Green Power Corridor for North-East Asia:

A Roadmap

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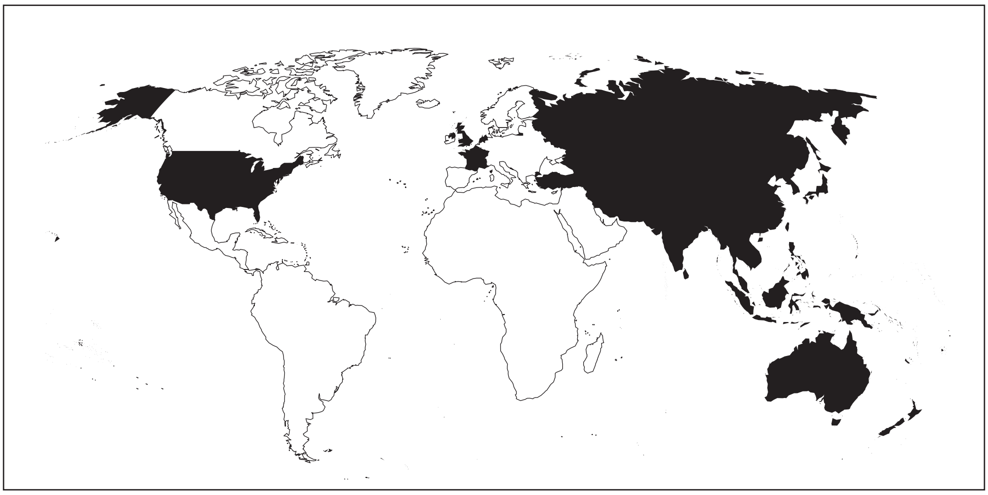

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Abbreviation

AC	Alternating Current
ADB	Asian Development Bank
AfDB	African Development Bank
AIIB	Asian Infrastructure Investment Bank
ARCO Norte	Northern Arc
ASEAN	Association of South East Asian Nations
ASG	Asian Super Grid
CAPEX	Capital Expenditures
CAPP	Central African Power Pool
CASA-1000	Central Asia South Asia Electricity Transmission and Trade Project
CCS	Carbon Capture and Storage
CEAC	Consejo de Electrificación de América Central
CECCA	Central America Clean Energy Corridor
CIDCA	China's Development Agency
COMELEC	Comité Maghrébin de l'Electricité
COP	Conference of Parties (United Nations Climate Change Conference)
CSP	concentrated solar power
DC	Direct Current
DPRK	Democratic People's Republic of Korea
EAEU	Eurasian Economic Union
ECA	Economic Commission for Africa
ECCAS	Economic Community of Central African States
ECOWAS	Economic Community of West African States
ECT	Energy Charter Treaty
EDF	Electricité de France
EIB	European Investment Bank
ENTSO-E	European Network of Transmission System Operators for Electricity
ERINA	Economic Research Institute for Northeast Asia
ESCAP	Economic and Social Commission for Asia and the Pacific
EU	European Union
GCC	Gulf Cooperation Council
GHG	Greenhouse gas
GPC	Green Power Corridor
$GtCO_2e$	Gigatonnes of CO_2 equivalent
GTI	Greater Tumen Initiative
GW	Gigawatt
HAPUA	Heads of the ASEAN Power Utilities/Authorities
IDB	Interamerican Development Bank
IEA	International Energy Agency
IFI	International Financing Institution
IPS/UPS	Intergrated Power System/Unified Power System
IRENA	International Renewable Energy Agency
IsDB	Islamic Development Bank
JICA	Japan International Cooperation Agency
JPEX	Japan Power Exchange
KEPCO	Korea Electric Power Corporation

KfW	Credit Institute for Reconstruction (German development bank)
KOREC	Electricity Regulatory Commission
KPEX	Korea Power Exchange
KRDV	Corporation for the Development of the Far East and the Arctic
kWh	kilowatt-hour
LCOE	levelised cost of electricity
LEAP	Low Emissions Analysis Platform
LNG	Liquified Natural Gas
MDB	Multilateral Development Bank
MERCOSUR	Southern Common Market (South American trade bloc)
MoU	Memorandum of Understanding
$MtCO_2e$	Million Tonnes of Carbon dioxide equivalent
MW	Megawatt
MWh	Megawatt-hour
NAPSI	Northeast Asian Power System Interconnection
NDC	Nationally Determined Contributions
NEAEI	Northeast Asian Electricity Interconnection
NEARPIC	Northeast Asia Regional Power Interconnection and Cooperation
NEMO	Next Energy Modeling system for Optimization
NRDC	National Development and Reform Commission
OCCTO	Organization for Cross-regional Coordination of Transmission Operators
ODECA	Organisation of Central American States
OPEX	Operational Expenditures
PFI	Public Financing Institution
PPA	Power Purchasing Agreement
REI	Renewable Energy Institute
RETA	Regulatory Energy Transition Accelerator
ROK	Republic of Korea
SAARC	Southern Asia
SADC	Southern African Development Community
SAPP	Southern African Power Pool
SGCC	State Grid Corporation of China
SGCE	Synchronous Grid of Continental Europe
SICA	Central American Integration System
SIEPAC	Central American Electrical Interconnection System
SINEA	Andean Electrical Interconnection System
TSO	Transmission System Operator
TW	Terrawatt
TWh	Terrawatt-hour
UHV	ultra-high voltage
UNIPEDE	International Union of Producers and Distributors of Electric Energy
USAID	United States Agency for International Development
USSR	Union of Soviet Socialist Republics
WAPP	Western African Power Pool
WB	World Bank

Contents

List of boxes, figures and tables

List of Box

List of Figures

List of Tables

Executive summary

Home to some of the world's largest and most energy- consuming economies, North-East Asia has a pivotal role to play in unlocking the global energy transition, achieving the Sustainable Development Goals and aligning the global economy with the targets of the Paris Agreement on Climate Change. Integration of higher shares of renewable energy into the power mix is one of the key priorities for economies across the world. For North-East Asian countries, accelerating the deployment of renewables can deliver multiple benefits including improvement of energy security and economic resilience, meeting emission and climate change mitigation targets, taking advantage of cheaper electricity sources and boosting the competitiveness of local energy-intensive sectors.

Enabling the further deployment of renewable energy resources, while contributing to economic growth and resilience, requires a flexible and strong power grid infrastructure. Power grid connectivity is widely accepted as one of the most efficient tools to boost flexibility and reliability of an energy system, while enabling quicker and enhanced intake of renewable energy sources.[1] In this context, investments in national grid infrastructure that enable and strengthen connectivity, and the integration of variable renewable energy resources like wind and solar PV, is a priority already pursued by many countries in the region.

At the same time, power grid connectivity beyond national borders can offer not only an important source of flexibility, enabling diversification of the generation resources and smoother electricity supply and demand patterns, it can also boost the availability of low-cost renewable electricity, contribute to social welfare and job growth, and bring numerous environmental benefits. The benefits and opportunities resulting from increased power grid connectivity in North-East Asia have been discussed in numerous studies for the past three decades, with several interconnection initiatives proposed.[2]

The Roadmap presented in this report offers 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 as well as the

1 IEA (2023) Managing Seasonal and Interannual Variability of Renewables; IEA (2021) Net Zero by 2050: A Roadmap for the Global Energy Sector; IRENA (2023): Solutions to integrate high shares of variable renewable energy, Power systems in transition: challenges and opportunities ahead for electricity security (IEA (2020).

2 UN ESCAP (2020) Regional power grid connectivity for sustainable development in North-East Asia: Policies and strategies.

gradual establishment of regional power grid connectivity in a way that boosts economic growth and energy security in the member countries. In addition, it allows for flexible and inclusive development that respects and responds to national policies, while at the same time enabling a faster energy transition.

In addition to the Roadmap, this report presents a comprehensive Connectivity Model for North-East Asia which, using the latest energy systems data and national energy policies of the member countries, assesses technical, economic and sustainability dimensions of cross-border grid, and renewables integration up to 2060. While considering several connectivity scenarios, the model clearly indicates the significant potential for regional power grid connectivity to contribute to the sustainable economic growth, and national and regional climate goals.

The Roadmap draws on the concept of the Green Power Corridor (GPC) developed by ESCAP to offer a regional vision for power grid connectivity that supports national emission reduction and renewables development goals, in this case in the specific context of the North-East Asian subregion. The GPC concept builds on six key building blocks: institutional framework, infrastructure backbone, financial arrangements, regulatory framework, social acceptance and, at the centre of the GPC concept, political accord, or the readiness of the national Governments in the region to support cross-border cooperation in the power sector, as both the prerequisite and the basis for the initiative.

While building on the regional and national energy and economic specifics of North-East Asian countries, the Roadmap also considers the decades-long history of cross-border power grid connectivity and power trade initiatives across different regions of the world. While not directly transferrable to the North-East Asian context, these initiatives nevertheless offer valuable lessons learnt that can help strengthen regional cooperation on power grid connectivity while maximizing benefits and managing risks.

While this report is being written during a turbulent time when political and economic tensions all over the world are creating barriers to full-fledged international cooperation, maintaining and strengthening regional ties is vital if efforts to keep global temperature rise below 1.5 C° are to succeed.[3] Even limited levels of bilateral and multilateral exchange on power grid connectivity among countries in the subregion will enable faster take-off of actual cooperation when the political climate allows it.

3 IEA (2022a), *The World Energy Outlook.*

Key takeaways

Reaching an agreement at the political level, even in principle, can facilitate faster implementation, draw in needed investments and signal a region's clean energy ambition. One central step North-East Asian countries need to take to enable full-fledged cooperation towards regional power grid connectivity is to signal their support for the idea. Political support, either in the shape of a formalized agreement or an informal but commonly agreed- upon statement of support is particularly crucial to boost the confidence of potential public and private investors in the feasibility of the initiative and provides a prompt to existing international organizations to engage on and support the further development of connectivity initiatives.

Working-level coordination in the near-term can go a long way towards creating a solid basis for regional cooperation in the long-term. The steps needed this decade to deliver the GPC vision are incremental in nature and do not require the establishment of new formal institutional structures or major investments. Yet these actions are crucial as they build the necessary institutional and regulatory foundation for long-term cooperation, one that is flexible and resilient to future uncertainties. Taking the initial step of launching a set of coordination platforms and working groups will enable the exchange of lessons learnt and coordination on future planning among the key stakeholders involved in all six GPC building blocks. It will be particularly important to facilitate peer-to peer dialogues between the utilities, electricity regulations authorities and government agencies of the North-East Asian countries involved in planning capacity-building and training programmes in the sector as well as national and regional financial institutions and experts involved in power grid systems analysis.

The delivery of the GPC is a multi-layered process that requires coordination among key stakeholder groups and an open dialogue with communities on the ground. The Roadmap envisions the 2030s as the "decade of implementation", when formal institutions are established (including the Regulatory Council and the Utilities Platform), construction of new connectivity infrastructure takes off, and a set of coordination mechanisms (including those on joint emergency responses, ancillary services coordination and data sharing) are established. For all these different structures to function most efficiently, enabling dialogue between all the key stakeholder groups will be of paramount importance.

At the same time, securing the buy-in of population groups most closely involved in, and impacted by GPC development (e.g., communities living in the areas where new renewable power generation capacities or transmission lines are to be deployed) via an open dialogue, and targeted capacity-building will help to both counter the practice of objecting to something that will affect one or take place in one's locality (NIMBYism) and maximize the socio-economic benefits of the initiative.

When the key institutions and pieces of infrastructure are in place, the GPC will enter into the final phase of organic development where connectivity between the member countries changes and develops together with, and in support of, national power systems and broader energy sector policy objectives.

Existing international platforms can provide institutional support during the initial stages of GPC implementation. The current institutional framework for regional cooperation on energy transition and connectivity in North-East Asia is somewhat fragmented. A set of established and well-recognized multilateral organizations and mechanisms covering broader economic cooperation can offer the needed foundation for further institution building. The history of connectivity initiatives in other regions suggests that international and regional economic cooperation organizations can play a supportive role by offering space for and enabling peer-level dialogue between the member countries as new institutions are developed or existing institutions strengthened. In North-East Asia, ESCAP and the Greater Tumen Initiative are two existing platforms that arguably can support GPC implementation in the early stages, while institutions such as the World Bank and the Asian Development Bank (ADB) can also play important roles, both in early and later stages of development.

