Regional Trends Report 2024

Energy Connectivity for Sustainable Development in Asia and the Pacific

Implementing the Regional Road Map on Power System Connectivity

ESCAP
Economic and Social Commission for Asia and the Pacific

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Foreword

As the Asia-Pacific region confronts the dual challenges of addressing climate change and increasing energy demand, it is increasingly urgent that countries transition to sustainable energy systems. The Regional Trends Report 2024 highlights the role of energy connectivity as an effective solution to increasing the share of renewables in the energy mix while addressing issues of access, security and affordability.

The region has made notable progress in expanding electricity access, especially in rural areas. However, millions of people still lack access to reliable energy, and, despite growing efforts to achieve national net-zero targets by around 2050, fossil fuels continue to be the dominant energy source in most countries. This situation underscores the need for effective policy frameworks and increased investments to facilitate the transition to cleaner energy systems. The report also emphasizes the growing importance of critical minerals in this transition, noting the need and opportunities for greater regional cooperation as the demand for essential minerals is expected to rise with the deployment of renewable technologies.

Across the region, progress on multilateral cross-border power system connectivity initiatives reflect growing momentum to cooperate across borders and share clean energy resources. This progress is also reflected in the status of ESCAP's Regional Road Map on Power System Connectivity, which serves as a framework for ESCAP member States to foster collaboration and implement effective and sustainable energy connectivity strategies.

The introduction of the ESCAP's Green Power Corridor Framework is another important development focusing on aligning connectivity initiatives with the Sustainable Development Goals. The framework emphasizes the importance of political agreement, institutional capacity, financial support, regulatory cooperation, infrastructure development and stakeholder engagement in creating a supportive environment for renewable energy integration. This report also introduces for the first time a set of metrics to enable the assessment of connectivity projects against relevant Sustainable Development Goal (SDG) targets.

Finally, the report highlights technological advancements that are key enablers of energy connectivity and facilitate the integration of renewable energy resources. Technologies such as high-voltage direct current (HVDC) systems, subsea cables, smart grids, and energy storage solutions are becoming increasingly accessible and affordable, helping to optimize electricity transmission and enhance grid reliability.

By enhancing cross-border electricity connectivity and trade, and promoting regional collaboration, reliance on fossil fuels can be reduced significantly while improving energy security and making clean energy more accessible and affordable for consumers. I hope that this report will provide insights and recommendations for accelerating the energy transition through power system connectivity in Asia and the Pacific.

Hongpeng Liu
Director, Energy Division, ESCAP

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The principal authors of the report were Yejin Ha, Anna Lobanova and Kimberly Roseberry (Energy Division), Xunpeng Xi and Daniel del Barrio Alvarez (consultants). Additional inputs and case studies were provided by Barry Jones (SuSca Group), Roble P. Velasco-Rosenheim (I-TRACK Standard Foundation) and Nam Le and Helene Marre Partnerships for Infrastructure (P4I).

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Comments on the report were provided by Emi Gui (Monash Sustainable Development Institute, Climateworks Centre), Henri Paillere and Phuong Nguyen (International Atomic Energy Agency (IAEA)), Tula Ram Poudel (South Asian Association for Regional Cooperation (SAARC) Energy Center), Joong Yeop Lee, Yong Chen and Adrian Gonzalez (International Renewable Energy Agency (IRENA)), Jiang Han and Xinzhi Xu (Global Energy Interconnection Development and Cooperation Organization (GEIDCO)), Nok Suttida Vanaphongsai (Agora), Karma Tshewang (Ministry of Energy and Natural Resources, Bhutan), Viktorya Keshsihyan (Ministry of Territorial Administration and Infrastructure of the Republic of Armenia), Jonathan Reeves (Foreign, Commonwealth and Development Office (FCDO), British Embassy, Nepal), Rena Kawahata (International Energy Agency (IEA)), Aayush Anand (Bharat Sanchar Nigam Ltd., India), S.K. Soonee (Regulatory Assistance Project), Mir Mohammad Hossein Zendehdel (Iran Grid Management Company), and Andrei Covatariu (Digitalization in Energy Task Force, United Nations Economic Commission for Europe).

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Abbreviation

AC	Alternating Current
ADB	Asian Development Bank
AERN	the ASEAN Energy Regulators Network
AIIB	Asian Infrastructure Investment Bank
AIMS	ASEAN Interconnection Master Plan Study
AMEM	ASEAN Ministers on Energy Meeting
APAEC	ASEAN Plan of Acton for Energy Cooperation
APEF	Asia Pacific Energy Forum
APG	ASEAN Power Grid
ASEAN	Association of Southeast Asian Nations
BBIN	Bangladesh-Bhutan-India-Nepal Initiative
BIMP PIP	Brunei Darussalam-Indonesia-Malaysia-Philippines Power Interconnection Project
BIMSTEC	Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation
BPDB	Bangladesh Power Development Board
CAREC	Central Asia Regional Economic Cooperation
CASA-1000	Central Asia South Asia Electricity Transmission and Trade Project
CASAREM	Central Asia South Asia Regional Electricity Market
CBAM	Carbon Border Adjustment Mechanism
CECP	China-ESCAP Cooperation Programme
CESI	Centro Elettrotecnico Sperimentale Italiano
CETMs	Critical Energy Transition Minerals
CO2	Carbon Dioxide
COP	Conference of the Parties (United Nations Climate Change Conference)
DERs	Distributed Energy Resources
ECO	Economic Cooperation Organization
ECO-REM	Economic Cooperation Organization Regional Electricity Market
EGAT	Electricity Generating Authority of Thailand
EIA	Environmental Impact Assessment
EMA	Energy Market Authority
ESCAP	United Nations Economic and Social Commission for Asia and the Pacific
EU	European Union
EV	Electric Vehicle
GDP	Gross Domestic Product
GEIDCO	Global Energy Interconnection Development and Cooperation Organization
GHG	Green House Gases
GMS	Greater Mekong Subregion
GPC	Green Power Corridor
GTI	Greater Tumen Initiative
GW	Gigawatt
GWh	Gigawatt-hour
HDI	Human Development Index
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
ICT	Information and Communication Technology
IEA	International Energy Agency
IGES	Institute for Global Environmental Strategies
IGFA	Inter-Governmental Framework Agreement

IRENA	International Renewable Energy Agency
ISEAS	Institute of Southeast Asian Studies
ITC	International Trade Center
JSC	Joint Stock Company
LPG	Liquefied Petroleum Gas
LTM PIP	Lao PDR-Thailand-Malaysia Power Integration Project
LTMS PIP	Lao PDR-Thailand-Malaysia-Singapore Power Integration Project
MEPs	Minimum Energy Performance standards
MOU	Memorandum of Understanding
MW	Megawatt
MWh	Megawatt-hour
NAPSI	North-East Asia Power System Integration project
NASA	National Aeronautics and Space Administration
NDC	Nationally Determined Contribution
NEAEI	North-East Asian Energy Interconnection
NEARPIC	North-East Asia Regional Power Interconnection Cooperation
NEPRA	National Electric Power Regulatory Authority
NZE	Net Zero Emissions
OECD	Organisation for Economic Cooperation and Development
OPERA	Office of the Pacific Energy Regulators Alliance
PHES	Pumped Hydro Energy Storage
PICs	Pacific Island Countries
PPA	Power Purchase Agreement
PPP	Purchasing Power Parity
REEs	Rare Earth Elements
RES	Renewable Energy Source
RPTCC	Regional Power Trade Coordination Committee
SAARC	South Asian Association for Regional Cooperation Energy Centre
SAGQ	South Asian Growth Quadrangle
SAREP	South Asia Regional Energy Partnership
SARI/EI	South Asia Regional Initiative for Energy Integration
SASEC	South Asia Subregional Economic Cooperation
SDGs	Sustainable Development Goal
SDGs-IAE	Sustainable Development Goals Impact Assessment framework for Energy projects
SPP	Smart Power Program
TAP	Turkmenistan-Afghanistan-Pakistan Initiative
TRADP	Tumen River Area Development Programme
TUTAP	Tajikistan-Uzbekistan-Turkmenistan-Afghanistan-Pakistan Initiative
TWH	Terawatt-hour
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	UN Framework Convention on Climate Change
UNRMS	the United Nations Resource Management System
US	United States
USAID	United States Agency for International Development
USD	United States Dollar
VPP	Virtual Power Plant
VRFB	Vanadium Redox Flow Battery

Executive Summary

This 2024 Regional Trends Report emphasizes the importance of energy connectivity in advancing sustainable development across the Asia-Pacific region, in particular achievement of Sustainable Development Goal (SDG) 7—access to modern energy resources. The report examines the status of SDG7 in the region, highlights the growing importance of critical minerals for energy transition technologies, provides an update on various power system connectivity initiatives in the region, presents the status of implementation of ESCAP's Regional Road Map on Power System Connectivity and ESCAP's Green Power Corridor Framework, and discusses technological advancements that have the potential to enhance power system connectivity. By outlining strategic pathways for power system integration and the challenges involved, the report seeks to better situate energy connectivity in the context of efforts to achieve energy security and sustainability across the region.

Status of SDG7

The Asia-Pacific region has made notable progress toward SDG 7, particularly in electricity access, with 98.3 per cent of the population connected to the grid as of 2022. This improvement is most pronounced in rural areas, where access has risen from 80.4 per cent in 2010 to 97.4 per cent. Despite these advancements, however, 62.4 million people, predominantly in rural and underserved areas, still lack reliable access to electricity. Access to clean cooking solutions also remains a major challenge with over a billion people in the region, particularly in rural areas still relying on inefficient and often harmful fuels for cooking. Countries such as India, China, and Bangladesh have launched programs promoting liquefied petroleum gas (LPG) and electric cooking technologies, but barriers such as high costs, lack of infrastructure, and logistical difficulties continue to hinder progress, especially in the Pacific Islands and conflict-affected regions.

The region has also witnessed strong growth in renewable energy capacity, particularly in solar photovoltaics (PV) and wind power. However, despite this growth, the overall share of renewables in total final energy consumption remains low at 16 per cent. The target set at COP-28 calls for a minimum of 16.4 per cent annual growth rate in renewables to achive tripling renewables by 2030 (IRENA, 2024). Many countries in the region continue to rely on fossil fuels, and the transition to renewable energy in sectors like industry and transport has been uneven. The slow pace of renewable energy deployment, combined with rising energy demand, calls for stronger policy frameworks and increased investments in renewable energy infrastructure, including through innovative financing mechanisms such as carbon markets.

The Role of Critical Minerals in the Energy Transition

For the first time the Regional Trends Report examines the growing importance of critical minerals to the energy transition. Increased deployment of energy transition technologies such as solar PV, wind turbines, batteries and electric vehicles (EVs) is leading to rising demand for critical energy transition minerals (CETMs) such as lithium, cobalt, copper and rare earth elements. The economies of Asia and the Pacific are both major suppliers of and a growing source of demand for these minerals, and therefore the energy transition has profound implications for the region.

The report highlights that by 2040, demand for lithium is expected to increase eightfold, driven primarily by the expansion of electric vehicles and battery storage technologies. Demand for copper is projected to increase by 50 per cent, while nickel, cobalt, and rare earth elements are expected to see a twofold rise. These minerals are vital to the development of low-carbon energy systems, but their extraction and processing present significant challenges related to environmental degradation, socio-economic externalities, and governance issues.

China, Australia, and Indonesia are major extractors of these minerals, but many other countries in the region are also rich in these resources. The report warns that poorly managed mineral development could lead to environmental harm, social conflict, and corruption, particularly in resource-rich developing countries. It emphasizes the need for sustainable and responsible extraction practices, international cooperation, and robust regulatory frameworks to ensure that the benefits of the critical minerals sector are shared equitably, and that environmental and social impacts are minimized.

Opportunities for collaboration on end-of-life management for circularity including recycling and innovative mining technologies are also highlighted as ways to mitigate the environmental impact of growing demand for critical minerals. The report calls for stronger international partnerships and governance structures to manage the growing importance of critical minerals in the global energy transition.

Cross-Border Power System Connectivity Initiatives in the region

Cross-border power system connectivity is recognized as a key driver of energy security and renewable energy integration in the Asia-Pacific region. Bilateral and multilateral initiatives are helping countries leverage regional clean energy resources more effectively and gain advantages from complementarities, though progress remains uneven.

The ASEAN Power Grid (APG), one of the most advanced cross-border initiatives in the region, aims to integrate electricity networks across the ten ASEAN countries, facilitating regional energy trade and supporting renewable energy development. For example, the Lao People's Democratic Republic (Lao PDR)-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP) is the first multilateral power trade in the region, enabling the cross-border trade of hydropower from Lao PDR to Singapore via the grids of Thailand and Malaysia.

In South Asia, a groundbreaking tripartite power sales agreement between India, Nepal, and Bangladesh has the potential to become the second multilateral power trade in the region, allowing Nepal to export 40 MW of hydropower to Bangladesh via India.

Projects like CASA-1000 are seeking to link the renewable energy-rich countries of Central Asia with energy-deficit countries in South Asia. Similarly, the Turkmenistan-Afghanistan-Pakistan (TAP) project and the broader TUTAP (Tajikistan-Uzbekistan-Turkmenistan-Afghanistan-Pakistan) initiative are also working to establish long-distance electricity connections, promoting energy security across borders.

Finally, the North-East Asia Power System Integration (NAPSI) Project is advancing efforts to connect China, Mongolia, and the Republic of Korea, leveraging Mongolia's vast wind and solar resources to supply clean electricity to its neighbors.

These initiatives showcase the potential of cross-border power system connectivity to address energy demand, improve energy security, and facilitate the integration of renewable energy resources. However, the region faces challenges including political differences, policy and regulatory inconsistencies, and the need for substantial infrastructure investments.

ECSAP's Regional Road Map on Power System Connectivity

The Regional Road Map on Power System Connectivity (Road Map), which was endorsed by ESCAP member States in 2021, provides a strategic framework to enhance regional cooperation and energy integration to 2035. It recognizes the critical role of transboundary power trade in achieving energy security and sustainability, emphasizing the need for coordinated efforts across national boundaries. The report presents the status of implementation of the Road Map's nine strategies, including examples from across the region and the role of ESCAP in supporting their implementation.

Several significant cross-border initiatives are helping to shape the region's power connectivity landscape. The Greater Mekong Subregion (GMS), for example, is home to multiple cross-border power projects, leveraging the hydropower potential of countries like Lao PDR and Myanmar to supply electricity to their neighbors. The South Asian Subregional Economic Cooperation (SASEC) program, involving countries such as India, Nepal, Bhutan and Bangladesh, aims to facilitate power trade and grid connectivity across South Asia.

Another prominent example is the Central Asia-South Asia Regional Electricity Market (CASAREM), a long-term vision that aims to establish a dynamic power market connecting Central and South Asia. Projects like CASA-1000 and TUTAP are key components of this effort, seeking to expand power trade between energy-abundant and energy-deficient regions.

Connectivity is not only limited to countries that share physical borders. In the Pacific, small island nations are exploring off-grid and microgrid solutions to increase power system resilience and enable energy transition. The Office of the Pacific Energy Regulators Alliance (OPERA) works to enhance cooperation among Pacific nations, with a focus on promoting the deployment of renewable energy and improving regulatory frameworks.

The Road Map strategies further highlight the importance of policy harmonization and regulatory alignment to enable the secure and seamless operation of interconnected grids. It also underscores the need for infrastructure investments, including both planning and financing, to support cross-border energy trade, with a particular emphasis on upgrading transmission networks and integrating renewable energy sources. Countries are encouraged to strengthen regional cooperation, adopt common and holistic regulatory frameworks, and align their energy policies to ensure the success of power system connectivity and electricity trading initiatives.

Energy Connectivity for Sustainable Development: the Green Power Corridor Framework

Strategy 9 of the Road Map emphasizes the need to align connectivity initiatives with sustainable development, as well as the importance of evaluating the impacts of these initiatives across different sustainability criteria. To this end, the Green Power Corridor (GPC) Framework was developed to promote sustainable energy connectivity and the integration of renewable energy resources across borders. The GPC Framework is designed to create a political, regulatory, and institutional environment that supports regional energy trade and the scaling up of renewable energy projects.

Six building blocks form the foundation of the GPC Framework: political agreement, institutional capacity, regulatory alignment, financial support, stakeholder engagement, and robust infrastructure. The Framework emphasizes the importance of securing political and regulatory commitments from participating countries, harmonizing policies to facilitate cross-border electricity trade, and securing financing for infrastructure investments.

A number of successful multilateral efforts in the region demonstrate the GPC Framework's principles in action. The Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC), for example, aims to strengthen energy cooperation across South and South-East Asia. SASEC and the Greater Tumen Initiative (GTI) are also examples of key platforms for advancing energy connectivity among their respective members.

The GPC Framework also emphasizes the necessity of engaging communities and stakeholders in energy projects to ensure social acceptance and equitable distribution of benefits. Public participation in decision-making processes and efforts to address social and environmental impacts are critical to achieving long-term sustainability.

The chapter also presents the GPC Metrics. While power system connectivity projects are primarily emphasized in the context of achieving SDG7, their development has potential implications – both positive and negative – for other SDGs as well. The GPC Metrics are intended as an evaluation method designed to visualize the impacts of energy connectivity across different SDGs, to aid in the planning and assessment of connectivity initiatives at any stage of their development.

Technological Enablers of Power System Connectivity

Finally, the report explores the role of emerging technologies in enabling the integration and optimization of cross-border power systems. The deployment of high-voltage direct current (HVDC) technology is a central focus, enabling long-distance electricity transmission with minimal losses. HVDC systems are essential for linking remote renewable energy sources, such as offshore wind farms, with major demand centers in neighboring countries.

Smart grids and digital platforms are also transforming energy management, enabling real-time monitoring and optimization of electricity flows across interconnected grids. These technologies are critical for balancing supply and demand, particularly in systems that rely heavily on intermittent renewable energy sources like solar and wind.

Energy storage systems, including battery storage and pumped hydro, play a vital role in stabilizing power grids by storing excess energy during periods of low demand and releasing it when needed. These technologies are crucial for managing the variability of renewable energy and ensuring reliable power supplies in interconnected grids.

In addition to grid technologies, innovations like undersea transmission cables and digital twin platforms are making cross-border energy trade more efficient and flexible. By leveraging these technological advancements, countries in the region can increase their energy security and accelerate the transition to clean energy.

Key Recommendations and Strategic Pathways for Implementing the Regional Road Map on Power System Connectivity

The report outlines several strategic recommendations to support the region's transition to clean energy and cross-border power system connectivity.

Political and Regulatory Coordination: Strengthen political commitments and align regulatory frameworks to facilitate cross-border electricity trade and energy cooperation.

Investment in Infrastructure: Prioritize investments in grid infrastructure, including HVDC transmission systems, smart grids, and energy storage, to enhance the resilience and efficiency of power networks.

Capacity Building and Knowledge Sharing: Encourage regional platforms to facilitate capacity building, knowledge sharing, and technical cooperation among countries, ensuring best practices are adopted in energy management and regulatory alignment.

Public Engagement: Foster public participation in energy projects to ensure social acceptance and equitable access to the benefits of energy connectivity.

There are significant opportunities to build on ongoing efforts to implement the Regional Road Map on Power System Connectivity enabling the achievement of a consistent and holistic approach to sustainable power system connectivity across the Asia-Pacific region. The opportunities highlighted in the report include:

- Developing the next set of milestones under the Regional Road Map through an inclusive consultative process for endorsement by member States (Strategy 1)
- Developing a regional cross-border electricity grid master plan based on mapping of the region's existing and planned high-voltage transmission network (Strategy 2)
- Developing model intergovernmental agreements and templates on cross-border electricity connections (Strategy 3)
- Supporting the formation of subregional associations of national regulators and develop standardized market rules and technical standards (Strategy 4)
- Identifying and carrying out pilot projects based on the subregional studies on multilateral power trade (Strategy 5)
- Developing protocols for transmission planning, scheduling and third-party access through the establishment of working groups with system operators, utilities and other stakeholders (Strategy 6)
- Creating an enabling investment environment through promoting innovative financing mechanisms, enhancing bankability of projects and streamlining project financing (Strategy 7)
- Building synergies among different capacity building efforts through better coordination and collaboration (Strategy 8)
- Applying the GPC Framework as an enabling tool for sustainable power system connectivity (Strategy 9)

To further strengthen regional cooperation on power system connectivity, a framework agreement that helps streamline cross-border electricity trade, ensure consistency in operational standards, and provide the necessary tools for collaboration and sustainable development could be considered. Ultimately any such agreement would need to be developed and agreed upon through a consultative, member State driven process, modelled after similar successful efforts in other areas of connectivity such as trade, transport and digital connectivity within Asia and the Pacific.

Introduction

At the 2023 United Nations Climate Change Conference of Parties (COP-28), the global community acknowledged the pressing necessity to enhance efforts to meet the Paris Agreement's target of limiting global warming to 1.5 degrees Celsius. In this context, nations pledged to work towards tripling installed renewable energy capacity and doubling the global average annual rate of energy efficiency improvements from around 2 per cent to over 4 per cent each year by 2030. This commitment signifies a collective recognition of the role that renewable energy and efficiency play in mitigating climate change. Translating this pledge into actionable strategies, the proposals discussed at COP-29 in 2024 underscored the central importance of enabling infrastructure, in particular grids and storage, and enabling environments in the form of green energy zones and corridors, in achieving these ambitious goals. The proposals called for substantial investment, specifically USD 680 billion annually in energy infrastructure, including constructing approximately 25 million kilometers of new transmission and distribution grids by 2030.

Cross-border grid infrastructure and green energy corridors are essential not only for enhancing the integration of renewable energy resources and improving energy efficiency but also for contributing to the achievement of Sustainable Development Goal 7. This goal aims to ensure access to affordable, reliable, sustainable, and modern energy for all, which remains a top priority in the Asia-Pacific region.

The Asia-Pacific region is experiencing rapid economic development, population growth, and urbanization, all of which are driving significant increases in energy demand. Electricity demand is projected to grow even faster due to the proliferation of technologies such as data centers, electric vehicles, and the increasing need for cooling due to climate change. This surge in energy demand presents regional economies with the dual challenge of sourcing larger amounts of clean energy while also adhering to decarbonization goals for the energy sector.

In this context, cross-border power system connectivity emerges as a key solution that can enable countries in the region to access secure, affordable, and renewable energy in the quantities necessary to meet their climate ambitions. Since the early 1990s, various subregions in Asia and the Pacific have engaged in discussions about power connectivity, recognizing its potential benefits for energy security and economic growth. This period has seen the emergence of several regional forums and agreements focused on energy trade and cooperation, laying the groundwork for comprehensive discussions on electricity interconnection.

However, despite the recognized advantages, the development of power system connectivity has often remained fragmented, characterized by bilateral and one-directional agreements primarily focused on hydropower. Significant challenges continue to impede progress, including political differences, regulatory inconsistencies, and the need for substantial upfront investments in infrastructure. Developing interconnected power grids and enabling cross-border and multilateral power trade necessitates comprehensive agreements, collaborative frameworks, and a significant long-term commitment from multiple stakeholders.

To address the complexities associated with power system connectivity in Asia and the Pacific, in 2021, ESCAP member States endorsed the "Regional Road Map on Power System Connectivity: Promoting Cross-Border Electricity Connectivity for Sustainable Development." This Road Map outlines nine strategic approaches aimed at increasing the integration of renewable energy, fostering regional cooperation, and enhancing investments in essential infrastructure.

Implementation of the Road Map has been progressing primarily at the subregional level, with each Asia-Pacific subregion exhibiting distinct characteristics and varying stages of development. For instance, while some subregions are establishing uniform or harmonized frameworks for electricity exchange and trade, others are still in the early stages of exploring cross-border initiatives. Nevertheless, a common thread among all subregions is the imperative to secure strong political commitments that are consistently maintained across all levels of government, and incorporated into national development plans across all relevant sectors. With the overarching political will in place, efforts are needed to build strong institutions that can effectively support and coordinate cross-border interconnections; establish financial arrangements to facilitate investments in large-scale projects; and create regulatory frameworks that provide effective governance and ensure seamless connectivity.

Moreover, the infrastructure backbone must be constructed with a focus on delivering economic, social, and environmental benefits. A holistic approach to infrastructure development not only helps to ensure the technical and economic viability of interconnection projects but also enhances the likelihood of social acceptance among the communities affected by these initiatives. The Green Power Corridor Framework, comprising these six essential components—political accord, institutional framework, enabling financial arrangements, regulatory framework, infrastructure backbone, and social acceptance—serves as the strategic building blocks for promoting successful and sustainable power connectivity in the Asia-Pacific region.

Advancements in technologies across generation, transmission, distribution, storage, grid management, electricity markets, and end-user technologies are fundamentally driving the development of more efficient, flexible, and resilient power system interconnections. These innovations are enabling integration of renewable energy sources more effectively and facilitate cross-border electricity exchanges.

However, not all countries in the region have the same level of access to these transformative technologies. Factors such as limited financial resources, lack of technical expertise, political and regulatory challenges, and underdeveloped infrastructure pose challenges in the deployment and adoption of these advanced solutions. This technological divide means that some countries struggle to modernize their power systems, leaving them more vulnerable to inefficiencies, grid instability, and energy shortages.

As the region moves forward to enhance energy connectivity, more effort is needed to ensure that all countries have the tools and resources to participate and benefit from power system integration. The implementation of the Road Map can contribute to strengthening regional cooperation for achieving the collective vision for a more integrated, resilient, and sustainable energy future.

This report has the following structure:

- **Chapter 1** provides an overview of the current progress towards achieving Sustainable Development Goal (SDG) 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. It also explores the crucial role of critical minerals in supporting the energy transition.

- **Chapter 2** discusses the various cross-border power system connectivity initiatives across the Asia-Pacific region, examining ongoing efforts, challenges, and opportunities for increasing regional electricity trade and power grid integration.

- **Chapter 3** outlines the progress made in implementing the Regional Road Map on Power System Connectivity, its strategies and milestones, highlighting key projects, policies, and initiatives aimed at strengthening grid interconnections and opportunities for making further progress.

- **Chapter 4** takes an in-depth look at the Green Power Corridor Framework, developed under Strategy 9 to provide a set of principles to guide sustainable interconnection projects and initiatives and metrics to measure their alignment to the SDGs.

- **Chapter 5** examines the technological advancements that are driving power system interconnections, with a focus on innovations in transmission, distribution and storage systems. It discusses how these technologies can enhance the flexibility, resilience, and efficiency of interconnected power systems, enabling greater integration of renewable energy.

Chapter 1

Sustainable energy development: Situation and trends

1.1. SDG 7 Progress in the Asia-Pacific Region

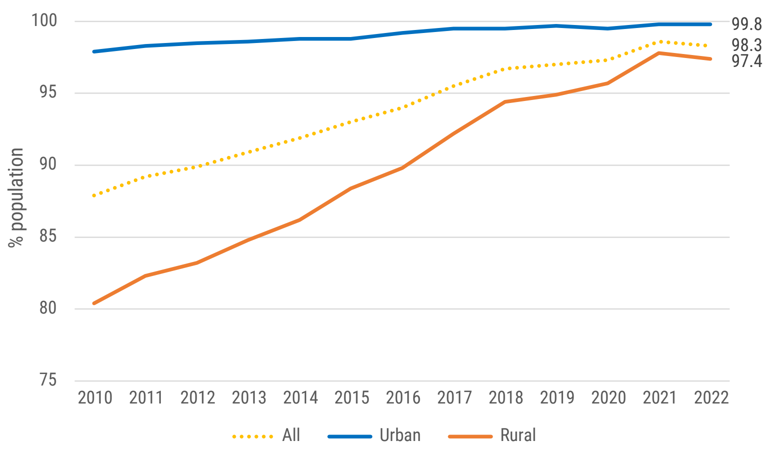
The Asia-Pacific region has made notable progress in advancing SDG 7 (Affordable and Clean Energy), but significant challenges remain. The region has seen substantial improvements in access to electricity, with a growing percentage of the population gaining access to reliable power. However, disparities persist, particularly in rural and underserved areas where energy access, particularly for clean cooking is still limited. While many countries are increasing their investments in energy infrastructure, the pace of progress varies considerably across the region. Some nations are successfully expanding electricity networks, increasing energy efficiency, and integrating renewable energy sources, while others face obstacles such as financial constraints, technical barriers, and inadequate policy frameworks. Uneven progress leaves the region on a path that falls well short of achieving Goal 7 targets for clean cooking, renewable energy and energy efficiency. At the same time, the pace and scale of progress in Asia and the Pacific lags well behind other global regions, where energy intensity is falling and renewable energy shares are rising at faster rates.

1.1.1. Energy Access

Electrification

Electrification is the area of greatest progress under Goal 7. The Asia-Pacific region is on a positive trend towards achieving SDG 7.1 by 2030, with the region having reached 98.3 per cent access in 2022 (Figure 1). Rural areas saw the greatest improvement with a notable upward trajectory from 80.4 per cent in 2010

Figure 1. Proportion of population with access to electricity in Asia and the Pacific



Source: World Bank.

to more than 97.4 per cent in 2022, though this represents a decline relative to the level of access in 2020. Urban areas have continuously increased their already relatively high electrification rates, nearly reaching universal access, reflecting a sustained focus on urban energy infrastructure even as urbanization has led to growing urban populations.

The substantial improvements in energy access rates in countries across the Asia-Pacific region are driven by a combination of robust government policies and planning, technological advancements, and international support. Governments have implemented aggressive rural electrification programmes, expanded grid infrastructure, and promoted the adoption of renewable energy sources to accelerate electrification. Technological innovations, particularly in decentralized energy solutions like solar home systems and mini-grids, have been instrumental in reaching remote and off-grid communities. Additionally, international organizations and financial institutions have played a crucial role by providing innovative funding, technical assistance, and capacity-building initiatives that have accelerated electrification.

Due to these factors, the Asia-Pacific region has witnessed a remarkable reduction in the total population without access to electricity. In 2010, nearly 495 million people lacked access to electricity, with a substantial disparity between rural and urban areas. By 2022, this number had decreased to 62.4 million. The reduction was predominantly observed in rural areas that have historically lagged behind urban regions in terms of electrification.

Clean Cooking

Progress towards achieving SDG 7 in the area of clean cooking in Asia and the Pacific remains a critical yet challenging aspect of energy access. Clean cooking solutions are pivotal for improving health, particularly for women and children, reducing environmental degradation, and enhancing overall quality of life. While the region has seen advancements in expanding access to cleaner cooking technologies, significant disparities and challenges persist, particularly in rural and low-income communities.

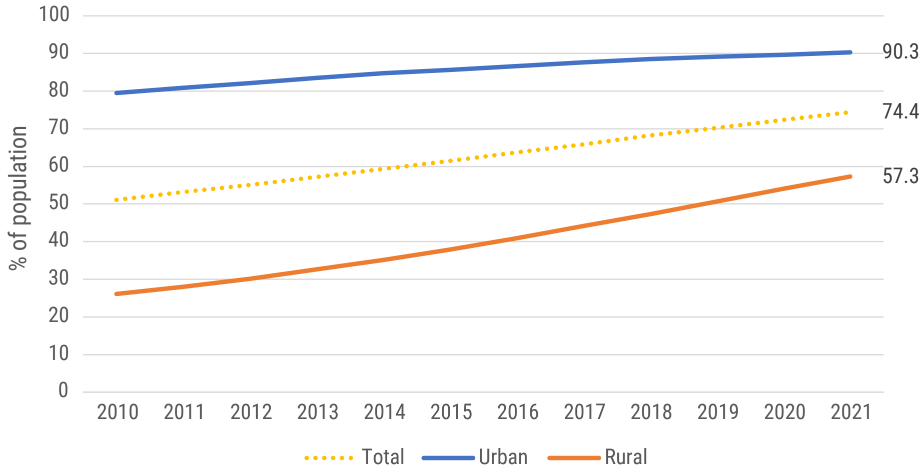
A notable advancement has been the increased adoption of improved cookstoves and cleaner fuels, such as liquefied petroleum gas (LPG), biogas, as well as electric cooking. Countries like India, China, and Bangladesh have launched large-scale initiatives to replace traditional biomass stoves with cleaner alternatives. More recent initiatives, such as in Bhutan with the support of ESCAP, are looking to transition households to electric cookstoves. All these programmes aim to reduce indoor air pollution, which is a major health hazard, and decrease the environmental impact of cooking practices. The expansion of such initiatives has contributed to a gradual decline in the number of households relying on solid fuels for cooking.

