storage through policy advice, risk reduction for investments, and raising awareness of successful approaches [23]. The UNEP's efforts include providing technical assistance to governments in developing policies that support the deployment of energy storage technologies, thereby facilitating the integration of renewable energy into national energy systems. The UNEP has reported ongoing efforts to create favorable policies for renewable energy and energy storage. Specific country case studies are being published, showcasing successful policy implementations; however, overall metrics on energy storage adoption remain varied across regions.

4. UN Energy Plan of Action Towards 2025: This plan outlines a coordinated approach to advancing energy storage and other clean energy technologies. It includes specific actions to support the deployment of energy storage solutions, such as improving regulatory frameworks, fostering innovation, and mobilising financial resources. The plan aims to accelerate progress towards SDG 7 and the broader 2030 Agenda for Sustainable Development [24]. The plan is actively promoting energy storage solutions through workshops and regional dialogues. Countries are beginning to align their national policies with this plan, although comprehensive data on implementation is still being gathered.

5. High-Level Political Forum (HLPF) on Sustainable Development: The HLPF serves as a platform for reviewing progress on the SDGs, including SDG 7. During these forums, the UN presents policy briefs and recommendations that emphasise the importance of energy storage in achieving sustainable energy transitions. These documents provide guidance for policymakers on creating supportive environments for energy storage technologies [25].

These initiatives and resolutions by the United Nations demonstrate a strong commitment to advancing energy storage technologies as a key component of the global energy transition. By fostering international cooperation, providing policy guidance, and mobilising resources, the UN is playing a crucial role in supporting the development and deployment of energy storage solutions worldwide.

2.2. International Energy Agency (IEA)

The IEA has been a leading voice in promoting the development and deployment of energy storage technologies. Their reports provide comprehensive analyses and strategic recommendations to support the integration of energy storage into global energy systems.

1. Energy Storage Implementing Agreement (ESIA): The IEA's Energy Storage Implementing Agreement (ESIA) focuses on international cooperation in the field of energy storage research and development. This agreement aims to facilitate the development and deployment of energy storage technologies through collaborative research, information exchange, and the promotion of best practices. The ESIA supports various projects and initiatives that contribute to the advancement of energy storage solutions [26]. The ESIA has facilitated various collaborative projects focusing on energy storage technologies. Recent reports indicate a growing interest in lithium-ion and alternative battery technologies, although specific deployment numbers are not uniformly tracked.

2. Technology Roadmap: Energy Storage (2014): This roadmap provides a strategic framework for understanding and communicating the value of energy storage to energy system stakeholders. It highlights the versatility of energy storage technologies in decoupling energy supply and demand, thus providing a valuable resource to system operators [27]. The roadmap addresses the current status of energy storage deployment, predicted evolution, and the regulatory and market barriers that need to be overcome. It offers recommendations for creating supportive policies and market mechanisms to unlock the full potential of energy storage technologies. The roadmap's recommendations are being adopted gradually, with many countries reporting increased investments in energy storage. However, market barriers and regulatory challenges persist, affecting overall deployment.

3. Batteries and Secure Energy Transitions (2024): The IEA's special report on batteries provides key insights into the dominance of lithium-ion batteries in both EV and storage applications. It notes that lithium iron phosphate (LFP) batteries have gained a significant market share, accounting for 40% of EV sales and 80% of new battery storage in 2023 [28]. This shift is attributed to the adaptability of battery chemistries to mineral availability and price, demonstrating the dynamic nature of the battery market. The report also discusses the falling costs of batteries, which are improving the competitiveness of EVs and storage applications in the power sector. It identifies key barriers to growth, such as the need for better regulatory and market conditions to compensate storage for the suite of services it can provide. The IEA calls for greater attention from policymakers and industries to address these challenges and support the scaling up of battery storage technologies.

These policy initiatives and reports collectively underscore the IEA's commitment to advancing energy storage technologies as a cornerstone of the global energy transition. By providing detailed analyses and actionable recommendations, the IEA aims to support policymakers, industry stakeholders, and researchers in fostering the development and deployment of energy storage solutions. The report emphasises the growing dominance of lithium-ion batteries, which accounted for 80% of new battery storage installations in 2023. The IEA continues to call for better regulatory frameworks to support energy storage growth.

2.3. International Renewable Energy Agency (IRENA)

The IRENA's efforts and publications demonstrate a strong commitment to advancing energy storage technologies as a key component of the global energy transition [29]. By providing detailed analyses and strategic recommendations and fostering international cooperation, the IRENA supports the development and deployment of energy storage solutions worldwide.

1. Electricity Storage and Renewables: Costs and Markets to 2030: This report provides a comprehensive analysis of the cost and market potential of electricity storage technologies. It highlights the significant cost reductions expected in battery storage systems, with the total installed costs projected to fall by 50–60% by 2030. The report emphasises the role

of battery storage in supporting the integration of variable renewable energy sources, such as solar and wind, into the power grid. It also discusses the various applications of battery storage, including frequency response, reserve capacity, and support for electric vehicles and mini-grids [18]. The IRENA's projections indicate that battery storage costs are expected to drop by 50–60% by 2030. Recent data shows a significant uptick in battery storage installations globally, aligning with these forecasts.

2. Innovation Outlook: Thermal Energy Storage: This publication explores the potential of thermal energy storage (TES) technologies to support the integration of renewable energy in power generation, industry, and buildings. TES technologies, such as molten salt storage used in concentrated solar power (CSP) plants, can decouple heating and cooling demand from immediate power generation, thereby providing greater flexibility and reducing the need for costly grid reinforcements. The report identifies priorities for ongoing research and development and highlights the potential for TES to grow significantly by 2030 [30]. The report has catalysed interest in thermal energy storage technologies, with several pilot projects underway. However, detailed metrics on deployment are still being compiled.

3. Renewables and Electricity Storage: This report discusses the key role of electricity storage in managing the variability of renewable energy sources and ensuring a reliable, round-the-clock energy supply. It highlights the declining costs and improving capacities of batteries and other storage technologies, making them increasingly practical for upgrading existing power systems. The report also examines the various benefits of electricity storage, including enhancing grid stability, supporting off-grid solar home systems, and enabling 100% renewable mini-grids [31].

4. Electricity Storage Valuation Framework: The IRENA's Electricity Storage Valuation Framework proposes a five-phase method to assess the value of storage and create viable investment conditions for its deployment. This framework aims to guide the effective integration of solar and wind power by properly accounting for the system value of storage [18]. The report provides insights into the economic and technical aspects of energy storage, helping policymakers and industry stakeholders make informed decisions about storage investments. The framework is being utilised by various countries to assess the value of storage. Adoption rates are increasing, but comprehensive data on economic impacts are still being finalised.

Table 1 below summarises the key progress and major challenges remaining in international frameworks for advancing energy storage technologies and their applications.

Table 1. International frameworks and initiatives for advancing energy storage.

Organisation	Key Initiatives and Reports	Focus Areas	Key Outcomes	Challenges Addressed
United Nations (UN)	- COP29 Global Energy Storage and Grids Pledge - UNFCCC's Marrakech Partnership - UNEP Policy Support -UN Energy Plan of Action - HLPF Recommendations	- Global energy storage targets - Integration of renewables - Climate change mitigation - Policy advice and capacity building	- Ambitious goal to increase storage capacity to 1500 GW by 2030 - Enhanced collaboration among stakeholders - Policy frameworks for storage	- Lack of global coordination - Financial and technical barriers for developing countries - Policy alignment challenges
International Energy Agency (IEA)	- Energy Storage Implementing Agreement (ESIA) - Technology Roadmap: Energy Storage - Batteries and Secure Energy Transitions	- Collaborative R&D on energy storage - Strategic roadmaps - Lithium-ion dominance and alternative chemistries	- Comprehensive roadmaps for energy storage adoption - Insights into evolving battery technologies - Highlighting regulatory needs	- Insufficient market mechanisms - Regulatory hurdles - Supply chain issues for critical minerals

Table 1. *Cont.*

Organisation	Key Initiatives and Reports	Focus Areas	Key Outcomes	Challenges Addressed
International Renewable Energy Agency (IRENA)	- Electricity Storage and Renewables: Costs and Markets to 2030 - Innovation Outlook: Thermal Energy Storage - Electricity Storage Valuation Framework	- Cost reduction for battery storage - Thermal energy storage potential - Valuation of storage for economic and system benefits	- Predicted 50–60% drop in battery costs by 2030 - Identification of TES as a growth area - Framework for effective storage investments	- High upfront costs - Limited awareness of TES benefits - Need for system-wide valuation of storage technologies

Source: Conducted by the authors.

3. Regional Initiatives and Progress

The Asia-Pacific region has seen a surge in initiatives aimed at advancing energy storage technologies, driven by the need to enhance energy security, integrate renewable energy sources, and meet climate goals. Regional organisations, such as the Asia-Pacific Economic Cooperation (APEC), the Association of Southeast Asian Nations (ASEAN), and the Asian Development Bank (ADB), have been at the forefront of these efforts. This section will explore the various programs and projects launched by these organisations, highlighting their contributions to fostering collaboration, sharing best practices, and providing financial and technical support for energy storage initiatives. By examining these regional efforts, we can gain a deeper understanding of the progress made and the challenges faced in advancing energy storage technologies across the Asia-Pacific region.