A GPC for North-East Asia can help to deliver the existing national climate and energy goals faster and more efficiently, while laying the basis for higher ambitions. As the GPC model presented in this report shows, the GPC vision does not require a revision of the current national climate and renewable energy targets by the North-East Asian countries. The benefits of a GPC for NEA can multiply exponentially with deeper integration of power systems and higher renewables targets. But even if implemented in the context of current targets, the GPC can help to strengthen the reliability of electricity supply, offer additional flexibility to national and subnational power systems in the region, alleviate air pollution and cut greenhouse gas emissions and, in general, allow countries to meet their targets more efficiently and securely.

Pursuing regional power grid connectivity is a no-regrets option, while North-East Asian countries have all the prerequisites to leverage it as a powerful tool to serve domestic climate and energy transition goals. While there are certainly examples of connectivity initiatives in other regions that have not resulted in a tangible uptake in cross-border power trade or in more flexibility for connected power systems, there are none that have had any clearly negative effects on the involved countries or stakeholder groups within, and none that have been dismantled after development for economic or financial reasons. Moreover, where these initiatives have fallen short of their intended goals, it has primarily been because of insufficient investment or technical capacity among the participating countries. In contrast to many other regions of the world, North-East Asia has all of the required technical, financial, institutional and capacity-building resources to make sure the GPC is a meaningful initiative that delivers its maximum potential.

Summary of the Action Roadmap: Gradual, managed and inclusive development of the GPC for North-East Asia			
	Political accord	Institutional framework	Infrastructure deployment
Phase I **Laying the groundwork**	• GPC Roadmap for NEA is recognized by the NEA Governments	• Interim secretariat on NEA GPC (NEA GPC IS) established • NEA utilities dialogue launched- NEA energy regulator dialogue launched • Expert NEA power grid connectivity WG created • Cross-stakeholder WG launched • A Master Plan for GPC in NEA based on the Roadmap is developed and approved by the member countries	• Pre-feasibility studies building on the GPC modelling results are conducted • a set of bilateral priority projects is agreed upon • Informal dialogue btw. national TSOs, exchanges on national grid planning and RES connection • Grid connection agreement reached on the first batch of projects • Siting, permitting and procurement take place • Capacity enhancement of existing bilateral interconnectors' proceeds
Phase II Implementation	• MoU on multilateral cooperation on power grid connectivity signed • Intergovernmental agreement on power sector cooperation signed	• Regional Regulatory Council created • NEA NTSO-E is established	• Construction of newly planned bilateral interconnections and RES generation bases is underway • New interconnectors and RES capacities begin operations.
Phase III **Organic development**	• Regular meetings of high-level political stakeholders are organized		• Need for and potential benefits of full or partial regional power grid synchronization are studied • Feasibility studies on multilateral interconnectors in the region • Master Plan for GPC in NEA is updated

Summary of the Action Roadmap: Gradual, managed and inclusive development of the GPC for North-East Asia			
	Financing arrangements	Regulatory framework and trade mechanisms	Capacity building and social inclusion
Phase I **Laying the groundwork**	• Mechanism for financing the NEA GPC Secretariat is developed and agreed upon • Dialogue involving key international financing institutions takes place to enable peer learning • Set of financing instruments for GPC is proposed for consideration to the NEA secretariat	• Expert WG conducts a mapping of NEA regulatory frameworks to identify overlaps/ synergies and gaps • Pee-to-peer dialogue between national regulatory authorities is initiated • Templates and a core set of standards and requirements are developed and proposed for new bilateral power trade agreements	• International workshops sharing lessons learnt are organized • Cross-country dialogues mapping the capacity-building needs take place • Cross-stakeholder coordination WG is engaged to discuss and design a set of GPC education and training programs • Agreement on the funding and provision of education facilities is reached
Phase II Implementation	• PPAs between the participating utilities have been signed • Project agreements with the supporting IFIs are signed • New RES generation facilities are co-financed by private investors	• NEA utilities platform is formalized into a Regulatory Council • NEA NTSO-E is formalized • Mechanisms to coordinate ancillary services within bilateral trade arrangements are established • Joint emergency response mechanisms are developed • Data sharing mechanisms to enable faultless operation are mapped	• Education and training programs are developed and launched, including with support of IFIs • Public information and awareness raising campaigns are developed • Local CSO communities and labour organizations are invited to accompany the GPC planning and implementation process
Phase III **Organic development**	• Dialogue aimed at developing a transparent legal framework for GPC investments is launched • Follow-up projects within GPC entail 50-60% private finance • PFIs continue supporting GPC, focusing on technical assistance and capacity building	• Harmonization of national regulatory frameworks takes off • (optional) a regulatory framework for multilateral power trade is proposed and a pilot multilateral power trade project is launched • Regional power trade rules and regulations developed and confirmed, bilateral arrangements slowly phased out	• Graduates from the GPC education and training programs drive the implementation of the GPC in NEA • Ongoing public information and awareness-raising campaigns offer regular updates on the implementation of the GPC

Introduction

Cross-border power grid connectivity is not a new topic to the countries of North-East-Asia. In fact, several countries in the subregion have been trading electricity with their neighbours for several decades now, with at least eight bilateral interconnectors operational to date in the continental part of the region.

The idea of further promoting regional power grid connectivity in North-East Asia has been explored since the mid-1990s, when one of the first studies on the connectivity potential and related benefits was released by the Melentiev Energy Systems Institute (Belyaev et al., 1994). Since then, more than 140 scientific articles, including feasibility studies, on the topic have been released and several connectivity models proposed.[1]

Although high-level political cooperation on the issue has not taken off so far, several cooperation initiatives between some of the key stakeholders have been launched. Among them are the Memorandum of Understanding (MoU) on joint research and a plan to promote an interconnected electric power grid in North-East Asia signed in 2016 by the utility companies of China (State Grid Corporation of China, SGCC), Japan's major telecommunications corporation Softbank (Softbank, 2016), Republic of Korea (Korea Electric Power Corporation, KEPCO), and the Russian Federation's power systems operator (PJSC Rosseti), as well as the follow-up agreement by SGCC and KEPCO to partially implement a regional connectivity vision by proceeding with a bilateral power interconnector between the Republic of Korea and China, and an MoU between Rosseti and Mongolia's largest mining company, Erdenes Mongol LLC on joint research and development of integration links of North-Eastern Asia's power grids (Rosseti, 2019).

There are several challenges that have, to date, inhibited deeper cross-border cooperation on power grid connectivity. Among them are geographic constraints including: long distances between major power generation and load centres; rough terrain in many parts of continental North-East Asia and the need for submarine cables to interconnect Japan and the Republic of Korea. Infrastructure constraints include the lack of infrastructure needed for the construction of transmission lines in scarcely populated areas, a lack of expressed demand in the past as all countries in the region relied primarily on domestic power generation (with the exception of Mongolia), largely fossil fuel-based with less need to manage system flexibility; and, finally, political tensions including historical sentiments, territorial disputes and geopolitical rivalries which, despite 70 years free of military conflicts, have impeded closer cooperation.

Although significant, the challenges listed above are not unique to the North-East Asia sub-region. At the same time, recent technical, political, financial, and socio-economic developments – both within the region and globally – have provided a new momentum for deeper cooperation on power system decarbonization and power grid connectivity in North-East Asia.

1 For a full overview of literature on the topic of power grid connectivity in North-East Asia see UN ESCAP (2020): RPG in NEA for Sustainable Development.

First, the recent decade saw an unprecedented downward cost curve for key renewable technologies, in particular solar PV and onshore and offshore wind, with new technologies including floating offshore wind and floating solar, concentrated solar power (CSP) and others being brought to a commercial scale. The global weighted average levelized cost of electricity (LCOE) of newly commissioned utility-scale solar PV projects has declined by 88% since 2010, and onshore and offshore wind by, respectively, 68% and 60%, with almost two-thirds of newly installed renewable power in 2021 cheaper than the cheapest coal-fired generation in the G20 countries (IRENA, 2022). The affordability and availability of renewable technologies as well as political support granted in some key markets has led to an exponential growth of renewable generation capacity during the recent years – a trend that has shown to be resilient in face of both the COVID-19 pandemic and the recent geopolitical turbulences. In 2022, 83% of newly installed power generation capacity was estimated to come from renewables, 90% of which from solar and wind (IRENA, 2023b), whose share in the global power generation mix is expected to reach 35% in 2025 (IEA, 2023c).

Electric power transmission technology has also evolved dramatically in recent years, enabling higher capacity transmission over longer distances and with less losses, including via long-distance submarine transmission (Gordonnat and Hunt, 2020), as well as more flexible operations and better monitoring due to digitalization and more efficient use of communication technologies (Hernandez-Callejo et al, 2019). These technological advancements are enabling a shift in the power systems in many economies, including those in North-East Asia, which now seek ways to adapt to accommodate increasingly higher shares of variable renewable energy resources. In this context, facilitating connectivity within national power grid systems and across borders gains new urgency as one of the key tools to boost the systems' flexibility and overall resilience. (IEA, 2022, 2023a,b).

Second, power systems decarbonization has increasingly taken centre stage in global politics, driven both by: (a) the acknowledgement of most countries of the urgency to reduce greenhouse gas emissions in line with Paris Agreement targets; and (b) by a desire to insulate national economies and energy systems against external shocks resulting from global commodity price and supply volatility. All countries in North-East Asia have ratified the Paris Climate Agreement. Japan and the Republic of Korea have committed to reach net-zero greenhouse gas emissions by 2050, and China and the Russian Federation have announced their intentions to do so by 2060. Mongolia also announced their Vision 2050 which includes plans to reduce reliance on fossil fuels and become an exporter of renewable energy. Despite the ongoing global polycrisis testing these countries' economic, political, health and energy systems, these goals remain in place and, in some cases, have become more ambitious. In 2022, Japan updated its renewables target to reach 36%-38% of its electricity mix by 2030, and committed to reach a predominantly decarbonized power sector by 2035, as part of a G7 commitment. In 2023, the Republic of Korea unveiled a new renewables target of 30.6% in 2035 and a goal to cut its greenhouse gas emissions by 40% by 2030. China's fourteenth five-year plan aims to double renewables generation by 2025 from the 2020 level; the country maintains its position as a global leader in renewable capacity deployment, accounting for 45% of global renewable additions in 2022, and projected to set a new record by 2024, expanding its share to 55% of global annual renewable capacity deployment (IEA, 2022b, 2023d).

Third, responding both to the growing demand for clean energy and climate policies, energy finance is undergoing significant shifts, with public finance flows in particular increasingly directed to facilitate the deployment of clean energy at home and abroad. Key multilateral development banks, including the ADB and the World Bank, are revisiting their energy policies to shift financing away from fossil fuel-based to renewable power generation and enabling infrastructure. The world's largest economies, including China, Japan and Republic of Korea, have ended new direct government support for unabated thermal coal power generation in third countries. Japan has furthermore, as part of a G7-wide commitment, joined the COP26 Statement on International Public Support for the Clean Energy Transition, aiming at, with a few exceptions, shifting all international public finance out of fossil fuels and into clean energy projects.

Fourth, a plethora of new connectivity initiatives, all aimed at facilitating energy transition, have emerged, enabling access both to finance and technology for ramping up clean energy infrastructure. These initiatives include a focus on power grids within a broader set of infrastructure project priorities (e.g., the Green Belt and Road Initiative, the Partnership for Global Infrastructure and Investment, the Global Gateway), or focus specifically on power grid connectivity (e.g., the Green Grids Initiative).

Finally, the ongoing global polycrisis, in particular the fundamental shifts in global commodity markets, has accelerated the above trends towards decarbonizing energy and, as an immediate step, power systems in most key regions of the world. In North-East Asia, Japan and the Republic of Korea, in particular, have been hit hard by the unprecedented spikes in coal, gas and oil prices and uncertainty over future supply – major drivers of fiscal stress in 2022 as electricity and heat price subsidies drained national budgets.

All the above trends are driving a new momentum for the faster roll-out of renewable power generation. In this context, power grid connectivity plays an increasingly important role as a key piece of enabling infrastructure for delivering climate targets, energy security and economic resilience. Deployment of a flexible and robust power grid infrastructure is already a priority for most countries in North-East Asia, as can be seen within their respective national grid development plans. China has been revolutionizing its domestic power system by interconnecting the regional grids, as well as the renewable generation sites with the load centres via ultra-high-voltage (UHV) transmission lines and embarking on an extensive power market reform. Similarly, Japan is planning national grid expansion measures under the current National Grid Development Master Plan. The Republic of Korea's KEPCO aims at expanding its network and is developing an offshore grid plan to unlock the country's vast offshore wind potential.