However, despite these efforts, access to clean cooking solutions remains uneven across the region. Rural areas and marginalized communities often face barriers to adopting clean cooking technologies due to high costs, limited infrastructure, and lack of awareness. In many instances, the availability of subsidized clean cooking solutions is insufficient to meet the needs of all households. Additionally, the transition from traditional biomass to cleaner fuels is often hindered by logistical challenges, such as supply chain issues and the need for complementary infrastructure development. This results in a clear disparity between urban areas of the Asia-Pacific region that, in 2021 had an access rate of 90.3 per cent, and rural populations where reliance on clean fuels and technologies (cooking, heating and lighting) only reached 57.3 per cent. The most challenged economies include Pacific Island developing economies, land locked developing countries and nations experiencing conflict.

Challenges and Opportunities for Energy Access

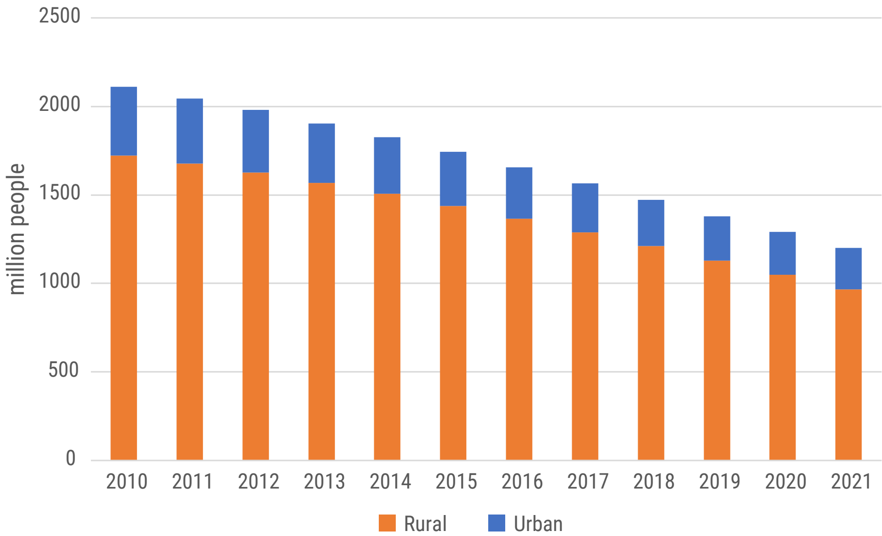
Despite impressive progress, several challenges persist for energy access in the Asia-Pacific region. Ensuring affordable access to electricity and clean cooking remains a significant challenge, particularly for rural and low-income households, necessitating efforts to manage energy costs and implement inclusive pricing mechanisms. While access rates in terms of households being provided an electrical connection have improved, the

Figure 2. Percentage of population with primary reliance on clean fuels and technologies



Source: World Health Organization.

Figure 3. Population without access to clean fuel and technologies



Source: ESCAP based on data from World Health Organization.

quality and reliability of electricity supply can vary significantly, requiring further investments in grid stability, maintenance, and upgrades to ensure consistent and reliable energy services. Remote and geographically challenging areas continue to face barriers to accessing power grids and cooking fuel distribution networks, highlighting the need for solutions that consider local contexts and leverage decentralized energy systems to overcome these obstacles and reach last-mile populations.

Electric cookstoves offer a promising pathway to closing the gap on clean cooking, but their adoption is dependent on access to quality electric services as electric cooking is among the highest-tier clean cooking technologies and an essential part in achieving low-carbon energy transition. Integrating electric cooking into power planning for both on-grid and off-grid solutions while raising awareness of its advantages and benefits can help drive consumer choice and the transition away from unhealthy cooking methods.

1.1.2. Renewable Energy

In the Asia-Pacific region, renewable power shows robust growth, driven primarily by the expansion of solar PV and wind power. The global expansion in renewables capacity in 2023 was led by Asia contributing 326 GW or 69 per cent of the total 473 GW added worldwide (IRENA, 2024). Governments in the region have increasingly prioritized renewable projects, aiming to address energy security concerns and mitigate climate change impacts. According to the International Energy Agency (IEA), globally, by 2025, renewables are expected to surpass coal as the predominant source of electricity generation. Asia-Pacific countries, particularly China and India, are defining this global trend.

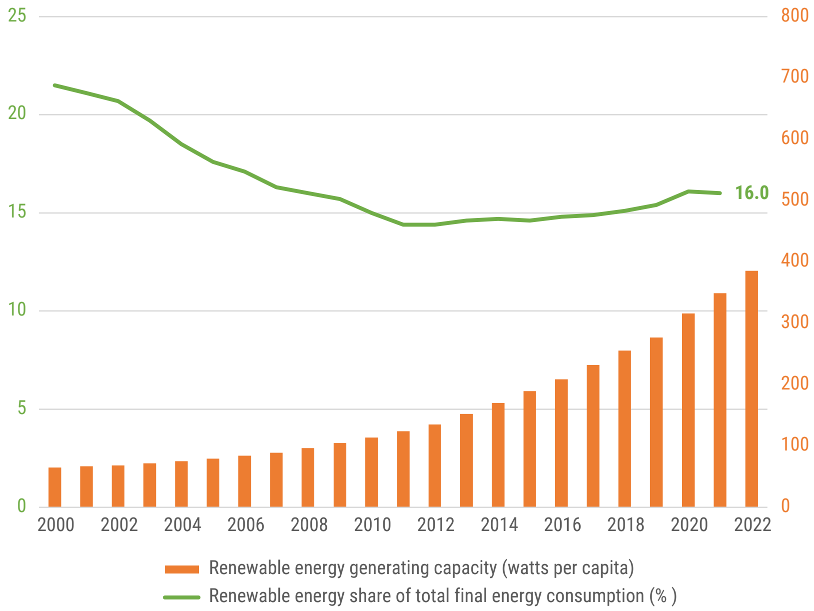
The pace of large capacity additions has been enough to increase the share of renewable energy in the power sector on a watts per capita basis. However, progress increasing the region's total share of renewable energy in total final energy consumption has been weak, due to the fast pace of demand growth in the region compared to Europe and the United States where demand has been stable over the past decade. The last 10 years of data of the share of renewable energy in final energy consumption show limited progress, and a slight decline in 2021 to 16 per cent (Figure 4), highlighting the region's continued reliance on fossil fuels. In 2022, the region's renewable energy capacity reached 385.8 watts per capita, but Asia-Pacific continues to lag behind the global average of 424.1 (Figure 5).

Challenges and opportunities for renewable energy

Progress increasing the total share of renewable energy consumption has been slow due to a variety of reasons including regulatory and market barriers, lack of enabling environment, inadequate procurement schemes and insufficient action to de-risk investments in renewables. The growth in renewables is also struggling to keep up with the rapid rise in energy demand across not only the power sector, but also industrial and transport sectors. In addition, across Asia-Pacific countries the introduction of renewable energy across sectors is marked by significant disparities, reflecting uneven advancements in the transition to cleaner energy sources.

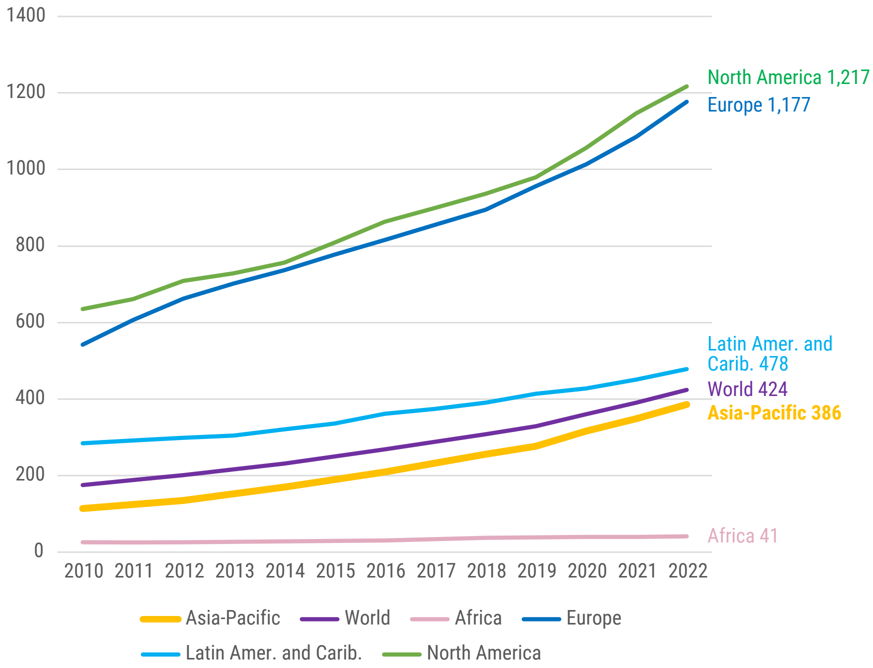
While some nations, in particular those with robust policy environments and the capacity for substantial investments, have successfully

Figure 4. Renewable energy capacity additions and share of total final energy consumption in Asia and the Pacific



Source: ESCAP based on data from IRENA, IEA and UN Statistics Division.

Figure 5. Renewable electricity capacity (Watts per capita)



Source: IRENA, IEA and UN Statistics Division.

boosted their renewable power capacities—leveraging solar PV, wind, geothermal and hydro power—others lag behind due to financial constraints, technical limitations, and inadequate policy support. Developed economies with advanced energy infrastructure and strong governmental commitment have made notable strides in integrating renewables into their energy mix. Conversely, many developing and emerging economies struggle to scale up renewable energy projects due to challenges such as high initial costs, limited domestic capacity and access to technology, and insufficient grid infrastructure.

Despite the obstacles, the region holds substantial opportunities for progress. The Asia-Pacific region is endowed with abundant renewable resources, including solar, wind and geothermal potentials, which can be harnessed to meet growing energy demands sustainably. Continued expansion of renewables in industry and transport sectors is crucial to achieving renewable energy targets. The pace of progress for renewables-based heat has been relatively steady, driven by growth in modern bioenergy uses. Liquid biofuels are experiencing robust expansion in the transport sector, although further adoption is required to meet ambitious blending targets. Promisingly, the industrial and residential sectors are witnessing increased use of renewable heat, particularly from bioenergy.

Importantly, countries in the region are leading the world in developing and deploying renewable energy technologies, and these advances, coupled with the electrification of end uses and decreasing costs of renewable energy and battery storage systems are making renewable resources increasingly economical across sectors.

The uneven progress across sectors and economies highlights the need for targeted support and international cooperation to bridge the gaps and ensure that all countries can benefit from the shift towards sustainable energy. One key example where enhanced cooperation is required is cross-border power grid connectivity, which offers a key strategy for enabling higher shares of renewable energy in the power mix while maximizing the utilization of renewable resources that are distributed unevenly across the region. Implementation of ESCAP's Regional Road Map on Power System Connectivity can help to enhance energy security, enable efficient resource utilization, and facilitate the integration of renewable energy sources, ultimately leading to more reliable and cost-effective electricity supply across interconnected regions.

To accelerate progress on renewable energy deployment, governments must continue to develop policy frameworks to create an enabling environment for renewables, while international cooperation and investment is needed to drive the development of innovative solutions and infrastructure, fostering a more inclusive and resilient energy transition.

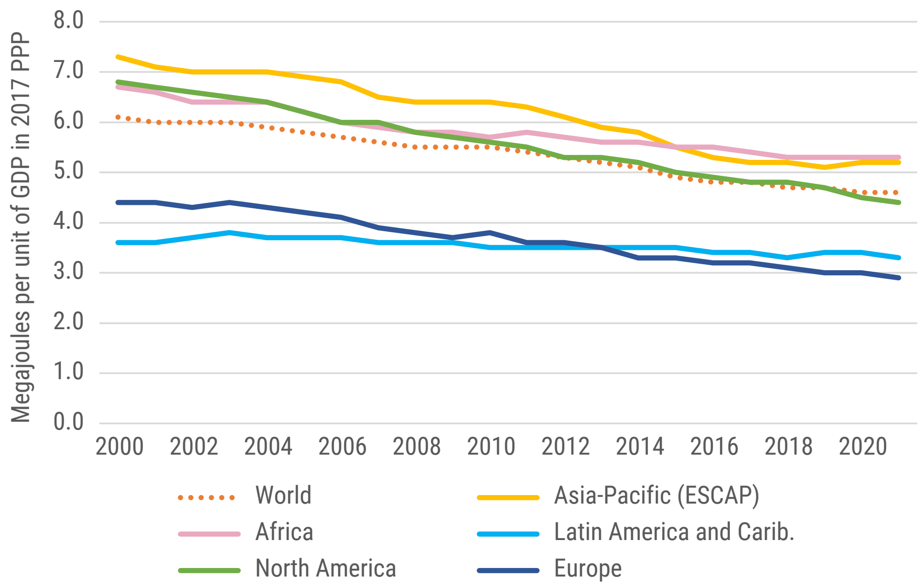
1.1.3. Energy Efficiency

Figure 6 illustrates energy efficiency progress from 2000 to 2021across different regions in terms of megajoules per unit of GDP (in 2017 PPP). The Asia-Pacific region, represented by the yellow line, exhibits a steady decline in energy intensity, indicating an overall trend of improved energy efficiency over the two decades. However, the region stagnated in the last two years and still has energy intensity well above the world average, as well as above North America, Latin America and the Caribbean, and Europe (Figure 6). The trend reflects the impact of policies and investments in energy-efficient technologies and practices, although further advancements are required to match the lower energy intensities achieved by other regions. At the same time, progress has dramatically slowed compared to the period from 2010-2015, when the region experienced robust annual improvements of 3.0 per cent on average. From 2015 to 2020, energy intensity fell just 1.1 per cent annually, and progress ground to a halt in 2021, putting the region and the world further off-track from reaching the target of doubling the rate of energy intensity improvement. To support achievement of SDG 7, the region must meet the global target rate of 3.8 per cent for the period 2021-2030 (Figure 7). It is important to note that energy intensity is only an indirect measure of energy efficiency and should be considered in conjunction with other structural aspects of the economy. For example, high energy intensity is often the outcome of high levels of manufacturing activities which is a large component of economic activity in the Asia-Pacific region, compared to European countries where low-energy-demand service sectors are more prominent.

Challenges and opportunities for energy efficiency

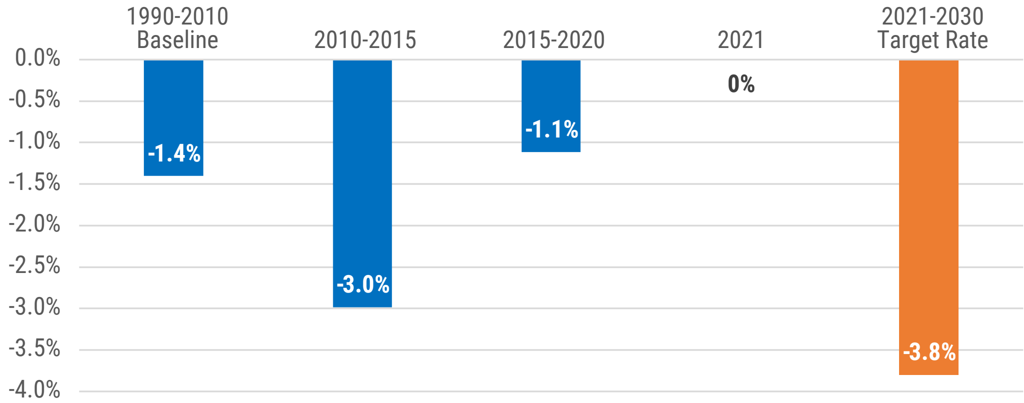
In the Asia-Pacific region, there are substantial opportunities for energy efficiency improvements across the buildings, industry, and transport sectors. In the buildings sector, the widespread adoption of energy-efficient appliances through the introduction and enforcement of minimum energy performance

Figure 6. Energy intensity across global regions, 2000-2021



Source: ESCAP based on data from IEA.

Figure 7. Average annual changes in regional primary energy intensity by period, 1990-2030



Source: ESCAP based on data from IEA.

standards (MEPS) can drastically reduce energy consumption. Already, most Asia-Pacific countries have adopted MEPS for at least some appliances, though they require expansion and strengthening. Encouraging the growth of energy service companies and the market for energy efficiency also provides opportunities for energy efficiency gains(World Bank, 2016). The rise of average temperatures and the increased frequency of extreme heat events from climate change is driving rising power demand from space cooling. Energy systems in many contexts are strained during hot weather from the spike in space cooling appliance use. The impact of cooling on peak demand could be mitigated through increased energy efficiency of cooling systems and reducing cooling loads through architectural passive design strategies.

The residential and commercial sectors can achieve significant savings by upgrading to energy-efficient lighting and high-volume air conditioning (HVAC) systems, incorporating passive cooling strategies into building design, and utilizing energy management systems to optimize power usage. While building codes and regulations governing commercial buildings do incorporate many of these aspects, few countries have mandatory residential building energy codes, even though the residential sector represents the bulk share of future floor space, and overall enforcement of standards is often weak. Implementing regulations and providing incentives for both businesses and consumers to adopt energy-saving technologies and approaches will be crucial in realizing these opportunities and advancing the region's overall energy efficiency.

In the transport sector, transitioning to electric vehicles (EVs), improving public transportation infrastructure, and promoting non-motorized transport options can lead to considerable reductions in energy consumption.

1.2. The role of critical minerals in the energy transition: the perspective from Asia and the Pacific

The shift to low-carbon energy resources, crucial for achieving the Paris Agreement goal of limiting temperature rise to well below 2 degrees Celsius, is driving increasing demand for critical minerals. Clean energy technologies typically require significantly more mineral inputs than fossil fuel technologies (IEA, 2021), and material intensity is anticipated to rise alongside the level of decarbonization (World Bank, 2020). Limiting global warming to 1.5 degrees Celsius, as outlined in the International Energy Agency's (IEA) Net Zero Emissions (NZE) Scenario, necessitates a rapid increase in demand for key minerals (IEA, 2024). This trend presents both opportunities and challenges for the mining and mineral sectors. International cooperation, along with other measures such as governance and regulation, is important for promoting sustainable development in this interconnected world and its complex international supply chains. This is particularly true for the Asia-Pacific region, which is both a major supplier of and source of demand for critical energy transition minerals (CETMs).

Outlook

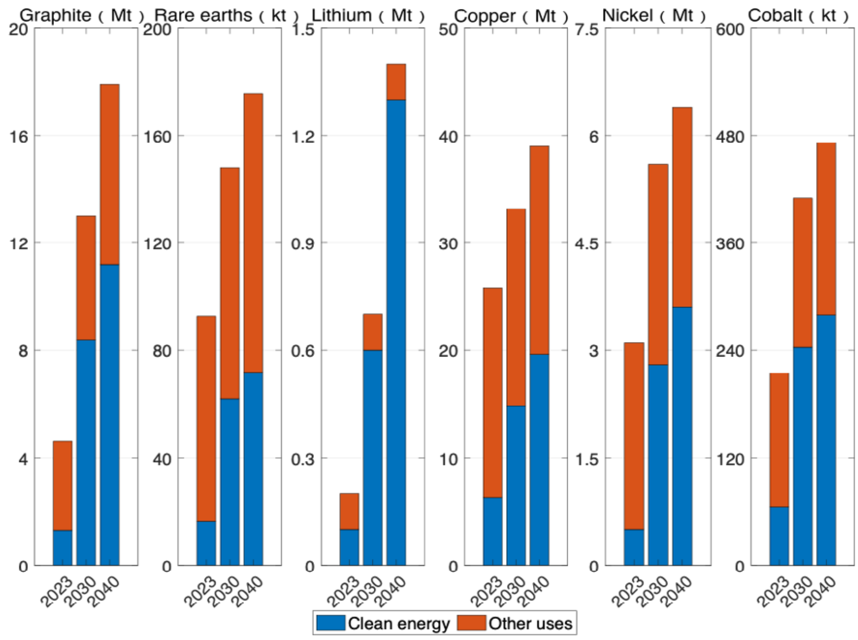
While there are numerous outlooks for critical minerals, there is broad agreement across all of them that energy transition will lead to increasing demand. The IEA's most recent critical minerals outlook (IEA, 2024) provides a useful reference. Under the IEA's NZE Scenario, demand for copper is projected to increase by 50 per cent by 2040, demand for nickel, cobalt, and rare earth elements (REEs) is expected to double, and demand for graphite quadruples. Lithium stands out with a projected eightfold growth by 2040, driven by its vital role in battery technologies.

Demand for these inputs is driven by multiple sectors with the clean energy sector emerging as the largest consumer in most cases. Battery storage and EVs, for example, are expected to become the largest consumers of lithium and nickel by 2040 (IEA, 2021). Also, critical minerals for the expansion of transmission and distribution infrastructure (cables, wires and transformers etc.) is expected to rise in the coming years.

Opportunities and Challenges

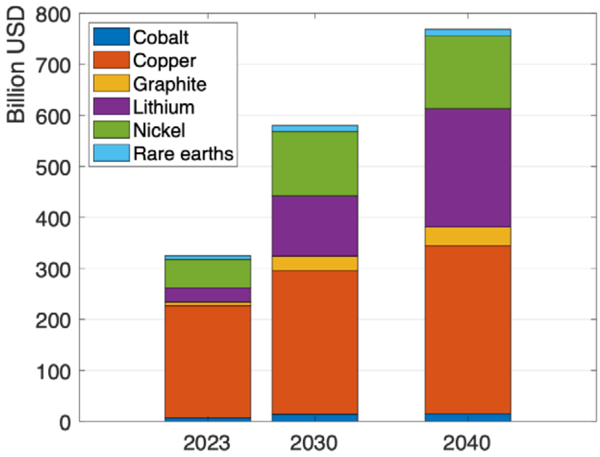
Increased demand for CETMs from expanded use of modern renewable energy and energy-efficiency technologies, as well as parallel growth in demand for information and communication technologies (ICT), implies in turn an increase in their exploration and extraction. This raises environmental and social development challenges, but also creates economic development opportunities. Under the IEA's NZE Scenario, the total market value of selected key energy transition minerals more than doubles by 2040, increasing from USD 325 billion in 2024 to USD 770 billion in 2040 (IEA, 2024). Copper holds the largest market value at USD 330 billion, while the lithium market significantly expands to USD 230 billion by 2040, becoming the second-largest market, followed by nickel. The graphite market is projected to grow by six times by 2040.

Figure 8. Global demand for key CETMs (lithium, copper, cobalt, nickel, REEs, graphite) in the Net Zero Scenario, 2023-2040



Source: IEA.

Figure 9. **Market value of key energy transition minerals in the Net Zero Scenario, 2023-2040**



Source: IEA.

Assuming these demand projections hold to be true, ensuring sufficient growth in critical mineral supply is crucial for enabling clean energy transitions. Economic activity related to the extraction and processing of CETMs holds the promise to help alleviate poverty through the direct and indirect creation of jobs (UNEP, 2020) and by generating public revenue. Additionally, improved infrastructure access driven by the critical minerals sector can enable businesses and households to increase their output and productivity, fostering further job growth.

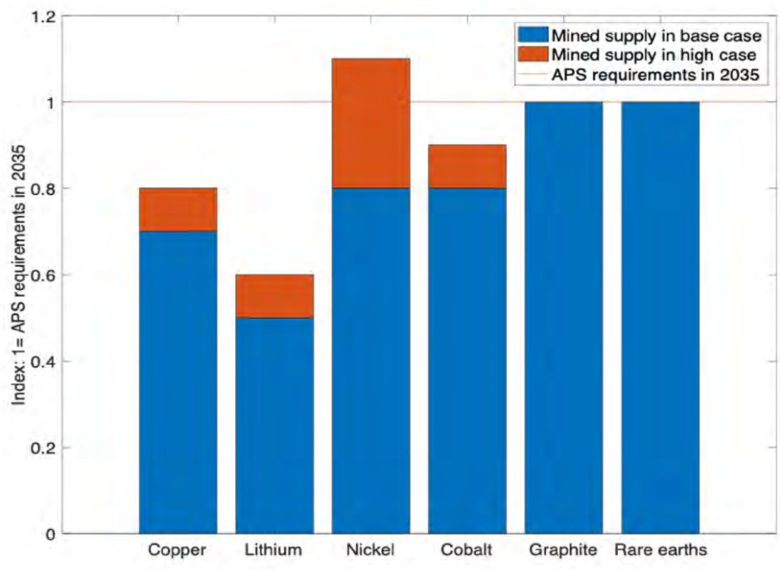
However, the development of critical minerals also presents significant challenges. Poorly managed mineral development can lead to significant negative consequences including environmental degradation, greenhouse gas emissions, social disruption, and corruption. Within the energy sector itself, challenges amid the energy transition process include insufficient investment, supply chain vulnerabilities, and obstacles to innovation and cost declines. Despite substantial investments in mineral supply and the announcement of numerous projects, significant supply gaps remain for some critical minerals. For example, according to the IEA, even assuming high levels of production, anticipated supply of copper and lithium falls well short of meeting anticipated demand by 2035 under the Announced Pledges Scenario. Achieving the more ambitious NZE Scenario will require approximately USD 800 billion in mining investments from now until 2040 (IEA, 2024).

The vulnerability of the global supply of CETMs is another major challenge faced by the sector. The geographical concentration of mining operations is likely to remain high in most instances (IEA, 2024). Moreover, refining capacity is notably more concentrated, with China claiming nearly 50 per cent of the market value by 2030. No single country can drive the necessary changes on its own, as the global nature of these supply chains involves navigating a diverse array of legal frameworks and local contexts. High levels of supply concentration raise the risk of potential disruptions due to physical accidents, geopolitical events, or other developments in key producing and refining countries, with significant implications for the pace of energy transitions. The IEA's N-1 analysis[1] of the sector (IEA, 2024) finds that in most cases, the N-1 level of supply is significantly lower than material requirements, even for minerals that are considered well-supplied on a global scale.

The environmental impact of mining remains a major concern. Traditional mining activities

1 The N-1 test assesses supply-demand balance under the assumption that the largest global supplier is removed from the market

Figure 10. Expected supply from existing and announced projects and primary supply requirements in the Announced Pledges Scenario, 2035



Source: IEA.

already pose substantial ecological risks. Anticipated growth in investment needs combined with a general sense that the "low hanging fruit" in the mining sector has mostly been exhausted has the potential to drive development into more environmentally and socially sensitive areas. Supply-side issues are exacerbated by downstream challenges such as unmitigated emissions, improper e-waste disposal, and inadequate recycling and implementation of circular economy practices. Other challenges include obtaining a social license for mining, the prevalence of resources in land controlled or occupied by indigenous and vulnerable communities, low participation of women in the industry, and the unique difficulties posed by artisanal and small-scale mining. Weak institutions and insufficient coordination, both at national and international levels, further complicate the situation (ESCAP, 2023).

The perspective from Asia and the Pacific

Countries in the Asia-Pacific region will play a crucial role in the future of the CETM sector, not only because of abundantly available resources but also because of growing demand for CETMs within the region.

ESCAP member States possess approximately 30 per cent of the world's known reserves of cobalt, copper, and lithium, 41 per cent of bauxite, 53 per cent of graphite, 59 per cent of nickel, 75 per cent of rare earth elements (REEs), and 80 per cent of lead (ESCAP, 2023). The prominence of ESCAP member States in critical mineral production is even more significant. Collectively, the Asia-Pacific region is the world's largest supplier of cobalt, copper, lithium, and bauxite. As of 2019, the region accounted for 63 per cent of the world's bauxite production, 66 per cent of lithium production, 70 per cent of graphite production, 74 per cent of nickel and lead production, and 96 per cent of REE production (United States Geological Survey, 2021). Many resource-rich Asia-Pacific countries export critical minerals for processing elsewhere, thereby playing a crucial role in the global critical mineral trade and supply security (ESCAP, 2023).

Actions towards sustainable development

Governments and companies must manage the environmental and social impacts of increased demand for CETMs. To achieve the collective objectives outlined in the SDGs, it is crucial that resource development incorporates economic, environmental, social, and governance factors at every stage of the lifecycle (ESCAP, 2023). A comprehensive approach to supply security and sustainability must address the demand side, which is essential for narrowing supply-demand gaps and mitigating the potential environmental and social harms associated with resource extraction and use. Investment across the supply chain is crucial, but equally vital is unlocking the potential of resource circularity including recycling, innovation, and behavioral change to encourage reuse and responsible consumption. The IEA estimates that recycled quantities of copper, lithium, nickel and cobalt from clean energy applications could meet 10-30 per cent primary supply requirements for key minerals by 2040 (IEA, 2024).

Developing comprehensive transformation strategies requires an in-depth assessment of the sustainability of a country's CETM development. This is especially important because many of these resources will be sourced from developing and less developed countries, which have historically faced challenges such as the 'resource curse' and various social, economic, and environmental issues related to resource development.

The United Nations Resource Management System (UNRMS) provides a comprehensive framework for sustainable resource management, emphasizing environmental, social, and economic viability (UNECE, 2022). To complement and support the implementation of UNRMS, ESCAP has developed a Sustainability Assessment Tool centered around a structured collection of indicators which acts as a "health checklist" to help identify priority areas where UNRMS could be applied.[2]

Potential for regional and international cooperation

International collaboration, including knowledge sharing and capacity-building initiatives, can support resource-rich countries in the Asia-Pacific region in overcoming obstacles and promoting the sustainable and responsible management of their critical mineral resources. By facilitating the exchange of best practices and expertise, cooperation among countries within the region and with international partners can enhance the responsible development of the critical mineral sector.

Promoting the sustainable development of critical minerals requires coordinated efforts among countries. As supply chains become more global and diverse, policy changes in one country can have significant impacts on others. Given the concentration of resources in a few countries, regional planning and close cooperation with neighbours are both necessary and desirable (ESCAP, 2023). This is particularly true given the potential economic decoupling or supply chain fragmentation driven by increasing geopolitical tensions among major countries. Efforts such as the ASEAN Principles for Sustainable Minerals Development, which were endorsed by ASEAN Ministers in 2023,[3] and the UN Secretary General's Panel on Critical Energy Transition Minerals (see box) demonstrate the value of collaboration at the sub-regional, regional, and global levels, and the importance of inclusive stakeholder consultations.

Priority actions in international cooperation for critical minerals development could be initiated along the supply chain, from production through trade and investment to consumption. Global standards and coordination efforts should be adopted to support responsible extraction and processing for sustainable development. Green finance coordination is essential to meet investment requirements for resilient and transparent supply chains, infrastructure, and human capital, ensuring long-term viability (UNEP, 2016). Additionally, international collaboration is needed to enhance supply chain transparency, facilitate free markets for critical minerals, and promote responsible sourcing practices to mitigate risks and prevent corruption (OECD, 2016). Technological

2 For additional information on the Sustainability Assessment Tool, see https://www.unescap.org/projects/critical-raw-materials-sustainability-assessment-tool

3 ASEAN, 9th AMMin Declaration on Promoting ASEAN as an Investment Destination for Sustainable Minerals Development. See https://asean.org/wp-content/uploads/2023/11/02-Final-Declaration-on-ASEAN-as-a-Sustainable-Minerals-Investment-Destination.pdf

Box 1. Secretary General's Panel on Critical Energy Transition Minerals

In 2024, the UN Secretary General launched the Panel on Critical Energy Transition Minerals.[4] Co-chaired by the European Union (EU) and South Africa.The Panel is made up of 24 countries and 14 non-state actors and aims to build trust among stakeholders by addressing key issues in the area of critical minerals development, focusing in particular on those metals and materials required for the energy transition. The Panel builds on existing standards and initiatives, particularly the UN Working Group on Transforming the Extractive Industries for Sustainable Development[5]. The primary output of the panel is a set of common and voluntary principles to build trust, guide the transition and accelerate the race to renewables.

While the Panel is organized around implications of the energy transition for the minerals sector, it has potential relevance to the extractive industries more broadly. The seven principles developed by the CETM Panel address a range of relevant issues, focusing in particular on: human rights; environmental integrity and biodiversity; benefit sharing, value addition, and economic diversification; investment, finance and trade; good governance; and, multilateral and international cooperation.

In addition, the Panel developed five actionable recommendations: accelerate greater benefit sharing, value addition and economic diversification; traceability for accountability; establish a Global Mining legacy fund; empower artisanal and small-scale miners towards responsibility; and, material efficiency and circularity targets to balance consumption and reduce environmental impacts.