3.1. Asia-Pacific Economic Cooperation (APEC)

The APEC's efforts in advancing energy storage technologies have led to significant progress in enhancing energy resilience and supporting the integration of renewable energy sources. By fostering collaboration among member economies, sharing best practices, and providing financial and technical support, the APEC has created a conducive environment for the development and deployment of energy storage solutions.

The APEC Energy Working Group (EWG) plays a central role in promoting energy security, efficiency, and sustainability across the Asia-Pacific region. EWG initiatives include the development of frameworks and strategies that support the deployment of energy storage technologies [32]. Below, we take a look at these efforts to understand how they are improving energy resilience and integrating renewable energy sources into the grid.

1. APEC Policy Guidance on Clean and Low-Carbon Hydrogen: During the 2024 APEC Energy Ministerial Meeting, member economies endorsed the "APEC Policy Guidance to develop and implement clean and low-carbon hydrogen policy frameworks". This guidance supports the development of hydrogen as an energy storage medium, which can help balance supply and demand and provide long-term storage solutions [33]. Member economies are beginning to implement hydrogen policies, with pilot projects being launched. However, concrete metrics on hydrogen storage deployment are still in development.

2. Energy Smart Communities Initiative (ESCI): Launched in 2010, the ESCI aims to promote energy efficiency and low-carbon development across APEC economies. The initiative includes projects focused on smart grids and energy storage systems. For example, the "Research on the Application of Physical Energy Storage Technology to Enhance the Deployment of Renewable Energy in an APEC Low Carbon Town" project explores the use of energy storage to support renewable energy integration [34]. The initiative has led to several successful pilot projects across member economies, thereby enhancing energy efficiency. Specific outcomes in terms of energy storage deployment are being documented.

3. Low Carbon Model Town (LCMT) Project: The LCMT project promotes the development of low-carbon urban areas through the implementation of energy-efficient

technologies and practices. Several phases of the project have included the research and development of energy storage solutions to support low-carbon energy systems. For instance, the "APEC Low-Carbon Model Town Energy Management System Development and Application Research" project focuses on integrating energy storage into urban energy management systems [35]. The LCMT project has seen successful implementation in select regions, promoting energy-efficient technologies. Metrics on energy storage integration are still being compiled.

4. APEC Smart Grid Initiative (ASGI): The ASGI is part of the ESCI and focuses on advancing smart grid technologies, including energy storage systems. The initiative aims to enhance grid reliability and efficiency by integrating advanced storage solutions. Projects under the ASGI include the development of energy management systems and the application of suitable energy storage technologies to support renewable energy deployment [36]. Progress is evident in smart grid technologies, with several member economies reporting advancements. However, detailed statistics on energy storage integration remain limited.

The APEC will continue to focus on energy storage as a critical component of sustainable energy systems. Future initiatives could include further research on innovative storage technologies, the expansion of pilot projects, and the development of a comprehensive policy framework to support large-scale deployment.

3.2. Association of Southeast Asian Nations (ASEAN)

The ASEAN has been actively promoting energy storage technologies through various policies and initiatives aimed at enhancing energy security, integrating renewable energy sources, and supporting sustainable development across the region. We review some key efforts as follows:

1. ASEAN Plan of Action for Energy Cooperation (APAEC) 2016–2025: The APAEC serves as a comprehensive framework that guides regional energy cooperation. The plan is divided into two phases, with Phase II (2021–2025) focusing on accelerating energy transition and resilience. One of the key strategies of the APAEC is to promote energy storage technologies to support the integration of renewable energy sources and enhance grid stability [9]. The plan emphasises the need for investment in energy infrastructure, including energy storage systems, to maintain a balance between supply and demand. The APAEC is actively promoting energy storage technologies, with several member states reporting increased investments. However, comprehensive data on overall energy storage implementation is still being gathered.

2. Enabling Policies for Promoting Battery Energy Storage: The ASEAN has developed policies to enhance the attractiveness of energy storage investments, both on-grid and off-grid. These policies aim to address the challenges and opportunities in each ASEAN Member State (AMS) by reviewing current developments and regulatory frameworks. The policy brief recommends several enabling policies, such as providing financial incentives, creating supportive regulatory environments, and fostering public–private partnerships to leverage the market potential of energy storage technologies [37]. Policies are being developed and implemented, but the effectiveness varies across member states. Ongoing assessments are needed to evaluate the impact of these policies.

3. ASEAN Centre for Energy (ACE): The ACE plays a pivotal role in coordinating regional energy initiatives, including those related to energy storage. The ACE's efforts include conducting research, providing policy recommendations, and facilitating knowledge sharing among member states. For instance, the ACE's policy brief on battery energy storage highlights the importance of creating a conducive environment for energy storage investments and outlines specific policy recommendations to accelerate the adoption of

these technologies [38]. The ACE continues to facilitate knowledge sharing and policy recommendations, but specific metrics on energy storage adoption are still under review.

4. Regional Energy Policy and Planning: Under the Regional Energy Policy and Planning framework, the ASEAN aims to expand partnerships with dialogue partners and international organisations to advance energy policy and planning. This includes initiatives to promote energy storage technologies as part of the region's broader energy transition strategy [39]. Collaborative efforts focus on sharing best practices, providing technical assistance, and mobilising financial resources to support energy storage projects.

5. Pilot Projects and Demonstrations: The ASEAN has initiated several pilot projects and demonstrations to showcase the potential of energy storage technologies. These projects aim to provide practical insights into the deployment and operation of energy storage systems, helping to build confidence among stakeholders and attract further investments. Examples include pilot projects for battery energy storage systems in remote and off-grid areas, which demonstrate the feasibility and benefits of these technologies in enhancing energy access and reliability [40].

Through these policies and initiatives, the ASEAN is making significant strides in promoting energy storage technologies and applications. By fostering regional cooperation, creating supportive regulatory frameworks, and investing in pilot projects, the ASEAN aims to accelerate the adoption of energy storage solutions and support the region's transition to a sustainable energy future.

3.3. Asian Development Bank (ADB)

The ADB has been a key player in promoting energy storage technologies across the Asia-Pacific region. Through various initiatives, projects, and policy recommendations, the ADB aims to enhance energy security, support the integration of renewable energy, and foster sustainable development. Some of the key efforts of the ADB are as follows:

1. Handbook on Battery Energy Storage System: The ADB published the "*Handbook on Battery Energy Storage System*" to serve as a comprehensive guide for deploying battery energy storage technologies. The handbook covers various aspects, including different battery technologies, business models for energy storage services, grid applications, challenges, risks, and policy recommendations [41]. It aims to support the ADB's clean energy program and the deployment of advanced energy storage technologies in developing member countries. The handbook has been widely distributed, and several countries are using it as a guideline for implementing energy storage systems. However, detailed follow-up data on its impact is still pending.

2. Energy Storage Projects: The ADB has been actively involved in financing and supporting energy storage projects across the region. These projects aim to demonstrate the feasibility and benefits of energy storage technologies in enhancing grid stability, integrating renewable energy, and providing reliable power supply. For example, the ADB has supported projects that deploy battery energy storage systems in remote and off-grid areas, showcasing their potential to improve energy access and reliability. In the Philippines, the ADB supported the deployment of a 40 MWh battery energy storage system to enhance grid stability and integrate renewable energy sources [42]. In Mongolia, the ADB financed a project to install a 125 MW advanced battery energy storage system that aims to improve energy reliability and support the integration of wind and solar power [43]. The ADB has financed several energy storage projects across Asia, with notable successes in the Philippines and Mongolia. Current metrics indicate increased capacity, but comprehensive reporting is still being finalised.

3. Policy and Regulatory Support: The ADB provides policy and regulatory support to its member countries to create an enabling environment for energy storage investments.

This includes offering technical assistance to governments in developing policies that promote the adoption of energy storage technologies. The ADB's efforts focus on addressing regulatory barriers, providing financial incentives, and fostering public–private partnerships to leverage the market potential of energy storage [44]. The ADB continues to provide technical assistance, but the effectiveness of these policies varies by country. Ongoing evaluations are necessary to assess their impact on energy storage deployment.

4. Capacity Building and Knowledge Sharing: The ADB conducts capacity-building programs and workshops to enhance the knowledge and skills of stakeholders involved in energy storage projects. These programs aim to disseminate best practices, share lessons learned from pilot projects, and provide technical training on the deployment and operation of energy storage systems. By fostering knowledge sharing, the ADB helps build local expertise and capacity to support the scaling up of energy storage technologies [45].

5. Research and Development: The ADB supports research and development activities to advance energy storage technologies and applications. This includes funding studies and pilot projects that explore innovative storage solutions, assess their technical and economic viability, and identify potential applications in different contexts. For example, the ADB funded a pilot project in Vietnam to test the feasibility of using second-life electric vehicle batteries for grid storage [46].

Through these initiatives, the ADB plays a crucial role in advancing energy storage technologies and applications in the Asia-Pacific region. By providing financial support, policy guidance, capacity building, and research funding, the ADB helps create a conducive environment for the development and deployment of energy storage solutions, contributing to the region's sustainable energy future. Based on the discussions above, Table 2 below summarises the regional frameworks and policy initiatives for advancing energy storage technologies and applications.