However, achieving the level of flexibility needed for the increasingly renewables-based power systems in the future requires further solutions aside from strengthening the national power grid infrastructure; within national borders, demand-side response and storage will arguably be the largest sources of the system flexibility. Another key ingredient to both boost power system flexibility and drive down the cost of the transition, is power grid connectivity beyond national borders. Power grid connectivity between North-East Asian countries cannot only be an important source of flexibility, enabling diversification of generation resources and smoother electricity demand patterns – it can also boost the availability of low-cost renewable electricity, contribute to social welfare and job growth as well as bring numerous environmental benefits. The benefits and opportunities resulting from increased power grid connectivity have been discussed in numerous studies for the past three decades, with several interconnection initiatives proposed (among others, the Asian Super Grid, the North-East Asia Energy Interconnection, the North-East Asia Power System Interconnection).

Amidst the above developments, increasing power grid connectivity can enable faster roll-out of renewable generation capacities as well as ensure delivery of climate and energy security targets.

While commendable and necessary, national efforts are not sufficient on the global quest towards a net-zero emissions economy. As the IEA has pointed out in its Net Zero Emissions Scenario, international collaboration will be critical to success, and can make the transition towards clean energy systems faster, less difficult and at lower cost, while the lack thereof can postpone it by several decades (IEA, 2021).

As highlighted above, all prerequisites to unlock the benefits of regional power grid connectivity in the region, including technical, financial and policy drivers, are in place. Missing in North-East Asia are a common framework within which international cooperation can take place, and agreement on a set of actions to take towards greater connectivity and power markets integration.

In chapter 1, this report introduces the GPC for North-East Asia framework, based on a set of principles developed within ESCAP's GPC and guided by international lessons learnt on regional power grid connectivity.

Chapter 2 presents a Connectivity Model for North-East Asia which, using the latest energy systems data and national energy policies of the member countries, assesses technical, economic and sustainability dimensions of cross-border grid and renewables integration up to 2060 under several connectivity scenarios.

Chapter 3 presents a summary of the analysis of cross-border power grid connectivity initiatives in various regions of the world. It then draws several lessons from the historic development of these initiatives, showing strategies that have proven successful across different geographic, political and economic contexts, as well as pointing out some potential risky or inefficient approaches to power grid connectivity, in hope that these might be a useful reference for the GPC in North-East Asia.

Finally, Chapter 4 proposes a Roadmap, comprised of 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. It focuses on the gradual establishment of regional power grid connectivity in a way that boosts economic growth and energy security in the member countries while enabling faster energy transition.

Chapter 1

The Green Power Corridor concept

Despite the widely demonstrated benefits of regional power grid interconnection, regional cooperation on power grid connectivity has not yet fully taken off in North-East Asia. Challenges to cooperation range from geographic specifics of the region through technical aspects to, critically, lack of an institutional framework and political will to support such an initiative. None of these challenges are insurmountable. A jointly agreed vision outlining goals and benefits of regional power grid connectivity that is supported by an actionable Roadmap, including a clear timeline and cooperation strategies for each implementation stage, can assist member countries in addressing them.

The GPC for North-East Asia is proposed here to create a common language and vision for regional cooperation on power grid connectivity.

A 'Green Power Corridor' is therefore defined as:

An initiative that provides an enabling institutional, financial, regulatory, political, and social environment for strengthening the regional power grid connectivity for increased access to clean, affordable, and secure electricity supply. A GPC supports national emissions reduction and renewables development goals and is developed in coordination with the national energy strategies, power grid development plans, and regulatory frameworks.

The GPC concept builds off and relates to the strategies of ESCAP's "Regional road map for power system connectivity: promoting cross-border electricity connectivity for sustainable development" (Road Map).[2] In particular, strategy 9 of the Road Map focuses on the need to "ensure the coherence of energy connectivity initiatives and the Sustainable Development Goals." The strategy points to the importance of ensuring that connectivity projects are aligned with sustainability criteria, including as defined in the context of the Sustainable Development Goals (SDGs), and it calls for development of:

A set of principles to enable the assessment of interconnection projects against economic

2 See https://www.unescap.org/our-work/energy/energy-connectivity/roadmap

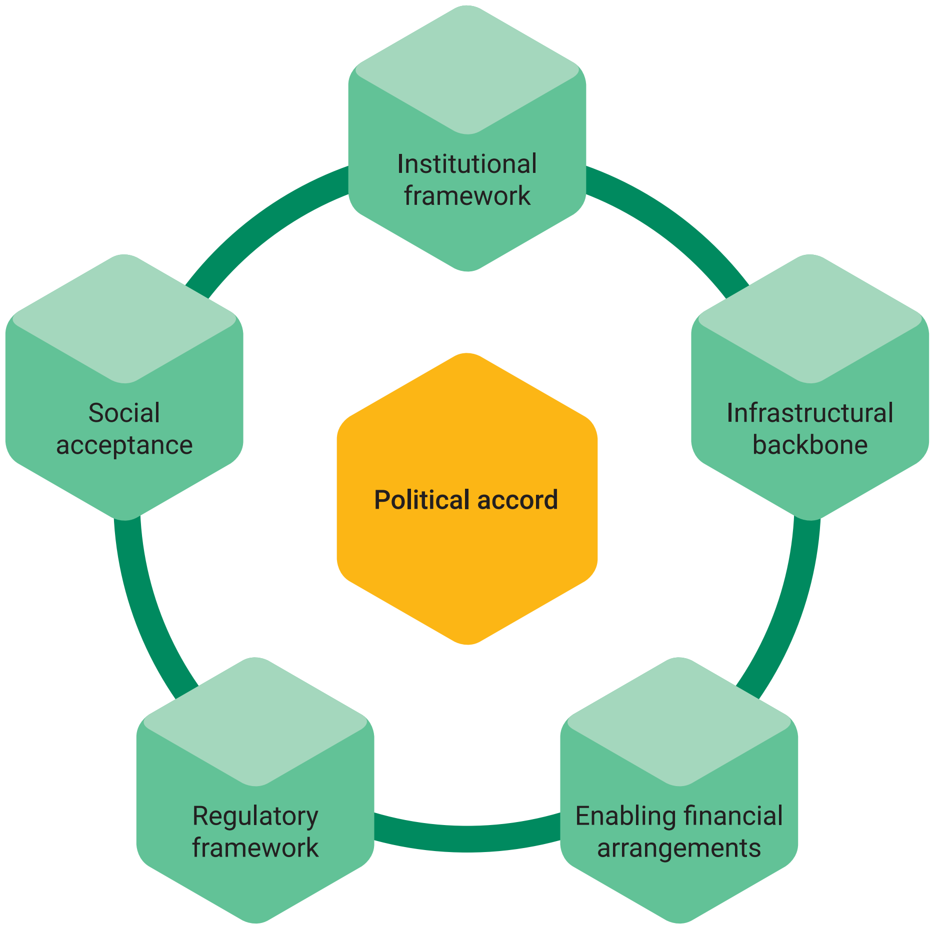
outcomes, efficiency and sustainability criteria and to ensure coherence with the Sustainable Development Goals.

The GPC concept has been developed in the context of meeting this strategic goal. Based on reference research of more than 70 studies and articles, and consultations with member States and experts through the Expert Working Group on Energy Connectivity, ESCAP has developed the GPC Framework, which contains a set of principles organized into six building blocks (figure 1).

- **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.

- **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.

Figure 1. GPC Framework



- **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 seamless 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 CO_2 emissions from power generation.

Each GPC building block contains a set of relevant principles that can guide and support implementation. These principles are presented in chapter 4 of this report and linked to specific elements of, and timelines for, the GPC Roadmap for North-East Asia.

The implementation of the GPC initiative will be an evolutionary process, taking place step-by-step and growing in scale from bilateral to multilateral power grid connectivity. The regulatory and institutional arrangements will be developed accordingly to support the respective stage of infrastructure development. In some cases, building blocks can be developed in parallel, and in other cases an iterative approach will be necessary – for example, the development of appropriate institutional arrangements to enable the financing and development of cross-border interconnections. These incremental steps should nevertheless be guided by a commonly agreed long-term vision for an increasingly integrated regional power system, which is a key to unlock the full socio-economic and technical potential of the GPC. Existing studies have largely focused on economic and technical aspects of the interconnection, with only a few presenting a more holistic approach and linking power grid connectivity to the sustainable development agenda. Yet, these studies already indicate considerable potential for regional power grid connectivity to contribute both to sustainable economic growth and to national and regional climate goals.

According to one of the most recent studies on the North-East Asian Power System Interconnection (NAPSI) performed by EDF and ADB (2019), the implementation of an interconnection between North-East Asian member States would, depending on the design, result in an additional 17 Mt to 210 Mt of CO_2 emissions reduction in North-East Asia by 2036 (ADB and EDF 2019).

Studies focusing on the Asian Super Grid suggest that the construction of large-scale power generation facilities such as Gobitec could create up to 400,000 new jobs in the solar PV sector and about 480,000 jobs in the wind sector, thus contributing to poverty alleviation and diversification of the economy in Mongolia. At the regional level, the implementation of the ASG would create an additional 140,000 jobs in the construction and maintenance of the transmission lines (ECT, 2014; REI 2017), resulting in improvements of living conditions and higher accessibility to social services. There will also be benefits in terms of better human health due to reduction of particulate matter (SO_2, NO_x, C) in the air and cleaner heating and cooking for poorer households in the Democratic People's Republic of Korea, North-East China, and Mongolia.

Studies by the Melentiev Institute focusing on the economic aspects of all-of-region power grid interconnections, estimate that the integration of the North-East Asia countries' systems through cross-border lines will result in total savings of more than US$ 24 billion annually, including more than 65 GW of savings in installed capacity, savings of nearly US$ 80 billion in investment costs, and fuel savings of US$ 10 billion per year (Podkovalnikov et al., 2015). Also, the weighted average cost of electricity is substantially lower in an interconnected North-East Asia – with an estimated 34% decrease from US$ 0.1 per kWh among isolated national power systems to US$ 0.066 per kWh in an interconnected one (Khamisov and Podkovalnikov, 2018).

Studies show that even establishing bilateral interconnections can offer additional flexibility to national and subnational power systems, reducing the need for load shedding (REI, 2019; see chapter 2). The potential of regional power grid connectivity to contribute to the security of supply in an increasingly decarbonized power system and to increase the overall system flexibility has been furthermore demonstrated by existing regional power systems, such as in the European Union.

None of these studies, however, reflect the latest policies and announced targets of the countries in question, nor do they take into account many of the elements detailed in the GPC concept. The modelling conducted by the Stockholm Environment Institute (SEI) for this project does take these latest assumptions and the GPC approach into account. This is described in more detail in the next chapter.

Chapter 2

Modelling the grid for the Green Power Corridor

2.1. Overview of the GPC model

The GPC Model was developed as an analytical tool for examining the technical, economic and sustainability implications of enhanced power integration within North-East Asia. This modelling endeavour was undertaken with a set of clear and ambitious objectives, each designed to offer valuable insights into the complex landscape of power system integration. At the core of modelling are the following key objectives:

1. **Assess technical, economic, and sustainability dimensions of power system integration.** This multifaceted evaluation ensures that integration efforts not only are technically feasible but also contribute to economic growth and environmental sustainability. It addresses questions about the potential benefits of interconnecting diverse power grids, in terms of generation mix, economic efficiency and the long-term environmental implications.

2. **Ground analysis in latest available information.** To construct a robust foundation for assessing the impacts of future grid integration, the modelling process placed great emphasis on grounding its analysis in the latest available information. This entailed meticulous data collection and research to ensure that the model accurately depicts the current state of power systems in North-East Asia as well as reflecting national policies and plans – in particular, decarbonization plans as delineated in Nationally Determined Contributions [NDCs] and net-zero commitments.

3. **Seek a consensus view of potential of integration based on national inputs.** Recognizing the importance of collaboration and shared regional vision, the GPC modelling actively sought input, collaboration and validation from national stakeholders.