4 For additional information on the UN Secretary General Panel on Critical Energy Transition Minerals, see https://www.un.org/en/climatechange/critical-minerals

5 For additional information on Secretary-General's Working Group on Transforming the Extractive Industries for Sustainable Development, see https://www.greenpolicyplatform.org/initiatives/working-group-transforming-extractive-industries-sustainable-development.

cooperation can drive innovation, reduce dependence on critical minerals, and optimize energy planning through the development and transfer of efficient, low-emission technologies and recycling initiatives. Through collaborative efforts, countries can diversify supply sources, harmonize regulations, and implement effective risk mitigation strategies, thereby creating a more resilient and transparent global market for CETMs (IEA, 2024).

Conclusion and key messages

The Asia-Pacific region has made notable advancements in achieving SDG 7. By 2022, under the target of energy access, electrification rates reached 98.3 per cent, with rural areas experiencing significant growth from 80.4 per cent in 2010 to over 97.4 per cent. However, disparities persist, especially in clean cooking access, where only 57.3 per cent of rural populations rely on clean fuels compared to 90.3 per cent in urban areas. Efforts like improved cookstoves and cleaner fuels have been implemented, particularly in countries such as India and China. Despite these strides, challenges remain, including financial constraints and inadequate policies, hindering further progress.

The region's reliance on fossil fuels continues to impact the share of renewable energy, which was just 16 per cent in 2021, reflecting a need for enhanced policies and investments. While there is robust growth in solar and wind power, the integration of renewables into the total energy mix is slow due to rising energy demand across various sectors. Opportunities lie in leveraging the region's abundant renewable resources and improving cross-border connectivity to enhance energy security and resource utilization.

Energy efficiency is another area where increased progress is essential. Although the region has shown a decline in energy intensity, it still lags behind the global average. Enhancing energy efficiency in buildings, industry, and transport can yield significant reductions in energy consumption.

Critical minerals play a crucial role in the energy transition, particularly in achieving the goals outlined in the Paris Agreement. As the demand for clean energy technologies rises, the need for critical minerals for developing batteries, renewable energy technologies and electric vehicles is also increasing rapidly. The Asia-Pacific region is pivotal in this context, possessing significant reserves of critical minerals, including approximately 30 per cent of the world's cobalt and lithium. However, this demand also presents challenges, including potential environmental degradation, social disruption, and issues related to supply chain vulnerabilities. For instance, reliance on a limited number of countries for mining and processing these minerals increases risks of supply disruptions due to geopolitical tensions.

To address these challenges, there is need for sustainable resource management and regional cooperation. The establishment of the UN Secretary General's Panel on Critical Energy Transition Minerals aims to develop common principles for responsible sourcing and governance. This collaborative approach is essential for ensuring that the growth of the critical minerals sector contributes to sustainable development while mitigating tis negative impacts.

With the window of opportunity to achieve SDG 7 rapidly closing, Asia-Pacific nations need to strengthen policy frameworks, foster regional cooperation, and invest in infrastructure and technologies to address the remaining challenges. The path forward involves balancing rapid development with sustainable practices, ensuring that all populations benefit from affordable and clean energy solutions while mitigating the impact on the environment.

Chapter 2

Cross-border power system connectivity initiatives in Asia and the Pacific

2.1. Drivers of cross-border power system connectivity in the Asia-Pacific region

The Asia-Pacific region, home to over half of the world's population, currently accounts for about 50 per cent of global primary energy demand and 60 per cent of global carbon emissions. The region's vibrant economic development, industrialization and rapid urbanization are set to drive significant increases in demand for energy. Power system connectivity offers an opportunity for countries to affordably and rapidly meet rising demand, while also enabling and accelerating energy transition. Progress on cross-border power system connectivity, however, has been slow, remaining mainly at the stage of bilateral agreements between neighboring countries. In comparison, other parts of the world including in Europe, the Americas, and Africa, have established formal multilateral power trading markets and in some cases incentives and financing mechanisms for developing cross-border transmission infrastructure.

There are many reasons for the relatively slow progress in expanding and deepening cross-border power connectivity and trade in the Asia-Pacific region, but a common and most pronounced challenge is a lack of or differentiated political will arising from historical geopolitical issues and differing national priorities, strategies and energy policies.

Nonetheless, in addition to the well-established economic benefits of trading electricity across borders, the emergence of notable driving forces for cross-border power interconnections and trade of renewable resources are helping the region build momentum for expanding bilateral and multilateral power trade.

A key driver is the need for countries to substantially increase the deployment of renewable energy resources to achieve SDG 7 and Paris Agreement targets for reducing GHG emissions, as well as COP-28 pledge to triple global renewable energy capacity by 2030.

Despite these pledges and commitments, as discussed in Chapter 1, the share of renewables in total final energy consumption remains stagnant for the region as a whole, with most progress on renewables uptake and capacity growth concentrated in a few countries. To achieve tripling renewable capacities by 2030, accelerating and scaling up cross-border power system integration has become an urgent priority.

The path to decarbonizing the energy sector requires a comprehensive and multifaceted approach, and for many countries in the region with less diverse supplies of energy and geographic limitations, accessing renewable energy sources outside their borders provides the most economic opportunity for increasing the share of renewables in their energy systems. Even for resource-rich countries, the integration of large volumes of renewables requires investments in complementary technologies like storage systems for grid stability, the need for which could be substantially reduced by expanding grids and enabling power trade across borders.

Table 1. Paris Agreement Pledges by Asia-Pacific countries

Party	NDC MITIGATION COVERAGE				
	Mitigation Summary				
	Mitigation Type	Mitigation Target	Baseline Year	Target Year	Net Zero Year
Afghanistan	Relative emission reduction	13.6% (conditional)	BAU	2030	2050
Armenia	Absolute emission reduction	40%	1990	2030	2050
Australia	Absolute emission reduction	43%	2005	2030	2050
Azerbaijan	Absolute emission reduction	35%	1990	2030	N/A
Bangladesh	Relative emission reduction	6.73% (unconditional), 21.85% (conditional)	BAU	2030	N/A
Bhutan	Policies and actions	Remain carbon neutral	N/A	N/A	Achieved
Brunei Darussalam	Relative emission reduction	20%	BAU	2030	2050
Cambodia	Relative emission reduction	41.7%	BAU	2030	2050
China	Carbon intensity reduction	65%	2005	2030	2060
Democratic People's Republic of Korea	Relative emission reduction	16.4% (unconditional), 52% (conditional)	BAU	2030	N/A
Fiji	Relative emission reduction	30% (energy sector)	BAU	2030	2050
Georgia	Absolute emission reduction	35% (unconditional), 50-57% (conditional)	1990	2030	N/A
India	Carbon intensity reduction	45%	2005	2030	2070
Indonesia	Relative emission reduction	31.89% (unconditional), 43.2% (conditional)	BAU	2030	2060
Iran (Islamic Republic of)	Relative emission reduction	4% (unconditional), 12% (conditional)	BAU	2030	N/A
Japan	Absolute emission reduction	46%	2013	2030	2050
Kazakhstan	Absolute emission reduction	15% (unconditional), 25% (conditional)	1990	2030	2060
Kiribati	Relative emission reduction	13.7%, 12.8% (unconditional), 62.5%, 61.8% (conditional)	BAU	2025, 2030	2050
Kyrgyzstan	Relative emission reduction	16.63% and 15.97% (unconditional), 36.61% and 43.62% (conditional)	BAU	2025 and 2030	2060
Lao People's Democratic Republic	Relative emission reduction	60% (unconditional)	N/A	2030	2050
Malaysia	Carbon intensity reduction	45% (unconditional)	2005	2030	2050
Maldives	Relative emission reduction	26% (conditional)	BAU	2030	2030
Marshall Islands	Absolute emission reduction	45%	2010	2030	2050
Micronesia (Federated States of)	Absolute emission reduction	65% from electricity generation	2000	2030	2050
Mongolia	Relative emission reduction	22.7% (unconditional), 27.2%, 44.9% (conditional)	BAU	2030	N/A

Mongolia	Relative emission reduction	22.7% (unconditional), 27.2%, 44.9% (conditional)	BAU	2030	N/A
Myanmar	Absolute emission reduction	emission reduction/avoidance of 245 MtCO2 (unconditional), 415 MtCO2 (conditional	N/A	2030	2050
Nauru	Policies and actions	N/A	N/A	2030	2050
Nepal	Policies and actions	Renewable energy generation increase	N/A	2030	2050
New Zealand	Absolute emission reduction	50%	2005	2030	2050
Pakistan	Relative emission reduction	15% (unconditional), 50% (conditional)	BAU	2030	2050
Palau	Policies and actions	22% (energy sector), 45% (renewable energy), 35% (energy efficiency)	2005	2025	2050
Papua New Guinea	Absolute emission reduction	Carbon neutrality (Energy industries sub-sector)	N/A	2030	2050
Philippines	Relative emission reduction	2.71% (unconditional), 72.29% (conditional)	BAU	2020-2030	N/A
Republic of Korea	Absolute emission reduction	40.0%	2018	2030	2050
Russian Federation	Absolute emission reduction	30%	1990	2030	2060
Samoa	Absolute emission reduction	26%	2007	2030	2050
Singapore	Peak of carbon emissions	65 MtCO2e	N/A	2030	2045
Solomon Islands	Absolute emission reduction	14% and 33% (unconditional), 41% and 78% (conditional)	2015	2025 and 2030	2050
Sri Lanka	Relative emission reduction	4% (unconditional), 14.5% (conditional)	BAU	2030	2060
Tajikistan	Absolute emission reduction	30-40% (unconditional), 40-50% (conditional)	1990	2030	N/A
Thailand	Relative emission reduction	20% (unconditional), 25% (conditional)	BAU	2030	2065
Timor-Leste (East Timor)	Policies and actions	N/A	N/A	N/A	N/A
Tonga	Absolute emission reduction	13% (Energy sector)	2006	2030	2050
Türkiye	Relative emission reduction	21%	BAU	2030	2053
Turkmenistan	Absolute emission reduction	Stablisation of GHG emissions	2000	2030	N/A
Tuvalu	Absolute emission reduction	60% (economy wide), 100% (electricity generation sector)	2010	2025	2050
Uzbekistan	Carbon intensity reduction	35%	2010	2030	2050
Vanuatu	Absolute emission reduction	Close to 100% RE in electricity generation (conditional)	2010	2030	2050
Viet Nam	Relative emission reduction	7.3% and 9% (unconditional), 27% by 2030 (conditional)	BAU	2025, 2030	2050

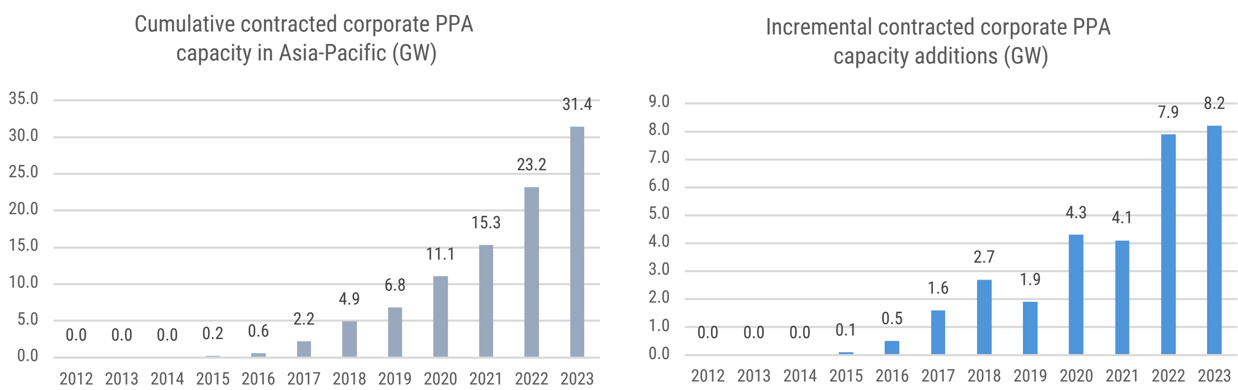
Source: IGES NDC Database version 7.7.

The potential economic benefits of power system connectivity have been well recognized in the region and a number of sub-regional and multilateral initiatives are at various stages of development. Now with the imperative to decarbonize the power sector, national energy objectives are becoming more aligned, providing policymakers with added incentive to move forward on cross-border collaboration.

Closely linked to national commitments and pledges on climate action, private sector demand for renewables is also playing an important role in driving energy transition, which in turn can incentivize governments to consider supplying clean energy to businesses through grid integration. In part, this demand is a direct result of government strategies and policies to promote the use of renewable energy in the private sector. For example, the European Union's Carbon Border Adjustment Mechanism (CBAM) which will be fully implemented starting January 2026, requires all European importers to purchase CBAM certificates corresponding to the carbon emissions associated with their goods, effectively making carbon intensive products more expensive for EU buyers. This potentially has large implications for the Asia-Pacific region considering that the EU is its third largest trading partner. As CBAM targets carbon-intensive products such as steel, iron, cement and aluminum which are major exports to the EU from countries in the region, greater efforts are being made to improve the carbon efficiency of these industries.

As an indication of the private sector's commitment to clean energy, over 430 companies have joined RE100, a global initiative aimed at accelerating the transition to renewable energy by bringing business leaders to source 100 per cent of their electricity from renewables. The combined demand of RE100 members has reached 565 terawatt hours (TWh) per year, which, if RE100 was a country, would be equivalent to the eighth largest electricity consuming country in the world (RE100 Climate Group, 2024). The Asia-Pacific region is dominating new membership to RE100 with 62 per cent or 36 new members joining from the region in 2023 as a growing number of businesses find value in being recognized as leaders and advocates of sustainable development. At the same time, a report by RE100 finds Asia Pacific markets to be among the most challenging in the world for companies to switch to 100 per cent renewable power. For example, Australia and Japan have higher renewable costs compared to other markets, while renewables are not available for corporate sourcing in the Republic of Korea. Singapore has limited domestic availability of or potential to develop renewables and the Russian Federation has limited options to purchase renewables. Moreover in China, regulatory complexities make it difficult for companies to source renewables (RE100 Climate Group, 2024).

Figure 11. Corporate PPA Capacity Growth and Additions in the Asia-Pacific Region



Source: ESCAP based on data from Wood Mackenzie (2023) "Route to green energy: Asia Pacific's corporate renewable procurement"

Box 2. A system for regionally recognized renewable energy certificates in Asia and the Pacific

Renewable Energy Certificates (RECs) are an accounting mechanism that evidence the generation of one megawatt-hour of electricity from renewable sources. They capture facts or attributes of power generation, such as location, time, and the type of renewable energy used. RECs enable the tracking, transfer, and claim of attributes associated with renewable generation, and can be transacted in either bundled or unbundled forms. Bundled transactions involve the purchase of both electricity and REC from a single actor, while unbundled transactions involve the purchase of RECs separately from physical electricity. Overall, RECs enable consumers to claim the use of renewable electricity, and to conduct transparent reporting on the origin of power they purchase, be it bundled or unbundled.

RECs serve two purposes globally: tracking compliance with renewable energy mandates and facilitating voluntary clean energy procurement. Compliance markets mandated REC use under regulations such as Renewable Portfolio Standards (RPS). In contrast, voluntary markets allow organizations to purchase RECs to demonstrate their use of renewable energy, often in alignment with reporting guidance set by disclosure or accounting frameworks like the Greenhouse Gas Protocol. The Asia-Pacific region is well-equipped to support both market types, offering a variety of REC products that meet the needs of buyers and sellers across the region. The International Renewable Energy Certificates for Electricity (I-REC(E)) is available in most Asia-Pacific markets for voluntary use, while some individual countries have developed tracking systems, primarily for compliance market purposes.

Beyond their immediate use in domestic markets, RECs also play an important role in supporting regional cooperation and trade across Asia and the Pacific. As regional bodies seek to expand multilateral power trade through initiatives like the APG and the LTMS-PIP, RECs serve as a key instrument to denominate the cross-border transfer of clean power and associated environmental claims. They are all a requirement of most electricity buyers seeking to engage in cross border transactions. While tracking systems such as the I-REC(E) currently allow cross-border REC transactions, the reporting frameworks (to which electricity consumers submit annual reports) do not generally recognize cross-border transactions anywhere in the Asia-Pacific region—creating potential barriers to buyer acceptance of cross border transactions. More can be done to formalize the views of governments and the private sector on cross-border REC and clean electricity transactions, potentially impacting the views and permissions afforded by international reporting systems like RE100 and Science Based Targets Initiative (SBTi).

The ASEAN subregion is currently leading efforts to develop replicable models that could set global precedents for the recognition of specific cross-border transaction by international frameworks. Initiatives underway include (i) developing bilateral recognition structures for the use of cross-border I-RECs redemptions (aligned with guidance promulgated by reporting frameworks), (ii) conceptualization of subregional governance bodies to empower national actors using shared REC systems, and (iii) preparation of associated framework materials to guide REC transactions within the subregion. Together, these initiatives seek to enhance regional collaboration, increase cross-border electricity trade and the commercial viability of projects, and increase the collective bargaining power of export nations as it relates to REC use under trade agreements like the CBAM.

Authors: Barry Jones, RECs and Supply Chain Specialist, SuSca Group and Roble P. Velasco-Rosenheim, Director of Partnerships and APAC, I-TRACK Standard Foundation

One option for Asia Pacific corporations for sourcing renewables is through off-site green power purchase agreements (PPA). The region's market for PPA has set a new record at 31.4 GW contracted by the end of 2023, a 35 per cent increase from 2022 (Wood Mackenzie, 2023). This trend shows that there are significant potential opportunities for, and benefits of providing companies' access to renewable energy through cross-border power system interconnections. Initiatives like the Green-Term Ahead Market (G-TAM) and Green Day Ahead Market (G-DAM) operated by the Indian Electricity Exchange (IEX) are also creating a new market segment for trading in renewables.

Emerging technologies are also catalyzing cross-border power connectivity by enabling larger volumes of electricity to be transmitted securely over longer distances and challenging terrains. While Chapter 5 provides a more in-depth discussion on technological enablers for cross-border connectivity, a few key technologies that are facilitating cross-border power connectivity are described in the following paragraphs.

<ins>High-voltage direct current (HVDC) technology</ins>

HVDC technology allows for efficient transmission of electricity over long distances with minimal losses, enables interconnection between grids that operate on different frequencies, and can support the efficient and secure integration of large-scale renewable energy sources. The Asia-Pacific region is the hub of cutting edge HVDC technology and related platforms to regulate and protect HVDC grids.

<ins>Smart grids and digitalization</ins>

Smart grids use digital technology to monitor and manage the flow of electricity in real-time, ensuring a stable and reliable power supply across interconnected regions. This is crucial for balancing supply and demand, especially with variable renewable energy sources like wind and solar. Special meters in houses and businesses, and sensors along transmission and distribution lines, can constantly monitor demand and supply, while synchrophasors measure the flow of electricity through the grid in real-time, allowing operators to foresee and avoid, or identify and manage, disruptions.

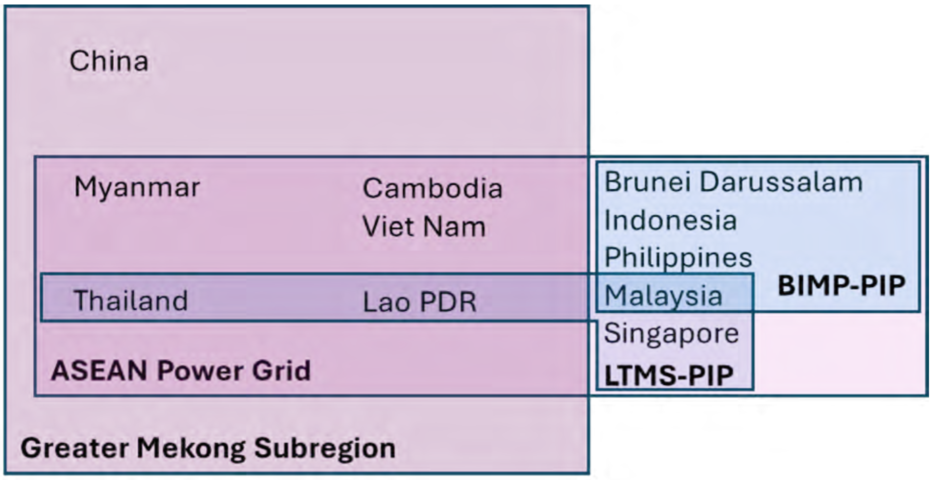
<ins>Energy storage systems</ins>

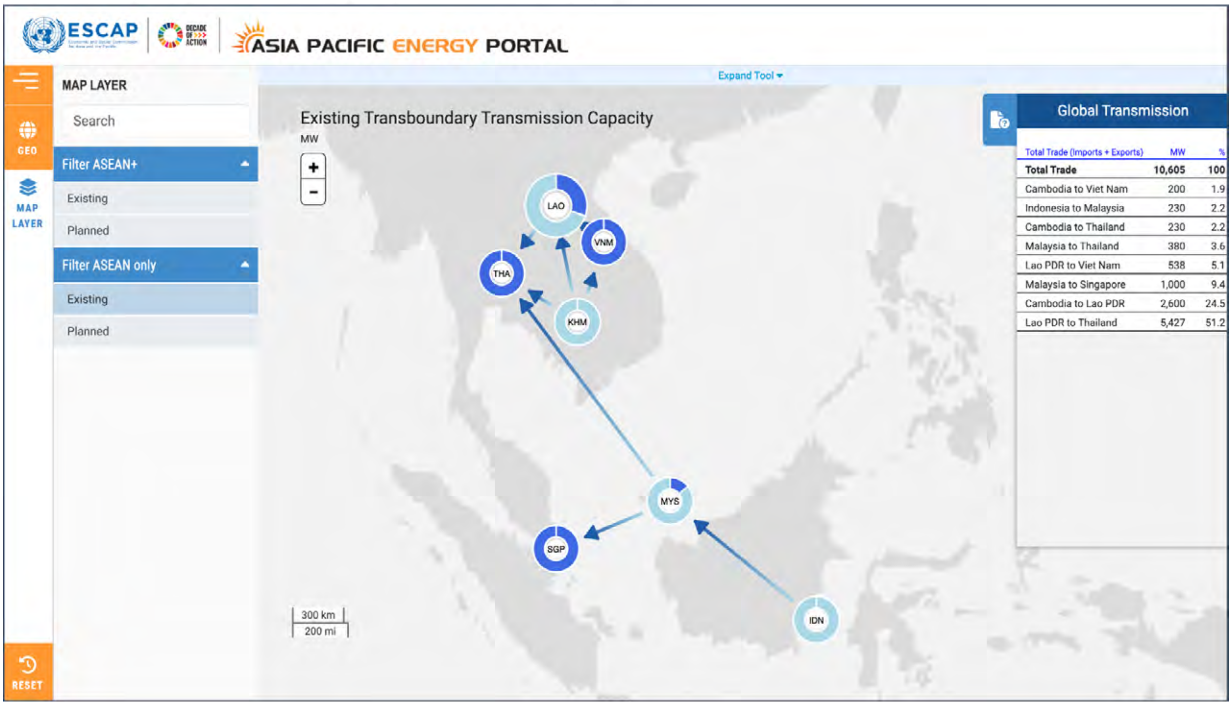
Advanced energy storage solutions, such as lithium-ion batteries and pumped hydro storage, help to balance supply and demand by storing excess energy during periods of low demand and releasing it during peak demand.

These grid-enhancing technologies are critical in supporting cross-border power interconnections as they enable the efficient, reliable and integrated operation of interconnected grids and exchange of renewable energy across borders.

2.2. Cross-border power system connectivity and energy cooperation initiatives in the Asia-Pacific region

2.2.1. South-East Asia





Source: Asia Pacific Energy Portal

Table 2. Multilateral energy cooperation and power interconnection initiatives in South-East Asia

Initiative	Key milestones
ASEAN Power Grid (APG)	• 2nd ASEAN Informal Summit adopted the APG as part of ASEAN Vision 2020 (1997) • ASEAN Plan of Action for Energy Cooperation (APAEC) 1999-2004 identified the APG as one of the six programme areas • ASEAN Interconnection Master Plan Study (AIMS) adopted focusing on initial interconnections among member states (2003) • MoU on the APG signed (2007) • AIMS II identified priority interconnection projects (2010) • AIMS III focused on increasing renewable energy integration through greater interconnection; phase 1 and 2 identified 18 interconnection projects (2022) • AIMS III Phase 3 to develop strategies for multilateral power trade (launched 2024)

Initiative	Key milestones
Lao PDR-Thailand-Malaysia- Singapore Power Integration Project (LTMS PIP)	• 32nd ASEAN Ministers of Energy Meeting recognized the proposed LTMS-PIP as a pathfinder project to enhance multilateral power trade (2014) • Launch of Lao PDR- Thailand- Malaysia Power Integration Project (LTM-PIP) (2018) • Singapore entered the LTM-PIP and launched LTMS PIP (2021) • LTMS-PIP Agreement to trade 100 MW of renewable hydropower signed for two years until 2024 (2022) • Announcement of phase II of the LTMS-PIP with electricity traded increased from 100 MW to 200 MW until 2026 (2024)
Brunei Darussalam-Indonesia- Malaysia-Philippines Power Interconnection Project (BIMP PIP)	• BIMP-PIP launched (2023)
Greater Mekong Subregion (GMS) Economic Cooperation	• Economic Cooperation Program among the six GMS countries (Cambodia, China, Lao PDR, Myanmar, Thailand, Viet Nam) launched (1992) • Formation of the subregional Electric Power Forum (1995) • Establishment of the Experts Group on Power Interconnection and Trade (1998) • Developed the GMS Strategic Framework (2002) • Endorsement of the GMS Policy Statement on Regional Power Trade (2000) and Inter-governmental agreement to implement the policy statement signed (2002) • Regional Indicative Master Plan on Power Interconnection developed (2002) • Establishment of the Regional Power Trade Coordination Committee (RPTCC) (2003) • MOU on establishing a Regional Power Coordination Centre signed (2012) – discussions ongoing • RPTCC transitioned to the GMS Energy Transition Task Force (ETTF) (2022)

Recent developments in focus

Lao PDR- Thailand- Malaysia- Singapore Power Interconnection Project (LTMS- PIP)

The LTMS-PIP is a key initiative in the ASEAN region representing the first multilateral cross-border electricity trading agreement to be operationalized. As such, the initiative has been called a "pathfinder project", leading the APG towards the goal of a fully interconnected region.

Following the successful launch and operation of the Lao PDR- Thailand- Malaysia Power Integration project (LTM-PIP) in 2018, with the first transfer of 100MW of power between Lao PDR and Malaysia through Thailand occurring in 2019, Malaysia renewed and expanded the contract for another two years (2020-2021) to purchase 300MW of hydropower. In 2022, Singapore joined the trading chain, creating what is now known as LTMS-PIP.

The actual amount of energy flows in LTMS since the start of LTMS-PIP in June 2022 was around 260 GWh. However, due to severe droughts in Lao PDR in 2023, energy flows all but stopped. This illustrates the need for LTMS countries to diversify the source of renewable energy traded in order to mitigate seasonal patterns and weather events that can have a negative impact on not only the volume of trade but grid stability and reliability.

For example, as shown in Table 2, in addition to the large existing hydropower resources in Lao PDR, Thailand has substantial solar energy resources that could potentially be used to supply clean electricity to its neighboring countries.

A notable development expected to facilitate the trade of clean electricity is the announcement by the Malaysian government in April 2024 to enable the Malaysian Energy Exchange to buy and sell cross-border "green electricity". During the pilot phase (100MW), utilizing the existing connection between peninsular Malaysia and Singapore, renewable energy bidders in Singapore will be able to purchase energy through an auction system.

Table 3. Renewable energy potentials in LTMS (GW)

Country	Solar	Wind	Biomass	Hydro	Geothermal
Lao PDR	983	11.9	1.2	26	0.1
Malaysia	337	53.3	4.2	28	-
Thailand	3509	62	18	15	-
Singapore	0.3	0.3	-	-	-

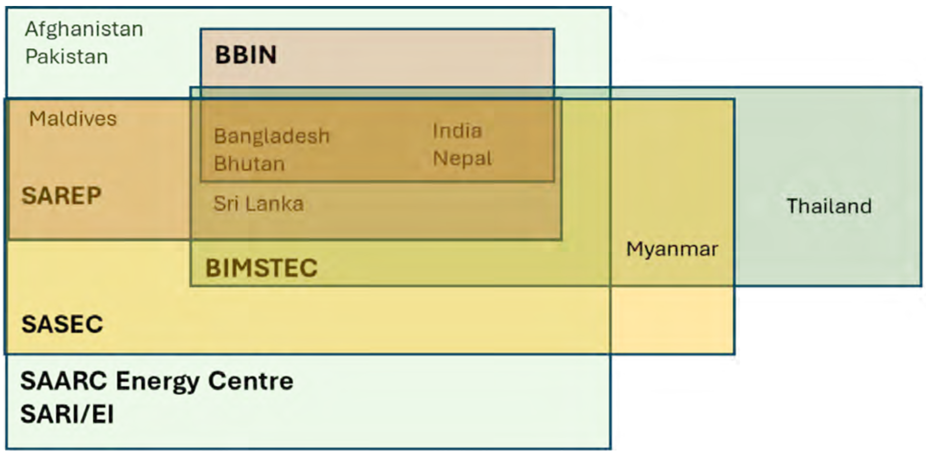
Source: IRENA (2022)

While the LTMS-PIP has played an instrumental role in demonstrating the benefits of multilateral power interconnections, it also highlighted a number of challenges. While the extension and expansion of the agreement was announced in 2024 for phase II which will add another two years of electricity trading under LTMS-PIP, there are still some of the underlying issues that the four countries need to come to an agreement on. One such issue involves finding an agreed method for calculating wheeling charges. In an effort to operationalize the LTMS-PIP as early as possible, the LTMS countries forged ahead without deciding on a transparent and fair methodology for allocating transit costs. In order to resolve this, further discussion is needed on which methodology best reflects the situation of LTMS and to a larger extent, the ASEAN Power Grid.

Another key challenge is outdated infrastructure. Apart from the undersea cable upgrade in 2022 connecting Malaysia and Singapore, the LTMS-PIP has been using existing infrastructure with limited capacities. Considering the future requirements for integrating substantially larger quantities of variable renewable energy into the grids, while phasing-out thermal generation plants acting as balancing assets, and rising demand for electricity itself, there is pressing need to invest in grid upgrades.

At the 42nd ASEAN Ministers on Energy Meeting held in September 2024, the importance of establishing necessary regulatory, policy, commercial and technical frameworks to advance cross-border electricity was recognized. In particular, the need for upgrading cross-border interconnections and deploying related technologies such as subsea cables was highlighted. In this regard, the Meeting noted investment requirements to finance regional interconnection projects to advance the APG, and welcomed the initiative by the Asian Development Bank (ADB) and World Bank to establish a dedicated financing facility for the APG.

2.2.2. South and South-West Asia



Source: Asia Pacific Energy Portal

Table 4. Multilateral energy cooperation and power interconnection initiatives in South and South-West Asia

Initiative	Key milestones
Bangladhes-Bhutan-India-Nepal	• South Asian Growth Quadrangle (SAGQ- Bangladesh, Bhutan, India, Nepal) approved by the SAARC Council of Ministers with a focus on six sectors including energy (1996) • SAGQ create the SASEC Program in 2001 with support from ADB → Continued discussion on BBIN energy cooperation • Tripartite power sales agreement among India, Nepal and Bangladesh (2024)
South Asia Regional Energy Partnership (SAREP)	• SAREP launched with the aim of accelerating transition to clean energy, mitigate climate change and promote energy security (2020)
South Asia Subregional Economic Cooperation (SASEC)	• Established in 1997 with BBIN countries. Maldives, Sri Lanka join in 2014, and Myanmar in 2017 • SASEC Energy Working Group established (2001) • SASEC Electricity Transmission Utility Forum established (2013) • SASEC Operational Plan adopted (2016) • Subregional Strategic Development Road Map launched (2017)
Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC)	• Established (1997) • Renamed as BIMSTEC, during the First Summit Bangkok (2004) • Plan of Action for Energy Cooperation in BIMSTEC formulated during the first BIMSTEC Energy Ministers' Conference (2005) • MOU for establishment of BIMSTEC Energy Centre signed (2011) • MoU for the establishment of BIMSTEC Grid Interconnection Committee signed (2018)
SAARC (South Asian Association for Regional Cooperation) Energy Centre	• Established (2006) • SAARC Inter-Governmental Framework Agreement (IGFA) for Energy Cooperation signed (2014)
South Asia Regional Initiative for Energy Integration (SARI/ EI)	• Established (2000) • Phase I: capacity building and information exchange (2001-2004) • Phase II: focused on legal and regulatory frameworks for cross-border trade (2004-2007) • Phase III: groundwork for regional energy market formation (2007-2012) • Phase IV: focus on institution building and establishing the South Asia Regional Energy Market (2012-2022)

Recent developments in focus

Bangladesh- Bhutan- India- Nepal Initiative (BBIN)

Among countries in South and South-West Asia, Bangladesh, Bhutan, India and Nepal have made notable progress on power system integration in recent years, and are looking to engage in and expand cross-border electricity trade, leveraging both seasonal and spatial complementarities in power generation resources.