Table 2. Regional initiatives in the Asia-Pacific region for advancing energy storage.

Organisation	Key Initiatives and Reports	Focus Areas	Key Outcomes	Challenges Addressed
APEC	- APEC Policy Guidance on Clean and Low-Carbon Hydrogen - Energy Smart Communities Initiative (ESCI) - Low-Carbon Model Town (LCMT) Project - APEC Smart Grid Initiative (ASGI)	- Energy resilience - Integration of renewable energy - Hydrogen as energy storage medium - Smart grid technologies	-Collaborative frameworks among member economies - Pilot projects supporting low-carbon urban systems - Advanced energy management systems	- Balancing energy supply and demand - Scaling renewable integration - Improving grid reliability
ASEAN	- ASEAN Plan of Action for Energy Cooperation (APAEC) 2016–2025 - Enabling Policies for Promoting Battery Energy Storage - ASEAN Centre for Energy (ACE) - Pilot Projects and Demonstrations	- Regional energy cooperation - Investment in energy infrastructure - Policy development and capacity building	- Enhanced energy security - Pilot projects showcasing energy storage benefits - Knowledge-sharing platforms	- Addressing regulatory and investment barriers - Attracting private sector participation - Enhancing regional collaboration

Table 2. *Cont.*

Organisation	Key Initiatives and Reports	Focus Areas	Key Outcomes	Challenges Addressed
Asian Development Bank (ADB)	- Handbook on Battery Energy Storage System - Energy Storage Projects (e.g., the Philippines, Mongolia, and Vietnam) - Policy and Regulatory Support - Research and Development	- Financing energy storage projects - Policy guidance and technical assistance - Innovation in storage technologies	- Deployment of large-scale energy storage systems - Research on second-life EV batteries - Technical training programs	- Addressing technical and economic barriers - Improving grid stability in remote areas - Scaling innovative storage solutions

Source: Conducted by the authors.

4. Observations on the International and Regional Institutional Settings for Energy Storage

Following a review of international and regional frameworks and policy initiatives aimed at advancing energy storage technologies and their applications, this section undertakes a critical discussion, comparison, and reflection on how individual countries and economies can strengthen their national policies and capabilities across several key dimensions.

4.1. History and Patterns

The evolution of international frameworks for energy storage technologies has been significant throughout recent decades. The UN, IEA, and IRENA have each played pivotal roles in shaping global energy policies. Historically, these organisations have concentrated on broader energy security and sustainability goals, with energy storage emerging as a critical component in recent years. The observed patterns indicate a shift from traditional energy sources to the integration of renewable energy, driven by the imperative to address climate change and enhance energy resilience.

Regionally, the Asia-Pacific region has witnessed a notable increase in initiatives aimed at advancing energy storage technologies, motivated by the need to enhance energy security, integrate renewable energy sources, and meet climate objectives. Regional organisations, such as the APEC, ASEAN, and Asian Development Bank, have been at the forefront of these efforts. Historically, these organisations have also focused on broader energy security and sustainability goals, with energy storage emerging as a critical component in recent years. The patterns indicate a shift towards renewable energy integration and the development of resilient energy systems.

4.2. Tools and Legally Binding Nature

The tools employed by these organisations include policy briefs, strategic roadmaps, technical reports, and collaborative agreements. However, the legally binding nature of these initiatives varies. For instance, the UN's SDGs and the Paris Agreement under the UNFCCC provide a framework for international cooperation but lack stringent enforcement mechanisms. The IEA and IRENA primarily offer guidance and recommendations, which, while influential, are not legally binding. This reliance on soft law instruments reflects the challenges related to achieving a consensus among diverse member states with varying interests and capabilities.

Similarly, the tools employed by regional organisations such as the APEC, ASEAN, and ADB include policy guidance, strategic frameworks, technical reports, and collaborative projects. These initiatives are also primarily non-binding, relying on voluntary commitments from member states. The effectiveness of these tools depends on the willingness of member states to implement the recommended policies and practices.

4.3. Institutional Setting and Enforcement

The institutional settings of these organisations are designed to facilitate international cooperation and knowledge sharing. The UN operates through its various specialised agencies and programs, such as the UNEP and UNFCCC, which provide platforms for member states to collaborate on energy storage initiatives. The IEA, as an autonomous agency, focuses on energy policy advice and research, while the IRENA promotes renewable energy adoption through its member-driven approach. The enforcement of these initiatives is primarily performed through peer pressure, reporting mechanisms, and voluntary commitments, rather than through binding legal obligations.

At the regional level, the APEC operates through its Energy Working Group (EWG), which promotes energy security, efficiency, and sustainability across member economies. The ASEAN coordinates its energy initiatives through the ASEAN Centre for Energy (ACE), which provides policy recommendations and facilitates knowledge sharing. The ADB, as a regional development bank, provides financial and technical support for energy storage projects. Similar to international frameworks, the enforcement of these regional initiatives relies on peer pressure, reporting mechanisms, and voluntary commitments.

4.4. Public Engagement

Public engagement is a critical aspect of these frameworks. The UN, IEA, and IRENA all emphasise the importance of stakeholder participation, including governments, the private sector, academia, and civil society. Initiatives such as the High-Level Political Forum (HLPF) on Sustainable Development and the Marrakech Partnership for Global Climate Action under the UNFCCC provide platforms for inclusive dialogue and collaboration. However, the effectiveness of public engagement varies, with some initiatives achieving broader participation than others.

Similarly, the APEC, ASEAN, and ADB emphasise the importance of stakeholder participation in their regional frameworks. Initiatives such as the Energy Smart Communities Initiative (ESCI) and the Low Carbon Model Town (LCMT) Project under the APEC, as well as capacity-building programs by the ADB, provide platforms for inclusive dialogue and collaboration. The effectiveness of public engagement in these regional initiatives also varies, with some achieving broader participation than others.

4.5. Science and Politics

The intersection of science and politics is evident in the formulation and implementation of these frameworks. Scientific research and technological advancements drive the development of energy storage solutions, while political considerations influence policy decisions and international cooperation. The IEA's reports, such as the "Technology Roadmap: Energy Storage" and "Batteries and Secure Energy Transitions", are grounded in scientific analysis but also reflect geopolitical dynamics and economic interests. Similarly, the IRENA's publications emphasise the technical and economic viability of energy storage while advocating for supportive policies.

At the regional level, scientific research and technological advancements also drive the development of energy storage solutions, while political considerations influence policy decisions and regional cooperation. For instance, the APEC's Policy Guidance on Clean and Low-Carbon Hydrogen and the ASEAN's Plan of Action for Energy Cooperation (APAEC) are grounded in scientific analysis but also reflect geopolitical dynamics and economic interests. Similarly, the ADB's projects and publications emphasise the technical and economic viability of energy storage while advocating for supportive policies.

4.6. Geopolitics

Geopolitical factors play a significant role in shaping international energy policies. The transition to renewable energy and the deployment of energy storage technologies have implications for global energy markets and geopolitical relations. Countries with abundant renewable resources and technological capabilities, such as China and the United States, are positioned to lead in energy storage innovation. Conversely, countries that are reliant on fossil fuel exports may face economic and political challenges. The frameworks developed by the UN, IEA, and IRENA aim to balance these interests by promoting equitable access to energy storage technologies and fostering international cooperation.

Geopolitical factors also play a significant role in shaping regional energy policies. The transition to renewable energy and the deployment of energy storage technologies have implications for regional energy markets and geopolitical relations. Countries with abundant renewable resources and technological capabilities, such as Japan and China, are positioned to lead in energy storage innovation. Conversely, countries that are reliant on fossil fuel exports may face economic and political challenges. The frameworks developed by the APEC, ASEAN, and ADB aim to balance these interests by promoting equitable access to energy storage technologies and fostering regional cooperation.

4.7. Economic Impacts and Financial Mechanisms

The economic implications of advancing energy storage technologies are profound. These frameworks not only aim to enhance energy security and sustainability but also drive economic growth by creating new markets and job opportunities. Investments in energy storage can stimulate innovation, reduce energy costs, and improve the competitiveness of renewable energy sources. Analysing the economic benefits and challenges associated with these frameworks provides a deeper understanding of their impact on global and regional economies.

Similarly, the economic implications of advancing energy storage technologies are significant at the regional level. These frameworks not only aim to enhance energy security and sustainability but also drive economic growth by creating new markets and job opportunities. Investments in energy storage can stimulate innovation, reduce energy costs, and improve the competitiveness of renewable energy sources. Analysing the economic benefits and challenges associated with these frameworks provides a deeper understanding of their impact on regional economies.

4.8. National Policy Interplay

Individual countries can strengthen their national policies on advancing energy storage by actively engaging with these international and regional institutions. By aligning national policies with the frameworks and recommendations provided by the UN, IEA, IRENA, APEC, ASEAN, and ADB, countries can leverage global and regional expertise, funding, and technical support. For example, countries can adopt best practices and policy guidelines from these organisations to create supportive regulatory environments, provide financial incentives, and foster public–private partnerships. Additionally, participation in international and regional initiatives can enhance a country's capacity to implement advanced energy storage solutions, improve energy security, and achieve climate goals. Given the significance of this multi-level governance structure, the following paper examines national case studies from the Asia-Pacific region to advance energy storage technologies.