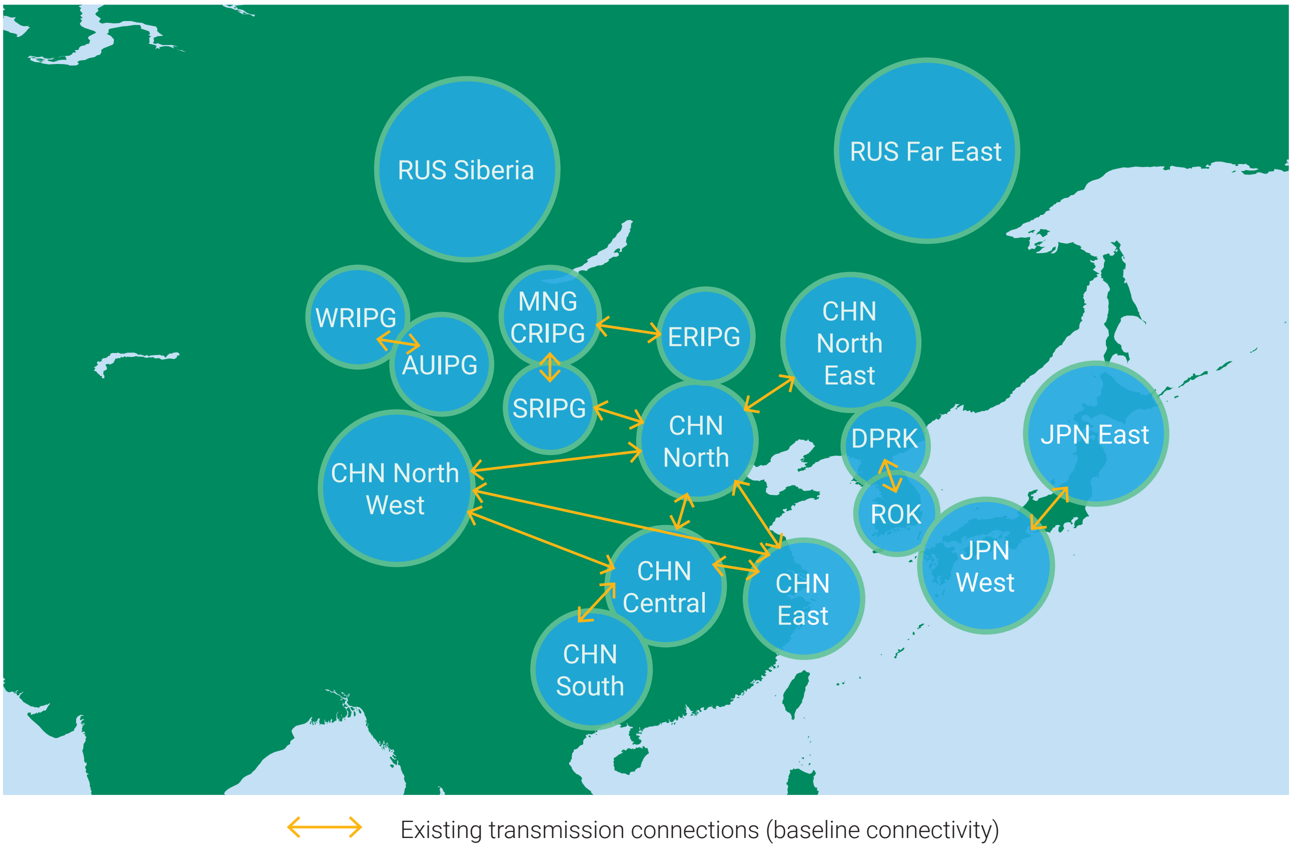
4. **Provide a credible, transparent modelling platform that supports further dialogue and action toward integration.** The modelling process was dedicated to developing a credible and transparent platform that allows

stakeholders to understand the assumptions, methodologies and results of the analysis. This transparency ensures that all parties involved can have confidence in the modelling outcomes and encourages further steps toward integration.

The GPC Model facilitates the assessment of power system integration within the region. It incorporates six countries: China, the Democratic People's Republic of Korea, Japan, Mongolia, the Republic of Korea and the Russian Federation. The existing transmission infrastructure in the region is vital to assessing the potential for interconnections and associated benefits and challenges. Hence, the modelling disaggregated each country into multiple regions wherever indicated by the real-world grid configuration (figure 2).

China is divided into six regions to represent its regional power grids. The Democratic People's Republic of Korea is modelled as a unified national region, reflective of its centralized national power grid. Japan is modelled with two major regional grids: the Eastern Japan Grid and the Western Japan Grid. The eastern grid serves the eastern part of Japan, including Tokyo, and the western grid covers the western part of the country, including Osaka. The two grids operate at different frequencies but are interconnected to promote reliability and supply stability. Mongolia's electricity landscape is captured through the modelling of its five independent power systems, which are sparsely connected. The Republic of Korea, like the Democratic People's Republic of Korea, operates a centralized, national power grid, and hence is modelled as a single region. In the case of the Russian Federation, the real-world

Figure 2. GPC Model structure



MNG CRIPG Mongolia Central Region Integrated Power Grid; MNG WRIPG Mongolia Western Region Integrated Power Grid; MNG AUIPG Mongolia Altai-Uliastai Integrated Power Grid; MNG SRIPG Mongolia Southern Region Integrated Power Grid; MNG ERIPG Mongolia Eastern Region Integrated Power Grid; CHN North China North; CHN Northwest China Northwest; CHN Central China Central; CHN South China South; CHN East China East; CHN Northeast China Northeast; DPRK Democratic People's Republic of Korea; ROK Republic of Korea; JPN West Japan West; JPN East Japan East; RUS Siberia Russian Federation Siberia; RUS Far East Russian Federation Far East.
Source: SEI

configuration includes multiple regional grids. In the context of the Model, two key regions which have connections with other countries covered by the model are considered: Siberia and the Far East Electric Power System. However, it is important to note that due to data limitations, detailed modelling for the Russian Federation Far East and Siberia was not completed at the time of this report's writing. The results discussed in this chapter therefore exclude the Russian Federation unless otherwise noted.

GPC Model structure. The blue circles indicate the 17 grid regions represented in the model and yellow arrows between regions indicate existing transmission connections in the Baseline connectivity case. Russian Siberia and Russian Far East are included in the Model's structure but were not simulated for this report due to data limitations.

Each region is characterized by distinct electricity demand in various economic sectors and employs different technologies to supply energy to meet the demand. On the demand side, the model represents all major sectors, including the residential, industrial, commercial and transport sectors as well as agriculture, forestry and fishing for each of the 15 grid regions whose electricity systems are modelled in detail. On the supply side, electricity generation and storage are modelled, with generation capacities generally aggregated by technology and region. The model horizon stretches to 2060 to allow for long-term planning and foresight.

The transmission network is represented in a simplified form with one network node per region. All high voltage (>=110kV) connections between the regions are modelled. Intraregional transmission and distribution are not explicitly simulated, although average losses in transmission and distribution networks are taken into account.

The Model is implemented as a cost-optimization model using the LEAP (Low Emissions Analysis Platform) and NEMO (Next Energy Modeling system for Optimization) tool kit. A detailed description of the Model's methods and inputs can be found in the Appendix.

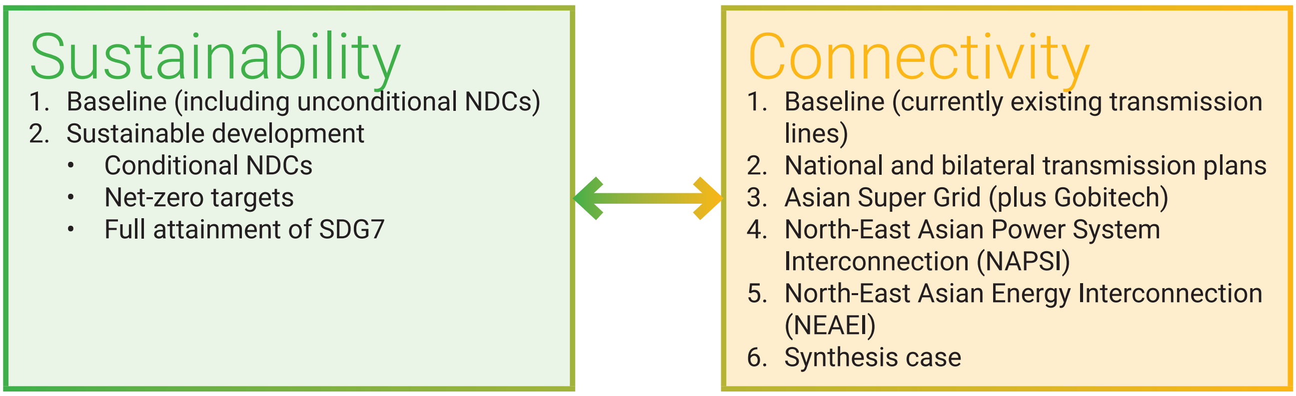
2.2. Model scenarios

Sustainability policies are crucial in determining the technical, cost and emission impacts of cross-border electricity exchange. The scenario structure of the Model reflects the need to assess the interplay between sustainability policies and connectivity options. Two sustainability cases and six transmission connectivity cases were explored; the combination of each sustainability case with each of the connectivity cases was simulated in the Model to illuminate interactions between these policy choices (figure 3).

2.2.1. Sustainability cases

The Baseline sustainability case incorporates projections of future energy consumption, production

Figure 3. Overview of scenario structure of the GPC model



Source: SEI

and emissions under business-as-usual conditions. The unconditional components of the modelled countries' most recent NDCs are implemented, but otherwise national energy and climate policies remain unchanged. The same power technologies continue to be used in each region, although their relative contributions evolve depending on electricity production requirements, resource constraints and costs.

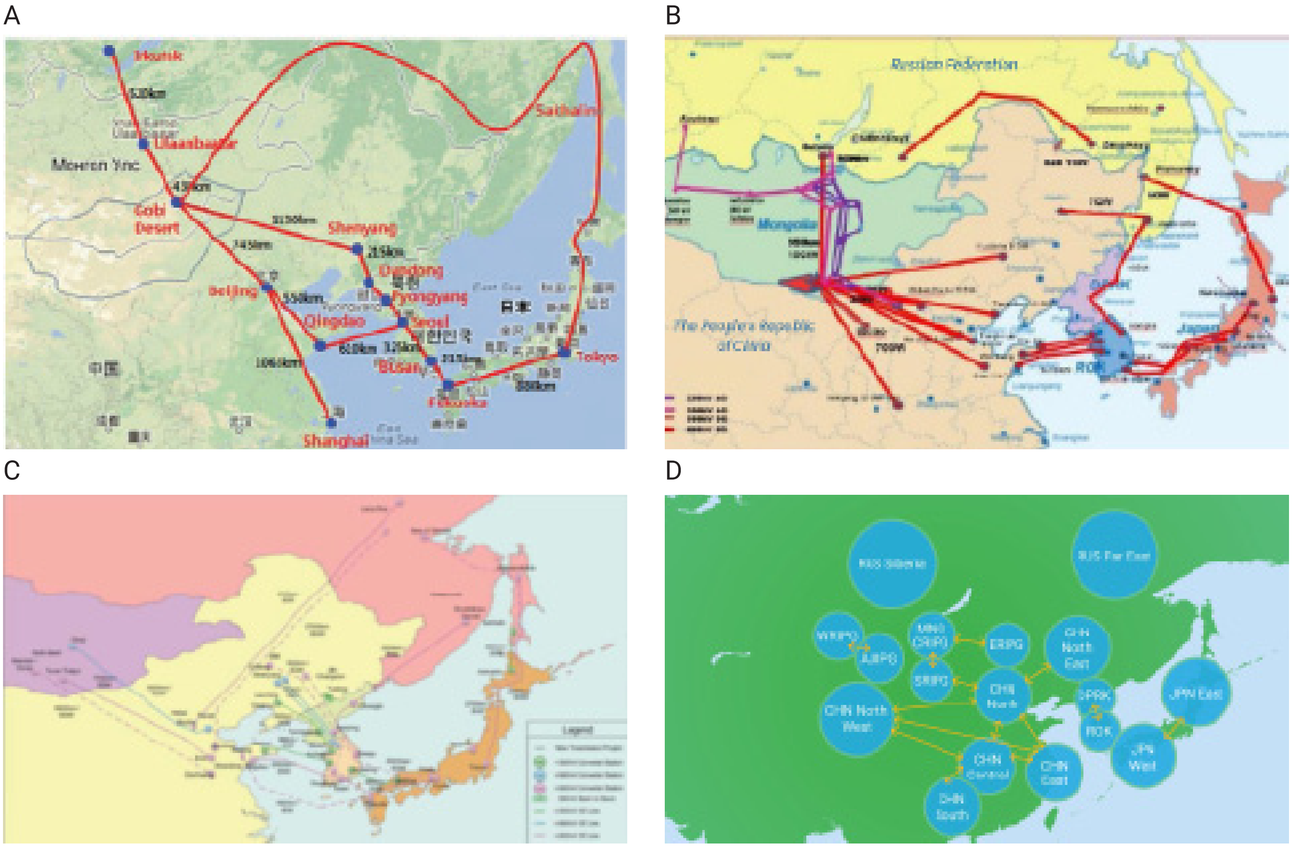
The Sustainable Development case considers several key changes compared to the Baseline, including:

- Implementation of the conditional measures in the study countries' NDCs;
- Realization of net-zero greenhouse gas (GHG) emission commitments (Japan and the Republic of Korea) attain net-zero by 2050; China attains net-zero by 2060, and its GHG emissions peak before 2030);
- Full attainment of SDG 7
- Implementation of other relevant measures in the countries' energy and climate plans such as coal phase-outs, zero-carbon power targets and the deployment of emerging technologies like carbon capture and storage (CCS), hydrogen fuel cells and advanced nuclear power.