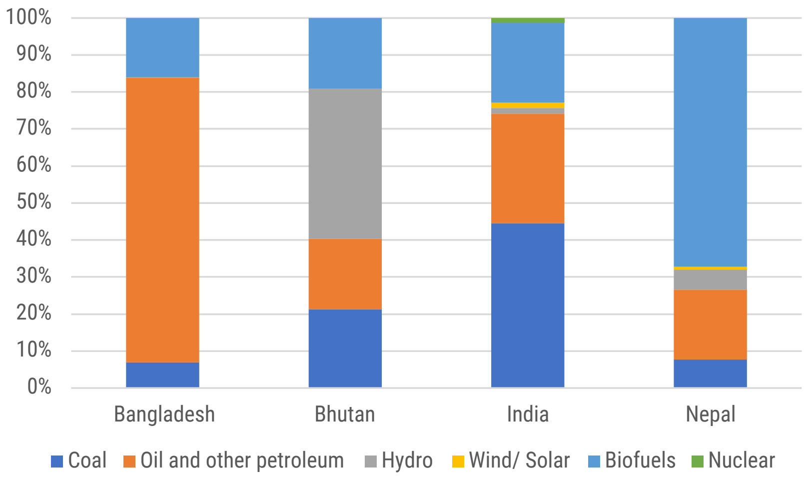
Bangladesh has made significant strides in its power grid interconnection with India. In 2022, the Bangladesh Power Development Board (BPDB) announced plans to increase its electricity import capacity from India to address rising domestic energy demands. Currently, Bangladesh imports around 1,200 MW of electricity from India and is actively pursuing the construction of additional transmission lines to enhance its capacity further.

In addition to infrastructure expansion, Bangladesh is also looking to diversify its energy sources. In early 2023, the BPDB signed a memorandum of understanding with India to establish a framework for importing electricity from renewable sources including solar and wind. This partnership aims to support sustainable energy development and align with Bangladesh's commitment to increasing the share of renewables in its energy mix.

Bhutan similarly is continuing to strengthen its hydropower collaboration with India where a Joint Vision Statement on India- Bhutan clean energy partnership was announced in March 2024. In addition to existing hydropower projects jointly developed by the two countries, new hydropower projects as well as green hydrogen and solar energy projects are being explored. Furthermore, Bhutan is looking into opportunities to enhance its energy ties with Bangladesh and Nepal.

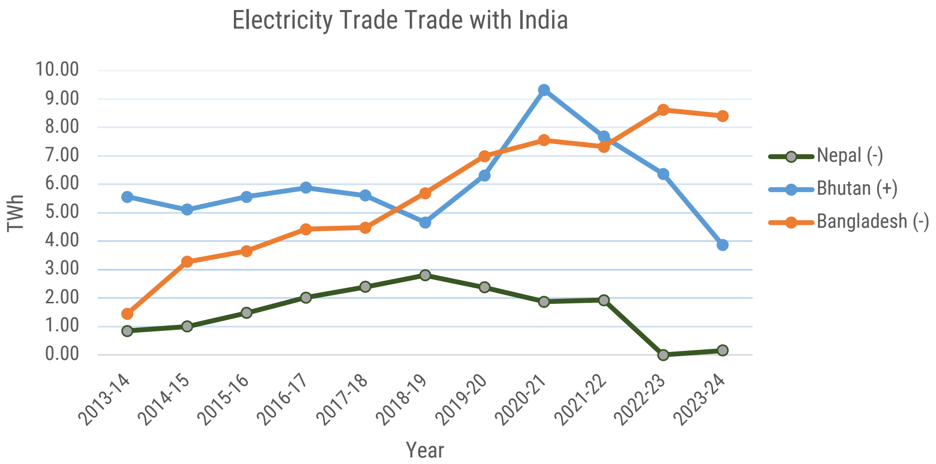
Alongside these bilateral agreements and projects, a ground-breaking tripartite power sales agreement among India, Nepal and Bangladesh has been signed in October 2024, marking the first multilateral trading arrangement in the region, and a significant step toward power system integration. Under the new agreement Nepal will export 40 MW of hydropower to Bangladesh on a seasonal basis through the Indian grid. Similarly, in January 2024, Nepal and India opened three new cross-border transmission lines to support the long-term agreement for Nepal to export 10 GW of power to India, with further plans to export an additional 5 GW to other neighboring countries via India in the next twelve years.

Figure 12. Total energy supply by source in BBIN countries (2021)



Source: IEA, Bhutan Ministry of Energy and Natural Resources (Bhutan data is for 2022)

Figure 13. Cross Border Trade of Electricity between India and its Neighboring Countries, 2013-14 to 2020-21 (BU)/(TWHs)

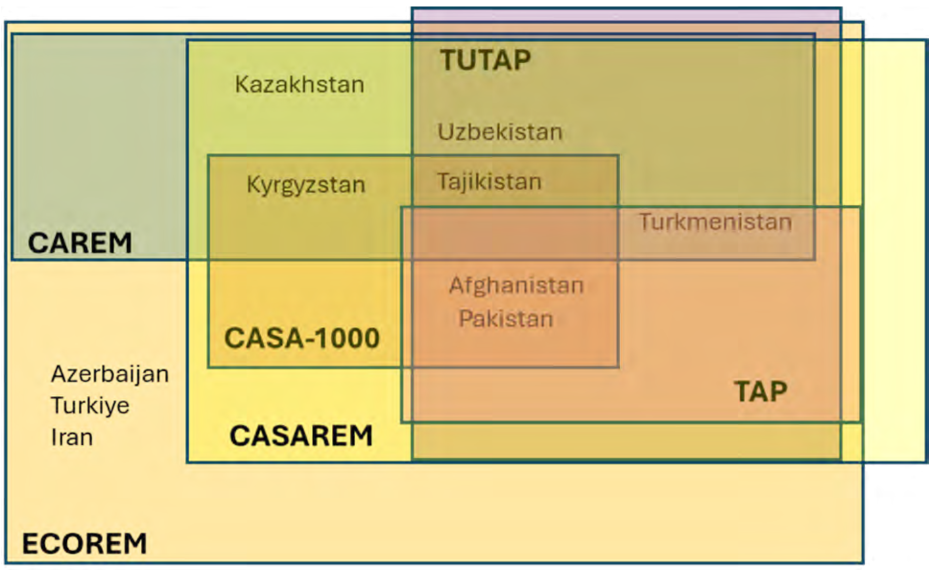


Source: Grid Controller of India Ltd. https://posoco.in/en/ and Annual Report, Ministry of Power, India (2023-24)

In addition, Nepal and Bhutan have been participating in the Indian Power Exchange Platform (IEX), where the exchange of power takes place on an auction basis, and Bangladesh is likely to join this exchange platform soon.

With these recent developments highlighting the commitment of the BBIN countries to regional cooperation and sustainable energy development, an important next step is to move towards establishing a multilateral and dynamic market for power trade. While long-term power purchase agreements provide a secure and predictable trading environment, a dynamic system offers additional benefits in terms of optimizing resource allocation, supporting efficient and effective integration of variable renewable energy sources, and lowering transaction costs.

2.2.3. Central Asia and South Asia



Source: Asia Pacific Energy Portal

Table 5. Multilateral energy cooperation and power interconnection initiatives in Central Asia and South Asia

Initiative	Key milestones
Turkmenistan-Afghanistan- Pakistan (TAP) power interconnection project	• MOU for tripartite negotiation signed (2015) • Framework Agreement for TAP Power Interconnection Project signed (2018) • Phase I linking Turkmenistan and Afghanistan completed (2021) • Phase II ongoing
Tajikistan- Uzbekistan-Turkmenistan-Afghanistan- Pakistan power interconnection project (TUTAP)	• Framework Agreement to formalize commitment to TUTAP (2014) • Construction of TUTAP transmission lines and infrastructure commenced (2017)
Central Asia South Asia power interconnection project (CASA-1000)	• MOU signed (2013) • Approved by the World Bank Board (2014) • Agreed to the “Core Project Agreements” (2015) • Framework Agreement signed (2016) • Construction commenced (2017) • Operation to commence (2024-2025 - estimated)
Central Asia South Asia Regional Electricity Market (CASAREM)	• CASA-1000 Framework Agreement includes the creation of CASAREM (2016) • Feasibility studies are being conducted (2018 -)
Economic Cooperation Organisation Regional Electricity Market (ECOREM)	• High-level proposal made (2012) • A coordination meeting held by ESCAP (2024)

Recent developments in focus

Economic Cooperation Organization Regional Electricity Market

In 2012, during the second Economic Cooperation Organization (ECO) High Level Experts Group Meeting on Energy in Türkiye, a proposal to establish the ECO Regional Electricity Market (ECO-REM) was made by Iran, and in 2013, this proposal received additional support during the 23rd ECO Regional Planning Council Meeting in Iran.

The member States of ECO[6] have diverse energy supply and demand patterns, ranging from fossil-fuel and hydropower-rich countries to ones with limited domestic energy resources, and including energy import, export, and transit countries. As a whole, however, these countries possess significant untapped energy potential, renewable energy sources in particular, that could, if developed in coordination with increased cross-border and regional connectivity, contribute to regional energy security and reductions in energy sector carbon emissions. Fully unlocking the benefits of renewable energy resources to meet energy sustainability, affordability, and security goals requires the ECO countries to combine efforts to reduce regulatory, technical and economic barriers to develop and trade the diverse range of low-carbon energy resources available to them.

At the same time, initiatives among different subsets of countries in Central Asia and South Asia including CASA-1000 (Afghanistan, Kyrgyzstan, Pakistan,

6 Available from the Member States section of the Economic Cooperation Organization website (https://eco.int/).

Table 6. Regional cross-border electricity trade (TWh) in 2023

	Kazakhstan	Uzbekistan	Kyrgyzstan	Tajikistan	Turkmenistan	Afghanistan	Pakistan	Iran (Islamic Republic of)	Azerbaijan	Türkiye
Kazakhstan		–	1.44 0.07	–	–	–	–	–	–	–
Uzbekistan	–		–	0.91	4.01	1.82	–	–	–	–
Kyrgyzstan	0.07 1.44	–		0.01 0.02	1.77	–	–	–	–	–
Tajikistan	–	0.91 0.80	0.02 0.01		–	1.53	–	–	–	–
Turkmenistan	–	4.01	1.77	–		1.42	–	1.74**	–	–
Afghanistan	–	1.82	–	1.53	1.42		–	0.71	–	–
Pakistan	–	–	–	–	–	–		0.50*	–	–
Iran (Islamic Republic of)	–	–	–	–	1.00* 0.89*	0.71*	–		0.03 0.03	0.15*
Azerbaijan	–	–	–	–	–	–	–	0.03 0.03		1.58
Türkiye	–	–	–	–	–	–	–	0.15*	0.151*	

Source: Kazakhstan (Bureau of National Statistics, CDC "Energia"); Uzbekistan (CDC "Energia"); Kyrgyzstan (CDC "Energia", estimated data); Tajikistan (ITC Trade Map, CDC "Energia"); Turkmenistan (CDC "Energia", National Statistical Committee of the Kyrgyz Republic, Media Turkmen (ORIENT, 2024), UN Comtrade); Afghanistan (National Statistics and Information Authority, CDC "Energia"); Pakistan (EIA, NEPRA); Iran (Islamic Republic of) (US Energy Information Administration, Iran Grid Management Company, National Statistics and Information Authority of Afghanistan, National Electric Power Regulatory Authority of Pakistan, CDC "Energia", National Statistical Committee of the Kyrgyz Republic, State Statics Committee of the Republic of Azerbaijan, Turkish Electricity Transmission Corporation).

Note: * – data for 2022; ** – estimated; green figure = exports; red figure = imports

Tajikistan), TUTAP (Afghanistan, Pakistan, Tajikistan, Turkmenistan, Uzbekistan) and TAP (Afghanistan, Pakistan, Turkmenistan) were able to make promising progress, demonstrating the willingness of countries in the region to step-up power interconnections and trade by linking Central Asia's excess energy resources with South Asia's energy shortages. It is also worth noting that CASA-1000, TUTAP and TAP are part of the wider plan for realizing the Central Asia-South Asia Regional Electricity Market (CASAREM).

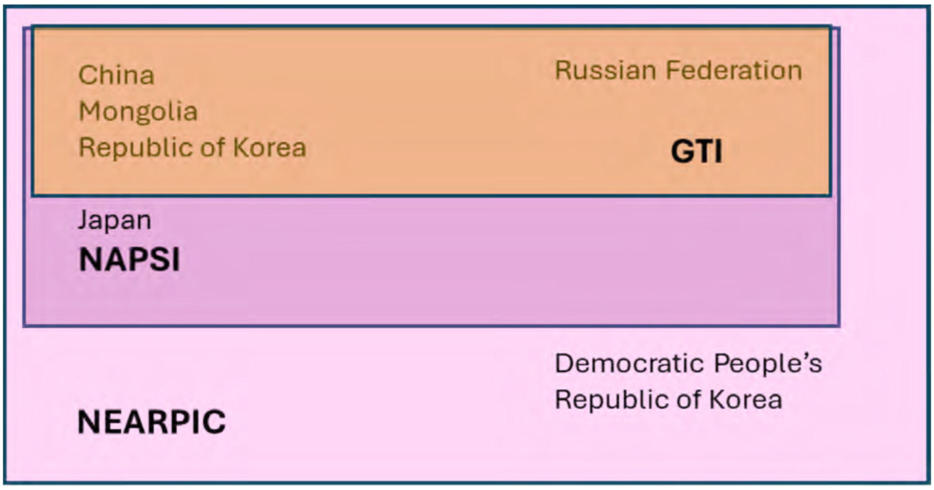
While recognizing that the establishment of a regional electricity market encompassing a larger number of countries with diverse energy market profiles and resources would enhance the benefits of power trade through increased resource optimization, grid resilience and facilitate greater renewable energy integration, ECO-REM faces a number of challenges which has hindered its progress. Some of these challenges include securing continued funding from international financial institutions, logistical issues and political stability (Table 7).

Table 7. Key common and specific challenges for the ECO-region

Issues	Mostly common issue for the region	Specific issue for a few countries from the region
Economic and political issues		
Long standing political issues		+
Territorial disputes in the region		+
International economic sanctions		+
Long-term economic sustainability issue	+	
High level of income inequality and poverty		+
Limited foreign direct investments	+	
Issues for power markets		
Gaps in the legal and regulatory framework for power markets		+
Lack of strategy planning for power markets		+
Lack of or limited regional and/or subregional power markets		+
Lack of a political consensus for subregional power markets		+
Low level of energy infrastructure development		+
Issues with energy security of power supply in countries, including power shortages, high share of the electricity import, issues with energy connectivity inside countries		+
Diverse country-specific demand-supply patterns and supply security (i.e. some countries have power abundance from own generation, while some experience power shortages)		+
Low availability of primary energy resources		+
Initial level of power market development (and different power market development status)		+
Inflexible energy tariff regulation and lack of cost-recovery tariffs		+
Insufficient development of renewable energy power		+
Dependence from import of energy technologies (lack of equipment for the production, transmission and distribution of electricity; lack of capacities to produce the equipment for alternative RES) and lack highly qualified specialists with international experience	+	
Limited data sharing opportunities	+	

Source: ESCAP (2024, forthcoming) "Regional Road Map on Power System Connectivity"

2.2.4. East and North-East Asia



Source: Asia Pacific Energy Portal

Table 8. **Multilateral energy cooperation and power interconnection initiatives in East and North-East Asia**

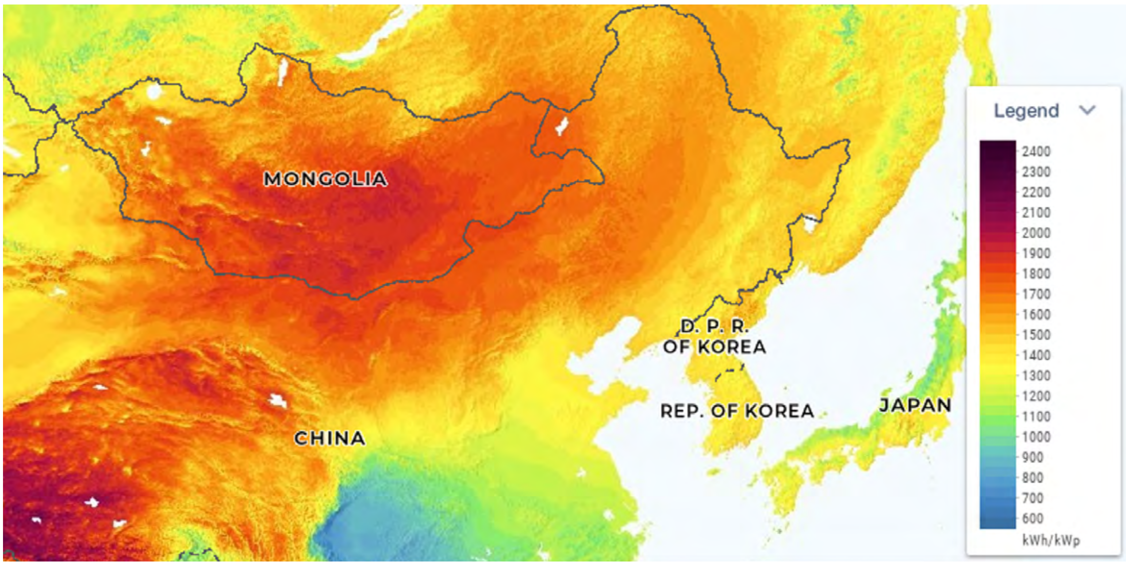
Initiative	Key milestones
North-East Asia Power System Integration (NAPSI)	• Project launched (2017) • Phase I: developed overall strategy (2017-2020) • Phase II: conducted feasibility studies (2021-2024)
North-East Asia Regional Power Interconnection Cooperation (NEARPIC)	• Launched (2016) • Steering Committee formed (2018) • Green Power Corridor Roadmap for North-East Asia launched (2023)
Greater Tumen Initiative (GTI)	• Originally launched as Tumen River Area Development Programme (TRADP) (1991) • Agreement on the establishment of the TRADP Consultative Commission launched (1995) • Tumen Secretariat launched (1996) • Renamed the Greater Tumen Initiative with five priority sectors including energy (2005) • Energy Board created (2007)

Recent developments in focus

North-East Asia Power System Integration Project (NAPSI)

The North-East Asia Power System Integration Project (NAPSI) is an ambitious initiative launched in 2017, led by the Asian Development Bank aimed at enhancing regional electricity connectivity among China, Mongolia and the Republic of Korea with possible buildout to Japan and the Russian Federation at a later stage. The project seeks to create an electricity market that optimizes power generation and distribution across these countries using Mongolia's vast wind and solar energy resources (Figure 14 and Figure 15).

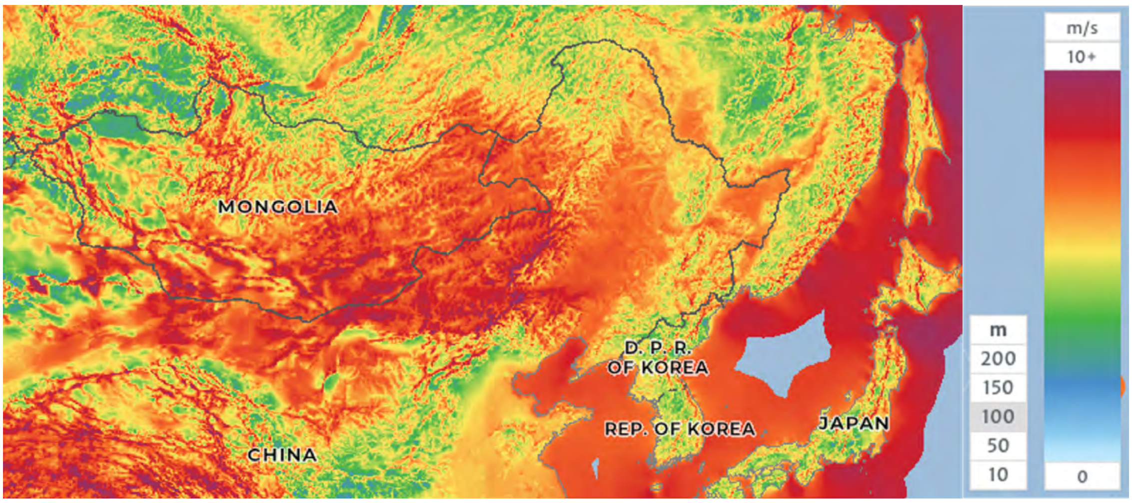
Figure 14. Solar potential in North-East Asia



Source: Global Solar Atlas (2023)

Disclaimer: The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by the United Nations

Figure 15. Wind potential in North-East Asia



Source: Global Solar Atlas (2023)

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Despite North-East Asia being home to some of the largest energy producing and consuming countries in the world, regional power trade and cooperation have been limited to bilateral trade between China and Mongolia, China and the Russian Federation, and Mongolia and the Russian Federation. Mongolia's electricity imports accounted for around 22.3 per cent (2,447.6 GWh) of total electricity generation in 2023 (Energy Regulatory Commission of Mongolia, 2023). The electricity imported from China is mainly used for supplying power to the Oyu-Tolgoi mines, while electricity from the Russian Federation (a much smaller quantity) supplies power to the main grids.

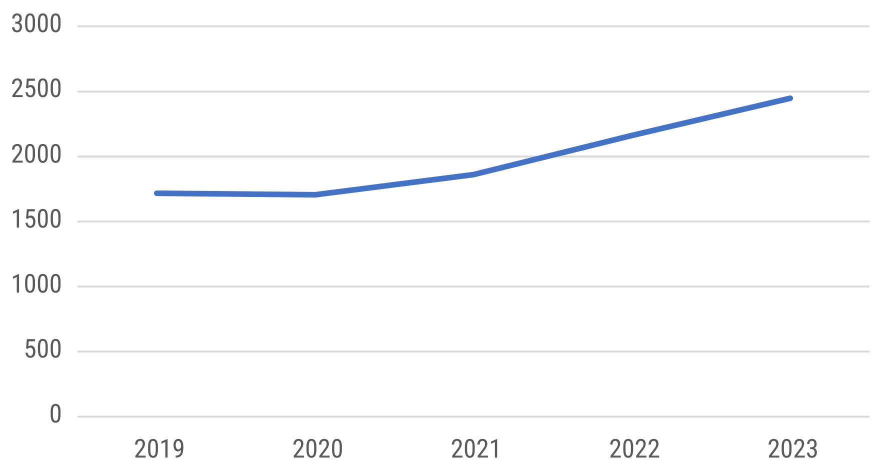
The steady rise in electricity imports by Mongolia (Figure 16) indicates that Mongolia's domestic supply of energy cannot meet its increasing demand, and despite the huge potential, renewable energy development remained stagnant at around 10 per cent of total power generation. There are several interrelated factors slowing the progress of Mongolia's development of renewable resources, one of which is the higher cost of renewables compared to coal-generated electricity due to grid infrastructure limitations and difficulties in scaling up renewable energy projects.

The North-East Asia Power System Integration (NAPSI) Project aims to help resolve these issues through cross-border grid connectivity, which would bring required investments for infrastructure development and allow renewable projects to achieve economies of scale.

During Phase 1 of the NAPSI Project (2017-2020), an overall strategy for NAPSI was developed, demonstrating its value in promoting sustainable power system interconnection in the region. The strategy identified three main components for realizing NAPSI; (i) development of 5 GW of solar and wind generating capacity in the South Gobi region of Mongolia, (ii) construction of a transmission interconnection between South Gobi and China, and (iii) construction of an undersea transmission interconnection between China and the Republic of Korea. Phase II of the NAPSI Project (2021-2024) aimed at developing a buildout strategy following the identified components above, as shown in Figure 17.

Phase II of the NAPSI Project concluded in May 2024 and produced a feasibility study on developing 5 GW solar and wind power generation capacity in Mongolia's South Gobi

Figure 16. Mongolia's electricity import (GWh)



Source: Energy Regulatory Commission, Mongolia

Figure 17. Proposed design of NAPSI Phase 1

source: NAPSI (year)

Disclaimer: The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by the United Nations

region, a study of the transmission interconnections from the South Gobi renewable generating base to China financial analysis of the cost of exporting power to the Republic of Korea, and an analysis of potential alternatives for renewable power production in the South Gobi region, including green hydrogen.

An important next step to operationalize the NAPSI Project is for China and Mongolia to enter into a bilateral agreement to secure infrastructure investment.

2.2.5. Pacific

OPERA

- Cook Islands
- Federal States of Micronesia
- Fiji
- French Polynesia
- Kiribati
- Marshall Islands
- Nauru
- New Caledonia
- Niue
- Palau
- Papua New Guinea
- Samoa
- Solomon Islands
- Tonga
- Tuvalu
- United States
- Vanuatu

Table 9. **Multilateral energy cooperation and power interconnection initiatives in the Pacific**

Initiative	Key milestones
Office of the Pacific Energy Regulators Alliance (OPERA)	• Established (2016) • MOU with the Pacific Community (SPC) signed to formalize OPERA under SPC (2021) • OPERA Business plan for 2021-2026

Recent developments in focus

Office of the Pacific Energy Regulators Alliance (OPERA)

The Pacific island countries (PICs) face extreme challenges when it comes to clean, affordable and secure access to energy. Their geographical isolation and dispersion complicate energy infrastructure development and small population sizes make it economically unfeasible to extend centralized electricity grids. Furthermore, while some countries have access to renewable energy resources such as solar, wind and hydropower, many others lack these resources and rely heavily on imported fossil fuels for electricity generation, which are not only costly but also contribute to greenhouse gas emissions and environmental degradation. Exacerbating the energy access issue is the subregion's high exposure to natural disasters, in particular extreme weather events, which often lead to damages to power generation and distribution systems.

As such, investments in off-grid solutions or micro-grids and energy storage systems that enable the wider use of renewable energy resources are being prioritized in many PICs. Regional cooperation centered around knowledge exchange, capacity building and promoting best practices, has been a key strategy to accelerate the development and deployment of some of the emerging technologies that have the potential to support energy access. As development finance is critical to PICs in enhancing energy sector development, regional cooperation mechanisms have been helping to raise awareness and to provide a platform for the countries to voice their collective concerns.

OPERA, launched in 2016 with support from ADB, was established to enhance cooperation among energy regulators across PICs, driven by the recognition that effective energy regulation is crucial for achieving sustainable energy goals in the Pacific region.

Since its establishment, OPERA has been fostering regional integration and working to improve regulatory capacity to facilitate energy sector reforms, promote renewable energy investments, and to ensure energy services are accessible, affordable and reliable.

Box 3. Energy transition in the Pacific Islands: Technologies, financing and regulatory reforms

To realize effective energy transition in PICs, the integration of innovative technologies, robust financing mechanisms and supportive policy reforms are essential to overcome the inherent and unique challenges facing these countries. On the technology front, microgrids have emerged as an attractive solution to address the challenges of remoteness and small population sizes which often make access to electricity through national grids prohibitively costly. Microgrids are helping the PICs reduce their reliance on imported fossil fuels, increase energy resilience and integrate renewable energy sources such as solar and wind. The declining cost and increasing efficiency of battery storage over the past decades has been a key enabler of microgrids in the Pacific. Between 2010 and 2021, the cost of lithium-ion battery packs fell by around 89 per cent from over USD 1,100 per kWh to USD 137 per kWh with projections of further reductions in the coming years. Many PICs including Fiji, Vanuatu, Samoa, and Tonga have developed solar microgrids combined with battery storage systems to significantly improve energy access and security as well as contributing to national carbon reduction goals.

These projects have benefitted from a variety of financing options that are now being offered by multilateral development banks and financing facilities to help reduce the risk and burden of high upfront investment of renewable energy projects. Some of the financing mechanisms include blended finance, green bonds, crowdfunding and community financing. In 2017, Fiji became the first PIC to issue a sovereign green bond, raising funds for climate resilience and renewable energy projects, demonstrating that PICs can tap into international capital markets for climate-related projects. For smaller-scale renewable energy projects, community-led financing initiatives have been explored to leverage local resources and provide greater ownership to communities. For example, Vanuatu's Rural Electrification Project has utilized a Pay-As-You-Go model to allow rural households to access solar home systems. Users pay for the energy generated through small, manageable payments, increasing affordability while providing energy access to remote areas.

Concurrently, regulatory reforms, particularly improvements in tariff setting practices are playing a critical role in providing a stable and investment-friendly environment for the greater deployment of renewable energy. For example, Fiji's feed-in-tariff scheme has been revised to offer guaranteed prices for electricity generated from renewable sources through long-term power purchase agreements. Also, Tonga has plans to gradually phase-out fossil fuel subsidies to create a level playing field for renewable energy projects.

Regional cooperation to pool resources and knowledge can help further lower the cost of renewable energy technologies and enhance the affordability and scalability of renewable energy projects in the region.

Conclusion and key messages

The Asia-Pacific region is seeing growing momentum for cross-border power system connectivity, driven not only by economic benefits but increasingly the need to accelerate the energy transition by connecting to renewable resources across borders. Concurrent efforts by governments to meet national net-zero targets and by the private sector to source clean energy are invigorating discussions and actions on power connectivity and trade at the subregional level, and enabled by technological advancements allowing for interconnection across long distances and challenging terrains.

In South-East Asia, the APG is moving forward, with the LTMS-PIP acting as a pathfinder project for multilateral power trading, as well as the recent launch of the BIMP-PIP. Additionally, the AIMS III Phase 3 focusing on operationalizing ASEAN multilateral power trade, launched in 2024, has been recognized by the Ministers of Energy of ASEAN member countries as a strategic path to enhancing renewable energy integration.

In South Asia, the tripartite agreement signed by Bangladesh, India and Nepal represents the beginning of multilateral power trading. With active trade occurring bilaterally between Bhutan and India, interest from neighbouring countries such as Sri Lanka, and current and future plans for infrastructure development, the operationalization of the tripartite agreement has potential to set the stage for the expansion of multilateral power trade in the region.

In Central Asia and South Asia, there are a number of projects underway including CASA-1000, TAP and TUTAP linking the region's vast renewable energy resources in Central Asia to South Asia. At the same time, discussions to develop a wider electricity market encompassing all of these projects under the proposed ECO-REM is also occurring with a roadmap being launched in 2024.

In North-East Asia, the NAPSI project has just completed a detailed plan for infrastructure build-out from Mongolia to China in 2024.

In the Pacific, although power connectivity is not a viable option due to the vast distances and small market size, the establishment of OPERA is enabling cooperation among the PICs to share and adopt best practices in regulations promoting clean and resilient energy systems.

Each subregion has its own unique set of opportunities challenges, driven by differing political and economic contexts and resource availability. However, a common factor across all areas is the need to secure robust support and commitment from a diverse array of stakeholders. ESCAP's Regional Road Map on Power System Connectivity, discussed in the following chapter, outlines the strategies and actions necessary to develop sustainable interconnection projects throughout Asia and the Pacific.

Chapter 3

Regional Road Map on Power System Connectivity: Strategies, implementation and opportunities

3.1. Regional Road Map on Power System Connectivity

In 2017, ESCAP's Committee on Energy acknowledged the crucial role of energy connectivity in achieving sustainable development and the potential benefits of transboundary power trade for the power sector's sustainability. The Committee emphasized the need for a strategic roadmap to promote regional energy connectivity through expert discussions and intergovernmental processes.

The significance of energy connectivity and cross-border energy trade for achieving Sustainable Development Goal 7 was reaffirmed in the Ministerial Declaration of the Second Asian and Pacific Energy Forum, organized in 2018.[7] The Declaration further called for enhanced regional cooperation to improve energy connectivity. During the Forum, member States highlighted the role of improved energy connectivity to achieve a low carbon future and identified the Expert Working Group on Energy Connectivity as a platform for developing of a regional road map on electricity interconnection.

In response, the Regional Road Map on Power System Connectivity (Road Map)[8] was developed and endorsed at the 77th Session of the Commission in 2021.