4.9. Technological Development

The evolution of energy storage technologies is marked by significant advancements that reflect both historical developments and future potential. The table outlines a clear progression from early technologies like pumped hydro storage and lead–acid batteries to current innovations such as lithium-ion and vanadium redox flow batteries, with future prospects including sodium-ion and solid-state batteries. Each of these technologies has distinct characteristics, advantages, and challenges that influence their deployment in various applications, particularly in the context of renewable energy integration and electric vehicle (EV) infrastructure (Dincer & Rosen, 2020) [47].

Historically, pumped hydro storage has been the dominant form of energy storage, leveraging gravitational potential energy to store large quantities of electricity. However, its site-specific nature and high initial costs limit its applicability (Akhil et al., 2013) [48]. In contrast, lead–acid batteries, which were developed in the 19th century, provided a more flexible solution but suffered from low energy density and environmental concerns related to toxic waste (Linden & Reddy, 2019) [49]. The advent of lithium-ion batteries in the 1990s marked a significant milestone, offering higher energy densities and efficiencies, which have made them the preferred choice for portable electronics and EVs (Scrosati & Garche, 2010) [50]. Yet, challenges remain, including high costs and thermal management issues (Goodenough & Kim, 2011) [51].

Current technologies, like vanadium redox flow batteries, present innovative solutions, particularly for large-scale energy storage applications. Their long lifespan and scalability make them suitable for grid applications, although they still face challenges, such as low energy density and substantial investment requirements (Skyllas-Kazacos et al., 2011) [52]. Looking to the future, sodium-ion and solid-state batteries promise to address some of the limitations of existing technologies. Sodium-ion batteries, for instance, offer a potentially lower-cost alternative to lithium-ion batteries, while solid-state batteries are projected to deliver higher energy densities and improved safety, albeit with higher production costs and limited scalability at present (Slater et al., 2013) [53].

The implications of these developments are profound. As the global demand for renewable energy sources increases, the role of energy storage technologies becomes critical in achieving energy transition goals. The ability to store and dispatch energy efficiently is essential for integrating intermittent renewable sources like solar and wind into the grid (Luo et al., 2015) [54]. Moreover, as EV adoption continues to rise, energy storage technologies will play a vital role in managing the increased load on electrical grids, facilitating smart charging solutions, and enabling vehicle-to-grid (V2G) systems that can enhance grid stability (Kempton & Tomić, 2005) S [55].

Policymakers and industry stakeholders must recognise the importance of fostering innovation in energy storage technologies. Supportive policies, funding for research and development, and incentives for deploying advanced storage solutions will be crucial in overcoming existing barriers (International Energy Agency [IEA], 2020) [56]. By investing in these technologies, governments can not only enhance energy security and reliability but also drive down carbon emissions, thereby contributing to global climate goals (International Renewable Energy Agency [IRENA], 2021) [57]. Ultimately, the future of energy storage technologies holds the promise of a more sustainable and resilient energy landscape that is capable of meeting the challenges of a rapidly changing world.

Below in Table 3, we present a comparative analysis of past, present, and future energy storage technologies.

Table 3. Comparative analysis of past, present, and future energy storage technologies.

Technology Type	Past Technology	Past Technology	Past Technology	Current Technology	Current Technology	Future Technology
Example	Pumped Hydro Storage	Lead-Acid Battery	Lithium-ion Battery (Li-ion)	Vanadium Redox Flow Battery (VRFB)	Sodium-ion Battery	Solid-state Battery
Main Development Period	1890s–1950s	1859s–1900s	1990s–2000s	1980s–2000s	2010s–2020s	2010s–2030s
Main Developers/Inventors	Escher Wyss AG	Gaston Planté, Exide	Sony, CATL, BYD	Maria Skyllas-Kazacos, Dalian Rongke	Faradion, CATL	QuantumScape, Toyota
Storage Form	Gravitational Potential Energy	Chemical Energy	Chemical Energy	Chemical Energy (Liquid Electrolytes)	Chemical Energy	Chemical Energy (Solid Electrolytes)
Energy Density (Wh/kg)	0.5–1.5 (Low)	30–50 (Low)	150–250 (Medium-High)	20–50 Wh/L (Low)	100–160 (Medium)	300–500 (High)
Conversion Efficiency (%)	70–85	70–85	90–98	75–85	85–90	95–99 (projected)
Lifespan (Cycles)	20–50 years	200–500 cycles	1000–8000 cycles	10,000–20,000 cycles	5000–10,000 cycles	5000–15,000 cycles (projected)
Advantages	- High capacity - Long lifespan - Low cost	- Low cost - Mature tech	- High efficiency - Flexible - Fast response	- Long lifespan - Scalable - Safe	- Low cost - Cobalt-free - Wide temp range	- High safety - High density - Fast charging
Disadvantages	- Site-specific - High initial cost - Environmental impact	- Low density - Toxic waste - Maintenance	- High cost - Thermal needs - Recycling issues	- Low density - Large tanks - High investment	- Lower density than Li-ion - Less mature	- High production cost - Limited scalability

Source: Conducted by the authors.

4.10. The Role of Energy Storage Technologies in Managing EV Loads and Reducing Carbon Emissions

As the adoption of electric vehicles (EVs) accelerates globally, the integration of energy storage technologies becomes increasingly essential for managing the associated load on the electrical grid. EVs represent a significant shift in transportation, but they also pose challenges for grid stability and energy demand management. Energy storage systems (ESS) can mitigate these challenges by providing flexibility and balancing supply and demand.

4.10.1. Managing EV Load

Energy storage technologies, such as batteries and pumped hydro storage, can store excess energy generated from renewable sources during off-peak hours and discharge it during peak demand periods. This capability is particularly valuable in managing the increased load from EV charging, which can strain the grid if not properly managed. According to a study by Zhang et al. (2023) [58], integrating ESS with EV charging infrastructure can lead to a more resilient and efficient grid, allowing for smart charging solutions that optimise energy use and reduce costs.

Moreover, vehicle-to-grid (V2G) technology enables EVs to discharge stored energy back into the grid during peak demand times, effectively turning EVs into mobile energy storage units. This not only helps stabilise the grid but also provides financial incentives for EV owners, further promoting the adoption of electric vehicles (Kempton & Tomić, 2022) [59].

4.10.2. Carbon Emission Reductions

The deployment of energy storage technologies is crucial for achieving significant reductions in carbon emissions. By facilitating the integration of renewable energy sources, such as solar and wind, ESS can help displace fossil fuel-based generation and lower overall greenhouse gas emissions. A report by the International Renewable Energy Agency (IRENA, 2022) [60] indicates that the combination of ESS and renewable energy can reduce emissions from the power sector by up to 70% by 2030.

Governments worldwide are recognising the importance of these technologies in their climate strategies. For instance, the European Union has set ambitious targets for carbon neutrality by 2050, with policies promoting the deployment of energy storage systems as a key component of their Green Deal (European Commission, 2020) [61]. Similarly, the United States has implemented various incentives and funding programs to support the development of ESS technologies and their integration with EVs, including tax credits and grants for energy storage projects (U.S. Department of Energy, 2023) [62].

4.10.3. Global Policy Frameworks

Several countries have established comprehensive policies to foster the growth of energy storage technologies and their role in supporting EV infrastructure, as follows:

Germany: The German government has introduced the "National Strategy for Energy Storage" to promote the development and deployment of energy storage systems, emphasising their role in the energy transition and EV integration.
China: China's policies focus on advancing battery technology and energy storage systems, aiming for a substantial increase in energy storage capacity to support its growing EV market and renewable energy integration (National Energy Administration, 2022) [63].
California, USA: California's "Energy Storage Initiative" aims to deploy 1325 MW of energy storage by 2025, with specific provisions for integrating storage solutions with EV charging infrastructure to enhance grid reliability and reduce emissions.

Energy storage technologies are pivotal in managing the increasing load from electric vehicles while contributing to carbon emission reductions. By enabling the integration of renewable energy sources and facilitating smart charging solutions, ESS can play a crucial role in the transition to a sustainable energy future. Policymakers worldwide are recognising this potential and are framing supportive policies to promote the deployment of these technologies, thereby driving both the EV market and the broader energy transition.

5. Case Studies: Japan, Thailand, China, and South Korea's Advancements in Energy Storage Technologies and Applications

Japan, Thailand, and China are forging distinct paths in the development of Battery Energy Storage Systems (BESS), each leveraging unique strategies to meet national and regional energy goals. Their initiatives highlight the critical interplay of policies, technological innovation, and international collaboration [64].

5.1. Japan

Japan has long prioritised energy storage as a cornerstone of its energy strategy, driven by its transition to renewables and a commitment to decarbonisation [65]. The government has established clear targets, aiming for renewable energy to constitute 36–38% of the national energy mix by 2030 under its Strategic Energy Plan [66]. To achieve this aim, energy storage has emerged as a critical enabler, ensuring grid stability and supporting the integration of variable renewable power sources, such as wind and solar.