2.2.2. Connectivity cases

To assess the potential benefits for electricity supply costs, stability and sustainability, six different connectivity cases were explored in the modelling. In the Baseline case, only existing high voltage transmission connections are included (figure 2) – there is no future increase in interregional transmission. Beyond the baseline, the Model examines a connectivity case comprising firm current plans for improving interregional

Figure 4. Maps of the transmission lines



Disclaimer: The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by the United Nations.
Source: ESCAP (2021), SEI

transmission (National and Bilateral Plans) and four cases based on major past proposals for enhanced grid connectivity in North-East Asia (figure 4).

Figure 4 shows the maps of the transmission lines included in the (a) Asian Super Grid (plus Gobitech), (b) North-East Asian Power System Interconnection, (c) North-East Asian Energy Interconnection and (d) Synthesis connectivity cases. Lines involving Russian regions were not modelled.

National and Bilateral Plans: This case involves the implementation of grid integration plans in Mongolia and the creation of a Weihai-Incheon transmission line connecting China and the Republic of Korea (Gazryn Zurag Co., Ltd., 2023; ESCAP, 2020). In Mongolia, four major intranational lines are added. The total capacity of all new transmission lines in this case is 2.84 GW, with construction scheduled to occur between 2025 and 2028.

Asian Super Grid (ASG): The ASG case introduces a more extensive network, featuring nine significant new interregional transmission connections and the deployment of 100 GW of solar and wind power in Mongolia (figure 4a) (Asian Development Bank 2014). The total capacity of all new transmission lines is 72 GW, with flexibility in construction timing, as the ASG plan does not specify construction dates. The new solar and wind power in Mongolia is expected to be built by 2038.

North-East Asian Power System Interconnection (NAPSI): This case encompasses seven significant new inter-regional transmission connections and the installation of 10 GW of solar and wind power in Mongolia (Figure 4b) (Asian Development Bank 2020). It is based on Scenario 2 (10 GW integrated AC configuration) from the NAPSI study. The total capacity of the new transmission lines is 16 GW, and both the new transmission infrastructure and the solar/wind facilities are projected to be constructed by 2036.

North-East Asian Energy Interconnection (NEAEI): The NEAEI case comprises 16 significant new inter-regional transmission connections, with a total capacity of 94.75 GW (figure 4c) (Huang 2018). Construction of these lines is phased between 2025 and 2050, allowing for gradual expansion of the network.

Synthesis Case: In the synthesis case, elements common to other connectivity cases are integrated, resulting in six significant new interregional transmission connections (figure 4d). The total capacity of all new lines is 42 GW, and the model determines the optimal construction timing.

These connectivity cases represent diverse approaches to regional power system integration, incorporating various transmission connections and renewable energy deployment strategies. Each case explores different timelines and capacities to assess the potential benefits and challenges of enhanced connectivity within the North-East Asia region. For a full list of transmission lines included in each of the connectivity cases, see Appendix.

2.3. Results

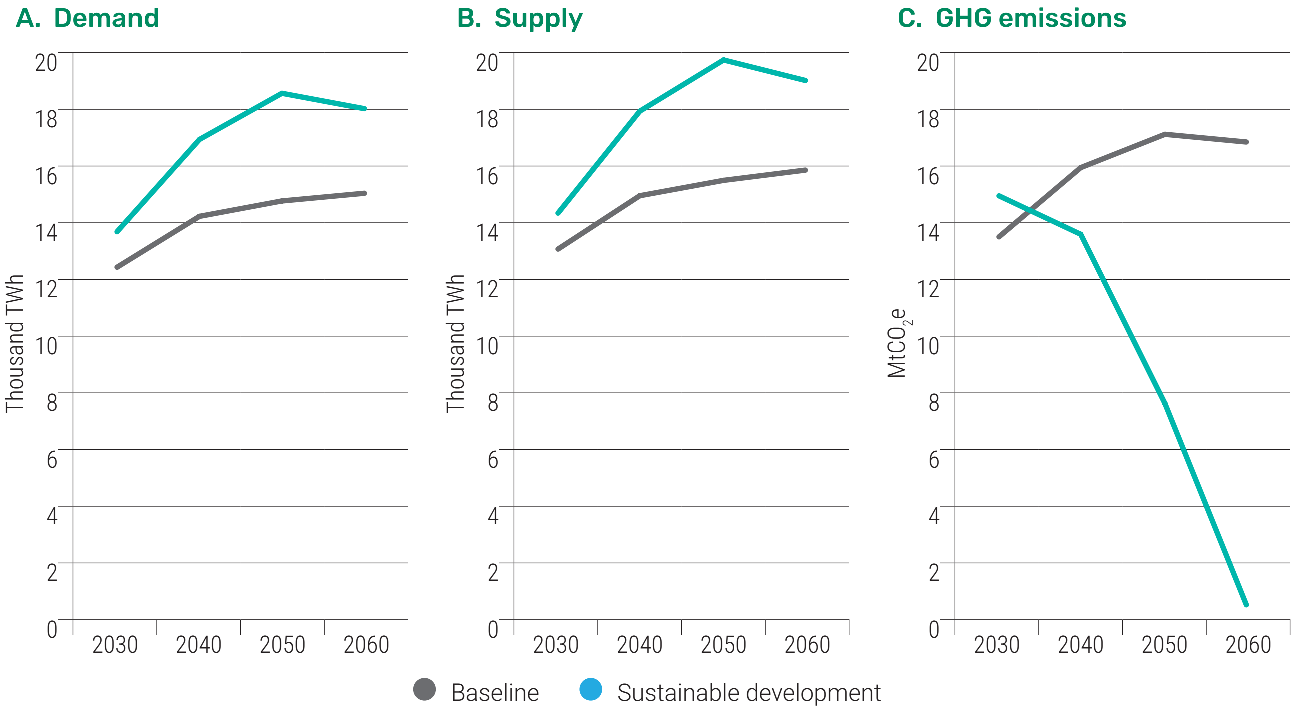
The modelling analysis shows that increased regional connectivity reduces system costs and accelerates the deployment of low-cost renewable power in the region, irrespective of whether sustainable development policies are pursued. However, pursuing national plans for sustainable development has important implications for energy demand, the generation mix and GHG emissions reductions even with baseline connectivity.

2.3.1. Comparison of baseline and sustainable development sustainability cases

Figure 5 shows a comparison of (a) electricity demand, (b) electricity supply and (c) GHG emissions of all regions in the Baseline and Sustainable Development sustainability cases with only existing transmission lines in place (Baseline connectivity case).

When pursuing sustainable development policies, demand for electricity is projected to increase faster than in the Baseline sustainability case, owing to greater electricity access and the electrification of end uses (figure 5a). Energy efficiency measures attenuate the rise in demand, but final consumption of electricity is still 26% higher than in the Baseline case by 2050. In contrast to the Baseline case, where electricity demand continues to grow until the end of the modelling period, demand peaks in the

Figure 5. Comparison of electricity demand, electricity supply and GHG emissions



Source: SEI

Sustainable Development case in 2050, after which it starts to decline.

The predominant sources of electricity generation in the Sustainable Development case are solar, wind and nuclear power, each contributing significantly and sharing roughly equal proportions in the long term. These are supplemented by hydropower, other renewables (e.g., biomass, wave and tidal), and coal and gas with CCS, which become more prominent after 2040. Up until 2040, non-CCS coal constitutes nearly 50% of the overall fuel mix. However, this technology begins to be phased out after that point, reflecting the impact of net-zero mandates. This contrasts with the Baseline sustainability case, in which solar and wind become more important over time (their share of the generation mix increases 84% between 2020 and 2060), but non-CCS coal continues to provide 29% of electricity in the last decade of the simulation.

In both the baseline and sustainable development cases, electricity supply increases to meet growing demands (figure 5b), with substantial new generation and storage capacity deployed. Assuming baseline connectivity, total generation and storage capacity rises from under 3 TW in 2020 to 5.1 TW in 2060 in the Baseline sustainability case, and to 7.4 TW in 2060 in the Sustainable case. Part of the extra growth in the sustainable development case is due to the greater uptake of variable renewable technologies, which have lower capacity factors than traditional generation technologies and must be backed up by dispatchable capacity to assure the security of supply.

Again, assuming Baseline connectivity, in the Baseline Sustainability case GHG emissions from electricity generation peak around 2050 at almost 8 giga-tonnes of CO_2-equivalent ($GtCO_2e$). In contrast, in the Sustainable Development case, decarbonization policies lead to a steep decrease in GHG emissions from around 7 $GtCO_2e$ in 2030 to close to zero emissions by 2060 (Figure 5c).

2.3.2. Implications of enhanced grid integration

Throughout North-East Asia, countries are pursuing sustainable development policies that are inscribed in national plans, NDCs and other instruments. To reflect this policy context, the following discussion focuses primarily on the impact of enhanced connectivity cases within the Sustainable

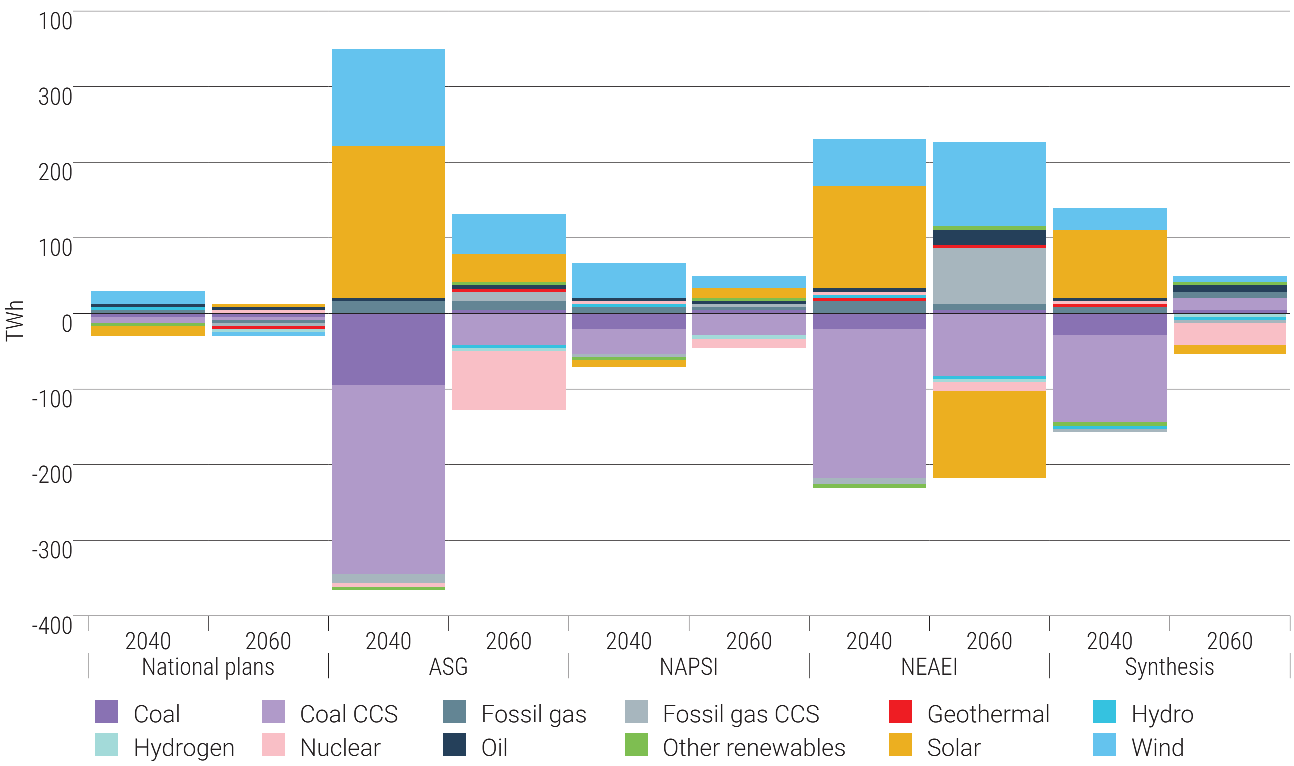
Development sustainability case. This helps to better understand what additional benefits can be obtained by pursuing increased regional connectivity. In some respects, premising the discussion on the Sustainable Development case provides a conservative assessment of the benefits of increased connectivity in the region. If planned decarbonization targets and measures are not realized or are delayed, certain benefits of improved connectivity are likely to be greater (box 1).