The Road Map, subtitled "Promoting cross-border electricity connectivity for sustainable development", provides an agreed, non-binding reference framework for regional cooperation towards achieving power grid integration over the period 2020 to 2035, highlighting the importance of regional cooperation in energy, including universal access to sustainable energy, energy efficiency, and transboundary power trade. The Road Map contains a vision, a set of principles, and nine strategies to support increased power system integration and sustainable development.

Vision and principles

Enhanced power grid connectivity and cross-border electricity trade offer significant potential to support the region's social and economic development while enabling a transition to more efficient, flexible, and low-emission energy systems. By developing subregional and regional mechanisms for power system integration, member States can develop enabling cross-border infrastructure and move from bilateral to multilateral trading to complement energy demand and resource availability within the subregions. This can improve electricity availability and affordability and enable the accelerated integration and use of renewable energy resources, contributing to Sustainable Development Goal 7 and other related goals.

7 ESCAP/74/27/ADD.1

8 For additional information on Regional Roadmap on Power System Connectivity, see https://www.unescap.org/our-work/energy/energy-connectivity/roadmap.

The Road Map recognizes the diverse circumstances and energy policy priorities of each country and subregion and is therefore intended to be adaptable to national and subregional contexts. Special consideration is given to the challenges faced by archipelagic countries, where power grid integration is complicated by geographic factors and fuel transport needs. Understanding these unique challenges and developing appropriate policies, regulations, and business models is crucial for effective power grid connectivity.

3.2. Road Map strategies, milestones, status of implementation and opportunities for further development

There are numerous examples across the region of member State efforts to implement the Road Map strategies and advance power system connectivity through regional cooperation. As highlighted in Chapter 2, these efforts have culminated in meaningful progress at the subregional level. The following sections present the Road Map strategies in detail, along with case studies and examples of their implementation. It also describes areas where ESCAP has sought to provide direct and indirect support for strategy implementation, and identifies opportunities for forward-looking action.

Strategy 1: build trust and political consensus for cross-border electricity trade

Enhancing power system connectivity and establishing cross-border electricity trade among countries requires sufficient levels of trust and political will. Fostering trust and political consensus among member States for a long-term vision of energy connectivity and overcoming barriers to progress requires continuous work, which can be supported and facilitated by independent intergovernmental organizations, subregional cooperation organizations such as ASEAN and SAARC, and multilateral banks, to name just a few. Such organizations can also provide technical support to develop coordinated action plans for power grid connectivity and electricity trade within a mutually agreed framework.

Key milestone: A regional meeting on grid integration convened regularly from 2021 onwards.

Projects and activities to support the implementation of strategy 1:

Highlights from the region	ESCAP's support
- ASEAN Plan of Action on Energy Cooperation Phase II (APAEC, 2021-2025) - ASEAN Ministers on Energy Meeting (AMEM, annual) and Senior Officials Meeting on Energy (SOME, biannual) - Greater Tumen Initiative Energy Board meetings (annual) - BIMSTEC Energy Centre (launched in 2023) - SAARC Energy Centre Governing Board Meeting (annual) - Asia Clean Energy Forum (annual) - CAREC Energy Ministers' Dialogue - Singapore International Energy Week (annual)	- Expert Working Group meetings on Energy Connectivity (biannual) - Asian and Pacific Energy Forum (Ministerial level, most recently held in 2023,[9] next forum to be organized in 2027) - ESCAP Committee on Energy (2025, every two years)

Opportunities for further development:

The timeline for the implementation of the Road Map is guided by milestones under each of the strategies, many of which are to be achieved by 2025. To implement the Road Map by 2035, the next set of milestones that are ambitious and result in concrete actions for advancing sustainable cross-border connectivity should be developed and agreed on by the countries in the Asia-Pacific region through increased commitments and consensus-building around the need for grid interconnections.

9 https://unescap.org/events/2023/apef3

Strategy 2: develop a regional cross-border electricity grid master plan

Currently, grid interconnectivity in the Asia-Pacific region operates mostly on a bilateral basis. A fully interconnected region requires the development of a comprehensive grid master plan for interconnecting power grids. This plan should support energy security, grid stability, economic feasibility, and inclusiveness, addressing the concerns and demands of relevant stakeholders. The master plan would be voluntary, reflecting each country's energy policy priorities and power system context without being legally binding.

Key milestones: Regional grid master plan might be agreed by member States by 2025 and mapping of the region's existing high voltage transmission network by 2022.

Projects and activities to support the implementation of strategy 2:

Highlights from the region	ESCAP's support
- ASEAN Interconnection Masterplan Study (AIMS III) - BIMSTEC Grid Interconnection Master Plan Study - CAREC Energy Strategy 2030 - Global Energy Interconnection Action Plan for Promoting the 2030 Agenda for Sustainable Development (GEIDCO)	- Asia Pacific Energy Portal (power plant and transmission mapping)

Opportunities for further development

ESCAP has worked closely with member States and development partners to map the region's existing high-voltage transmission network. Ongoing efforts are focused on making this information available through the *Asia-Pacific Energy Portal*. The grid mapping exercise will serve as the foundation for developing a regional master plan. The Expert Working Group on Energy Connectivity will be a critical platform for ensuring that the proposed grid plan is developed inclusively and in line with subregional interconnection masterplans.

Continuous monitoring and updating of the grid master plan, supported by comprehensive data from partnerships with organizations like GEIDCO and TransitionZero, will help maintain momentum towards achieving the 2025 milestone and ensure the plan remains relevant and actionable.

Strategy 3: develop and implement intergovernmental agreements on energy cooperation and interconnection

Political commitment through agreements, or memorandums of understanding among member States in each subregion is a vital step for enhancing energy connectivity. Examples from other regions, including the various African Power Pools, demonstrate the importance of such agreements in signaling political commitment within a set timeframe. Efforts such as those led by ASEAN, SAARC, and BIMSTEC, and those organized by development partners such as ADB's Greater Mekong Subregion Energy Transition Task Force and Central Asia Regional Economic Cooperation (CAREC) Programme have strategic processes involving agreements on energy cooperation, ministerial committees, and working groups to promote integration.

To further energy connectivity, it is essential for regions with existing agreements to ratify and expedite implementation. Regions without such agreements should learn from the experiences of power pools in other regions to enhance collaboration and adopt strategic approaches for energy cooperation.

Key milestones: At least one intra-subregional high-level meeting on energy connectivity held on the initiative of member States in cooperation with ESCAP by 2022 and at least one additional grid interconnection agreement in place for all subregions by 2025.

Projects and activities to support the implementation of strategy 3:

Highlights from the region	ESCAP's support
- LTMS-PIP (2022) - BIMP-PIP (2023) - Singapore's conditional approval of interconnections with Australia (1.75 GW), Cambodia (1 GW), Indonesia (1.4 GW), and VietNam (1.2 GW), and conditional licenses for 2 GW of imports from Indonesia (2024) - NAPSI Phase II (2021) - Bangladesh-India-Nepal trilateral cross-border electricity trade agreement (2024) - Pakistan-Iran transmission agreement (2023) - Tajikistan- Uzbekistan power trade agreement (2022)	- Ulaanbaatar Dialogue Energy Sessions held annually to strengthen energy cooperation in North-East Asia - North-East Asia Regional Power Interconnection and Cooperation (NEARPIC) Forum held annually to promote interconnection proposals in North-East Asia - Almaty Energy Forum held annually to support countries in Central Asia to accelerate energy transition through regional cooperation

Opportunities for further development

Model agreements and templates can serve as a tool to assist countries and subregions in the development of intergovernmental agreements for cross-border electricity projects, including by helping to identify key issues concerning power connectivity and trade. Given the complexities and long-term nature of interconnector projects, there are many potential barriers that could hinder and prolong the negotiation process. In this regard, comprehensive and adaptable templates can have significant operational value in informing negotiations for the development and operation of cross-border energy projects.

Strategy 4: coordinate, harmonize and institutionalize policy and regulatory frameworks

Policies, regulations, and standards for power systems vary among countries, depending on national context and priorities. Enabling cross-border interconnection and trade requires some level of alignment. Developing frameworks to support this alignment is crucial for successful integration.

The Road Map strategy calls for the establishment, with the assistance of intergovernmental and multilateral institutions, of subregional forums or associations of national regulators. These platforms would enable capacity-building, knowledge-sharing, and the harmonization of regulations. In regions without such associations, their establishment could help develop common regulations for cross-border electricity trade, including licensing, open access, grid code harmonization, and subregional transmission pricing frameworks.

Key milestones: Analysis of gaps in grid policies, regulations and standards in each subregion by 2023 and subregional associations of national regulators formed by 2025.

Projects and activities to support the implementation of strategy 4:

Highlights from the region	ESCAP's support
- ASEAN Energy Regulatory Network (AERN) - South Asia Forum of Infrastructure Regulators (SAFIR) - SAARC Council of Experts of Energy Regulators (Electricity) (CEERE) - Initiation of Grid/ Network Codes development to facilitate the harmonization and integration of the regional electricity market in South Asia - Greater Mekong Subregion has also drafted the Regional Grid code in 2021, which is under ratification process by its member states - OPERA	- Asia Pacific Regulatory Forum on Power System Connectivity (annually since 2022) - Capacity building for regulators in ESCAP subregions

Opportunities for further development

To effectively implement strategy 4, it is important to enhance regional collaboration among national regulators. Establishing and supporting subregional associations of national regulators, as specified in the milestone, is vital for creating platforms that facilitate regular dialogue, capacity building, and knowledge sharing on regulatory best practices. The Asia-Pacific Regulatory Forum on Power System Connectivity, organized annually by ESCAP since 2022, aims to bridge existing gaps and promote discussions among energy regulators and other stakeholders across the region. Through this and similar forums, member States can exchange valuable experiences and lessons learned, which are essential for improving regulatory frameworks.

Additionally, the region can greatly benefit from developing standardized market rules and technical standards. These standards should promote transparency, establish fair pricing mechanisms, and create appealing regulatory frameworks that are adaptable to the specific contexts of each country. The formation of working groups and dedicated task forces can facilitate the drafting of these regulations. By addressing regulatory gaps, member states can pave the way for a more integrated and resilient energy landscape throughout the Asia-Pacific region.

Strategy 5: move towards multilateral power trade and create competitive markets for cross-border electricity

Transitioning from bilateral to multilateral electricity trade in the Asia-Pacific region is challenging but offers significant potential benefits. Multilateral trading can help to optimize regional energy resources, boost economic growth, expand renewable energy use, enhance reliability, enable reserve sharing, balance supply, and reduce costs while increasing system efficiency. Progressing towards transparent, fair, and competitive mechanisms for multilateral power trade is crucial for enabling regional power connectivity, leveraging diversity among countries to enhance competitiveness and reduce consumer costs.

Establishing multilateral power trade requires countries to address a range of issues, including establishing relevant intergovernmental agreements, such as on modalities for power purchase and trade, developing transmission service agreements, wheeling charges, deviation settlement mechanisms, dispute settlement mechanisms and creating acceptable payment security mechanisms. These issues are in many ways cross-cutting, and most, if not all require guidance or oversight from energy regulators. Forums of subregional regulators could initiate dialogue on developing these contractual documents and create regulations for electricity trade. Intergovernmental and multilateral institutions, at the same time, should collaborate with governments, regulators, and decision-makers to promote multilateral cross-border electricity trade and competitive markets, aligning with national policy frameworks.

Key milestones: Development of subregional and Asia-Pacific studies to evaluate the economic, energy security, social and environmental aspects of multilateral electricity trade.

Projects and activities to support the implementation of strategy 5:

Highlights from the region	ESCAP's support
- LTMS-PIP - ASEAN Interconnector Study: Taking a regional approach to decarbonization (DNV, 2024) - Accelerating the ASEAN Power Grid 2.0 (ISEAS, 2023) - Transforming regional electricity markets in South and South-East Asia for a greener and more sustainable future (National Bureau of Asian Research, 2022) - Facilitating power trade in the Greater Mekong Subregion (ADB, 2022) - Enhancing regional power trade in Central Asia (World Bank, 2021)	- ESCAP study on "Improving energy connectivity in Bangladesh-Bhutan-India-Nepal for achieving SDG 7 goal, with specific focus on the Nort-Eastern Region of India" (forthcoming) - ESCAP study on "Regional road map on power system connectivity- ECO regional electricity market: promoting cross-border electricity connectivity for sustainable development" (2024) - ESCAP study on "Green Power Corridor Roadmap for North-East Asia" (2023)

Opportunities for further development

The subregional studies carried out by ESCAP and other stakeholders on multilateral power trade have identified key issues and recommendations for realizing and expanding power trade. These include garnering stronger political support, building institutional capacity, and developing a trading model suitable for the subregion, among others. While each subregion is at a different stage of development, strategy 5 could be implemented further through pilot projects and/or political agreement on the next steps, and developing policy recommendations for enabling trade between and across subregions.

Strategy 6: coordinate cross-border transmission planning and system operation

Cross-border power interconnection requires the physical connectivity of transmission systems, as well as clear rules, regulations and common standards for power exchange. Power companies should ideally plan and develop adequate transmission infrastructure to facilitate access for developers of cross-border power generation projects. Coordination in transmission planning, metering connections, protection schemes, and dispatch scheduling among technical institutions and power utilities is essential for the safe and reliable flow of electricity.

Key milestones: Establishment of coordinated mechanisms for cooperation among system operation and transmission utilities.

Projects and activities to support the implementation of strategy 6:

Highlights from the region	ESCAP's support
- Greater Mekong Subregion Energy Transition Task Force (supported by ADB) - Heads of the ASEAN Power Utilities / Authorities (HAPUA) - Electric Power Council for the Commonwealth of Independent States (EPC-CIS) - Singapore announced target to import up to 4 GW of low-carbon electricity by 2035 - Bangladesh, China and Myanmar, and Bangladesh reached an agreement on trilateral power trading, which uses ±660 kV three-terminal DC with a capacity of 4 GW	- In partnership with the ASEAN Centre for Energy (ACE) South-East Asia Energy Transition Partnership (SEA ETP), and the Clean, Affordable and Secure Energy (CASE) for South-East Asia on the ASEAN Power Grid Advancement Program, launched to support system operators and utilities among other stakeholders towards multilateral power trade

Opportunities for further development

There are significant gaps for advancing regional cooperation and technical integration. Further efforts are required on guidance and capacity building on the harmonization of grid codes, development of technical regulations, and protection schemes within and across the subregions. This could be supported by establishing dedicated working groups or task forces involving system operators, utilities, and technical experts from each subregion. Establishing clear protocols for transmission planning, scheduling, and third party access to transmission infrastructure will be important.

Strategy 7: mobilize investment in cross-border grid and generation infrastructure

Funding capital-intensive transmission infrastructure, particularly for cross-border projects, can be challenging, especially for developing countries, where capital costs can be relatively high. Historically funding has primarily come from the public sector with the support of international financial institutions and multilateral development banks. Power grid infrastructure requires substantial investments, making innovative financial instruments essential to improve project bankability and reduce financing costs. These projects also need stable policy and regulatory environments that reduce investment barriers through streamlined permitting and improved planning practices.

Cross-border projects have the additional complexity of involving different regulatory and policy regimes. In addition to agreeing on cost sharing and recovery methods, successful projects tend to have clearly defined dispute-resolution procedures, including for the underlying electricity trade arrangements. Additionally, it is necessary to address taxation and tariffs issues, and to mitigate the risks of currency volatility. Innovative financial instruments can also be used to make cross-border projects more attractive, including blended financing and the use of special purpose vehicles, climate finance and green bonds, and renewable energy certificates.

Key milestones: Subregional platforms, convening financial institutions, utilities and governments, created to advance financing of power system connectivity projects.

Projects and activities to support the implementation of strategy 7:

Highlights from the region	ESCAP's support
- CASA-1000 financed by the World Bank, ADB, Islamic Development Bank, European Investment Bank - India-Nepal electricity transmission project financed by the World Bank and ADB - Monsoon Wind Project financed by ADB - Indonesia- Malaysia cross-border interconnection financed by ADB - ASEAN Catalytic Green Finance Facility financed by ADB and other regional/ global organizations - ASEAN Power Grid Finance Facility jointly launched by ADB and World Bank - Millennium Challenge Corporation (MCC) to fund Nepal portion of Butwal (Nepal)-Gorakhpur (India) 400 kV cross-border transmission line and associated substations	- Green Grids Initiative Asia Pacific Working Group (meetings and projects) including: • Feasibility study playbook (2024 forthcoming, USAID SPP as part of Green Grids Initiative Asia Pacific Working Group workplan) • White paper on Performance based finance for green grids (2024 forthcoming, Green Grids Initiative Asia Pacific Working Group and Finance Working Group) • Principles for Interconnector Development[11]

Opportunities for further development

Streamlining regulatory processes, removing barriers to investment, and ensuring clear guidelines and planning procedures are required to create an investment-friendly environment. These measures will boost investor confidence and attract private sector participation in cross-border projects. Collaborative efforts between ESCAP, financial institutions, governments, and other stakeholders could focus more on organizing workshops and meetings that address investment barriers. These partnerships can help develop tailored financial instruments and policy recommendations that meet the specific needs of cross-border infrastructure projects. By leveraging partnerships with multilateral development banks, climate finance institutions, and think-tanks, ESCAP can promote research and knowledge-sharing on innovative financing mechanisms, helping to ensure sustainable funding for grid and generation projects across the Asia-Pacific region. Member States can also consider creating subregional platforms that bring together financial institutions, utilities, regulators and governments to advance financing for power system connectivity projects.

Strategy 8: build capacities and share information, data, lessons learned and best practices

The Asia-Pacific region possesses extensive knowledge and experience in the energy and power sectors, yet data and information sharing within and across countries remains inadequate. While some intergovernmental institutions collect and publish data, it is often outdated, incomplete, and non-standardized. Public access to power sector data varies by country, limiting availability of information both nationally and regionally.

Increased sharing of information, data, lessons learned, and best practices through capacity-building programs will substantially contribute to power connectivity efforts. ESCAP collaborates with other intergovernmental institutions to develop and maintain comprehensive data, leveraging platforms like the Asia-Pacific Energy Portal, a free and open resource that aggregates energy sector data from across the region.[11]

Access to and the ability to leverage data is also critical to the successful deployment of new and innovative technologies. Governments, power utilities, and multilateral financial institutions should devise capacity-building plans to share expertise in areas such as new technologies,

10 Green Grids Initiative (2023), Principles for Interconnector Development Phase 2, available at 67825b_9855d6c1dfa54e449bf99be50d5e672b.pdf (greengridsinitiative.net)

11 https://asiapacificenergy.org/

energy efficiency, smart grids, system operation, and electricity markets. A more collaborative approach would enhance regional knowledge and integration in the power sector.

Key milestones: Capacity-building, knowledge generation and data support plans developed and resources identified to support member States.

Projects and activities to support the implementation of roadmap strategy 8:

Highlights from the region	ESCAP's support
- Capacity building workshops carried out by subregional platforms, development partners and international organizations - Data sharing platform for ASEAN under developed by the ASEAN Centre for Energy with support from USAID South-East Asia Smart Power Program	- Capacity building for regulators (North-East Asia, South Asia, Central Asia, South-East Asia, Pacific on topics including 'Renewables integration and its impact on electricity systems and markets' and 'the regulatory governance of regional electricity markets', 'Potential role of low and zero carbon fuels, including hydrogen, in regional energy trade', 'Planning tools for integrating renewable energy into island grids')[12] - Capacity building on data-sharing for ASEAN utilities

Opportunities for further development

Collaborative efforts between intergovernmental institutions like ESCAP and member States can focus on improving the accessibility and completeness of power sector data through further development of platforms such as the Asia-Pacific Energy Portal. This involves updating existing databases, ensuring data transparency, and fostering a culture of sharing among countries. Governments and multilateral financial institutions should support these efforts by investing in comprehensive data management systems and promoting public access to critical energy information.

On capacity building, as many subregional, regional and global entities have been providing capacity building to regional stakeholders, coordination through regular meetings to find opportunities for collaboration and building synergies could be explored. Examples of such coordination include in South Asia, the Cross-border Trade Working Group Meetings organized by USAID SAREP Secretariat inviting development partners, institutions, organizations working on projects and initiatives in South Asia. Similar efforts also exist in ASEAN where annual donor coordination meetings are being organized to discuss, among others, capacity building efforts to advance the ASEAN Power Grid.

Strategy 9: ensure the coherence of energy connectivity initiatives and the Sustainable Development Goals

Enhanced energy connectivity in the Asia-Pacific region offers significant potential economic benefits and numerous positive externalities related to sustainable development, such as reducing greenhouse gas emissions, improving energy access in remote areas, and job creation.

Aligning cross-border energy connectivity developments with the Sustainable Development Goals (SDGs) can enhance overall benefits. Connectivity projects should be planned, implemented, and operated in a way that considers national circumstances and priorities, ensuring economic and system security while positively impacting society and the environment.

Key milestones: A set of principles to enable the assessment of interconnection projects against economic outcomes, efficiency and sustainability criteria and to ensure coherence with the Sustainable Development Goals agreed by member States by 2023.

12 The Economic and Social Commission for Asia and the Pacific online community is available at https://community.unescap.org/

Projects and activities to support the implementation of strategy 9:

Highlights from the region	ESCAP's support
- Global Electricity Development Index (GEIDCO)	- Development of Green Power Corridor Framework (principles, metrics and case studies) (See Chapter 4)

Opportunities for further development

Application of ESCAP's Green Power Corridor Framework's metrics and principles can help guide the evaluation and implementation of cross-border energy projects, ensuring alignment with national priorities and SDGs. The Framework encompasses aspects that extend beyond achievement of SDG 7, including economic viability, environmental impact, social inclusiveness, and resilience to climate change, thereby promoting sustainable development outcomes across the region. The Framework's principles have informed the development of the COP-29 "Green Energy Pledge: Green Energy Zones and Corridors".[13] Action plans emerging from the pledge will directly contribute to the implementation of Strategy 9. The Green Power Corridor Framework is presented in more detail in Chapter 4.

3.3. Advancing the Regional Road Map on Power System Connectivity: A framework agreement on power system connectivity

Since its endorsement in 2021, the Road Map strategies and milestones have been actively implemented through a number of projects and initiatives. With many of these milestones now met or in progress, the region has the opportunity to leverage the Road Map strategies and initiatives like the Green Power Corridor Framework as a foundation for further work. One possibility is a framework agreement on power trade, to provide a more concrete strategic pathway that can provide numerous benefits for the Asia-Pacific region. A regional framework on power system integration would build off the Road Map by:

- Solidifying political commitment. A regional framework agreement can help member countries commit to a long-term vision and overcome some of the barriers of country-to-country geopolitics and social buy-in.
- Supporting standard harmonization. A framework agreement would allow for the development of relevant common or harmonized minimum technical standards and enhanced regulatory frameworks to support interoperability between national grids, facilitating smoother energy trade and reducing operational costs.
- Enhancing energy security and reliability. Implementing common or harmonized protocols under a framework agreement can help prevent outages and enhance the reliability of energy supply across interconnected regions by improving ancillary services, maintenance and emergency response.
- Supporting regional policy alignment. A framework agreement could foster collaboration among countries to align energy policies which facilitate joint investments in infrastructure, technology, and innovations that benefit all participating countries.
- Improving capacity building. A framework agreement could promote coordinated and institutionalized knowledge-sharing and capacity building efforts.
- Unlocking infrastructure investments. Cooperative financing could be encouraged through a framework agreement, for example by helping to identify common projects of interest and priority interconnectors.
- Supporting renewable energy integration. A framework agreement could outline specific

13 https://cop29.az/storage/1135/COP29-Declarations-and-Pledges-Letter.pdf

targets for renewable energy integration and promote norms and best practices for integrating renewable sources into national grids.

The experience and lessons from existing regional agreements and frameworks in trade, transport and digital connectivity supported by ESCAP (see Box. 4) demonstrate that a power system focused framework agreement could effectively promote energy trade, enhance grid integration and support sustainable development across the region.

Conclusion and key messages

The Regional Road Map on Power System Connectivity is being implemented by ESCAP member States, development partners, subregional cooperation mechanisms, financial institutions and other key stakeholders aiming to enhance regional cooperation and energy integration to 2035.

Box 4. Regional framework agreements, intergovernmental agreements and initiatives to promote and facilitate connectivity in areas of trade, transport and digitalization

The Asia-Pacific region has a rich history of establishing intergovernmental agreements and initiatives to enhance regional connectivity. Three notable examples are the Framework Agreement on Paperless Trade, the Intergovernmental Agreement on the Asian Highway Network, and the Asia-Pacific Information Superhighway initiative.

The Intergovernmental Agreement that established the Asian Highway Network (AHN)[14] entered into force in 2005 with the aim to facilitate seamless transport and trade within the region. The network spans approximately 141,000 km across 32 countries in Asia, linking major economic centres. The Agreement created a comprehensive framework for planning, building, and maintaining these roads, thereby fostering regional cooperation in transport infrastructure development. It also has enabled countries to share best practices, promote safety standards, and enhance logistics efficiency. Stemming from the AHN, the Intergovernmental Agreement on Road Transport along the Asian Highway Network was signed in 2016 by China, Mongolia and the Russian Federation, to operationalize AH 4 and to promote the development of the economic corridor along the road network.

The Framework Agreement on Facilitation of Cross-border Paperless Trade in Asia and the Pacific (CPTA)[15] entered into force in 2021, with 5 signatories and 13 parties to the agreement. Its primary objective is to promote cross-border trade by enabling the electronic exchange and mutual recognition of trade-related data and documents. The agreement aims to improve the efficiency and transparency of international trade, enhance regulatory compliance, and facilitate interoperability among national and subregional systems.

14 See https://treaties.un.org/pages/viewdetails.aspx?src=treaty&mtdsg_no=xi-b-34&chapter=11&clang=_en

15 See https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=X-20&chapter=10&clang=_en

The Asia-Pacific Information Superhighway (AP-IS) initiative focuses on enhancing digital connectivity across the region. It aims to improve broadband access, reduce digital divides and promote regional cooperation in ICT development. The AP-IS framework encourages countries to adopt common policies and standards to facilitate data-sharing and collaboration.

With many of the milestones near their implementation deadline of 2025, it is a timely moment to take stock of the achievements and explore opportunities for further development. To highlight some of these opportunities:

- Develop the next set of milestones under the Regional Road Map through an inclusive consultative process for endorsement by member States (Strategy 1)
- Develop a regional cross-border electricity grid master plan based on mapping of the region's existing and planned high-voltage transmission network (Strategy 2)
- Develop model intergovernmental agreements and templates on cross-border electricity connections (Strategy 3)
- Support the formation of subregional associations of national regulators and develop standardized market rules and technical standards (Strategy 4)
- Identify and carry out pilot projects based on the subregional studies on multilateral power trade (Strategy 5)
- Develop protocols for transmission planning, scheduling and third-party access through the establishment of working groups with system operators, utilities and other stakeholders (Strategy 6)
- Create an enabling investment environment through promoting innovative financing mechanisms, enhancing bankability of projects and streamlining project financing (Strategy 7)
- Build synergies among different capacity building efforts through better coordination and collaboration (Strategy 8)
- Apply the GPC Framework as an enabling tool for sustainable power system connectivity (Strategy 9)

These are just examples of the issues or areas of focus a Power System Connectivity Framework Agreement could address. Ultimately any such agreement would need to be developed and agreed upon through a consultative, member State-drive process, modelled after similar successful efforts in other areas of connectivity such as trade, transport and digital connectivity within Asia and the Pacific.

Chapter 4

Enabling Sustainable Connectivity: the Green Power Corridor Framework

As discussed in Chapter 3, Strategy 9 of the Regional Road Map for Power System Connectivity in Asia and the Pacific highlights the need to "ensure the coherence of power system connectivity initiatives and the Sustainable Development Goals."

Implementation of Strategy 9 is being supported through the development of the "Green Power Corridor Framework" (GPC Framework), defined as a framework which provides an enabling institutional, financial, regulatory, political and social environment for strengthening regional power grid connectivity for increased access to clean, affordable and secure electricity supply.

The GPC Framework is structured around six building blocks, each of which contain a set of practical and flexible principles, and a set of metrics for evaluating the impacts of connectivity initiatives on sustainable development. The GPC Framework aims to guide power system connectivity efforts in such a way as to ensure their alignment with and support for sustainable development, for example by ensuring that cross-border transmission line development and power trade enables increased renewable energy deployment and integration. Green Power Corridors can also help in meeting other sustainability goals, such as increased access, and broader policy objectives like lower costs to consumers, measures to mitigate impacts of connectivity efforts on affected communities, and increased energy security.

4.1. Building blocks and Principles of the Green Power Corridor Framework

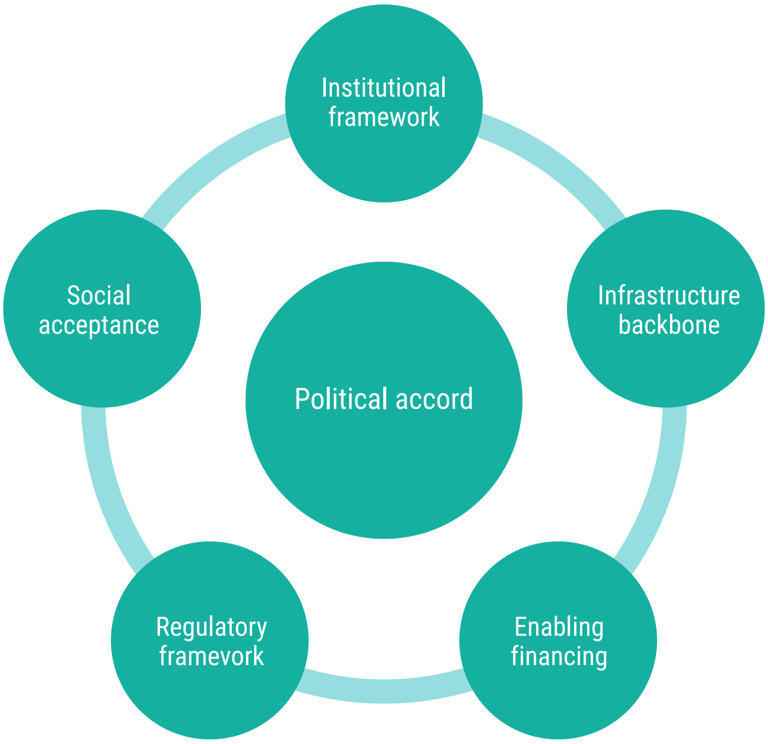
The GPC Framework is structured around six core themes or building blocks. Each of these building blocks includes one or more guiding principles which are in turn supported by proposed actions, relevant case studies, and where possible tools to guide their implementation. Sustainable development has multiple cross-cutting dimensions. Therefore the building blocks are strongly linked to, and intended to be complementary of, the Regional Road Map strategies. The following section outlines the building blocks and principles.

Political accord

Political accord is a fundamental building block of power system connectivity initiatives, and necessary to ensure connectivity is aligned with and supportive of sustainable development. In the context of the GPC Framework, political accord includes the following core principles:

Principle: Develop an overarching vision to guide, support and enable development of power system connectivity projects at all levels, including allocation of responsibilities and resources as appropriate.

The Road Map provides a high-level vision for connectivity across the region, stating that the Road Map "is intended to provide an agreed reference framework for regional cooperation towards achieving power grid integration



over the period from 2020 to 2035." However, the Road Map does not articulate what level or nature of power grid integration should be achieved in that timeframe. Therefore, it is incumbent on political leaders to further detail and articulate a vision for power system connectivity, in collaboration with relevant partners (e.g. groups of neighbouring countries, or common members of sub-regional organizations).

It is important that visions, when articulated, are consistent with policy objectives while also remaining aligned with sustainability objectives, in particular the Sustainable Development Goals (SDGs) of the 2030 Agenda and commitments made under the Paris Agreement. Therefore, it may be helpful for this vision to be underpinned by some basic modeling linked to specific SDG targets and other objectives such as Nationally Determined Contributions (NDCs), and to contain a high-level, stepwise road map for future development. As ***political accord*** is a fundamental building block, it should also provide clear guidance on the development of other building blocks.

Principle: Formalize political accord through joint statements, Memorandums of Understanding (MoUs), and other forms of intergovernmental agreements.

While the overarching vision serves as an impetus for and guide to cross-border collaboration, key elements may need to be formalized in order to clarify responsibilities and enable progress. Political statements, MoUs, and other more formal agreements on modes of collaboration will give political weight to the process and provide the required mandate for the other building blocks of the institutional framework, while also allowing connectivity initiatives according to the specific contexts of the jurisdictions in question. These MoUs should include reference to aligned and agreed upon sustainability objectives, in particular in the power sector, such as renewable energy and carbon emission targets.