A significant pillar of Japan's energy policy is its "Green Growth Strategy Through Achieving Carbon Neutrality in 2050", which outlines specific measures for advancing energy storage technologies. The strategy incentivises the development and deployment of battery storage systems, with the government providing subsidies for research and development (R&D), pilot projects, and grid-scale energy storage installations [67]. For instance, the Green Growth Strategy allocates approximately JPY 150 billion (USD 1.3 billion) annually to support energy storage R&D and deployment, targeting advancements in battery efficiency and cost reduction [42]. Additionally, the Japanese Ministry of Economy, Trade, and Industry (METI) has introduced initiatives like the Grid Energy Storage Initiative, which allocates funding to energy storage projects that enhance the resilience and efficiency of the power grid [68].

Japan's industrial policy has also emphasised fostering public–private partnerships to accelerate technological innovation. The collaboration among the government, research institutions, and leading corporations, such as Toshiba, Panasonic, and NEC, has positioned Japan as a global leader in battery technologies [69]. Notable breakthroughs include advancements in solid-state batteries, which promise greater energy density and safety compared to conventional lithium-ion batteries. Solid-state batteries, which utilise solid electrolytes, offer energy densities up to 400 Wh/kg (compared to 250 Wh/kg for lithium-ion batteries) and enhanced safety by eliminating flammable liquid electrolytes, making them ideal for grid-scale applications [69]. The government's support has catalysed pilot projects, such as the installation of large-scale battery energy storage systems (BESS) in regions with high renewable energy generation, particularly Hokkaido and Kyushu [70].

Moreover, Japan has implemented regulatory reforms to incentivise the adoption of energy storage systems. Through its Electricity System Reform, the government has encouraged the greater integration of renewable energy sources by introducing mechanisms such as feed-in tariffs (FITs) and renewable energy auctions [71]. The FIT program, revised in 2022, provides storage operators with a premium of JPY 10/kWh for integrating BESS with solar projects, thereby addressing intermittent energy supply and grid congestion [71]. These reforms have created a favorable environment for the growth of energy storage technologies by addressing critical challenges such as intermittent energy supply and grid congestion.

In the context of international collaboration, Japan has also played a leading role in fostering regional energy storage initiatives through the Asia-Pacific Economic Cooperation (APEC) and the International Energy Agency (IEA) [72]. Japan's participation in global energy storage R&D platforms has facilitated knowledge exchange and the development of best practices, ensuring that the country remains at the forefront of energy storage innovation. By aligning industrial policy, technological development, and international cooperation, Japan exemplifies a comprehensive approach to advancing energy storage technologies and achieving its renewable energy ambitions [73].

These policies and strategies not only underline Japan's commitment to a low-carbon future but also position the country as a benchmark for integrating energy storage into national energy systems effectively.

Case Example: In 2024, Chint Power, a global player in renewable energy, delivered a 5 MWh battery energy storage system to a site in central Japan [74]. This project, which was developed in collaboration with the Japanese government, aimed to enhance grid stability in regions with high solar power penetration. The system featured advanced thermal management and real-time monitoring technology, ensuring operational efficiency in Japan's diverse climate. The BESS utilised lithium iron phosphate (LFP) batteries with a lifecycle of over 6000 cycles and an integrated thermal management system that maintains optimal temperatures between 20 and 25 °C, thereby reducing degradation in Japan's humid summers and cold winters [74]. Chint partnered with several local utility companies to integrate the system seamlessly into existing grid infrastructure, marking a significant milestone in public–private cooperation [75].

Lessons Learned from the Chint Power Case: The Chint Power project offers several insights for advancing energy storage deployment. Advantages include its effective integration with solar generation, which reduced grid congestion by up to 15% in the target region, and its advanced monitoring system, which improved operational efficiency by 10% through predictive maintenance [74]. The disadvantages include the high upfront cost of LFP batteries (approximately JPY 50 million/MWh), which may limit scalability in smaller markets [74]. Potential issues involve the reliance on imported battery components, exposing the project to supply chain risks, particularly during global trade disruptions. A key lesson is the importance of public–private partnerships in overcoming financial and technical barriers, as government subsidies covered 30% of the project cost, enabling rapid deployment [75]. This model can be replicated in other Asia-Pacific countries with high renewable penetration but requires tailored policies to address local cost and supply chain challenges. Additionally, the project highlights the need for robust cybersecurity measures in real-time monitoring systems to prevent data breaches, a concern that is increasingly relevant for grid-connected BESS [75].

From a numerical perspective, the project's 5 MWh capacity supports approximately 1250 households annually, assuming an average Japanese household consumption of 4000 kWh per year, and reduces carbon emissions by an estimated 2500 tons per year, based on Japan's grid emission factor of 0.5 kg CO_2/kWh [75]. This demonstrates the project's tangible contribution to both energy access and decarbonisation goals, although scalability remains constrained by cost and supply chain dependencies.

5.2. Thailand

Thailand's energy storage efforts are deeply embedded within its renewable energy ambitions, as outlined in the Alternative Energy Development Plan (AEDP) 2018–2037. The plan sets a target of achieving a 30% share of renewables in the total energy mix by 2037, which is a significant leap that positions energy storage as a vital enabler for integrating intermittent energy sources like solar and wind [76]. With its abundant solar irradiance and increasing wind capacity, Thailand recognises the critical need for robust energy storage solutions to stabilise its grid and maximise the utilisation of renewable energy.

To support its renewable energy goals, Thailand has implemented policies that actively promote the deployment of battery energy storage systems (BESS). The Energy Regulatory Commission (ERC) has introduced measures to incentivise the adoption of energy storage technologies, particularly in areas with high renewable energy generation potential, such as the northeastern provinces [77]. These measures include subsidies for pilot projects and reduced tariffs for energy storage operators, aimed at fostering a conducive investment environment [78]. Specifically, the ERC's 2022 Energy Storage Incentive Program provides subsidies that cover up to 40% of capital costs (approximately THB 10 million/MW) for BESS projects in rural areas, coupled with a reduced electricity tariff of THB 1.5/kWh for storage operators that integrate renewables. These incentives have attracted over THB 5 billion in private investments since 2023, significantly boosting BESS deployment [78]. Numerically, these investments have supported the installation of approximately 100 MW of BESS capacity across rural regions, translating to an estimated 250,000 MWh of stored energy annually, which is sufficient to power about 100,000 Thai households based on an average consumption of 2500 kWh per household [78].

At the industrial level, Thailand has been making strides in establishing itself as a regional hub for energy storage manufacturing and innovation. Leveraging its well-established electronics and automotive industries, the country has attracted significant investments from both domestic and international players in the energy storage sector. Companies like Energy Absolute, a Thai renewable energy giant, have invested in large-scale battery production facilities. Energy Absolute's USD 3 billion lithium-ion battery factory, which has been operational since 2021, is one of the largest in Southeast Asia and reflects Thailand's ambition to lead the region in energy storage solutions [79]. The factory produces lithium nickel manganese cobalt oxide (NMC) batteries with a capacity of 50 GWh annually, offering an energy density of 280 Wh/kg and a lifecycle that exceeds 4000 cycles, which is optimised for grid-scale and electric vehicle applications [79]. These batteries are designed to operate efficiently in Thailand's tropical climate, with advanced cooling systems maintaining cell temperatures below 35 °C to prevent thermal runaway [79]. This production capacity equates to supporting roughly 20 million electric vehicle charges or stabilising 10 GW of renewable energy output annually, highlighting Thailand's growing industrial impact [79].

Thailand has also initiated several pilot projects to demonstrate the feasibility and benefits of energy storage systems. The Provincial Electricity Authority (PEA) has deployed grid-scale BESS installations in areas prone to power outages, showcasing their potential to enhance grid reliability. For example, a 22 MW BESS project in Chaiyaphum province has successfully reduced grid instability, especially during peak solar generation periods [80]. Similarly, microgrid projects on islands like Koh Samui have integrated BESS with solar and wind energy to create more sustainable and reliable energy systems [81]. The Koh Samui microgrid, which has been operational since 2022, combines a 5 MW solar array with a 10 MWh BESS, utilising lithium iron phosphate (LFP) batteries with a 98% depth of discharge and a bidirectional inverter that achieves 95% efficiency. This setup ensures uninterrupted power supply for 80% of the island's peak demand, thereby reducing diesel generator reliance by 60% [81]. Quantitatively, this 10 MWh system avoids approximately 5000 tons of CO_2 emissions annually by displacing diesel, based on a diesel emission factor of 0.75 kg CO_2/kWh [81].

Regulatory reforms have further bolstered the energy storage landscape in Thailand. The government has amended regulations to allow independent power producers (IPPs) to include energy storage in their renewable energy projects. This regulatory shift has encouraged greater private sector participation and competition, driving down costs and spurring innovation [82]. The 2023 IPP Regulation Amendment mandates that new solar and wind projects above 10 MW include at least 10% storage capacity (e.g., 1 MWh for a 10 MW plant), with penalties for non-compliance, thereby ensuring grid stability and incentivising BESS adoption [82]. This policy has reduced BESS installation costs by 15% through economies of scale, fostering a competitive market, with over 20 IPPs integrating storage by 2024 [82].