Electricity generation

Figure 6 shows the differences in electricity generation by technology in 2040 and 2060 of five enhanced connectivity cases compared to the Baseline connectivity case. All scenarios also include the Sustainable Development sustainability case. Enhanced connectivity cases show increased generation using lower-cost low-carbon technologies, such as solar and wind, which replace higher- cost low-carbon sources like coal with CCS and nuclear.

Looking across connectivity cases, the modelling shows that enhanced transmission facilitates the development of cost-effective low-carbon power sources, in particular wind and solar. These options displace more expensive low-carbon power technologies like nuclear and coal with CCS (figure 6). Additional transmission provides access to renewables that load centres would not otherwise be able to utilize, and it alleviates constraints caused by the full exploitation of low-cost renewable energy potential in regions with net-zero requirements. Better connectivity also supports the strategic siting of wind and solar in locations with optimal availability. In the more ambitious connectivity cases (ASG, NAPSI, NEAEI and Synthesis) in 2040, between 34 and 328 TWh of electricity generation are shifted to wind and solar from more expensive low carbon sources as well as coal. For ASG and NAPSI, this result owes something to these plans' assumed build-out of solar and wind power in Mongolia. However, similar results occur in the NEAEI and Synthesis cases, which do not presuppose such a build-out. Moreover, the total deployment of new solar and wind capacity in the ASG and NAPSI simulations exceeds the plans' targets (by about 100% in the case of ASG), demonstrating that the increase in transmission by itself induces greater wind and solar development.

Figure 6. Differences in electricity generation by technology in 2040 and 2060



Source: SEI

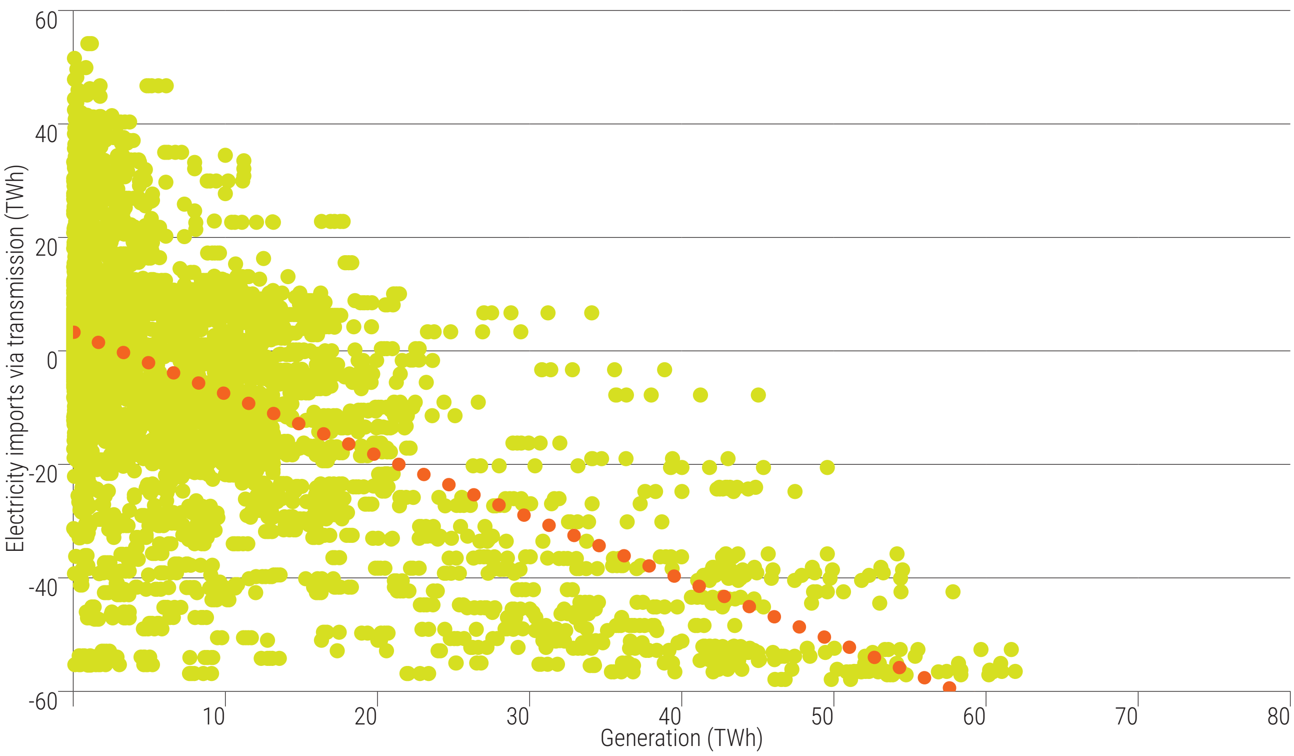
The geographic distribution of the changes in generation varies from scenario to scenario, depending on the location of new transmission lines and any assumptions about where new wind and solar capacity is added. In general, though, there is an increase in wind and/or solar production in China, Japan and Mongolia. This substitutes for other generation that would have occurred in China, the Republic of Korea and Japan.

The degree of change in the electricity mix scales with the number of additional transmission lines, although for ASG, the assumed deployment of 100 GW of solar and wind also plays an important role (see Appendix for a list of transmission lines in each connectivity case). For example, in National Plans, which includes only five smaller additional transmission lines, there is a modest shift of approximately 3 TWh towards different technologies compared to Baseline connectivity. Under NEAEI, however, the construction of 16 new transmission connections results in a shift of more than 200 TWh towards lower-cost, low-carbon technologies by 2060. The overall difference is even greater in the ASG case, where the deployment of 100 GW of solar and wind is mandated.

Figure 7 shows the relationship between onshore wind generation and transmission.Each dot represents a modelled region in a year, season, and hour of the day. Results are shown for the six transmission connectivity cases with Sustainable Development sustainability. For each 1 TWh drop in onshore wind generation, electricity imports via transmission increase by approximately 1 TWh, illustrating how transmission backfills for fluctuations in wind output.

The modellng shows a noteworthy relationship between variable renewable generation and the utilization of inter-regional transmission. This is evident in the correlation observed between transmission imports and renewable energy production, as depicted in figure 7 for onshore wind (for other variable renewable energy sources, please refer to Appendix). While there are differences between regions and time periods, the simulations reveal a consistent trend: for a 1 TWh decrease in

Figure 7. Relationship between onshore wind generation and transmission



y = 1.0889x + 3.2544; R^2 = 0.2322

Source: SEI

variable renewable generation in a region, there is a corresponding increase in transmission imports of about 1 TWh. This trade-off holds true for two other variable renewable generation technologies, offshore wind and solar, although these technologies exhibit a higher degree of variability about the trendline. The link between imports and variable renewable output shows how transmission is used to stabilize grids with increasing solar and wind penetration. The availability of transmission is a key factor in enabling greater wind and solar production, alongside storage, dispatchable thermal generation and demand-side management.

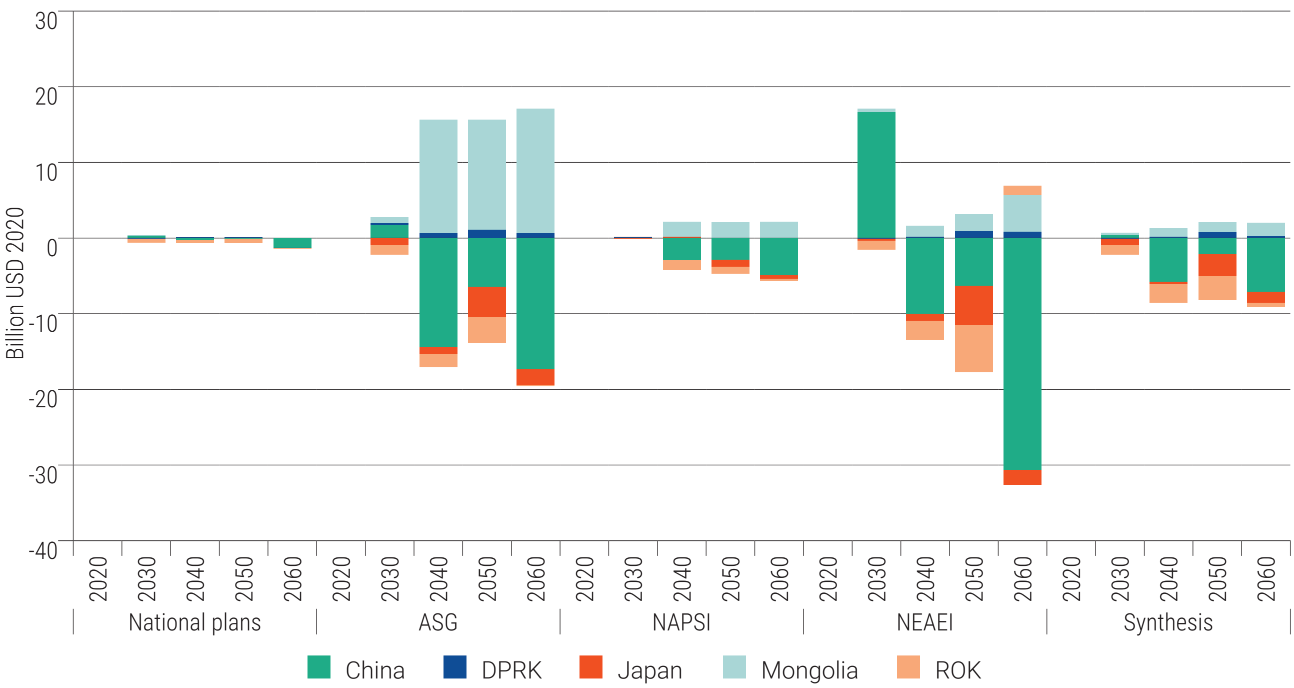
Electricity production costs

Figure 8 shows the differences in electricity production costs by region in the five enhanced connectivity cases compared to the Baseline connectivity case, all with the Sustainable Development sustainability case. The enhanced connectivity cases show lower costs compared to the Baseline particularly in China, Japan and the Republic of Korea. The cost increases in Mongolia are linked to investments in wind and solar capacity, primarily for power exports.

The modelling demonstrates that increasing transmission connectivity is cost-effective, with total annual net savings in the enhanced connectivity cases ranging from 1 to 29 billion 2020 US dollars per year after 2040 (when most of the new lines are constructed) (figure 8). These results account for the costs of electricity generation and storage (including capital, operation and maintenance, and input fuel costs) as well as transmission. In the Synthesis case, annual net savings in 2040-2060 period average 8 billion 2020 US dollars per year.

Much like the dynamics observed in the shifts in electricity generation, the extent of cost reductions is directly proportional to the number of newly established connections. Notably, the most substantial cost reductions are evident in the NEAEI case, while the National Plans connectivity case demonstrates the smallest cost reductions. The net costs savings generally increase during the modelling period. In absolute terms, the savings are most significant for China, but they constitute a relatively small fraction of electricity production costs in that country due to the size of the Chinese electricity systems. As figure 8 shows, there are projected net cost increases in Mongolia; these are tied to increased investments in wind and solar and can be expected to have a positive effect on the local

Figure 8. Differences in electricity production costs by region



Source: SEI

economy, including employment gains and indirect and induced economic impacts.