Institutional framework

Principle: Identify or, if necessary, establish inter-jurisdictional platforms for collaboration across all relevant areas.

The main objective for the institutional framework is to support, steer, and monitor the development and operation of cross-border connectivity initiatives. It is expected that the foundation or mandate for this would be defined in intergovernmental agreements and MoUs that identifies or, if necessary, establishes platforms for collaboration between the different key stakeholders from the region. Relevant areas for collaboration will need to be fully articulated among the collaborating jurisdictions, but relevant stakeholders would typically include power utilities, regulators, relevant Ministries, and possibly. generation owners, consumer groups, and civil society organizations. These platforms could function as coordinating mechanisms both within and across groups, and should include agreed upon or mandated activities related to sustainable development objectives

It is important to allow for national/sub-regional differences as countries/regions will have very different starting points, and therefore the most natural grouping of countries would likely be at the sub-regional level. At the same time, at the regional level, an overarching framework could define or propose guiding principles for sub-regional institutions to follow, and enable coordination between sub-regional platforms.

An illustration of how the vision and the MOU could govern this together with the high-level institutional framework is shown in the figure below.

Principle: Develop a common methodology for feasibility studies (including the required modeling).

A common methodology makes it easier to compare projects and take informed decisions based on the same criteria. Within South-East Asia, the USAID SPP program is currently developing a playbook for feasibility studies that could be used as a guiding or reference document for the region.

Principle: Commit to data transparency wherever possible, and data sharing with selected partners for sensitive data.

Models can only deliver accurate results when they use correct, up-to-date data. Standardizing data access across all relevant countries and sub-regions can help ensure that modeling efforts can use comparable datasets.

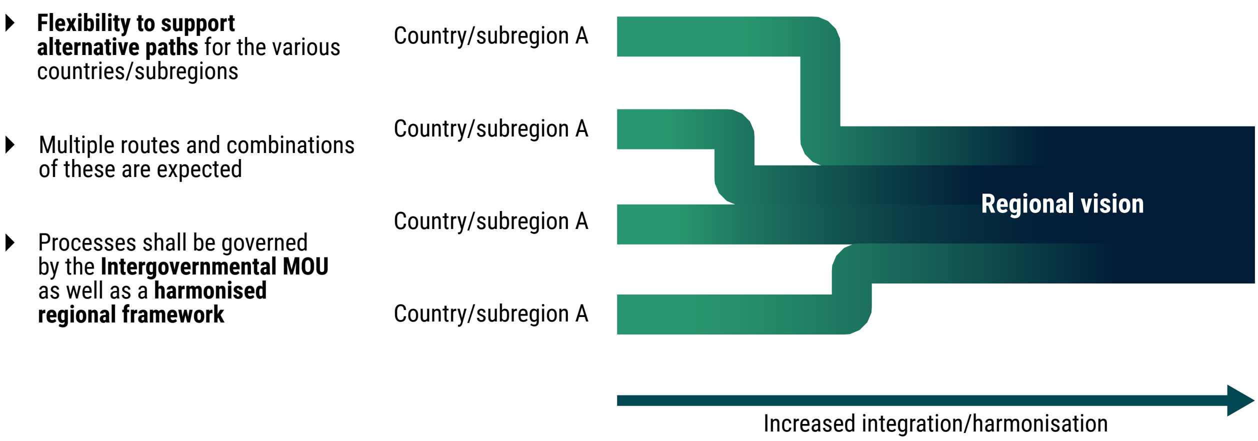
Principle: Update data on an agreed upon schedule.

Many projects successfully obtain initial data access but fail to maintain current information over time. Quality modeling depends critically on up-to-date data. Establishing a shared process for regular data updates will lead to more robust decision-making.

Infrastructure backbone

This building block focuses on infrastructure development that serves two key and interrelated purposes: strengthening national power grids and developing cross-border transmission lines. A strong infrastructure backbone can increase system flexibility, enable the integration of higher shares of renewable energy, and provided increased access to low-cost renewable electricity.

Principle: Coordinate cross-border and intra-jurisdictional infrastructure planning.



Principle: Least cost energy modeling approach including relevant sustainability parameters

Principle: Provide a transparent and open process for connecting renewable energy generation to the grid.

Enabling financing

Principle: Infrastructure development requires sustainable financial frameworks.

Principle: Leverage all forms of available financing to support the development of transmission infrastructure, both within and between jurisdictions .

Infrastructure development requires securing sufficient financing, which in turn means careful consideration of potential sources. The public sector has a traditionally important role to play, as infrastructure financing and development has often been state-financed. However, as a tool for increasing the pool of financing available and lowering financing costs, countries are increasingly exploring investments that involve or are even led by the private sector. These include, for example, merchant development, where a private investor takes on the task (and associated risks) of developing a new piece of transmission infrastructure.

Regardless of the source, however, the regulatory framework building block is crucial for enabling financing.

Regulatory framework

Principle: Develop harmonized grid codes that enable secure and flexible operations

Principle: Enable bilateral cross-border power trading arrangements through harmonized and coordinated procedures.

Principle: Establish multilateral trading arrangements that emphasize flexible and least-cost trading of electricity

Principle: Develop appropriate and consistent cost-sharing and cost-recovery mechanisms

All power systems, regardless of the regulatory model and policy environment they function under, have as a core goal enabling secure and efficient operations. How this goal is met, however, can differ significantly, which can be an obstacle to efficient power trade and operations across integrated power systems. An effective regulatory framework covering all interconnected countries can help resolve conflicting standards and regulations and enable the more equitable distribution of socio-economic benefits to participating countries. An effective regulatory framework could also be an enabler of increased investment in grid infrastructure, potentially enabling the inclusion of private investors.

An agreed upon regulatory framework is also important to enabling more flexible bilateral trade and multilateral, multidirectional trading.

The regulatory framework should allow for stepwise and differentiated implementation, to allow countries to choose when and how to integrate into the broader regional energy system.

Social acceptance

Principle: Establish inclusive stakeholder consultations processes

Principle: Develop targeted capacity building and other forms of training programs for all impacted social groups

Principle: Measure and make public the social benefits of increased connectivity

This building block aims to achieve three key objectives:

1. Ensure public support for increased power grid connectivity.
2. Boost capacity building efforts.
3. Enable maximum inclusion of relevant populations, especially vulnerable groups.

One key tool is to develop a clear strategy for stakeholder engagement, including for example all relevant consumer groups, not just the most directly involved parties. Infrastructure development often directly impacts local communities. Early involvement in infrastructure development plans can make these projects more successful.

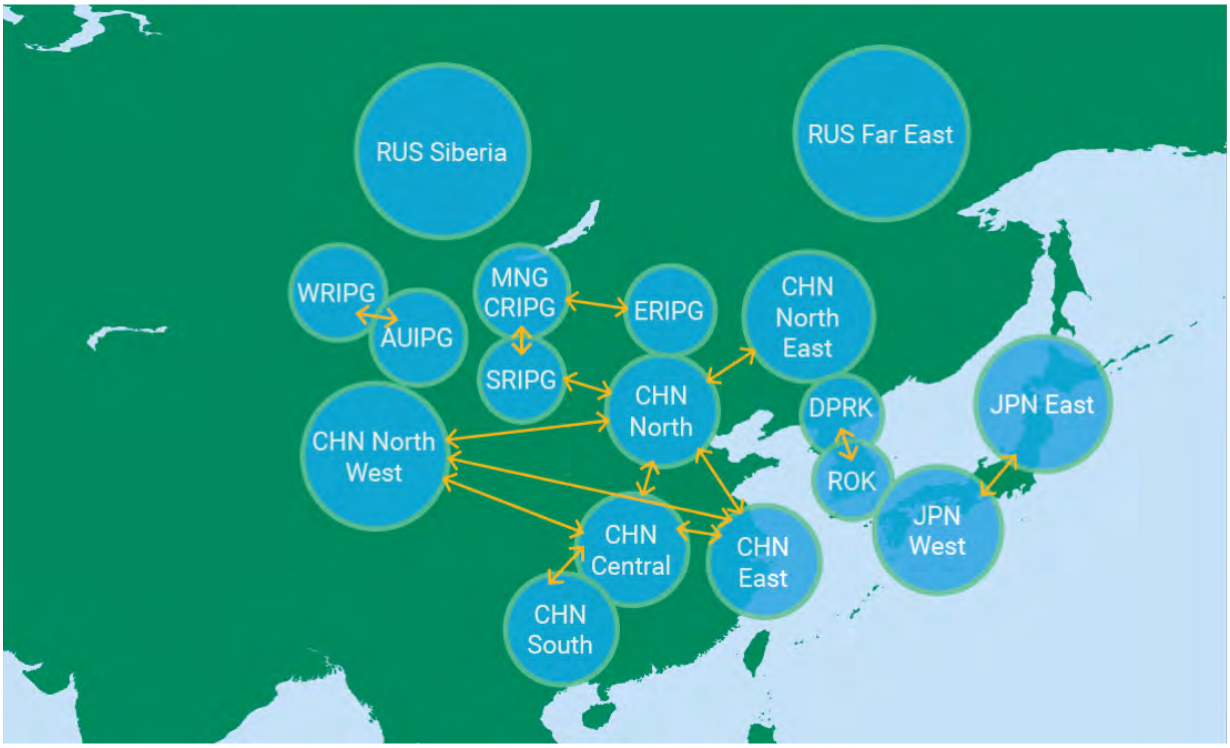
At the same time, it's important to clearly communicate the likely benefits of these projects, as well as any effects the changes will have on different groups.

4.2. Applications of the Green Power Corridor Framework: Green Power Corridor Roadmap for North-East Asia

In December 2023, ESCAP published a report entitled "Green Power Corridor for North-East Asia: A roadmap (ESCAP, 2023)" (GPC Roadmap), which applied the GPC Framework principles to develop a set of incremental, time-bound and concrete steps towards establishing an institutional and political cooperation base to support long-term development of cross-border clean power trade in North-East Asia.

Also to demonstrate the multifaceted advantages of enhanced grid connectivity in North-East Asia, the GPC Roadmap modelled different connectivity scenarios using the latest available energy systems data and national energy policies of North-East Asian countries. The scenarios were based on decades-long discussions on cross-border power grid connectivity and power trade proposals including the Asian Super Grid and the North-East Asian Energy Interconnection (NEAEI), as well as the Technical Assistance Project of the ADB on North-East Asia Power System Integration (NAPSI) which recently completed its Phase II study. These proposals pursue a common objective of integrating North-East Asia's abundant renewable energy sources to supply clean energy to the high demand centers of China, Japan and the Republic of Korea. Key findings include the following:

1. **Low-cost renewables adoption:** Enhanced transmission connectivity serves as a catalyst for the adoption of low-cost renewable power. This transition not only reduces overall system costs but also holds the promise of emission reductions, contingent on sustainability objectives. This underscores the critical



source: ESCAP (2023).

Disclaimer: The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by the United Nations

role of connectivity in advancing both economic and environmental goals.

2. **Scope matters:** The magnitude of benefits derived from enhanced connectivity is closely tied to the scope of transmission plans. Larger and more ambitious connectivity strategies yield more significant advantages, emphasizing the importance of bold and forward-looking regional integration efforts.

3. **Sustainable development synergy:** The economic advantages of improved connectivity become even more pronounced when aligned with sustainable development and net-zero plans. As nations strive to achieve carbon neutrality, connectivity can play a pivotal role in cost-effectively transitioning to cleaner energy sources.

Table 10. GPC Principles in the context of North-East Asia

GPC Building blocks	Strategies and actions for North-East Asia
Political accord	Readiness of national Governments to support cross-border cooperation in the power sector has been repeatedly stressed as the first necessary step on the road to regional power grid connectivity. A prerequisite and the basis for the GPC is therefore an agreement by the national Governments of the North-East Asian countries (as represented by the relevant ministries), expressed within an MoU or a similar document, to lead and support the incremental development of the GPC, in coordination with national energy strategies, and in alignment with the SDGs and the goals of the Paris Agreement on Climate Change. At an initial stage, even a principle-based statement of support can boost confidence of potential public and private investors and draw in additional support for the development of connectivity initiatives.
Institutional framework	There are a few existing platforms for North-East Asian countries to cooperate on cross-border energy connectivity issues, most notably the NEARPIC forum. However, to enable the implementation of an initiative of such systemic nature as the GPC, institutional arrangements need to be further developed and new ones created. With all member countries participating on equal footing such institutional arrangements can support, steer and monitor the development process and operation of the GPC. Setting up a working group or task force to support GPC implementation can be a first step.
Enabling financial arrangements	Although having very low operational cost, renewables-based power grid systems have a relatively high capital cost. Participation of public (bilateral and multilateral) finance needs to be secured to kick-off the first stages of infrastructure development, and unlock the private finance required for later stages of GPC's implementation. Securing the support of the multilateral development finance institutions (World Bank, ADB, AIIB and others) is crucial as the development of appropriate investment incentives and arrangements for the private sector are key in the long-term.
Regulatory framework	Developed in close coordination with national regulatory frameworks, the GPC will gradually require its own commonly agreed upon and harmonized framework to enable flawless and efficient operations, transparent power trade, and equitable distribution of socio-economic benefits of the GPC to participating countries.
Social acceptance	From its onset, the GPC should take into account the need to build public acceptance and support for increased power grid connectivity among populations in North-East Asia. Within the GPC, the member States will regularly provide information on the socio-economic benefits of such cooperation as well as support capacity building to enable maximum inclusion of the population (particularly vulnerable groups) in the initiative, and to avoid public misunderstanding and resistance to the regional cooperation. This is a key element, securing not only the public support, but also alleviating some of the security concerns.
Infrastructural backbone	The central element of the GPC, a carefully designed high-quality power generation and transmission infrastructure, will strengthen the national power grids, adding to their flexibility, enabling the upscale of renewable generation capacity and contributing to the access to low-cost renewable electricity for all. The deployment of the infrastructural backbone of the GPC will be guided by an elaborated technical model, outlining its development stages as well as demonstrating the flexibility potential of the increased power grid connectivity, the economic benefits in form of the overall lower cost of electricity and operations, social benefits, and the potential to reduce regional carbon dioxide emissions from power generation.

4. **Mutually beneficial trade:** New transmission lines foster a mutually beneficial trade relationship between connected regions. Notably, this equilibrium in trade is exemplified in the almost equal trade levels observed between Japan and the Republic of Korea. This balanced exchange underlines the resilience of interconnected grids in the face of supply and demand variability.
5. **Resource constraints alleviated:** Grid interconnection emerges as a valuable tool in alleviating resource constraints associated with decarbonization efforts. The ability to share resources and optimize their use contributes to the feasibility of transitioning to cleaner and more sustainable energy systems.
6. **Emission reduction potential:** Improved connectivity has significant GHG emission reduction potential even if sustainability goals are not fully realized, or if progress toward sustainability is slower than anticipated. If national decarbonization efforts do not proceed as planned, enhanced connectivity still provides emission reduction benefits in the short-to-medium term, and it limits cumulative GHG emissions. Adding international transmission connections does raise the possibility of carbon leakage if the linked countries have unequal decarbonization objectives. This should be kept in mind in the design of power trading schemes.

On the GPC Roadmap itself, the following table describes for each of the building blocks, recommended strategies and actions.

4.3. Green Power Corridor Framework Metrics

4.3.1. Energy and Energy connectivity projects and the Sustainable Development Goals

Access to modern and sustainable energy (SDG-7) is of vital importance for economic prosperity and social wellbeing. Evidence indicates that countries with higher GDPs also have higher energy consumption. Indeed, there are no examples of countries with low energy consumption and high GDPs. This is also observed in the Human Development Index (HDI), which is a more comprehensive measure than GDP. Additionally, SDG-7 has been demonstrated to be closely linked with a number of other SDGs (Zhou & Moinuddin, 2017). A study conducted by the International Council for Science investigated the interlinkages between SDGs. The findings revealed that SDG-7 has significant interactions at the goal level with SDGs 1, 2, 6, 8, and 13, as well as 58 target-level interactions. Of these, 46 were identified as positive, 10 as neutral, and 2 as negative (Nilsson et al., 2016) (International Science Council, 2017).

This recognition has prompted the development of analytical frameworks designed to assess the impact of energy projects on multiple Sustainable Development Goals (SDGs). One such framework is the Sustainable Development Goals Impact Assessment Framework for Energy Projects (SDGs-IAE), which helps identify both synergies and trade-offs inherent to specific energy projects (Castor et al., 2020). In this sense, the SDGs are also driving the creation of new methodologies for multi-criteria assessment of energy projects that incorporate broader societal impacts. Recent studies have suggested various methodologies based on energy justice and quantification of social-political barriers and drivers of net-zero energy (Castor et al., 2020; Mayer et al., 2024).

As observed for domestic projects, energy connectivity has a significant impact on several SDGs, many of which are spillover effects from increased access to sustainable energy and reduced electricity costs. Most previous studies have focused on these benefits, as well as on the reduction of greenhouse gas emissions. Additionally, energy connectivity has long been considered a form of functional cooperation that could improve relations between countries and foster cooperation in other areas as well. In some cases, energy connectivity has been pursued for its potential to promote peace (Kammen, 2015).

Furthermore, experience has shown that energy connectivity influences factors beyond those typically considered, which must be addressed during the evaluation process. Incorporating these considerations into the design process can facilitate greater alignment with countries' sustainable development goals and enhance social and political support. The following section presents a case study examining the potential application of desert control photovoltaics in Mongolia for regional electricity trade in North-East Asia.

4.3.2. Desert control photovoltaic in China and potential for export-led development in Mongolia

This case study examines the potential to enhance the alignment between the SDGs and energy connectivity projects, with a particular focus on combating desertification through the use of solar photovoltaic (PV) technology.

In recent years, photovoltaic (PV) projects designed to control desertification have emerged in northern and western China. These projects represent an innovative approach to addressing urgent environmental degradation issues and increasing energy needs. These projects entail the installation of solar panels in desert regions where land degradation in arid, semi-arid, and dry sub-humid areas is caused by factors such as climate change and human activities. The fundamental premise of desert control PV projects is the exploitation of vast, unproductive desert lands with abundant sunlight for the generation of renewable energy, thereby contributing to national energy security and sustainability. Concurrently, the installation of photovoltaic (PV) panels assists in stabilizing soil, reducing wind erosion, and establishing a microclimate conducive to vegetation growth. This contributes to combating desertification, a significant environmental concern that endangers biodiversity, agricultural productivity, and local livelihoods. The implementation of large-scale desert control PV projects facilitates the conversion of arid and semi-arid lands into productive areas, thereby establishing green corridors that can foster biodiversity, improve soil health, and enhance local climate conditions.

In China, the Inner Mongolia autonomous region has been pioneering efforts to combat desertification by integrating desert control method with renewable energy generation. Despite being one of China's most ecologically diverse areas, with extensive forests and grasslands, approximately 20 per cent of the land in Inner Mongolia suffers from desertification and sand encroachment. Led by Elion, a local private company with a long history of combating desertification in the region since the 1980s, the first desert control PV project in China was developed in 2016. With an energy capacity of 1GW and land coverage of approximately 52 million square metres, the project integrated licorice, pasture, and grass grids under and between the PV panels, using water-saving technologies such as drip and infiltration irrigation to optimize water resource conservation. The PV panels further improved the ecological environment by reducing water evaporation and shielding wind, thereby promoting plant growth. Compared to conventional desert planting and irrigation models, this approach saves more than 90 per cent of water and increases the survival rate of planting by more than 30 per cent.

In light of China's goal to achieve carbon peak by 2030 and carbon neutrality by 2060, China announced in 2022, plans to build over 450 GW of renewable capacity via northern and western desert bases to meet the climate goals. Inner Mongolia, serving as the pilot region for China's desert control PV projects, has been attracting significant investment from major state-owned utilities and PV manufacturers. By integrating desert control methods, it aims to reach 21.4GW of installed energy capacity by 2025 and 89GW by 2030 under the coordination of the local government and industry associations. This ambitious goal underscores the strategic importance of the desert control PV projects in China's national energy policy. In May 2024, China's National Energy Agency further issued new guidelines for seven provinces involved on the integration of photovoltaic development with desert control. These guidelines stress the importance of using tailored and holistic methods suited to local conditions, prioritizing the use of land under risk of desertification, and evaluating projects on their contributions to land restoration.

Desert control PV projects contribute to several SDGs. There is a clear positive impact to SDG 7 by providing renewable energy sources and increasing the share of renewable energy in the global energy mix (7.2). In terms of climate action (SDG 13), these projects help reduce greenhouse gas emissions by displacing fossil fuel-based energy generation. The large-scale adoption of solar energy in desert regions leverages one of the most abundant natural resources—sunlight—contributing significantly to national and global efforts to mitigate climate change. At the same time, the far-reaching influence of desert control PV projects extends to the quality of life on land, as outlined in SDG 15. The projects provide support for SDG 15 by addressing issues such as desertification, land degradation, and biodiversity loss. The installation of photovoltaic (PV) panels has the potential to enhance ecological conditions for vegetation growth on arid land. This can be achieved by increasing shade, reducing ground wind speed, and decreasing water evaporation. The integration of desert control methods into these projects facilitates the restoration of degraded land, the sustainable management of ecosystems, and the enhancement of local agricultural potential.

It is conceivable that these projects could contribute to additional SDG targets, thereby demonstrating multiple environmental, social, and economic benefits. For example, enhanced project design could markedly contribute to poverty alleviation (SDG 1) by creating employment opportunities and enhancing the economic standing of local communities. Geographical limitations and decades of resource extraction have resulted in significant economic stagnation in northern and western Chinese provinces. The creation of employment opportunities in construction, maintenance, and the operation of desert control photovoltaic (PV) projects has the potential to stimulate local economies and alleviate poverty. Furthermore, the project could enable local farmers and herdsmen to lease unused wasteland, thus providing them with additional income. Furthermore, the desert control project has the potential to advance gender equality (SDG 5) by implementing strategies to enhance women's capacity for gainful employment and skills development, and by facilitating their access to job opportunities. By concentrating on the empowerment of women through educational and professional opportunities within these projects, the initiative can facilitate the narrowing of the gender gap and encourage inclusive economic growth.

Nevertheless, the implementation of desert control PV projects entails a degree of compromise with regard to certain SDG targets. Although they make a substantial contribution to clean energy, climate change, and life on land, there may be potential conflicts with targets related to land use and ecosystem preservation. The construction of large-scale solar facilities has the potential to disrupt local ecosystems and biodiversity, in contradiction with SDG 15. Furthermore, the emphasis on renewable energy production may occasionally result in the overlooking of the immediate requirements of local communities with regard to agricultural or grazing lands, which could have an adverse impact on food security (SDG 2) and local economies (SDG 8). The resolution of these trade-offs necessitates meticulous planning and the involvement of relevant stakeholders to guarantee that the advantages of desert control PV projects are optimized while mitigating potential adverse consequences.

The success of these projects in China provides a model that can be adapted and applied in other regions facing similar challenges. In the context of the Green Power Corridor in North-East Asia, desert control PV projects can foster international cooperation in key energy export projects in the Gobi desert in Mongolia.

Mongolia presents a compelling case for the application of desert control PV technology, especially given its abundant solar energy resources and strategic position in North-East Asia. The country's vast southern regions, particularly around the Gobi Desert, are characterized by high photovoltaic electricity potential (PVOUT), making them ideal for large-scale PV installations. The integration of desert control PV technology in Mongolia could simultaneously address land degradation and contribute to the country's economic development and local livelihood.

4.3.3. Development of the GPC Metrics

The Green Power Corridor Metrics (GPC Metrics) are proposed as an evaluation method designed to visualize the impacts of energy connectivity across different SDGs. It assesses the alignment of each project with the relevant SDGs at the target level. Developed with a broad focus on energy connectivity across the region, three uses cases are considered.

- Export country case: construction of new generation power plants with more than half of the electricity output planned for export. It may include also the construction of additional transmission capacity.
- Transit country case: construction of transmission capacity across a county to facilitate the trade between neighboring countries. It may include some connections with the national grid for domestic use, but this is regarded as minimal. Otherwise, it is regarded as "import" project.
- Import country case: support the construction of new generation power capacity in a country with the purpose of importing the output for domestic use.

This section outlines the process for the design of the GPC metrics and includes instructions for their utilization. The GPC Metrics are the first iteration, and further improvements are expected to come with the feedback from policy-makers, stakeholders, and experts.

Interlinkages of energy connectivity projects and SDGs

To operationalize the set of metrics in practice, the interlinkage between energy connectivity projects and SDGs was conducted by reviewing the potential impact that these projects could have in achieving the sustainable development targets for the countries involved. The 169 targets were evaluated by considering the level of potential impact measured from 1 (lowest) to 5 (highest). It is important to note that at this stage, no specific technology or region was considered. The objective was to broadly identify relevant targets and SDGs that could be applicable to every project and region in Asia and the Pacific. Subsequently, the average value of each SDG was estimated. The degree of interlinkage between energy connectivity prototype projects and SDGs was then estimated as "Not at all" (for average values from 1 to 1.4), "Slightly" (1.5 to 2), "Moderately" (2.1 to 3), "Very" (3.1 to 4), or "To a very high degree" (4.1 to 5). Figures 18-20 summarize the results for that analysis for the three cases considered.

The impact of energy connectivity projects on export countries appears to be more substantial than on transit and import countries. This can be attributed to the fact that the majority of infrastructure investments will be allocated to the construction of the power plant. Nevertheless, it is essential to consider the numerous interconnections between this project and the broader development agenda concerning transit and import countries. These include the investment in new infrastructure, such as new transmission lines in transit countries, as well as the positive economic impacts resulting from increased energy security and diversification of the energy mix with the incorporation of more sustainable energy resources. Furthermore, these benefits are in addition to the overall advantages that more active and constructive regional collaboration can offer to all participating countries.

Screening of sustainable development targets

The second step consisted of a deeper analysis of the linkages between energy connectivity projects and sustainable development targets. It could be reasonable to focus only on an aggregated level for SDGs, selecting only those more relevant, but this could lead to misleading results, leaving several important elements

Figure 18. Assessed level of interlinkages of energy connectivity and SDGs (goal level) (export country case)

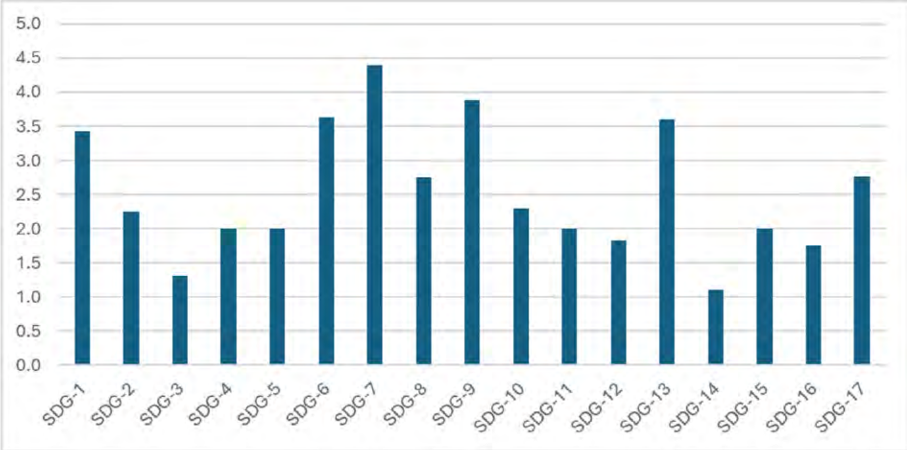


Figure 19. Assessed level of interlinkages of energy connectivity and SDGs (goal level) (transit country case)

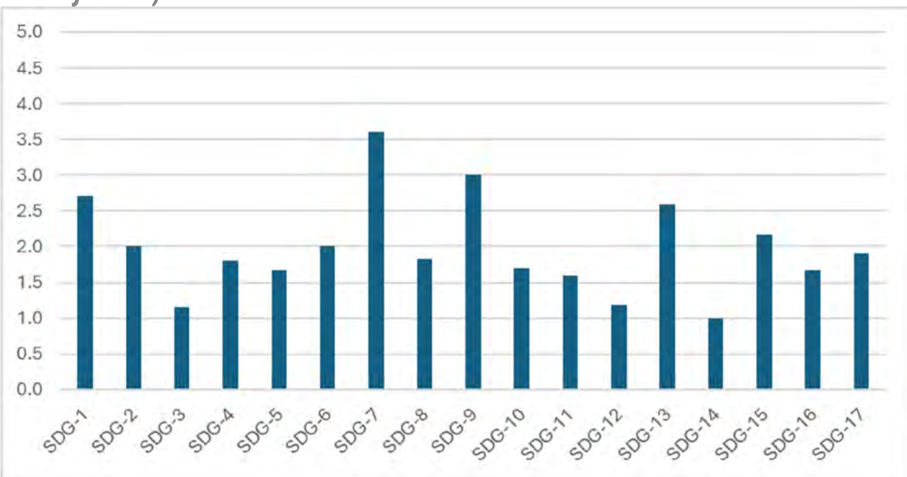
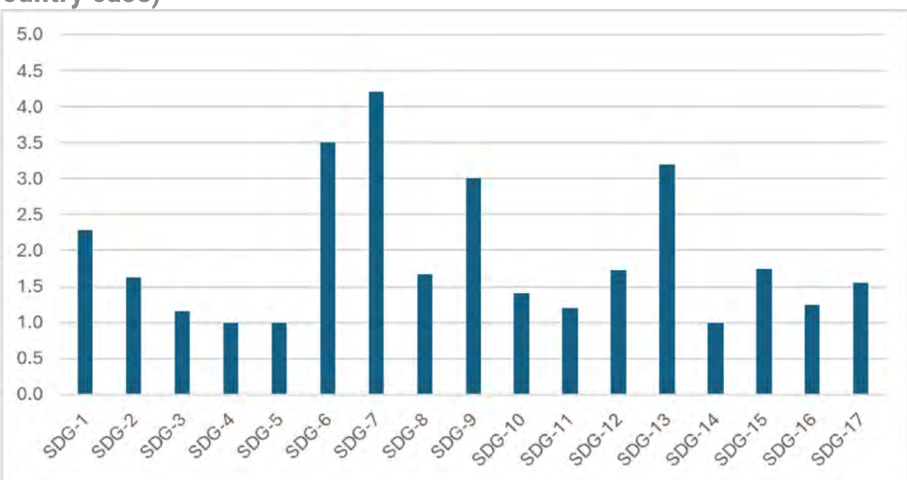
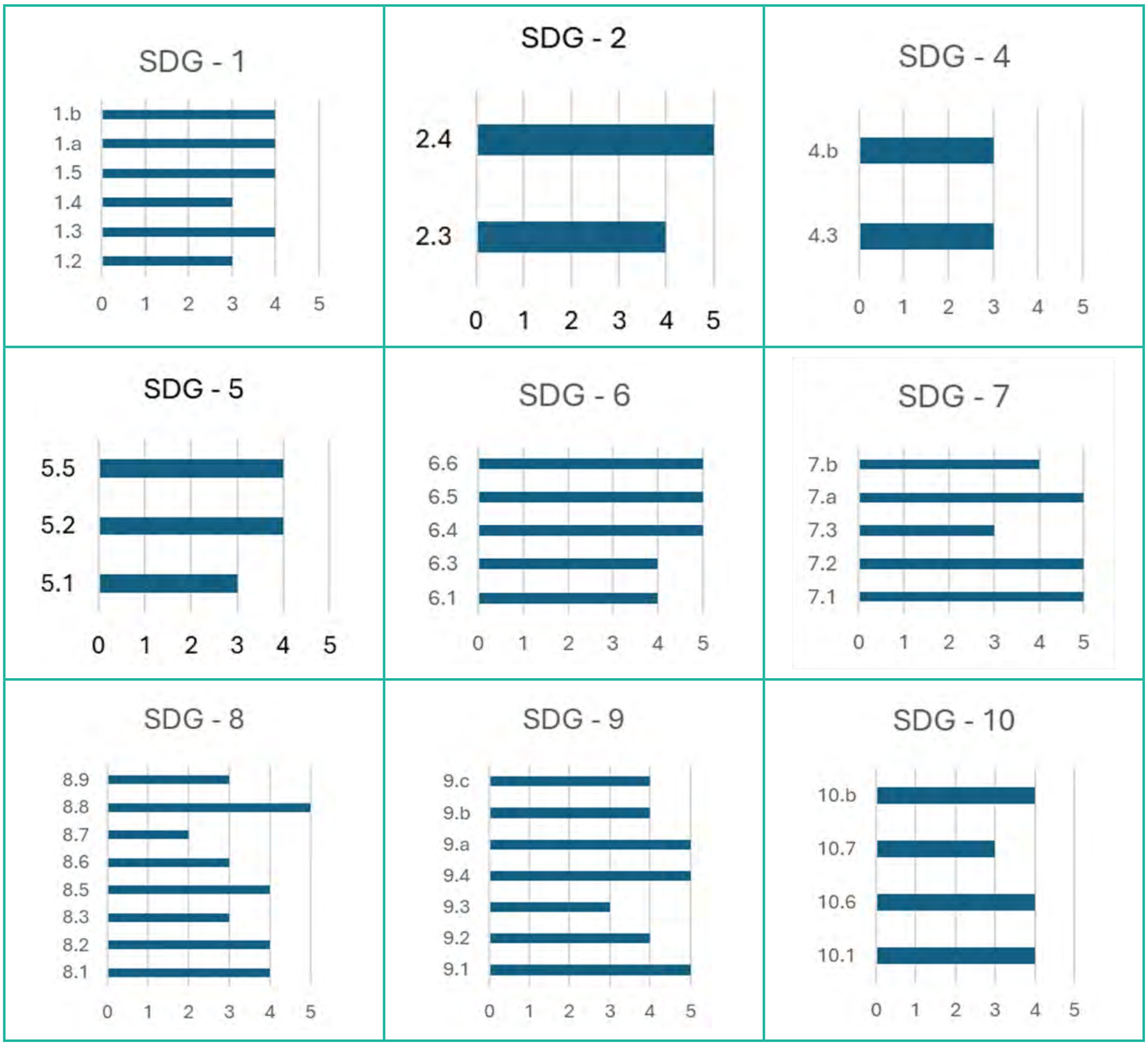