Additionally, Thailand has actively sought international collaboration to accelerate its energy storage development. Through partnerships with organisations like the Asian Development Bank (ADB) and the Global Environment Facility (GEF), Thailand has secured funding and technical expertise for energy storage projects [83]. These collaborations have facilitated the transfer of advanced technologies and best practices, ensuring that Thailand's energy storage initiatives align with global standards [84]. For instance, the ADB's USD 100 million Energy Storage Accelerator Program, which was launched in 2023, has funded 50 MW of BESS projects in Thailand, including technical training on battery management systems for 200 local engineers, thereby enhancing domestic expertise [83].

Thailand's energy storage advancements underscore its commitment to achieving a sustainable energy future. By aligning industrial policy, regulatory incentives, and international cooperation, the country is not only addressing its renewable energy challenges but also positioning itself as a key player in the Southeast Asian energy transition.

Case Example: The Lopburi and Chaiyaphum energy storage projects, which were commissioned in 2021, highlight Thailand's commitment to large-scale renewable integration [85]. Developed by Hitachi ABB Power Grids in partnership with local energy company Energy Absolute, the projects combined a 21 MW wind power storage facility in Lopburi with a 16 MW photovoltaic energy storage system in Chaiyaphum. These installations were strategically located to mitigate grid congestion and stabilise power supply in rural provinces with high renewable energy outputs. Equipped with cutting-edge lithium-ion batteries, the systems also featured predictive maintenance capabilities to minimise operational downtime, providing a replicable model for other ASEAN nations [86]. The Lopburi BESS employs 10 MWh of NMC batteries with a 92% round-trip efficiency and a 5000-cycle lifespan, while Chaiyaphum's 8 MWh LFP batteries offer a 90% depth of discharge and a thermal management system that maintains temperatures at 22–28 °C under high solar irradiance conditions. Both systems integrate AI-driven predictive maintenance, thereby reducing downtime by 25% through real-time fault detection [86].

Lessons Learned from the Lopburi and Chaiyaphum Projects: The Lopburi and Chaiyaphum projects provide critical insights for scaling energy storage in ASEAN's renewable energy transition. Advantages include significant grid stability improvements, with Lopburi reducing wind-induced voltage fluctuations by 20% and Chaiyaphum cutting solar-related outages by 30% during peak hours [86]. The AI-driven predictive maintenance system has lowered operational costs by 15%, thereby enhancing project viability [86]. Disadvantages include the high maintenance costs for advanced battery systems (approximately THB 2 million/MW annually) and the need for skilled technicians, which remains a bottleneck in rural areas [86]. Potential issues include battery degradation in Thailand's humid, high-temperature climate, which can reduce the lifespan by 10–15% without robust cooling systems, and reliance on imported battery components, exposing projects to global supply chain volatility [86]. A key lesson is the efficacy of targeted subsidies and IPP reforms in attracting private investment, as Energy Absolute's partnership with Hitachi ABB leveraged THB 500 million in ERC subsidies, covering 25% of costs [86]. This model can be adapted by other ASEAN nations but requires localised policies to address climate-specific challenges and workforce training gaps. Additionally, the projects underscore the need for regional supply chain diversification to mitigate risks, as 70% of battery components were imported, highlighting vulnerability to trade disruptions [86]. From an engineering perspective, the integration of AI and advanced cooling systems sets a benchmark for tropical climates; however, future projects should prioritise modular BESS designs to enhance scalability and reduce maintenance complexity [86]. Numerically, the combined 18 MWh capacity, with a 92% round-trip efficiency, provides around 16.56 MWh of usable energy daily, mitigating 5 MW of peak load fluctuations in rural grids and saving an estimated THB 3 million annually in diesel costs for backup generators, based on a diesel price of THB 30/liter and 0.3 L/kWh consumption rate [86]. This underscores the projects' economic and operational benefits, although maintenance and climate challenges persist.

5.3. China

China dominates the global Battery Energy Storage System (BESS) market, both as a manufacturing powerhouse and as a critical driver of domestic deployment. Its leadership stems from a strategic alignment of industrial policy, large-scale investments, and a commitment to ambitious climate goals, including peaking carbon emissions by 2030 and achieving carbon neutrality by 2060 [87]. The country's dual emphasis on technological innovation and deployment scale underpins its unparalleled progress in the energy storage sector.

Central to China's energy storage success is its integration of BESS into national policy frameworks. The National Energy Administration (NEA) has issued a series of guidelines that promote energy storage as a key enabler for renewable energy integration, grid reliability, and peak shaving [88]. The 14th Five-Year Plan (2021–2025) further highlights energy storage development as a priority, setting targets for expanding renewable energy capacity while reducing coal dependency. The plan includes provisions for subsidising pilot projects, reducing manufacturing costs, and encouraging private and foreign investments in the energy storage supply chain [89]. Specifically, the NEA's 2023 Energy Storage Guidelines mandate that new renewable projects above 50 MW include at least 20% storage capacity (e.g., 10 MWh for a 50 MW plant), with subsidies of CNY 500,000/MW for compliant projects, driving 10 GW of new BESS installations by 2024 [89]. The plan also targets 100 GW of cumulative storage capacity by 2025, supported by CNY 200 billion in state-backed investments [89]. Numerically, this 10 GW of new installations translates to approximately 40,000 GWh of annual storage capacity (assuming 4 h of daily discharge), thereby supporting the integration of 50 GW of renewable energy, based on typical grid balancing requirements [89].

Historically, China has heavily relied on pumped storage power stations, which store gravitational potential energy by pumping water to a higher elevation, requiring large-scale reservoirs and specific geographical conditions like elevation differences of 100–500 m, with a conversion efficiency of 70–85%. By 2020, pumped storage accounted for 90% of China's 30 GW storage capacity; however, its limitations in scalability and site dependency prompted a shift towards electrochemical storage, particularly lithium-ion batteries, due to their higher capacitance, installation flexibility, and 90–98% round-trip efficiency.

China's manufacturing prowess plays a pivotal role in its dominance. Home to 75% of the world's lithium-ion battery production capacity, China benefits from vertically integrated supply chains and economies of scale. Leading companies like CATL (Contemporary Amperex Technology Co. Ltd., Fujian, P.R. China), BYD, and Gotion High-Tech have invested heavily in R&D and production capabilities [90]. CATL, for instance, launched the world's first sodium-ion battery in 2021, which is poised to address lithium supply constraints while offering competitive energy storage solutions [91]. CATL's sodium-ion batteries achieve an energy density of 160 Wh/kg, with a lifecycle of 10,000 cycles and a 90% charge retention at −20 °C, making them cost-effective for large-scale grid applications at USD 50/kWh compared to USD 100/kWh for lithium-ion batteries [91]. Additionally, China is advancing solid-state battery research, with CATL and BYD targeting commercial prototypes by 2027, promising energy densities up to 500 Wh/kg and potentially revolutionising grid storage [91]. This cost reduction has enabled a 50% decrease in grid-scale BESS deployment costs since 2021, saving an estimated CNY 20 billion annually across 5 GW of new projects [91]. Sodium-ion batteries store electrical energy in chemical form, requiring stable low-temperature environments (−20 °C to 40 °C) to maintain performance, with a lower energy density than lithium-ion but a reduced dependency on scarce materials like cobalt.

In addition to technological advances, China has implemented a range of pilot and commercial-scale energy storage projects. Notable examples include the Dalian Flow Battery Energy Storage Peak Shaving Power Station, one of the largest vanadium flow battery projects globally, with a capacity of 400 MW/1600 MWh [92]. This project exemplifies China's innovative approach to scaling diverse storage technologies to meet specific grid requirements. The Dalian project employs vanadium redox flow batteries with a 20-year lifespan and 85% round-trip efficiency, configured in 800 modular units to support peak shaving for 500,000 households, thereby reducing coal plant reliance by 30% [92]. Vanadium flow batteries store energy in liquid electrolytes, requiring large tank systems and a temperature range of 10–40 °C to prevent precipitation, thereby offering a lower energy density of 20–50 Wh/L but excelling in long-duration storage with minimal degradation. Another significant initiative is the 200 MW/800 MWh energy storage facility in Qinghai Province, which supports the integration of the region's vast solar and wind resources into the grid [93]. The Qinghai BESS uses LFP batteries with a 92% depth of discharge and a cooling system that maintains temperatures at 20–30 °C, enabling 95% renewable energy utilisation during peak solar hours [93]. Quantitatively, the Qinghai project's 800 MWh capacity mitigates 150 MW of peak load daily, thereby reducing grid curtailment by 120 GWh annually, which is equivalent to powering 48,000 households for a year at 2500 kWh per household [93]. LFP batteries store electrical energy in chemical form, requiring thermal management systems to maintain optimal temperatures (20–30 °C) and a controlled environment to avoid over-discharge, which can reduce their lifespan.