These regional net savings translate to a reduction of up to 3% in the cost per kWh of electricity supplied, contingent on the connectivity case. This raises the possibility of cost savings for electricity consumers, such as households and electricity-intensive industries, although the extent of any such benefits depends on regulators and price-setting processes. Beyond direct savings per kWh of electricity purchased, consumers could also benefit from transmission improvements through having access to a more reliable, stable electricity supply, as well as through the local economic effects of transmission, generation, and storage projects. These impacts could include an increase in local economic output and employment, as indicated above, but also an improvement in the overall investment climate in a region.

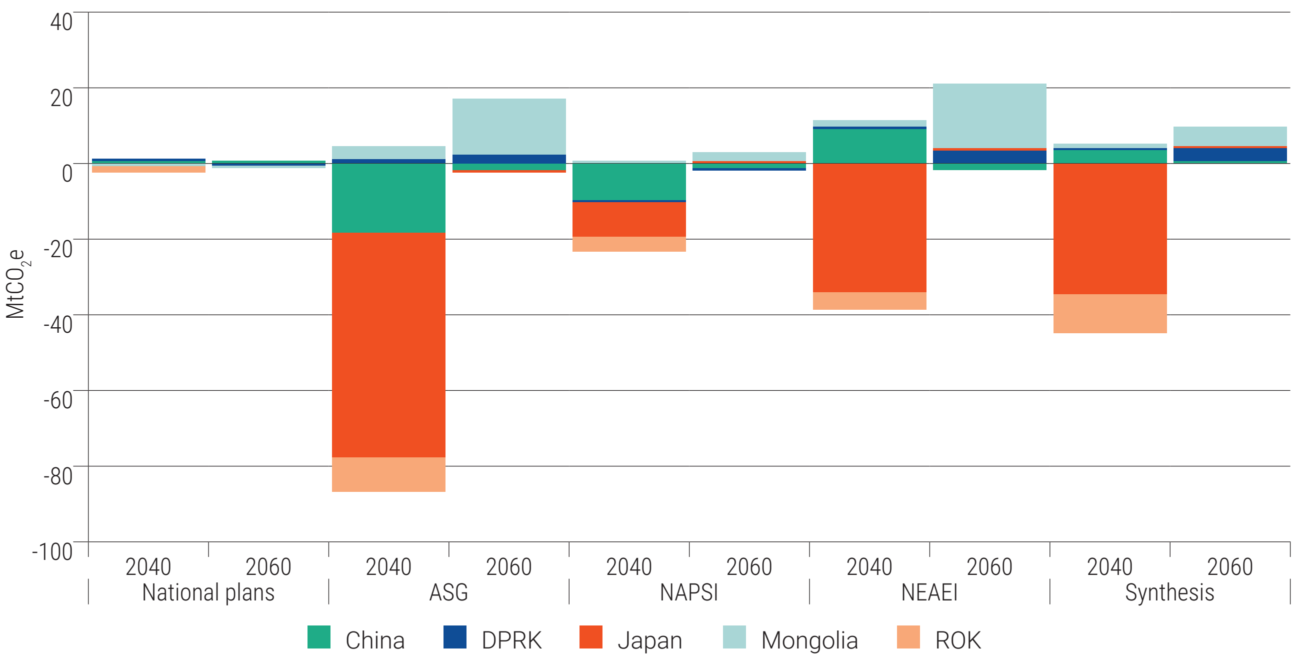
GHG emissions

Figure 9 shows changes in GHG emissions in the five enhanced connectivity cases compared to the Baseline connectivity case, all assuming the Sustainable Development sustainability case. An increase in cost-effective renewable power generation leads to accelerated decarbonization, dominated by reductions in Japan, the Republic of Korea and, in some cases, China. The Synthesis case is particularly effective in reducing emissions given its relatively small number of new transmission lines. Some carbon leakage is observed in Mongolia and DPRK.

The enhanced connectivity cases have a relatively modest impact on GHG emissions (figure 9). In general, additional transmission leads to emission reductions in the earlier years of the simulation, before net-zero targets in China, Japan and the Republic of Korea come into full effect. In 2040, for example, reductions across all regions range from zero to 80 mega-tonnes of CO_2e ($MtCO_2e$), depending on the connectivity case. This result is due to increased access to low-cost wind and solar that substitute for fossil sources that would otherwise be used.

The ASG connectivity case, which mandates the deployment of 100 GW of wind and solar capacity, achieves the maximum emission reduction in 2040. Remarkably, the Synthesis case attains the second-largest GHG reduction in that year, exceeding 40 $MtCO_2e$. This is achieved with only a fraction of the transmission lines in the NEAEI case (six compared to 16 lines), and without exogenous

Figure 9. Changes in GHG emissions in the five enhanced connectivity cases



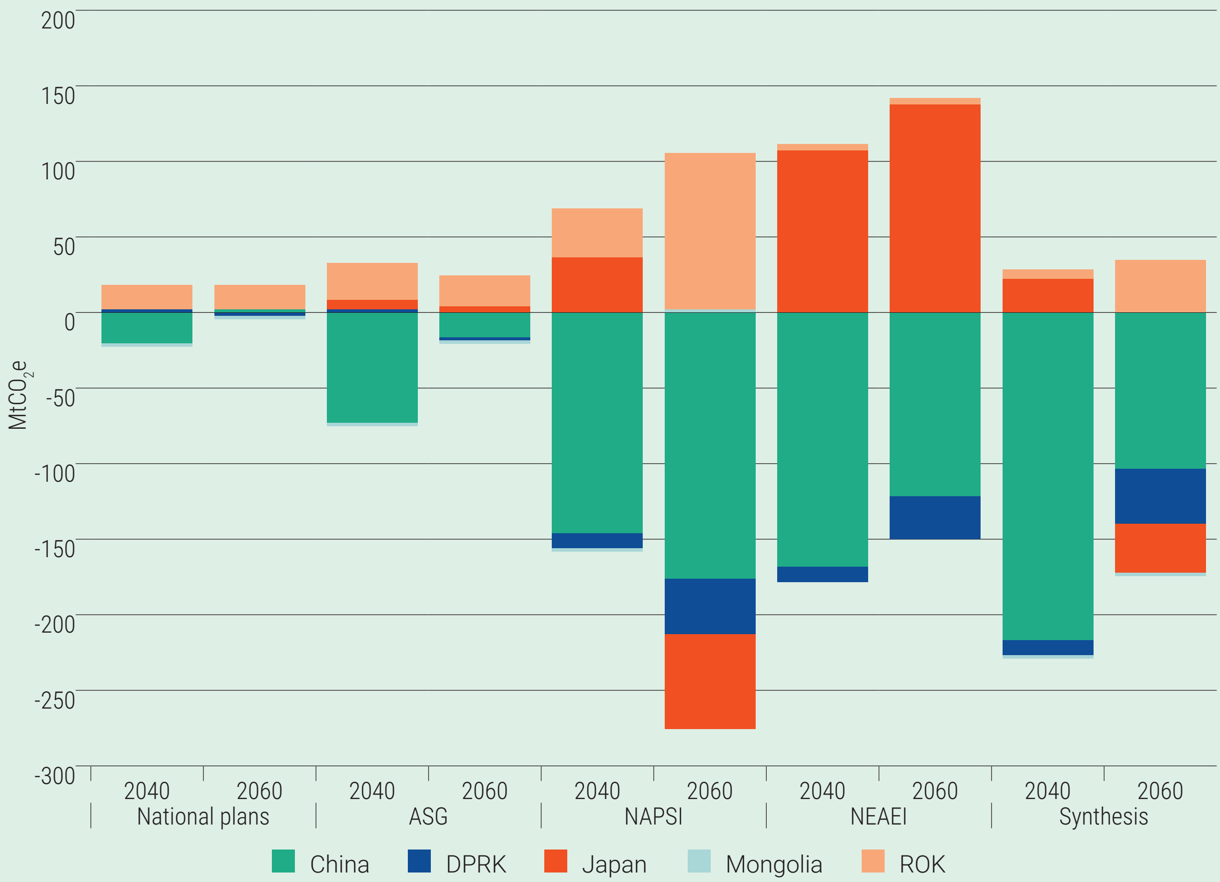
Source: SEI

mandates for the deployment of renewable energy. The findings in the Synthesis case underscore the fact that there can be significant differences in the emissions impacts of potential transmission lines. Connections that link regions with high wind or solar potential to regions with constraints on the local development of renewable power can be particularly useful for emissions abatement.

Box 1. Enhanced connectivity promises greater climate benefits if sustainable development is delayed

The GHG emission reduction benefits of increased transmission connectivity are significantly higher under Baseline sustainability assumptions than in the Sustainable Development case – more than twice as high for most transmission configurations and years (figure 10). This underscores the potential for connectivity to offer substantial advantages in scenarios where sustainable development and climate change mitigation efforts face delays. The reason is straightforward: improved transmission increases access to low-cost renewable power, which in turn substitutes for conventional carbon intensive generation (rather than higher-cost low-carbon power as in the Sustainable Development case). Another way to conceptualize this phenomenon is that transmission improvements offer a hedge against possible setbacks in implementing climate policy. If the generation fleet is not decarbonized as quickly as planned in a region, interconnections with other regions can help mitigate the overall emissions impacts.

Figure 10. Changes in GHG emissions in the five enhanced connectivity cases



Note: five enhanced connectivity cases compared to the Baseline connectivity case, all with Baseline sustainability
Source: SEI

By 2060, the enhanced connectivity cases no longer provide an emission benefit. At that point, the counterfactual (in the Sustainable Development case with Baseline connectivity) is a grid that is almost completely decarbonized anyway. Overall, the results show that while additional transmission may not be needed to realize net-zero targets, it can accelerate decarbonization and help limit cumulative GHG emissions, which is a critical factor in climate change.

The GHG emission reductions in earlier years are primarily observed in Japan and the Republic of Korea, and in some instances, in China (NAPSI and ASG). Interestingly, Mongolia and the Democratic People's Republic of Korea exhibit slightly higher emissions in both 2040 and, to a greater extent, in 2060 across the enhanced connectivity cases. This is evidence of some carbon leakage, as additional electricity is generated from fossil fuels in those countries and exported to regions with stringent climate requirements. Policymakers should pay attention to this possibility as plans for increased transmission connections are developed. It could be addressed through power purchase agreements for renewable energy, taxation schemes or other mechanisms.

As already mentioned, the modelling indicates that the GHG emission benefits of improved transmission connectivity should be significantly greater if national sustainable development policies face delays. This contingency is explored in box 1.

International electricity trade

The modelling finds that grid integration fosters increased cross-border electricity trade among participating countries, promoting economic cooperation and resource sharing. The establishment of new transmission lines proves mutually beneficial for both connected regions, facilitating two-way trade (table 1). Notably, this is particularly evident in the case of Japan and the Republic of Korea, where trade levels are almost equal, highlighting the balanced nature of this exchange. Importantly, trade becomes progressively more even as time passes, underscoring the evidence for long-term benefits for both trading partners.

This equilibrium in trade signifies enhanced grid resilience in the face of demand and supply variability. The interconnected grid is better equipped to absorb the fluctuations associated with variable renewable energy development and new source of demand. This improved resilience should contribute to the stability of the grid, ensuring a consistent and reliable energy supply even as renewable energy sources become more prominent, and ultimately advancing the collective effort towards sustainable and decarbonized energy systems.

2.4. Key takeaways

Key takeaways from the GPC modelling include the following findings. These core findings reinforce the

Table 1. International transmission imports and exports in TWh

Direction of trade	2040	2060
China to Mongolia	3	6
Mongolia to China	25	23
China to DPRK	51	43
DPRK to China	14	24
DPRK to ROK	49	42
ROK to DPRK	11	18
ROK to Japan	29	26
Japan to ROK	35	34
China to ROK	11	12
ROK to China	6	6

Note: trading under Synthesis connectivity case and Sustainable Development sustainability case

GPC approach and validate steps toward increased grid integration.

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 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.

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. **Commonalities in proposals:** Major past transmission proposals are diverse in their scope, objectives and recommendations, but they share common elements that offer a compelling foundation for future efforts toward grid integration. As illustrated in the Synthesis case, these commonalities can provide substantial economic, resource diversification, and sustainability benefits in the current policy, technology and cost environment.

7. **Emission reduction potential:** Improved connectivity has significant GHG emission reduction potential if sustainability goals are not fully realized, or if progress toward sustainability is slower than anticipated. If national decarbonization efforts 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.

The GPC modelling demonstrates the multifaceted advantages of enhanced grid connectivity in North-East Asia. While the modelling primarily focused on improving international connectivity, drawing from past plans and studies, the role of intranational transmission should not be overlooked. Enhancing intranational transmission connections can make an important contribution to successful regional integration, even in the absence of new international political agreements.