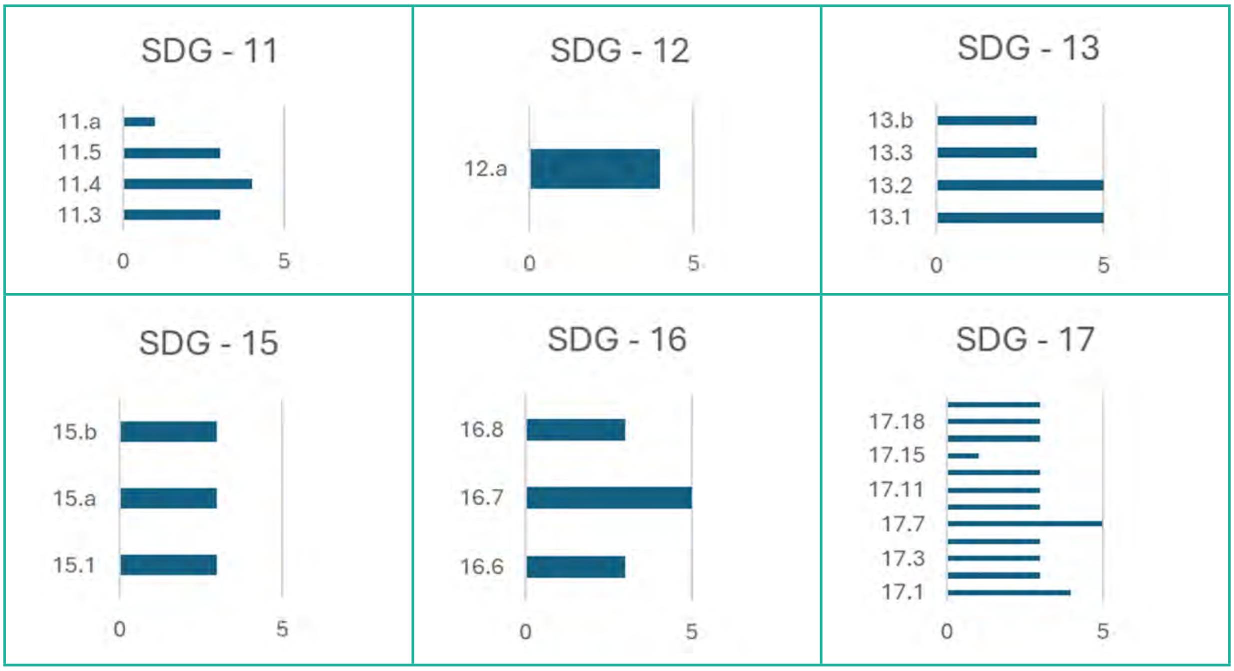
Figure 20. Assessed level of interlinkages of energy connectivity and SDGs (goal level) (import country case)



out of the analysis. The evaluation for export projects (the most common and initial test for these metrics), found that in several cases, the potential impact for certain targets was regarded as high (3 or more), even though the average at the goal level was lower. Indeed, only SDG 1 (no poverty), 6 (water), 7 (energy), 8 (industry), 9 (resilient infrastructure), and 13 (climate change) had high potential impacts at the goal level (see Figure 1). However, certain targets for all other SDGs are also considered relevant, except for SDG 3 (zero hunger) and 14 (life under water). This does not mean that no energy connectivity will have any positive or negative impact on realizing these goals. As offshore wind energy has become more widely adopted in Asia and the Pacific, SDG 14 will become more relevant. As such, GPC metrics are a live tool to be updated as the energy transition progresses in the region. The analysis was then expanded to the target level to avoid missing data in the subsequent evaluation method. The result was 69 identified targets for export-oriented projects (see Table 11).

Table 11. Identified sustainable development targets (value 3 or more) with high interlinkage with energy connectivity projects (export-oriented)





A questionnaire-based assessment tool for GPC Metrics

The next step is to propose a general framework for evaluating the alignment of projects with development goals and targets. This alignment occurs when the project has direct positive reinforcement in all or some of the metrics included in the SDGs framework for each target. The present version of the metrics is designed for ante studies and discussions. For that, the assessment tool is based on a series of questions to qualitatively evaluate the impact of the potential impact across a long list of relevant issues.

Specifically, respondents (stakeholders and/or experts) will rate the impact of the project as: very negative, negative, positive, very positive. There is an option also for no impact. The entire list of questions is provided below, although, in practice, an additional screening is being designed to fit the questionnaire better to each project's context.

SDG	How does this project impact the following in the EXPORTING / TRANSIT / IMPORT country?
1	Access to basic services (e.g. electricity, water, sewage, road...)
1	Population covered by social protection floors / systems
1	Rightful land tenure and land users
1	Economic and life impacts from natural disasters
1	Guide development assistance to complementary projects for essential services (health, education,...)
1	Pro-poor public spending
2	Agricultural productivity and income
2	Sustainability of agricultural practices
4	Access to technical, vocational and tertiary education
4	Access to scholarships

5	Equality and non-discrimination on the basis of sex/gender
5	Prevention of violence against women and girls
5	Participation of women in decision making in political, economic and public life
6	Expansion of access to drinking water
6	Expansion of wastewater treatment services
6	Reduce levels of water scarcity
6	Cooperation in transboundary rivers
6	Water related ecosystems (mountains, forests, wetlands, rivers, aquifers, and lakes)
7	Access to electricity and clean fuels and technology
7	Share of renewable energy in the national energy mix (fuels and electricity)
7	Improving energy intensity of the country (as primary energy per GDP)
7	International investment in clean energy in developing countries
7	Increase installed renewable energy generating capacity in developing countries
8	GDP per capita
8	GDP per employed person
8	Reduction of the proportion of informal employment
8	Reduction of unemployment
8	Reduction of youth unemployment
8	Safe and secure working environments for workers
8	Sustainable tourism
9	Accessibility to all season rural roads
9	Manufacturing value added and employment in industry
9	Access to finance for small-scale industrial enterprises
9	Reduction CO2 emissions per GDP
9	Guide international development funding to infrastructure in developing countries
9	Domestic technology development, research and innovation in developing countries
9	Expand access to information and communication technology
10	Income growth for the bottom 40 per cent of the population
10	Representation and voice for developing countries in international decision making
10	Inclusion of immigrant work force
10	Increase official development assistant and final flows to developing countries
11	Participatory role of local residents in project planning and development
11	Expand protection to cultural and natural heritage
11	Increase resilience of critical infrastructures against natural disasters
12	Installed renewable energy
13	Adoption and implementation of local disaster risk reduction strategies
13	Implementation of Nationally Determined Contributions
13	Education for sustainable development
13	Support country activities as part of the United Nations Framework Convention on Climate Change

15	Protection of forests and freshwater biodiversity
15	Domestic and international finance to protect biodiversity
15	Combat desertification

16	Finance for sustainable forest management
16	Promote transparency in institutions at all levels
16	Promote inclusive and responsive decision making

17	Increase voting rights of developing countries in international organizations
17	Increase significantly total government revenue, including from domestic taxes
17	Increase net official development assistance
17	Support additional financial resources mobilization to developing countries
17	Reduce debt burden by developing countries
17	Development, transfer, dissemination and diffusion of environmentally sounded technologies
17	Increase total value of financial and technical assistance committed to developing countries (including North-South, South-South, and trilateral cooperation)
17	Increase exports from developing countries
17	Development and implementation of mechanisms to enhance policy coherence for sustainable development
17	Increase the availability of official statistics
17	Increase census data

Visualization and interpretation of results

The assessment is expected to include multiple responses so to be more flexible in its interpretation. In that process, it is important to consider how the output of the assessment is expected to be utilized. Indeed, the GPC Metrics should be considered as an additional tool to incorporate in the development of the project and engagement of multiple stakeholders. By doing so, they help to visualize elements that represent an important lesson for other projects, as well as identifying some areas of the projects that could be further considered for improvements or some missed opportunities to have a positive impact across several SDGs. An explanation of the actions taken or the justification for the answers is requested in the form of a short explanation. Nonetheless, the answers for these questions are flexible so to allow multiple answers, which will show different perspectives. For that, the inclusion of a weighting factor will also be included as the tool is further developed.

An illustrative example is provided of two alternatives for the same project, a large-scale cross-border on-shore wind farm. The analysis of the first alternative shows the impact across several SDGs, highlighting not only the positive impact on SDG-7 (energy) but also on education and gender equality among several others. The metrics also facilitate two areas of possible concern or, at least, for further investigation. In this case, SDG-2 due to particular impacts on limited land for farming high value crops, and SDG-11 for affecting sacred land being crossed by transmission infrastructure and required works. The decision to change the layout, including also different wind turbine models to maintain similar generation capacity, helps to address these two concerns. Even more, in this process, identifying the particularities of the cultural heritage existing in the area allows to implement additional measures such as specific training for workers not familiarized with the local culture on how to behave.

Figure 21. Initial impact on SDGs before changing project design

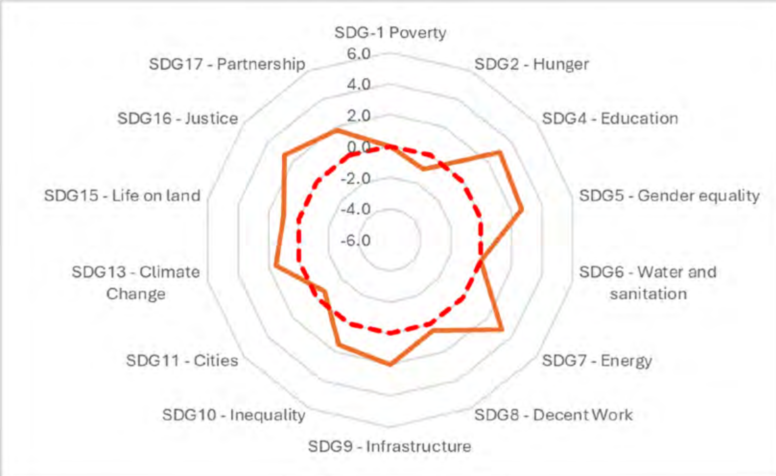
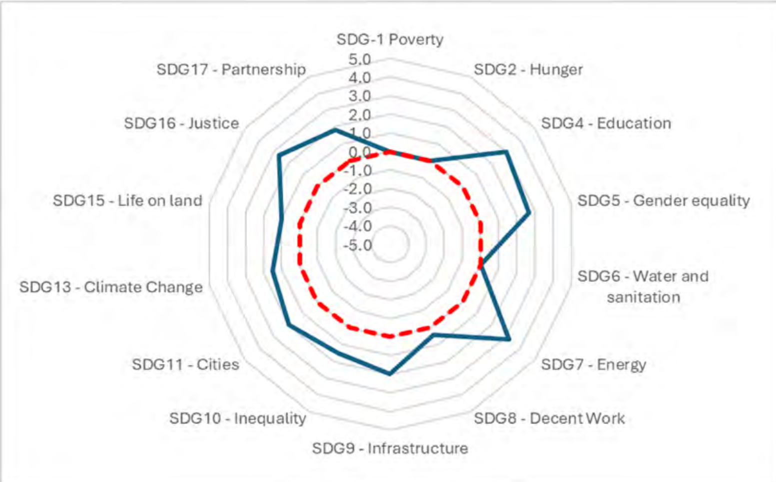


Figure 22. Impact on SDGs after changing project design



Conclusion and key messages

The Green Power Corridor Framework represents a strategic initiative aimed at enhancing regional power connectivity while promoting sustainable development. The six building blocks of the GPC Framework—political accord, institutional framework, enabling financial arrangements, regulatory framework, infrastructure backbone, and social acceptance—form a comprehensive foundation necessary for the successful implementation of cross-border power interconnection projects, aiming to achieve the desired economic, social, and environmental benefits.

The application of the GPC Framework principles in developing the interconnection roadmap for North-East Asia demonstrates how the GPC Framework can lead to a concrete, step-wise action plan for moving towards power system connectivity and trade, as well as comparing scenarios for establishing the optimal business-case for sustainable and economically feasible interconnections.

Additionally, the GPC metrics has been developed to be used as a tool by policymakers and stakeholders for aligning connectivity projects and initiatives to SDGs at any stage of development, providing an opportunity to not only consider different options but also to put in place policies and actions that could mitigate negative impacts and amplify positive ones.

Chapter 5

Technological Enablers of Power System Connectivity

5.1. Emerging grid technologies and energy connectivity

Modern technologies are profoundly transforming energy connectivity, enhancing the efficiency, reliability, and sustainability of energy systems. Innovations such as digital twin platforms, sub-sea cables, high-voltage long-distance cables, and battery storage systems are playing a crucial role in this process. These technologies are driving the development of a more interconnected and resilient global energy network. There are a number of innovative grid technologies to support the expansion and enhancement of energy transition.

Key emerging grid technologies include advanced conductors, high-temperature superconductors, storage as a transmission asset, dynamic line rating, advanced power flow control and grid inertia measurements. The implementation of these technologies can help dynamically control power flows, better understand actual line limits, and increase line capacity. For instance, dynamic line rating and advanced power flow control can significantly enhance grid capacity by managing power flows more effectively and utilizing natural cooling effects. High-temperature superconductors and advanced conductors offer substantial capacity improvements for individual lines, while innovative management systems provide real-time data and scenario analysis to optimize grid operations and integration of renewable energy sources.

The deployment of new technologies creates significant benefits, including increased grid capacity, accelerated grid expansion, and reduced investment costs. However, there are barriers to modern technologies adoption, such as regulatory and financial challenges, lack of incentives for innovation, and conservative investment climate of network operators.

Emerging grid technologies influence energy connectivity development by enhancing the efficiency, reliability, and sustainability of the electricity network. They enable better integration of renewable energy sources, reduce transmission losses, and provide real-time data for improved decision-making.

These technologies also facilitate the creation of more flexible and resilient energy systems, capable of adapting to changing demand patterns and integrating new energy sources seamlessly. By optimizing the existing grid infrastructure and accelerating the buildout of new network assets, technologies play a crucial role in advancing energy connectivity and supporting the transition to a more sustainable and autonomous energy system.

5.1.1. Digital twin technologies

A digital twin is a virtual representation of an object or system designed to reflect a physical object accurately. Compared to computer simulation, which typically focus on a single process, digital twins can run numerous simulations to examine multiple processes. The concept of digital twin technology was first introduced in 1991 by David Gelernter in “Mirror Worlds.” Dr. Michael Grieves later applied this concept to manufacturing in 2002. The term “digital twin” was coined by NASA in 2010, though NASA had already pioneered the use of digital twin technology as far back as the

1960s, by replicating voyaging spacecraft for study and simulation during space missions[16].

Digital twins offer numerous benefits, particularly in the areas of research and development, operational efficiency, and end-of-life product management. By leveraging digital twins, companies can enhance their research and design processes. The abundance of data generated by digital twins provides valuable insights into likely performance outcomes, enabling necessary product refinements before production begins. This predictive capability results in better-designed products and reduces costly errors during the manufacturing phase.

Moreover, digital twins contribute to greater efficiency throughout the production lifecycle. They mirror and monitor production systems in real time, facilitating the maintenance of peak efficiency and allowing for quick adjustments to optimize operations. This continuous monitoring ensures that manufacturing processes remain efficient and cost-effective. Digital twins also assist in managing products at the end of their lifecycle. They provide detailed information on the materials and components of products, helping manufacturers make informed decisions about recycling and final processing. By identifying which materials can be reused, digital twins support sustainable practices and reduce waste, contributing to a circular economy.

Use in energy sector

Digital twins are already used in the energy sector and have huge potential for further development (Chaouki Ghenai and others, 2022). In the generation sector, digital twins are used to design and optimize renewable energy systems, such as solar and wind farms. They enable real-time monitoring and control, facilitating fault detection and performance optimization. For instance, digital twins help simulate different scenarios to enhance the design of energy systems and validate their behavior before implementation. This application extends to other generation sources like wave energy, where digital twins predict system responses under extreme conditions, thereby improving efficiency and reducing costs.

For energy storage systems, digital twins focus on short-term decision-making for controlling and monitoring systems. They model batteries, power plant stations, and heating/cooling systems, providing insights into their operation and maintenance. Despite the benefits, challenges include the limited availability of real data, which hinders the full potential of digital twins in this area. They predict temperature responses in battery packs and optimize thermal energy storage, enhancing overall system efficiency and reliability.

Digital Twins also play a crucial role in energy transmission by supporting grid modeling, monitoring, and control (Chaouki Ghenai and others, 2022). They aid in fault detection and energy management, particularly in microgrids. In energy consumption, digital twins are primarily used in residential applications to model and optimize heating and cooling systems, and building energy management. Multi-energy systems, integrating generation, storage, transmission, and consumption, are increasingly leveraging digital twins for comprehensive analysis and optimization. These applications highlight the transformative potential of digital twin technology in making energy systems more sustainable, efficient, and resilient

Digital twins and grid development

The electric grid is a vast network that facilitates power transmission from producers to consumers. Traditionally, the grid relied on centralized, one-way transmission of electricity, however innovations in energy systems and fast development of renewable energy including DERs leads to the change in traditional grid development. In this case grids should evolve to meet these demands sustainably while maintaining high standards. The concepts of microgrids, smart grids, and virtual power plants (VPPs) are being explored to enhance energy management and reduce carbon emissions (Mhamud Hussen Sifat and others, 2023).

16 For additional information on the Digital Twin, see https://www.ibm.com/topics/what-is-a-digital-twin.

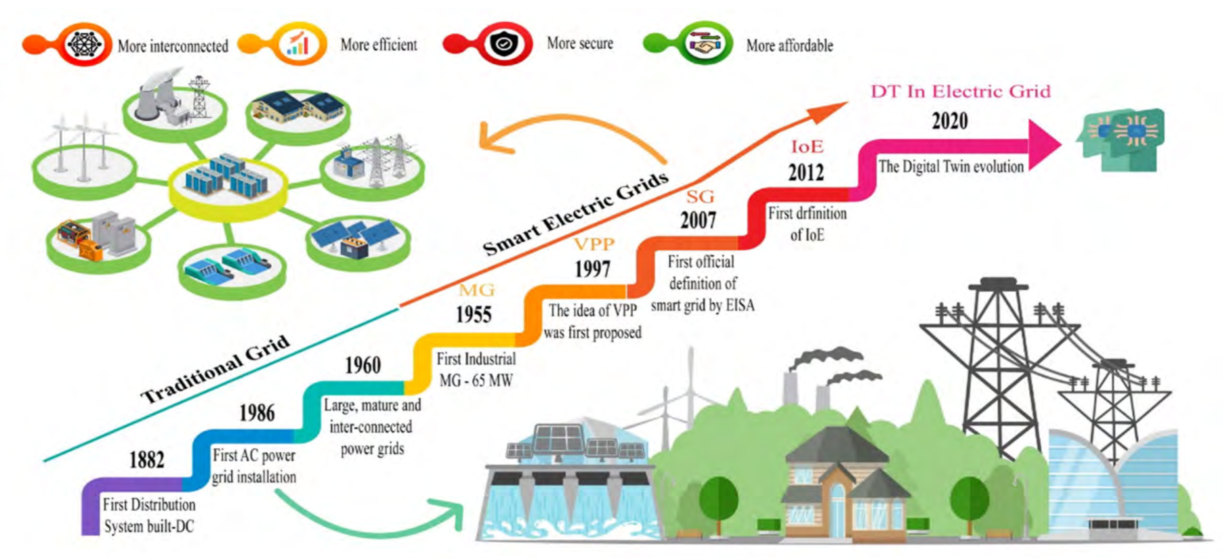
The complexity of the smart grids has increased, making the energy network more sophisticated each day. To optimize this network, numerous technologies are being integrated into the system. Smart grids provide intelligent services that help energy producers and suppliers manage their resources more efficiently by providing data on electricity usage. With global climate change driving attention towards sustainable technology, many countries are adopting renewable energy sources like solar and hydropower. As these renewable sources are added to the grid, technologies to enhance energy efficiency are also being researched.

Managing extensive network requires comprehensive planning, security tests, grid evaluations, and troubleshooting. Therefore, the future electric grid will rely on emerging digital twin technology, which offers simulation flexibility, new security frameworks, consumer-utility connection schemes, and real-time data analysis capabilities. Digital twins combine physical and virtual data throughout a product's lifespan, providing valuable insights that can enhance physical processes.

The digital twin grid concept takes this evolution a step further by creating a virtual clone of the physical grid. This clone can perform real-time analysis, integrate historical and current data, and predict future grid behavior. The digital twin grid can identify issues such as transmission losses, overheated lines, and power connection problems, and enable self-healing and decision-making processes. This capability is crucial for preventing outages and ensuring reliable energy distribution. The digital twin grid also enhances cybersecurity, making it resilient to cyberattacks and ensuring the protection of sensitive data related to grid operations and consumer information.

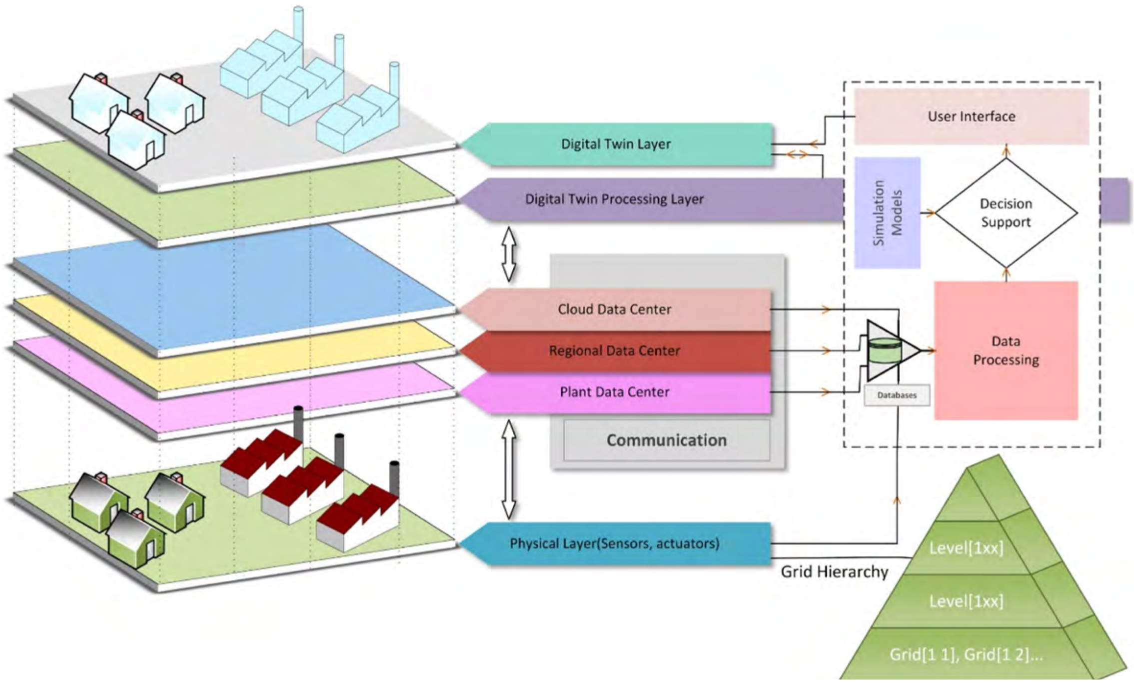
The implementation of a digital twin grid involves several components, including an online analysis framework, a cloud platform, and a robust communication system. The online analysis framework continuously monitors the grid's status, while the cloud platform provides real-time visibility and management capabilities to both producers and consumers. The communication system ensures seamless data exchange between physical sensors and the virtual twin, facilitating real-time monitoring and control. Despite these advancements, challenges remain, particularly in terms of data management, cybersecurity, and the integration of various technologies. Future research and development are needed to address these challenges and fully realize the potential of digital twin grids in enhancing the efficiency, reliability, and sustainability of energy systems.

Figure 23. Evolution of electric grids.



Source: Mhamud Hussen Sifat and others (2023), accessed at https://www.sciencedirect.com/science/article/pii/S2666546822000593

Figure 24. The concept of the electric digital twin grid



Source: Mhamud Hussen Sifat and others (2023), accessed at https://www.sciencedirect.com/science/article/pii/S2666546822000593

Implications for cross-border connectivity

Digital twins can play a crucial role in the development of cross-border power system connectivity by providing real-time insights, predictive maintenance, enhanced decision-making, optimized energy resource management and improved cybersecurity,. These advancements lead to more reliable, efficient, and sustainable power systems that benefit multiple countries economically and socially.

- *Real-time monitoring and management.* Digital twin technology allows for real-time monitoring and management of power systems across borders. By integrating real-time data from multiple countries, operators can have a comprehensive view of the entire power network. This holistic perspective helps in identifying potential issues and optimizing the flow of electricity between different regions.
- *Maintenance.* The predictive capabilities of digital twin technology enable early detection of potential faults and the implementation of preventive measures. This is particularly important in cross-border systems where coordination and timely responses are crucial. Digital twin technology ensures that minor issues are resolved automatically, minimizing disruptions and improving the reliability of the power supply across borders.
- *Enhanced decision-making.* With the ability to simulate various scenarios and analyze the performance of the grid under different conditions, digital twin technology supports better decision-making. This is vital for cross-border power systems where decisions must account for the regulatory, economic, and technical considerations of multiple countries.
- *Optimization of energy resources.* Digital twin technology helps in optimizing the use of renewable energy resources by accurately predicting their availability and performance. In cross-border contexts, this means that countries can better share and balance their renewable energy resources, reducing reliance on fossil fuels and enhancing overall energy security.

- *Cybersecurity.* Digital twin grids provide high levels of cybersecurity, which is essential for protecting cross-border power systems from cyberattacks. This ensures the stability and security of the interconnected power networks, fostering trust and cooperation among countries.

- *Policy and regulation:* The comprehensive data and insights provided by digital twin technology can inform policymakers and regulators in multiple countries. This data-driven approach helps in harmonizing standards and regulations, which is critical for the smooth operation of cross-border power systems.

- *Economic and social benefits:* By enhancing the efficiency, reliability, and sustainability of cross-border power systems, digital twin technology contributes to economic growth and social development. Reliable and efficient power connectivity supports industries, creates jobs, and improves the quality of life for people in interconnected regions.

Case studies

United Kingdom - National Digital Twin Programme (GOV.UK, 2023).

The project aims to test how digital twin-related technologies and processes can facilitate the delivery of long-term policy objectives, becoming self-sufficient in electricity from renewable sources, and meeting its net-zero target by 2040. It also examines how these technologies can support the improved delivery of regulatory requirements and strategic frameworks.[17]

The demonstrator project aims to model the island's electricity network, encompassing components from the 132kV interconnectors to local 400V transformers. It will leverage a flexible marketplace concept to optimize controllable heating, storage, and e-mobility services. This tool will facilitate understanding how better demand and generation balancing can be achieved and the potential for incorporating additional renewable energy sources to meet the island's energy needs. Central to this project is the ability to test different scenarios digitally, addressing crucial 'what if' questions.

Next steps involve identifying and understanding the needs of key stakeholders and defining the central problems that need solutions. By refining these challenges, an optimal solution will be developed, leading to the creation of a "minimum viable product" that will enter the testing phase. The approach emphasizes continuous refinement, acknowledging that plans improve with practical application and feedback. This mindset aims for the demonstrator to contribute significantly to the energy sector's transformation, supporting its goal of energy autonomy and net-zero target achievement.

Singapore

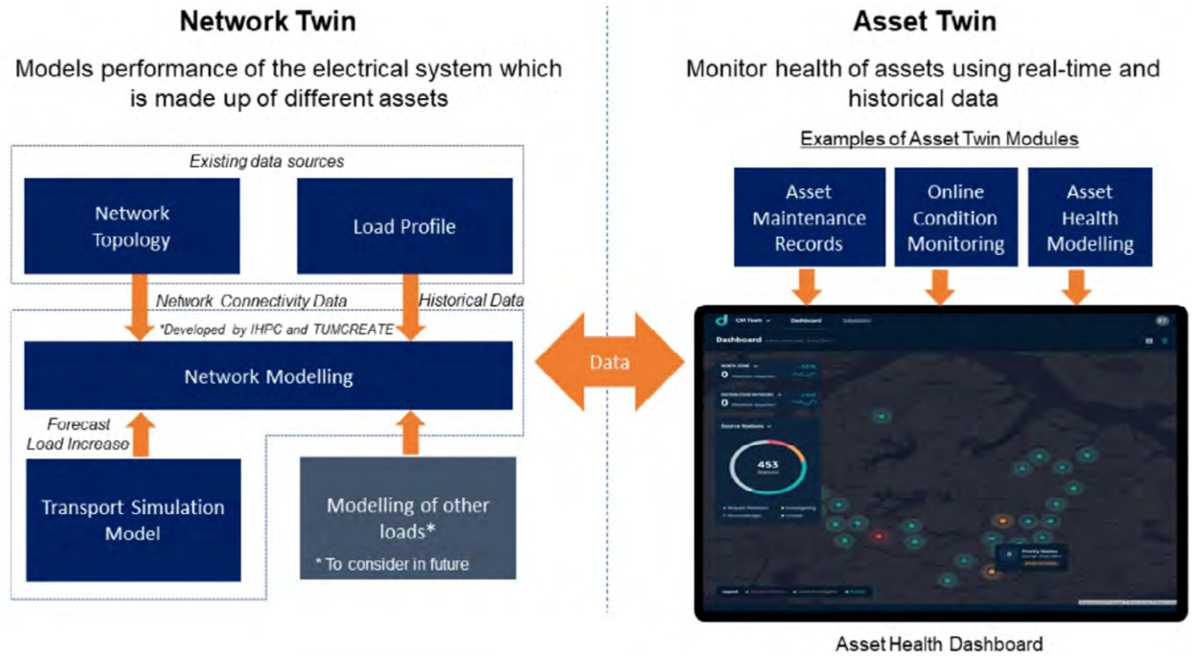
Singapore's first grid digital twin, supported by the Energy Market Authority (EMA), SP Group, and the Science and Technology Policy and Plans Office, functions as a virtual representation of the physical power grid, leveraging real-time and historical data. This innovative digital twin will enhance Singapore's power grid resilience and reliability while supporting the integration of cleaner energy sources. It consists of two primary models: the Asset Twin for managing grid assets like substations and cables, and the Network Twin for assessing the impact of new energy sources or consumers on the grid.[18]

Currently Digital Twin is in prototype stage, and expected to be fully operational in the coming years. Once deployed, it will help to improve grid planning, operation, and maintenance through advanced modeling and simulations. This approach promises more effective and efficient grid management compared to traditional methods, reducing the need for extensive physical inspections and optimizing infrastructure planning for various needs, such

17 For more information on the National Digital Twin Programme of UK see https://www.gov.uk/government/collections/the-national-digital-twin-programme-ndtp

18 Energy Market Authority, "Grid Digital Twin". Available at: https://www.ema.gov.sg/our-energy-story/energy-grid/grid-digital-twin

Figure 25. Singapore's first grid digital twin model



Source: SP Group (2021), accessed at https://www.spgroup.com.sg/about-us/media-resources/news-and-media-releases/Digital-Twin-for-National-Power-Grid

as electric vehicle chargers and solar energy systems.