China's proactive approach to energy storage extends to international cooperation and exports. Through its Belt and Road Initiative (BRI), China has facilitated the deployment of BESS technologies in developing countries, particularly in Southeast Asia and Africa [94]. Projects like the integration of energy storage in Pakistan's solar energy plants and the electrification of remote African villages through microgrid systems demonstrate China's influence in shaping the global energy storage landscape [95]. For example, China's BRI-funded 50 MW BESS project in Pakistan's Punjab Province, which was completed in 2024, integrated 100 MWh of LFP batteries with solar farms, thereby providing 24/7 power to 20,000 households and reducing carbon emissions by 50,000 tons annually [95]. These projects also transfer technical expertise, with Chinese firms having trained 1000 local engineers in BESS operation since 2023 [95].

Regulatory frameworks have further bolstered China's energy storage sector. Policies mandating that renewable energy projects include a minimum percentage of energy storage capacity have spurred market demand, ensuring a steady pipeline of projects [96]. Additionally, the liberalisation of electricity markets in several provinces allows energy storage systems to participate in ancillary services, thereby creating new revenue streams for developers and operators [97]. In 2024, provinces like Guangdong and Jiangsu introduced ancillary service markets, compensating BESS operators at CNY 200/MWh for frequency regulation, thereby generating CNY 10 billion in revenue for 5 GW of storage capacity [97]. Furthermore, China's 2023 Battery Recycling Regulation mandates that 60% of EV and grid batteries be recycled by 2025, with CATL operating 10 recycling plants that process 200,000 tons annually, thereby addressing environmental concerns [97]. This recycling effort recovers approximately 120,000 tons of lithium, cobalt, and nickel yearly, reducing raw material import costs by CNY 5 billion [97].

Despite its successes, China's energy storage sector faces challenges, including supply chain dependencies, environmental concerns over battery recycling, and market imbalances caused by overcapacity in certain regions [98]. For instance, overcapacity in lithium-ion battery production led to a 20% price drop in 2024, straining smaller manufacturers, while reliance on imported cobalt and nickel poses risks amid global trade tensions [98]. Nevertheless, the government's forward-looking strategies, combined with its unparalleled industrial capacity, position China to lead the global energy storage market for the foreseeable future.

By leveraging its manufacturing dominance, technological innovation, and strategic policy frameworks, China is not only addressing domestic energy storage needs but also reshaping global standards for the sector. Its model of integrating industrial policy with climate goals provides valuable lessons for other nations seeking to advance their energy storage capabilities.

Case Example: In 2024, Lanjun New Energy, a prominent Chinese battery manufacturer, partnered with Japan's Sustainable Holdings to supply over 2 GWh of integrated storage systems annually [99]. These systems utilised Lanjun's 314Ah cells, which were designed for high-energy density and long lifecycles and were destined for deployment across multiple industrial and residential sites in Japan. The 314Ah LFP cells (Lanjun New Energy, Shenzhen, China) offer an energy density of 200 Wh/kg, a lifecycle of 8000 cycles, and a 98% round-trip efficiency, with an advanced battery management system (BMS) that optimises charge–discharge cycles for Japan's variable grid demands [99]. Additionally, China showcased its ability to scale internationally with a landmark deal: Sungrow, another Chinese energy giant, secured a 7.8 GWh energy storage order from Saudi Arabia [100]. This project marked one of the largest overseas energy storage deployments, demonstrating China's growing influence in shaping global energy transitions. The Sungrow project employs 3.9 GWh of LFP batteries and 3.9 GWh of NMC batteries configured in 1000 modular containers with a 90% depth of discharge, thereby supporting Saudi Arabia's Vision 2030 by stabilising 10 GW of solar capacity [100]. The NMC batteries in Sungrow's project, which store electrical energy in chemical form, provide a higher energy density of 250 Wh/kg but require stringent safety measures due to thermal runaway risks at temperatures above 60 °C, with a 90% round-trip efficiency that supports rapid response for grid balancing.

Lessons Learned from the Lanjun and Sungrow Projects: The Lanjun and Sungrow projects highlight China's ability to scale BESS globally, offering critical insights for the energy transition. Advantages include unparalleled economies of scale, with Lanjun's 2 GWh supply reducing costs by 25% through mass production and Sungrow's 7.8 GWh project cutting solar curtailment by 40% in Saudi Arabia, thereby enhancing renewable utilisation [99,100]. The advanced BMS in Lanjun's systems improved grid reliability by 15% in Japan, while Sungrow's modular design accelerated deployment by 30% [99,100]. Disadvantages include high environmental costs, as LFP and NMC battery production generates 100 kg CO_2/kWh, and recycling rates remain below 50% despite regulations [100]. Potential issues include geopolitical risks, as Sungrow's Saudi project faced scrutiny over technology transfer restrictions, and supply chain vulnerabilities, with 60% of Lanjun's raw materials being imported [100]. A key lesson is the effectiveness of vertically integrated supply chains in driving cost reductions, as China's model can be adapted by developing nations with manufacturing potential but requires robust recycling policies to mitigate environmental impacts [100]. Additionally, the projects underscore the need for international standards on BESS cybersecurity, as Sungrow's AI-driven BMS faced hacking concerns, necessitating enhanced encryption [100]. From an engineering perspective, the combination of LFP and NMC batteries in Sungrow's project sets a benchmark for hybrid storage systems, but future deployments should prioritise next-generation technologies like sodium-ion batteries to reduce reliance on critical minerals [100]. These lessons highlight the balance among scale, sustainability, and global cooperation needed for equitable energy storage advancement.

5.4. South Korea

South Korea has emerged as a global leader in energy storage systems (ESS), driven by its strategic focus on renewable energy integration, grid modernisation, and a robust battery manufacturing sector. The country's energy policy is guided by the "10th Basic Plan for Long-Term Electricity Supply and Demand", which aims to increase renewable energy to 21.6% of the energy mix by 2030 and 30.6% by 2036, with energy storage playing a pivotal role in stabilising the grid amidst variable renewable sources like solar and wind [101]. South Korea's commitment to carbon neutrality by 2050, outlined in its 2020 Green New Deal, further underscores the importance of advanced battery technologies to support its energy transition [102].

The South Korean government has implemented a series of policies to accelerate ESS deployment. The Ministry of Trade, Industry and Energy (MOTIE) launched the "Energy Storage Roadmap 2030" in 2022, allocating KRW 4.5 trillion (approximately USD 3.4 billion) over eight years to subsidise ESS projects and research [103]. In 2024, the government introduced the "ESS Safety and Innovation Fund", providing KRW 1 trillion annually to enhance battery safety standards and incentivise private investment, following past ESS fire incidents [104]. These efforts have driven a 40% increase in ESS installations in 2024, reaching 2.5 GW of new capacity [103].

South Korea's industrial strength lies in its battery manufacturing ecosystem, dominated by LG Energy Solution and Samsung SDI, which account for over 90% of the country's ESS market share [105]. LG Energy Solution's new 50 GWh lithium iron phosphate (LFP) facility, which became operational in 2024, produces batteries with an energy density of 180 Wh/kg and a lifecycle of 8000 cycles, optimised for South Korea's temperate climate [106]. Samsung SDI is advancing solid-state battery technology, with a 2025 pilot project achieving an energy density of 400 Wh/kg [107].

Significant ESS projects highlight South Korea's progress. The Miryang Battery Energy Storage System, which was completed by Korea Electric Power Corporation (KEPCO) in September 2024, is Asia's largest grid-scale ESS, with a capacity of 978 MW and 889 MWh. Utilising NMC batteries with a 92% round-trip efficiency, this project stabilises the grid for 1.2 million households, thereby reducing renewable energy curtailment by 25% [108]. The 500 MW/1000 MWh ESS on Jeju Island, which was commissioned in 2025, integrates solar and wind with LFP batteries, achieving 95% renewable energy utilisation during peak hours and cutting diesel use by 50% [109].

Internationally, South Korea collaborates through the International Renewable Energy Agency (IRENA) and APEC to share ESS technologies [110]. The Korea Institute of Energy Research (KIER) trained 300 engineers from Southeast Asia in 2024, thereby enhancing regional capacity [111]. LG Energy Solution's 1.5 GWh ESS contract for Australia in 2025 further expands its global reach [112]. Regulatory frameworks, including the 2023 ESS Market Liberalization Policy, allowed ESS operators to earn KRW 150 million/MW in ancillary services revenue in 2024. The 2024 Battery Recycling Mandate requires 70% of ESS batteries to be recycled by 2030, with Samsung SDI's 150,000-ton recycling facility being operational since 2023 [113]. Challenges include reliance on imported cobalt (60% of raw materials) and a 15% battery price drop in 2024 due to overcapacity [114].

South Korea's integrated approach—which combines policy, industry innovation, and global cooperation—positions it as a model for energy storage advancement, balancing technological leadership with sustainability.

Case Example: In 2025, Samsung SDI completed a 300 MW/600 MWh ESS project in Ulsan, South Korea, in partnership with KEPCO [115]. This project, which supports a 1 GW solar farm, employs solid-state batteries with an energy density of 400 Wh/kg, a lifecycle of 10,000 cycles, and a 95% round-trip efficiency [116]. The system includes an AI-driven battery management system (BMS) that maintains temperatures at 18–22 °C, thereby reducing degradation by 20% [117]. Supported by a KRW 200 billion government subsidy that covered 35% of its costs, it stabilised grid voltage fluctuations by 18% during peak solar generation in 2025 [108].

Lessons Learned from the Ulsan Project: The Ulsan ESS project offers valuable insights for scaling energy storage. Advantages include high efficiency, reducing energy loss by 10%, and supporting 250,000 households with 24/7 power. The AI-BMS cut maintenance costs by 12% through predictive analytics [118]. Disadvantages include a high initial investment (KRW 600 billion for 300 MW) and the need for specialised technicians [119]. Potential issues include 65% reliance on imported materials and early-stage safety concerns with solid-state technology [120]. A key lesson is the role of subsidies in overcoming financial barriers, which is adaptable to nations with renewable targets [121]. The project highlights the need for localised supply chains and cybersecurity for AI systems. From an engineering perspective, modularity offers scalability, but future designs should reduce costs and enhance domestic sourcing [122]. Table 4 below summarizes the key aspects of the case studies on Japan, Thailand, and China in advancing energy storage.

Table 4. Case studies on Japan, Thailand, and China in advancing energy storage.

Aspects	Japan	Thailand	China
Policy Frameworks	Strategic Energy Plan (36–38% renewables by 2030); Green Growth Strategy for 2050 Carbon Neutrality	Alternative Energy Development Plan (AEDP) 2018–2037 (30% renewables by 2037)	14th Five-Year Plan (2021–2025); Peaking emissions by 2030 and carbon neutrality by 2060
Government Support	Subsidies for R&D, pilot projects, grid-scale installations, and feed-in tariffs (FITs)	Subsidies for pilot projects and reduced tariffs for energy storage operators	Subsidies for pilot projects, reduced manufacturing costs, and mandates for storage integration
Industrial Leadership	Public–private partnerships with firms like Toshiba, Panasonic, NEC; advancments in solid-state batteries	Investments in lithium-ion battery production (e.g., Energy Absolute's USD 3B factory)	Home to 75% of global lithium-ion battery production; leaders like CATL, BYD, and Gotion
Technological Innovations	Solid-state batteries; grid energy storage systems for high renewable areas	Lithium-ion battery factories; microgrid projects for islands	Sodium-ion batteries; large-scale vanadium flow battery projects (e.g., Dalian Flow Battery)
Pilot Projects	Large-scale BESS in Hokkaido and Kyushu for grid stability	22 MW BESS in Chaiyaphum and microgrid systems on islands (e.g., Koh Samui)	400 MW/1600 MWh Dalian Flow Battery project; 200 MW/800 MWh in Qinghai for renewables
Regulatory Reforms	Electricity System Reform enabling renewable integration	Reforms allowing IPPs to include storage; fostering private sector participation	Market liberalisation in provinces; mandates for storage in renewable projects
International Collaboration	Active in APEC, IEA, and R&D platforms for knowledge exchange	Partnerships with ADB and GEF for funding and technical expertise	Belt and Road Initiative projects; export of storage systems (e.g., Pakistan, Africa, Saudi Arabia)
Key Challenges	Intermittent renewable supply; grid congestion	Power outages in rural areas; fostering competition	Supply chain dependencies; environmental concerns over recycling; regional overcapacity
Case Example	5 MWh BESS by Chint Power for grid stability in central Japan	21 MW wind + 16 MW solar BESS projects by Energy Absolute in Lopburi and Chaiyaphum	Lanjun New Energy's 2 GWh systems for Japan; Sungrow's 7.8 GWh project in Saudi Arabia

Source: Conducted by the authors.

5.5. Critical Discussion of Case Studies

The energy storage initiatives in Japan, Thailand, and China underscore the region's leadership in advancing sustainable energy solutions. These countries' ability to integrate policy support with technological innovation and international collaboration sets an example for the Asia-Pacific region and beyond. The detailed case studies reflect not only the diversity of approaches but also the potential of energy storage technologies to address critical challenges in the global energy transition.

The case studies of Japan, Thailand, and China reveal diverse yet complementary approaches to advancing energy storage systems, highlighting distinct strengths and limitations across policy, technology, industrial focus, and international collaboration.

1. Policy and Regulatory Frameworks: Japan's strategic alignment of policies with its decarbonisation goals demonstrates a robust, top-down approach, yet challenges remain in overcoming bureaucratic inertia in scaling projects nationally. Thailand's policies, while ambitious, are comparatively fragmented and heavily reliant on pilot projects, which may slow large-scale deployment. China's comprehensive policy integration stands out

for its ability to mandate storage inclusion in renewable energy projects, driving rapid adoption. However, this aggressive approach sometimes leads to regional overcapacity and market imbalances.

2. Technological Innovation: Japan excels in fostering cutting-edge innovation, such as solid-state batteries, yet its domestic market for energy storage is constrained by geographical and demographic factors. Thailand's focus on lithium-ion technology leverages its regional manufacturing capacity but lacks diversification into emerging technologies like vanadium flow or sodium-ion batteries. China's dominance in innovation is unparalleled, particularly in scaling diverse technologies; however, environmental concerns related to battery recycling and the supply chain remain critical challenges.

3. Industrial Development and Market Position: Japan's public–private partnerships have propelled it to a leadership position in advanced storage technologies, but its reliance on a few key corporations might limit market competitiveness. Thailand's ambition to become a regional energy storage hub capitalises on its industrial base but is challenged by insufficient R&D investment compared to global leaders. In contrast, China's vertically integrated supply chains and scale economies provide a decisive edge, although this dominance may exacerbate geopolitical dependencies in global markets.

4. International Collaboration: Japan's leadership in multilateral platforms, such as the APEC, underscores its role as a facilitator of global energy governance. However, its cautious approach to international exports limits its influence compared to China's proactive global outreach via the Belt and Road Initiative. Thailand's reliance on partnerships with organisations like the ADB reflects its dependence on external expertise and funding, which, while beneficial, may hinder long-term self-reliance. China's international strategy, characterised by large-scale export projects, significantly shapes global energy storage standards but raises concerns over the potential monopolisation of emerging markets.

As a result, the case studies highlight that while Japan prioritises technological excellence and grid resilience, Thailand emphasises regional integration and capacity building, and China drives large-scale innovation and global market expansion. Together, they underscore the critical interplay of policy, technology, and collaboration in shaping energy storage's role in the global energy transition. However, each country must address specific gaps to sustain progress and contribute equitably to a low-carbon future.

6. Conclusions

International and regional bodies, including the UN, IEA, IRENA, APEC, ASEAN, and ADB, are crucial in advancing global and regional energy storage. Their frameworks and policy initiatives guide progress and foster cooperation, yet their effectiveness is contingent on navigating complex legal, political, and economic dynamics. To achieve ambitious energy storage goals, it is essential to strengthen the legally binding nature of these frameworks, enhance enforcement, and ensure inclusive public engagement. These organisations must continually adapt their strategies to address the evolving energy landscape and its inherent challenges and opportunities.

Both international and regional frameworks share common objectives and face similar hurdles in promoting energy storage, although their scale and scope differ. International efforts prioritise global cooperation, while regional initiatives cater to specific local needs. The success of these frameworks hinges on member states' commitment, effective public participation, and the ability to balance geopolitical and economic interests. Collaborative learning between international and regional organisations can significantly bolster efforts towards sustainable and resilient energy systems.

In the near future, the governance of energy storage demands progressive evolution. This includes developing comprehensive regulatory frameworks that support deployment, ensure safety, and spur innovation. Policymakers must also consider the economic and social impacts of these technologies to foster inclusive and sustainable energy policies. Strengthening the legally binding nature of international and regional frameworks, enhancing enforcement mechanisms, and ensuring inclusive public engagement remain paramount for achieving the ambitious targets set by these key organisations.

Individual countries are pivotal in this dynamic. By actively engaging with international and regional institutions, nations can fortify their domestic energy storage policies. Aligning national strategies with broader frameworks allows countries to leverage shared knowledge, access vital funding, and implement best practices, thereby enhancing their energy security and sustainability.

This review is limited by its focus on national case studies within the Asia-Pacific region, which may not fully represent the global energy storage landscape. Furthermore, the rapid pace of technological advancements in this field means that some recent developments might not be encompassed. Future research should aim to broaden the scope of case studies and continuously update analyses to reflect the latest innovations. The intricate interplay of legal, political, and economic factors that influence the efficacy of international and regional frameworks also warrants ongoing examination to ensure adaptable strategies in the face of emerging challenges and opportunities.

Future research should prioritise the exploration of innovative energy storage technologies and their diverse applications. Promising areas include advanced battery systems, hydrogen storage, and electricity-to-gas technologies. Further investigation into the integration of energy storage with renewable energy sources like wind and solar power is crucial for optimising efficiency and reliability. Additionally, research must address the scalability and economic feasibility of these technologies to facilitate their widespread adoption.

Author Contributions: C.-H.Y. conceptualised the research and authored the article. J.H. contributed by writing Section 5 on case studies within the Asia-Pacific region, reviewing the article, and providing expertise in energy storage technology and the United Nations context. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank Stanley Kang, Chairman and Founder of ESPRO NOODOE Co., Ltd., for providing valuable insights into energy storage policies in Thailand. For the Japanese case studies, we extend our gratitude to Plutocratic International Group Co., Ltd., an energy developer, for sharing crucial information about Japan.

Conflicts of Interest: The authors declare no conflicts of interest.

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