Aligned with Singapore's Green Plan 2030, which emphasizes greener energy sources and increased energy supply diversification, the Grid Digital Twin will play a crucial role in managing the complexities of a modern power system. With over 18,000 transformers and more than 27,000 km of underground cables across 11,000 substations, the Grid Digital Twin will ensure the grid is well-equipped to handle future demands and challenges while maintaining operational reliability.

5.1.2. Long-distance transmission cables

High Voltage Direct Current (HVDC) transmission systems have emerged as a crucial technology, particularly for long-distance and undersea power transmission. HVDC is an electric power transmission system which uses direct current (DC) for the bulk transmission of electrical power unlike the conventional systems with alternating current (AC) (Zimaran Rafique and others, 2022). HVDC line offers better voltage regulation as compared to the AC-based systems. HVDC technologies minimize losses and allow for more, efficient transmission lines (Dielectrics and Electrical Insulation Society, 2024). This technology is particularly crucial for connecting remote renewable energy sources, such as offshore wind farms, to the main grid. By facilitating the transfer of clean energy from production sites to consumption centers, these cables support the transition to a greener and more resilient energy infrastructure. These cables are engineered to offer higher capacity, improved efficiency, and enhanced reliability, addressing the increasing demands of modern power grids.

Developing HVDC systems involves advanced technology, particularly in converting and inverting electricity between AC to DC and vice versa. Ensuring these systems are reliable and efficient requires significant expertise and financial resources. There are limited number of companies producing such technologies, which makes supply limited. There are some examples below. Siemens Energy is a leading provider of HVDC technology, known for its innovative solutions in HVDC converters and transmission systems. ABB, now part of Hitachi Energy, is a pioneer in HVDC technology. They have been involved in many major HVDC projects worldwide, providing advanced HVDC converter stations and system solutions. NKT is a leading manufacturer of HVDC cables, known for its high-quality cable technology. They provide cables for both land and submarine HVDC applications, contributing to many large-scale projects (Michael C. Hjorth, 2023).

Challenges in developing HVDC:

- The initial setup costs for HVDC systems, including converters, cables, and installation, are very high. This financial barrier can be a significant challenge for many projects, despite the long-term benefits.

- HVDC systems, especially submarine cables, pose substantial maintenance and repair challenges. Identifying and repairing faults in remote or underwater locations can be complex and costly.

- Integrating HVDC links with existing AC networks is technically challenging. It requires sophisticated control systems to manage power flow and maintain grid stability.

- HVDC projects often face regulatory issues and environmental concerns, especially when they cross multiple jurisdictions. Navigating these regulatory frameworks and obtaining the necessary approvals can be time-consuming and complex.

- Managing space charge accumulation in insulation materials and effectively dissipating heat are critical for the reliability of HVDC systems. Advanced materials and cooling technologies are necessary to address these issues.

5.1.3. Submarine power cables

Submarine power cables have become essential in linking offshore renewable energy sources, such as wind farms, to onshore power grids and facilitating international energy trade. Initially developed in the early 19th century, these cables have advanced significantly, with modern installations including both AC or High Voltage AC (Alternating Current) and High Voltage DC (Direct Current) technologies.

The first successful attempt to lay a submarine telegraph cable occurred in 1850, linking England and France. This milestone marked the beginning of an era where nations could communicate instantaneously across vast distances. By the late 19th and early 20th centuries, submarine telegraph cables connected continents, facilitating global communication and trade[19].

Initially, submarine power cables were used for short-distance connections, but technological advancements allowed for longer and more robust installations. Several key technological advancements have advanced the development of submarine cables. HVDC technology allowed for efficiently transmitting large amounts of electricity over long distances with minimal losses, making them ideal for cross-border connections. HVDC cables are preferred for long-distance power transmission due to their efficiency and lower energy losses compared to Alternating Current (AC) cables. This technology has enabled the construction of extensive submarine power networks, connecting different countries and continents.

Improvements in insulation materials and armoring techniques have increased the durability and reliability of submarine cables. Modern cables are designed to withstand harsh underwater conditions and physical impacts from anchors and fishing activities. Advances in cable laying vessels and techniques have streamlined the installation process. Sophisticated and remotely operated vehicles and cable plows ensure precise placement and

19 European Subsea Cables Association, "Submarine Power Cables". Available at: https://www.escaeu.org/articles/submarine-power-cables/

burial of cables on the seabed, reducing the risk of damage.

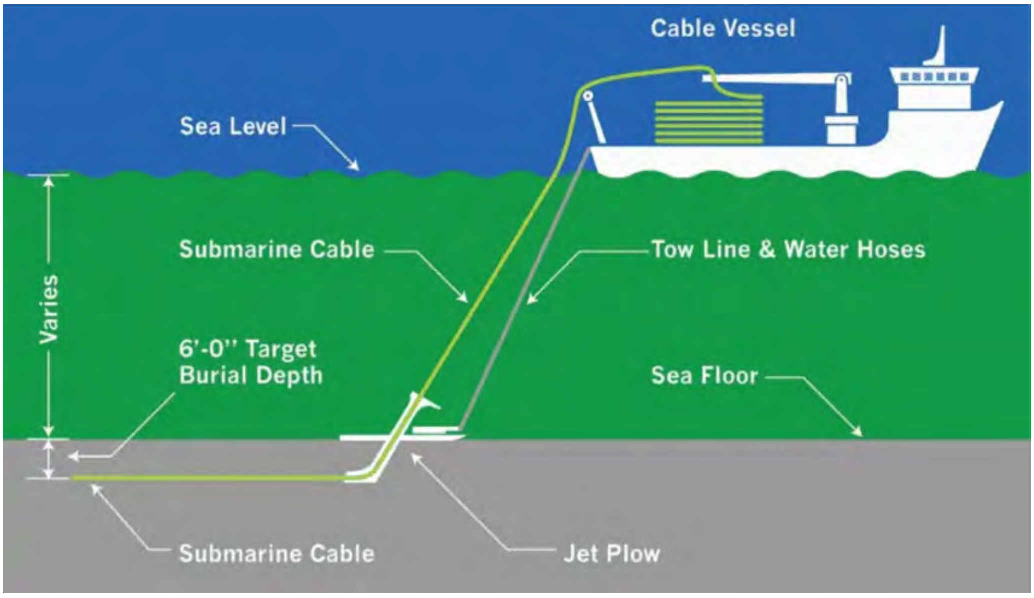
Submarine cables have revolutionized the way we transmit electricity and data across vast distances, playing a crucial role in global connectivity. The development of these cables has significantly influenced cross-border connectivity, enhancing international cooperation and economic integration as describted in the subsequent case examples.

Current challenges

Building submarine power cables presents numerous challenges.

- *Length and depth*. Some interconnector projects extend hundreds of kilometers, often through very deep sections. Deploying cables at great depths requires specialized equipment and techniques. These deepwater sections pose significant challenges for cable installation, including high lay tensions, when the force applied to a cable during the installation process is greater than recommended. The high lay tensions can lead to deformation of shape of the cable which put more pressure on the wires inside, especially at the points where cables are joined together (Jeremy Gordonnat and James Hunt, 2021).
- *Cable manufacturing and logistics.* The extensive length of the cable planned exceeds the average annual production capacity of HVDC cable manufacturers. Coordinating the manufacturing and delivery from multiple facilities adds complexity. Transporting and storing these cables also presents logistical issues, particularly due to the remote location of some installation sites.
- *Seabed conditions and congestion.* Some routes pass through areas which are characterized by shallow, congested seabeds with numerous existing pipelines and communication cables. This necessitates careful planning for cable burial and protection to avoid damage from fishing activities, ship anchors, and so on.
- *Geopolitical and environmental factors.* Crossing some territorial waters requires early and continuous engagement with local authorities to secure necessary permits and approvals. Additionally, the route selection must consider environmental impacts to the marine life (Bastien Taormina and others, 2018).

Figure 26. Submarine power cable installation



Source: Electrical Technology, Accessed at https://www.electricaltechnology.org/2018/02/submarine-cables-subsea-power-cables.html

- *Repair and maintenance*. The potential for cable damage during service necessitates planning for repair procedures, including laying additional cable for repairs. The selected route must allow for these procedures, which are more challenging in deepwater sections or areas with high seismic activity.

- *Cost and feasibility*: The estimated cost of the announced subsea cable development projects are very high, and primarily driven by the supply of HVDC cables.

Implication to development of cross-border connectivity

The development of submarine cables has had profound implications for cross-border connectivity in both energy and communication sectors:

- Submarine power cables enable countries to share energy resources, enhancing energy security and stability. For example, the NorNed cable, connecting Norway and the Netherlands[20], allows for the exchange of renewable energy, balancing supply and demand across regions. Such interconnectors facilitate the integration of renewable energy sources, reducing reliance on fossil fuels and supporting the transition to a sustainable energy future.

- Enhanced cross-border connectivity fosters economic growth by promoting trade and investment. Submarine cables enable countries to leverage their comparative advantages, such as access to renewable energy resources, and export surplus energy to neighboring regions. This not only boosts local economies but also strengthens international cooperation and interdependence.

- Submarine cables provide a resilient infrastructure for energy and data transmission, essential during natural disasters or geopolitical tensions. Redundant cable networks ensure that power can be rerouted, maintaining stability and continuity in critical situations.

- Cross-border projects involving submarine cables drive innovation and technological exchange. Collaborative efforts in research, development, and deployment of submarine cable technologies lead to continuous improvements and cost reductions, benefiting all participating countries.

- The integration of renewable energy sources into the power grid is a global priority. However, these sources are often located in remote or offshore areas, far from urban centers where the demand for electricity is highest. HVDC and submarine cables enable the efficient and reliable transmission of power from these remote locations, overcoming one of the significant challenges of renewable energy integration. This technology ensures that the energy generated from wind, solar, and other renewable sources can be transmitted over long distances without substantial losses, making it feasible to incorporate more renewable energy into the grid. This not only reduces dependence on fossil fuels but also enhances energy security by diversifying the energy supply.

- Grid stability and reliability are critical concerns for power system operators. The advanced insulation of HVDC cables help maintain consistent performance under varying environmental conditions. Additionally, HVDC systems are less susceptible to frequency fluctuations and can provide stable power transmission even over long distances. This stability is vital for integrating regional grids, enabling the development of a more interconnected and resilient global power network. By connecting various grids, countries can share resources, balance loads, and improve overall grid reliability.

The development of submarine cables has been a cornerstone in advancing global connectivity. Modern HVDC power links transformed international energy networks. By enabling cross-border energy trade, enhancing

20 Additional information on the NorNed Cable available from the Our Project section of TENNET website (https://www.tennet.eu/).

economic cooperation, and supporting the integration of renewable energy sources, submarine cables play a crucial role in shaping a connected and sustainable future.

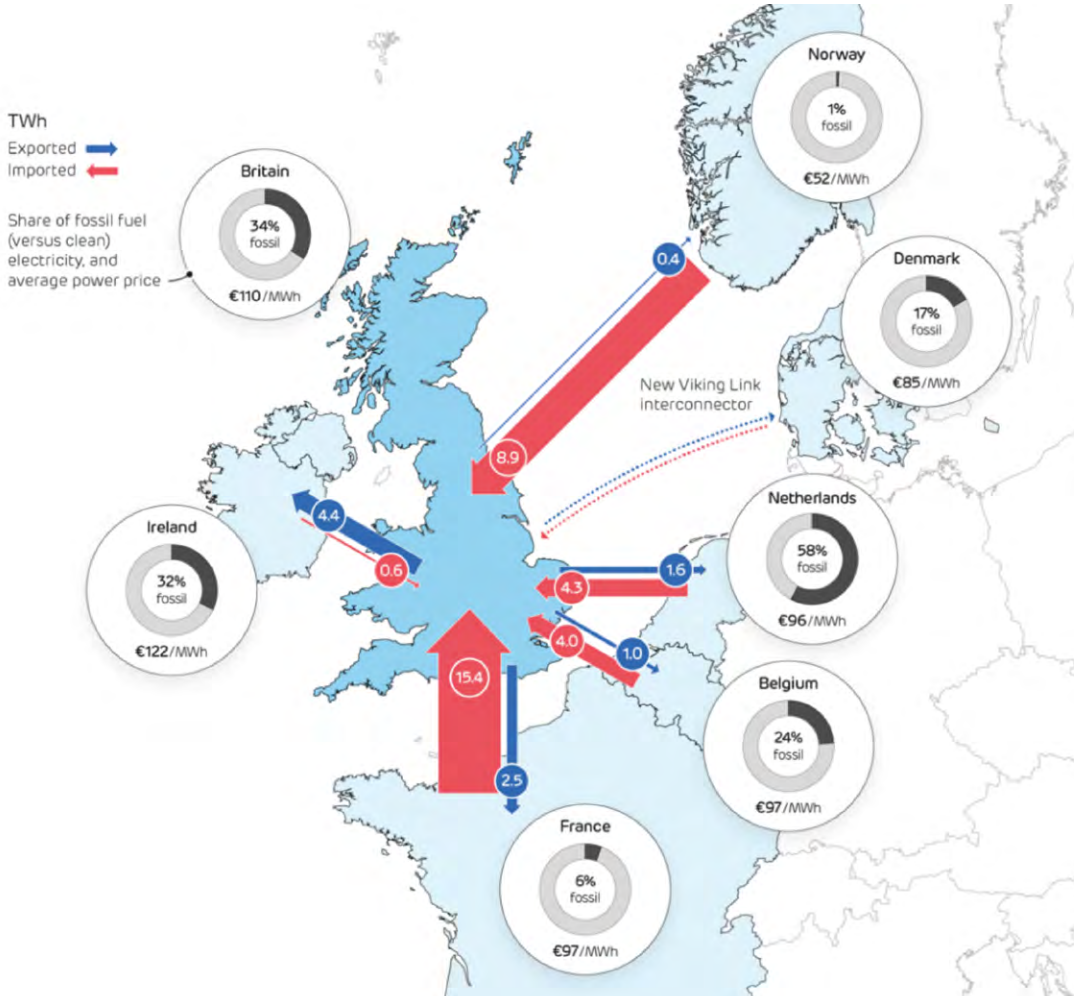
Case studies

World's longest subsea power cable connects UK to Denmark (Iain Staffell and others, 2023)

Viking Link is an undersea power cable, the longest globally, which lays 760 kilometers across the North Sea, connecting Lincolnshire in the UK to Jutland in Denmark. Initially capable of transmitting 0.8 GW, its capacity will increase to 1.4 GW with future upgrades. Denmark relies heavily on wind power, supplying almost two-thirds of its electricity. This is supported by a well-connected grid with links to Norway, Sweden, and Germany, allowing for effective management and export of surplus electricity. In its first days, the Viking Link transmitted an average of 660 MW to Britain, which already had the second-largest trade deficit for electricity in Europe. The Viking Link is expected to save spending for electricity to UK by providing access to cheaper Danish electricity.

The Viking Link enhances energy connectivity, optimizes grid performance, and supports renewable energy integration. By providing economic benefits and promoting grid resilience, it showcases the transformative potential of innovative grid technologies,

Figure 27. Electricity trade between Britain and neighbouring markets during 2023



Source: https://reports.electricinsights.co.uk/q4-2023/worlds-longest-subsea-power-cable-connects-britain-to-denmark/

Disclaimer: The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by the United Nations

underscoring the importance of continued investment in such advancements for sustainable energy goals.

Black Sea Submarine Cable Project[21]

The Black Sea submarine cable project aims to establish an underwater high-voltage transmission network connecting Georgia's electric power system with Europe. This 1155-kilometer-long cable will link Romania, enhancing South-East Europe's electricity import opportunities and enabling trade at hourly market prices. The project will support energy security in Europe and the South Caucasus, enhance renewable energy development, and increase transit capabilities.

Currently, Georgian State Electrosystem, in coordination with Italian consulting firm CESI, is conducting a technical-economic study (CESI, 2023). This study includes a desktop analysis of the project's technical and economic feasibility, as well as an assessment of its environmental and social impacts. The resulting Scoping Report outlines the main components and activities of the project and provides a preliminary evaluation of the potential environmental and social effects of its construction and operation. The report also emphasizes the importance of stakeholder engagement throughout the project's lifecycle.

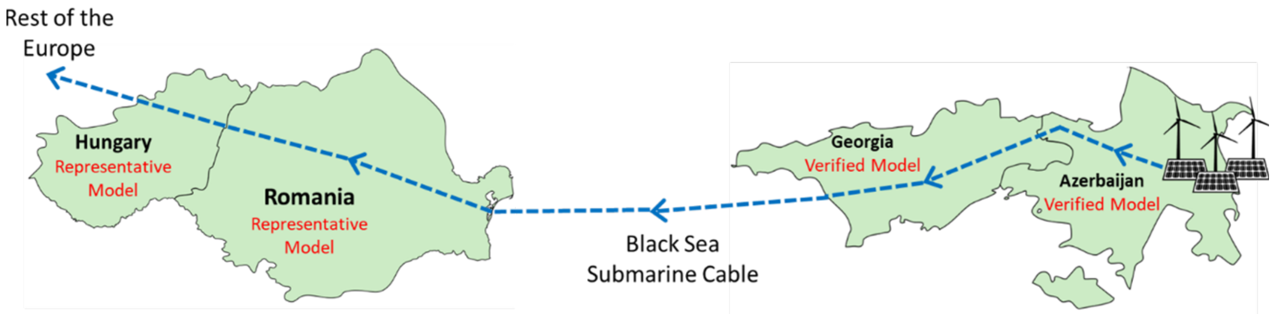
Future steps for the project include a detailed Environmental and Social Impact Assessment, along with geophysical and geotechnical studies of the Black Sea seabed to determine the best methods for implementation. The project design includes HVDC and optical fiber submarine cables, marine and pond electrodes, converter stations in both countries, medium voltage cable lines, terrestrial HVDC transmission cables, and HVAC overhead transmission lines. These components aim to ensure a reliable and efficient energy connection between Georgia and Europe, contributing to the broader goals of energy security, renewable energy development, and regional cooperation.

5.1.4. Energy storage systems

Energy storage systems have become crucial in modern energy management, driven by the need to balance electricity supply and demand and support the integration of renewable energy sources. These systems are critical for managing the intermittency of renewable energy, such as solar and wind, by storing excess energy produced during peak generation periods and releasing it when demand is high. Grid-scale energy storage is vital in achieving net zero emissions by 2050, providing short-term balancing, operating reserves, grid stability, investment deferment, long-term storage, and blackout recovery.

21 Additional information on the Black Sea Submarine Cable Project available from the Ongoing project section of GSE website (https://www.gse.com.ge/home).

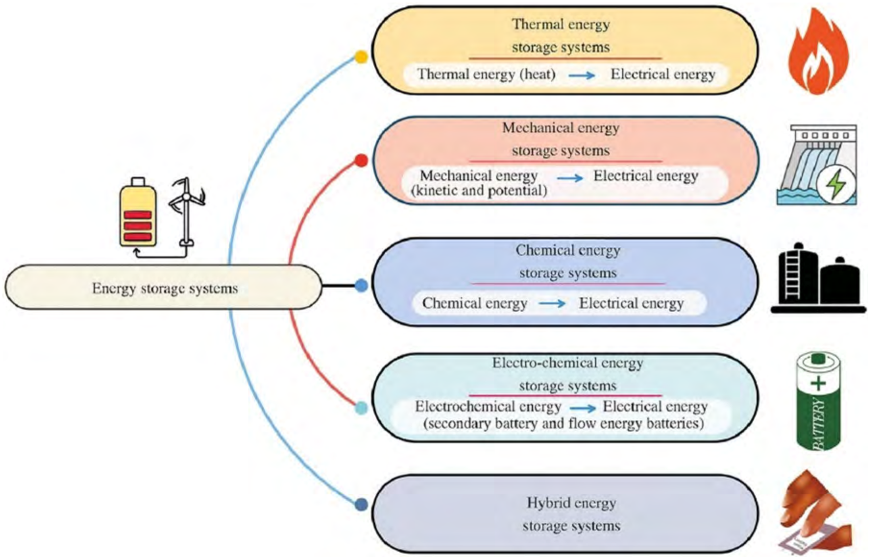
Figure 28. Black Sea Submarine Cable



Source: Georgian State Electrosystem JSC

Disclaimer: The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by the United Nations

Figure 29. Energy storage classification.



Source: https://www.sciencedirect.com/science/article/pii/S277268352200022X

Energy storage technology has evolved significantly from early systems like lead-acid batteries and pumped hydro storage to advanced systems such as lithium-ion batteries and thermal storage solutions. Energy storage can be classified into several categories based on the form of stored energy: Thermal, Mechanical, chemical, electrochemical, electrical energy storage and other, such as hybrid. Each category has distinct operating principles, advantages, and challenges (Mukrimin Sevket Guney and others, 2017).

The development of battery storage technology is experiencing significant advancements driven by the need for efficient and sustainable energy solutions. Pumped-storage hydropower, the most widely used technology, has significant potential, while batteries, the most scalable option, are experiencing rapid growth (Elixabete Ayerbe and others, 2022). Despite advancements, according to the IEA the current growth rate of grid-scale storage is insufficient to meet Net Zero Scenario targets.

In 2021, the global capacity of pumped-storage hydropower reached around 160 GW, providing over 90 per cent of global electricity storage. Most plants offer daily balancing, with the largest capacities in the United States. Grid-scale batteries, though smaller in capacity, are catching up. By the end of 2022, global installed battery storage was nearly 28 GW, a 75 per cent increase from 2021, driven primarily by the United States and China[22]. Lithium-ion batteries remain the dominant technology due to their high energy density and efficiency.

However, the rapid expansion needed for the IEA's Net Zero Scenario requires grid-scale battery storage capacity to increase 35-fold by 2030, reaching nearly 970 GW. Innovations in lithium-ion batteries continue, but further cost reductions depend on the prices of critical minerals. Flow batteries, like the vanadium redox flow battery, show high potential due to their long life and scalability.

Developers and other stakeholders are increasingly focusing on sustainability, with efforts to use recyclable materials and reduce reliance on rare elements. Integrating battery storage with renewable energy sources like solar and wind is becoming more prevalent to ensure stable power supply. Additionally,

22 Additional information on the Grid-scale Storage available from the Energy System-Electricity section of the International Energy Agency website (https://www.iea.org/)

there is a concerted effort to reduce costs, making energy storage more accessible and economical. The impact of geopolitical tensions , has also affected the supply and prices of key battery materials like nickel, cobalt, and graphite.

Developing and deploying storage systems involves several challenges:

- Advanced energy storage systems require sophisticated technology for energy conversion, storage, and retrieval.
- The upfront investment for energy storage systems infrastructure is substantial, although the long-term benefits can outweigh initial costs.
- Ensuring the longevity and reliability of energy storage systems, especially in harsh environments, is critical.
- Integrating energy storage systems with current AC power grids requires advanced control systems to maintain stability.
- Energy storage systems projects have to navigate complex regulatory frameworks and environmental concerns. A number of countries are supporting storage deployment through targets, subsidies, regulatory reforms and research support[23].

According to the IEA,[24] in order to facilitate the development governments should integrate storage solutions like pumped-storage hydropower and grid-scale batteries into long-term energy plans, assessing the need for flexibility alongside wind, solar, and grid capacity expansions. In liberalized markets, challenges such as long lead times and permitting risks slow down pumped-storage development, necessitating dedicated support mechanisms for stability.

Regulatory frameworks should be updated to allow flexibility options, preventing double charges and allowing storage to remove costly grid upgrades. Ownership issues, where storage is viewed as a generation asset, can be mitigated by allowing system operators to procure storage services from third parties.

Energy market designs should reward flexibility, enhancing the business case for grid-scale storage through measures like decreasing settlement periods. Critical mineral supply chains need diversification to ensure security, necessitating international cooperation for sustainable mining practices.

Policies should incentivize battery recycling to secure secondary supplies of critical minerals, complemented by commercializing second-life batteries from EVs through regeneration technologies. Despite challenges like refurbishing costs and lack of standardization, second-life batteries offer significant potential for grid-scale energy storage.

Implication to development of cross-border connectivity and energy transition

The development of various energy storage systems has significantly influenced the advancement of energy connectivity. By providing the means to store and manage energy more efficiently, energy storage enhances the reliability and stability of power grids, facilitating better integration of renewable energy sources. The following outlines some of the benefits of energy storage systems in cross-border connectivity and energy transition:

- *Enhancing grid stability and reliability.* Energy storage systems, such as batteries and pumped hydro storage, play a crucial role in balancing electricity supply and demand. They store excess energy generated during low demand periods and release it during peak demand times, ensuring a stable and reliable power supply. This capability is particularly important for

23 Additional information on the Grid-scale Storage available from the Energy System-Electricity section of the International Energy Agency website (https://www.iea.org/)

24 Additional information on the Grid-scale Storage available from the Energy System-Electricity section of the International Energy Agency website (https://www.iea.org/)

integrating intermittent renewable energy sources like solar and wind, which can fluctuate based on weather conditions. By smoothing out these fluctuations, energy storage helps maintain grid stability and prevents blackouts.

- *Facilitating renewable energy integration.* The integration of renewable energy into the power grid is a key goal for many countries aiming to reduce their carbon emissions and reliance on fossil fuels. Energy storage systems are essential for achieving this goal, as they can store energy generated from renewable sources and make it available when needed. This not only maximizes the use of renewable energy but also reduces the need for backup fossil fuel power plants. Technologies such as lithium-ion batteries, flow batteries, and thermal storage systems are particularly effective in supporting renewable energy integration.

- *Expanding energy access.* Energy storage systems also play a critical role in expanding energy access to remote and underserved areas. By enabling the storage of energy locally, energy storage can provide a reliable power supply to regions that are not connected to the main grid. This is especially important for rural and isolated communities, where extending the grid infrastructure can be prohibitively expensive. Off-grid energy storage solutions, such as solar-plus-storage systems, offer a sustainable and cost-effective way to provide electricity to these areas.

- *Promoting decentralized energy systems.* The development of advanced energy storage technologies supports the shift towards decentralized energy systems, where energy is generated and stored closer to where it is consumed. This reduces the reliance on centralized power plants and long-distance transmission lines, leading to lower transmission losses and increased energy efficiency. Decentralized energy systems, supported by energy storage, empower communities to manage their energy needs independently and contribute to a more resilient and sustainable energy infrastructure.

- *Reducing energy costs and environmental impact.* By improving the efficiency of energy use and reducing the need for peaking power plants, energy storage systems can help lower energy costs for consumers. Additionally, by facilitating the integration of renewable energy, energy storage contributes to a reduction in greenhouse gas emissions and other environmental impacts associated with fossil fuel power generation.

Case studies

<u>World's biggest flow battery in China</u> (Andy Colthorpe, 2022)

China has commissioned the first phase of what will become the world's largest flow battery, boasting a total capacity of 800MWh. Developed by the Huaneng Group, this project utilizes vanadium redox flow batteries (VRFB). VRFB systems can be easily scaled by increasing the volume, providing flexibility to meet varying energy demands. They also offer a long cycle life, often exceeding 10,000 cycles, making them a cost-effective solution over time. Unlike traditional lithium-ion batteries, VRFBs are non-flammable and operate at lower temperatures, reducing the risk of thermal runaway and enhancing safety.

The commissioning of this large flow battery underscores China's commitment to advancing renewable energy integration and grid stability. As the world transitions to cleaner energy sources, efficient energy storage becomes crucial. Large-scale systems play a crucial role in this transition by balancing supply and demand, storing excess energy during peak production times, and releasing it during high demand periods. This capability helps maintain grid stability and supports the integration of intermittent renewable energy sources, such as solar and wind.

Economically, the deployment of battery system can reduce energy costs by minimizing the need for peaking power plants, which are typically more expensive and less

Figure 30. Redox Flow Battery Storage Demonstration Project

Source: https://www.bestmag.co.uk/worlds-largest-flow-battery-begins-operations-after-six-year-of-planning-and-building/

environmentally friendly. Environmentally, it helps lower carbon emissions by enhancing the use of renewable energy and reducing reliance on fossil fuels. Additionally, such large-scale projects create jobs in construction, operation, and maintenance, supporting local economies.

However, the project faces challenges, including the high initial costs of VRFBs compared to other battery technologies. Continued research and development are needed to reduce these costs and make VRFBs more competitive. By improving grid stability, supporting renewable energy integration, and offering economic and environmental benefits, flow batteries are set to play a crucial role in the global transition to sustainable energy systems. Continued technological advancements and cost reductions will further bolster the adoption of flow batteries and support the growth of renewable energy worldwide.

Investigating a range of technologies for a sustainable energy transition in Lao PDR

With rapid shifts in technologies and costs, there is now a range of low carbon energy storage technologies and carriers that countries can tap into. Lao PDR is well-positioned to leverage its strategic location and renewable energy potential to substantially expand its clean energy export capacity to ensure sustainable growth.

Australia, through Partnerships for Infrastructure, its flagship infrastructure program in South-East Asia, is working with Lao PDR to investigate various such technologies including the key factors influencing their technical, market, and commercial feasibility in the Lao context. Technologies such as Pumped Hydro Energy Storage (PHES) and green hydrogen have the potential to help transform Lao PDR's energy sector and maximise its untapped renewable energy potential.

For example, in a country with substantial hydropower capacity like Lao PDR, PHES could be a practical solution to store surplus hydropower for use domestically during the dry season and for export. It could also provide essential system services to stabilise the grid as more variable renewable energy is installed. Modelling by the RE100 Group, Australian National University shows the important potential for PHES in Lao PDR with over 5,822 identified sites.[25] Australia is well placed to assist, having deployed its own large-scale energy storage solutions such as PHES to ensure the security and reliability of its increasingly renewable electricity grid.

Lao PDR is also assessing the potential to utilise excess hydropower output to produce green hydrogen and ammonia.[26] With Australia's support, Lao PDR is developing its national hydrogen and ammonia roadmap, paving the way for establishing a new green hydrogen industry with multiple potential applications and trade potential.

Australia's hydrogen strategy has been a key investment enabler for Australian industry and offers useful lessons for Lao PDR and other South-East Asian countries looking to finance their sustainable energy transition.

With the availability of such technologies, Lao PDR is in a good position to maximise its untapped renewable energy potential and further expand its electricity export capacity. To strengthen this further, Lao PDR and Australia are exchanging knowledge and experience in energy systems planning - including demand forecasting, scenario modelling, tariff setting, and regulation. Lao PDR is aiming to establish an energy regulatory body to oversee regulatory processes, grid interconnection codes, and service standards, which could greatly expand its capacity to contribute to power trading.

Conclusion and key messages

Emerging technologies are playing a transformative role in enhancing energy connectivity. Innovations such as digital twin platforms, HVDC systems, submarine power cables and advanced energy storage systems significantly contribute to improving the efficiency, reliability and sustainability of energy networks.

HVDC systems, in particular, allow for long-distance power transmission with minimal losses, making them well-suited for connecting remote renewable energy sources to demand centers. Smart grid technologies enable real-time monitoring and management of energy flows, allowing for better demand response and integration of distributed energy resources. Furthermore, advancements in energy storage, including battery storage systems, provide the necessary flexibility to balance supply and demand, especially in systems reliant on intermittent renewable sources like solar and wind. These technological enablers not only improve the efficiency of existing power systems but also support the transition to a more resilient and sustainable energy infrastructure across the region.

While these technologies are pivotal for advancing energy connectivity, for effective implementation, challenges such as creating incentives and conducive regulatory frameworks, high initial investment costs, and the need for skilled personnel must be addressed. As the demand for clean energy solutions increases, policymakers, industry stakeholders and financial institutions need to step up collaboration to foster innovation, streamline regulations and crowd in financial support for these technologies. Furthermore, to ensure least developed countries (LDCs) and small island developing states (SIDS) fully benefit from advancements in the power sector, it is essential to establish robust mechanisms and instruments for technology transfer and development cooperation. Such efforts can help bridge the technological gap and promote the deployment of sustainable energy technologies that cater to the unique needs of LDCs and SIDS.

25 The figure is based on potential greenfield, bluefield and brownfield sites. Greenfield: uses two off-river artificial reservoirs, bluefield: utilises at least one existing reservoir and its associated infrastructure, brownfield: uses at least one existing mine site and its associated infrastructure.

26 While the use of ammonia as energy carrier offers promising perspectives, it has not been covered in the current scope of work.

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