By promoting the adoption of low-cost renewables, reducing system costs, and potentially leading to emissions benefits, connectivity emerges as a powerful enabler of sustainable energy transitions in North-East Asia. Moreover, these benefits scale with the scope of connectivity plans, underlining the importance of forward-looking and collaborative integration efforts.

Chapter 3

Lessons from other regions and implications for North-East Asia in the new terrain

3.1. International lessons learnt for the successful development of a power grid connectivity roadmap for North-East Asia

As mentioned in the previous chapters, discussions on power grid connectivity in North-East Asia have been ongoing for almost 30 years, with multiple studies assessing the political, economic, social and technical challenges and benefits of increased power grid interconnection in the subregion. Despite these long-standing scientific efforts and ongoing multi-stakeholder processes (including the annual North-East Asia Power Interconnection and Cooperation (NEARPIC) Forum, the Greater Tumen Initiative (GTI) and initiatives put forward by the public-private sector, e.g., the MoUs between utilities in the region), as of yet there has been no full-fledged effort to develop regional power grid connectivity. A primary hurdle explaining this lack of progress is well-known and has been highlighted by many previous studies; the lack of consolidated political will to support the integration efforts.

Yet the experience of other regions in strengthening regional power grid connectivity clearly shows that, when it comes to large-scale, long-lived infrastructure such as cross-border power grid interconnections, lack of political readiness to cooperate and the challenge of trust consolidation are by no means exclusive to North-East Asia. In fact, in one way or another, every power grid integration initiative in the world has faced this same problem.

Regions that are now held up as examples of successful cross-border power grid connectivity efforts have gone through decades and sometimes centuries of socio-political turbulence – political tensions, decades of military and ethnic conflicts or, as in the case of the Global South in general, the legacy of colonial rule.

In addition, the prevalence of weak national power grids in low-income economies as well as different power market structures in the countries to be interconnected are features that have been true globally at least at some point in the past. Even the European Union, nowadays the most integrated multilateral power system, is no exception.

Despite these complexities, the fact that most countries in the world are part of at least one regional connectivity initiative shows that even the political challenges are not insurmountable, and there are processes and instruments that have proven effective in consolidating trust and fostering regional cooperation on the issue. North-East Asia can therefore draw lessons from other regions and find answers on how to overcome these hurdles and kick off cooperation on power grid connectivity.

At the same time, it is important to recognize that international experience does not offer a tailored solution to the North-East-Asian "connectivity slump", as it comes from different historic contexts and partly reflects region-specific cooperation patterns. Furthermore, connectivity initiatives in other regions show various stages of power grid infrastructure and market integration, not all applicable in a North-East Asian context. Drawing on these different contexts is nevertheless worthwhile for a comprehensive overview of available political and policy options and their possible outcomes. Despite inherent differences, it is safe to assume that instruments and institutional formats that have proven efficient across several different regional contexts can be, if adjusted, useful to fostering power grid connectivity in North-East Asia.

The observations below are made upon analysis of historic development of 17 subregional power grid integration projects (table 2). These initiatives have been studied to consolidate the main success and failure factors from different economic and historic contexts, the lessons learnt then fed into the recommendations for kicking off cooperation on development of a GPC for NEA.

The list of analysed initiatives is by no means exhaustive and they are comparable with limitations, as not every region has the same organizations and mechanisms for fostering cross-border power grid connectivity. Connectivity projects that are, as of now, being discussed, but have yet to move forward – e.g., the ARCO Notre project in Southern America or Medgrid in Northern Africa – are not considered for the purposes of this report. Furthermore, there are domestic integrated power markets that can offer valuable lessons in particular on the later stages of power grid connectivity efforts, when harmonization and, ultimately, liberalization of power trade comes into question (e.g., PJM in the United States of America or India's national integrated power market). These have been left out of the analysis, given that the political challenges in these cases are of a lesser relevance, or at least of a different nature.

Lesson 1. Power grid connectivity is an evolutionary process

The overview of existing regional power grid connectivity projects shows that it typically takes regions several decades to establish cross-border electricity trading on a regional scale. The average time span between the beginning of discussions on the benefits of connectivity and the actual implementation of the physical infrastructure and development of all the necessary accompanying institutions is 30 years (table 3).

Moreover, aside from a few exceptions – Central Asia-South Asia Electricity Transmission and Trade Project (CASA-1000), Gulf Cooperation Council (GCC) Interconnection Grid, Andean Electrical Interconnection System (SINEA) – bilateral interconnections precede multilateral connectivity efforts, with regional cooperation effectively building on existing infrastructure and trading arrangements. The European and United States-Canada power markets are the clearest examples, as the development of both national and cross-border grid interconnections has been truly evolutionary, developing since the early 1900s alongside the emergence and development of power transmission technologies. Connectivity in other regions also goes back to the early-to-mid 20th century, with the first cross-border lines beginning operations between India and Nepal in the 1920s, and a major connectivity wave taking place in the 1950s and 1960s. In this sense, North-East Asia fits within the general rule for developing regional power grid connectivity, as there are already several bilateral cross-border interconnections in operation and the discussions about developing regional efforts have been ongoing for almost three decades now.

Lesson 2. Economic/socio-economic rationale is one of the key drivers of cross-border connectivity

Economic integration has often been a fundamental driver for regional power grid connectivity.

Often economic organizations sparked the establishment of respective connectivity initiatives themselves – as did the Nordic Council in the case of NordPool, the Economic Community of West African States (ECOWAS) in the case of the Western African Power Pool (WAPP), the Economic Community of Central African States (ECCAS) for the Central African Power Pool, the Southern African Development Community (SADC) for the Southern African Power Pool (SAPP) and the Gulf Cooperation Council for the Gulf Cooperation Council Power Interconnection. In some cases, the economic integration organizations evolved for decades before they took up the issue of power grid connectivity. The Central American Electrical Interconnection System (Sistema de Interconexión Eléctrica de los Países de América Central (SIEPAC) is one such case. Launched in 2014, SIEPAC was developed under the auspices of the Central American Integration System (Sistema de la Integración Centroamericana (SICA), which was created as a successor to the Organization of Central American States (Organización de Estados Centroamericanos, ODECA), founded in the early 1950s.

Aside from the stand-alone connectivity projects, such as those mentioned above, some have been created explicitly as part of broader economic cooperation efforts, to take shape as one of the integration sectors covered by regional organizations, e.g., MERCOSUR interconnection, the ASEAN Power Grid, the SAARC Energy Ring, and the power market of the Eurasian Economic Union or (at present) the common power market of the European Union. Some of those initiatives driven by broader economic cooperation have been built on the back of former economic integration structures, most notably the power market of the Eurasian Economic Union, which brings together countries who were formerly part to the IPS/UPS, one of the world's largest power grid interconnections, linking the USSR, Mongolia and the Eastern European countries.

Although economic integration has generally provided a helpful foundation for kicking off cooperation on power grid connectivity in most regions, the depth of economic integration does not seem to determine the success or degree of integration of power grids and markets. There are examples of extremely successful economic spaces with relatively limited implementation of power grid connectivity to date (e.g., MERCOSUR, ASEAN), and ones with more rapid and efficient implementation (e.g., SIEPAC, GCCPI). A basic readiness to cooperate on economic issues has been more important, in turn creating the environment necessary to proceed on to more contingent issues, including regional power grid connectivity. Noteworthy, however, is also the fact that deep embeddedness of connectivity projects into wider regional integration initiatives can bear a risk of the former becoming too dependent on regional organizations. MERCOSUR is one such example, where, although all of the formal agreements have been accomplished, power grid connectivity did not take off on a scope planned as the project has been deprioritized within the organization and has not been receiving further political support since the mid-2000s.

Even in the absence of broader economic integration efforts, economics has been the primary driver of most successful interconnectors, with political considerations playing a less important role. Except for some connectivity projects within the European space, and MERCOSUR, where agreements on cross-border power trade have helped resolve some political issues – most importantly the issue of shared energy resources (water) – the motivation for boosting cross-border connectivity has been rather pragmatic in order to increase stability of the network, save on investments in new generation capacities and lower electricity prices. Nevertheless, development of these projects would not have been possible without political support, even though their rationale was based on practical considerations and potential economic benefits.

Lesson 3. International and non-governmental/private entities are key during the implementation phase

Although political support has proved essential in an establishment phase of all analysed connectivity cases, international and non-government entities have been the key drivers behind development of physical infrastructure and the implementation of necessary regulatory changes.

The role of multilateral development banks and national development banks cannot be stressed enough in enabling the implementation of connectivity initiatives in regions consisting primarily of emerging markets and developing economies. Public finance institutions (PFIs) have been instrumental in unlocking access to the needed finance through grants and concessional and non-concessional loans. For example, 50% of the financing needed for the SIEPAC interconnection was provided by the Interamerican Development Bank (IDB); the WAPP was supported by a consortium of PFIs including the Islamic Development Bank (IsDB), European Investment Bank (EIB), African Development Bank (AfDB), the KfW (German Investment Bank) and the Kuwait Fund for Arab Economic Development. These institutions have also played an important role in providing technical assistance to ensure successful implementation of connectivity initiatives, e.g., USAID played such a role in case of WAPP, and IDB in the case of SIEPAC. Furthermore, feasibility studies – one of the key steps ahead of the implementation phase – are frequently supported by PFIs (e.g., AfDB has financed the feasibility study for the CAPP interconnection; USAID is supporting feasibility studies for priority interconnectors of the ASEAN Power Grid; and, in North-East Asia, ADB has been playing such a role, enabling the technical assistance report for the NAPSI regional connectivity model).

Both PFIs and other international organizations including various United Nations agencies – e.g., the Economic Commission for Africa (ECA) in the case of the CAPP – also play an important agenda-setting and brokering role, by organizing workshops and conferences, convening summits of heads of government, and gathering State and non-State actors to develop common methodologies (Palestini, 2020). The IDB has been able to play such a role consolidating political trust, expertise and resources to work on the SIEPAC initiative.

Finally, utility companies (both State- and investor-owned) have proved essential to the successful launch and faultless operations of cross-border interconnections. Their voice is crucial on issues of harmonization of national standards and grid codes, and the establishment of power trade agreements as well as making sure cross-border connectivity has positive socio-economic spillovers by driving capacity building, creating new clean energy jobs and securing the buy-in of local populations. In fact, most "successful" cases of regional power grid connectivity were accompanied by some kind of utility coordination platform – the International Union of Producers and Distributors of Electric Energy (UNIPEDE). Later, the European Network of Transmission System Operators for Electricity (ENTSO-E) played such a role in the European space; Nordel, a body enabled cooperation between the transmission system operators in Denmark, Finland, Iceland, Norway and Sweden in the Scandinavian region ahead of the implementation of NORDEL grid; Consejo de Electrificación de América Central (CEAC) enabled utility dialogue in Central America and the Comité Maghrébin de l'Electricité (COMELEC) in the Maghreb region; and the heads of the ASEAN Power Utilities/Authorities (HAPUA) in ASEAN. Although less formalized, the power pools organized in the 1920s in the United States performed a very similar function. In the European case, utilities were among the first organizations to establish institutionalized cooperation formats across borders (UNIPEDE was established in 1925) and, aside from being a key voice on power grid connectivity, were among the drivers of European integration.

Lesson 4. Synchronization and market liberalization are not prerequisites to a functioning cross-border power trade

Most integrated power grids – e.g., the Western Interconnection in North America, the Synchronous Grid of Continental Europe (SGCE) and Nordpool in Europe, SIEPAC in Central America and the SAPP in Africa – are synchronized areas with competitive power markets that enable cross-border electricity trading. Synchronization and mechanisms for power trade are therefore often key instruments towards deeper integration of power systems within a given region.

However, international experience shows that power can be traded across borders within a multilateral arrangement even when neither of the two above conditions are in place. In fact, multilateral power trade was in most cases not a purpose in itself. Instead, connectivity projects develop taking into account the needs of the countries in the region as a priority. For example, the CASA-1000 project has a specific goal of optimizing hydropower resources in Kyrgyzstan and Tajikistan as well as serving electricity demand in Pakistan. The same applies to the first stage of the ASEAN power grid, for example the multilateral arrangement between Thailand, Singapore, the Lao People's Democratic Republic and Malaysia to export hydropower resources from the Lao People's Democratic Republic to Singapore via a combination of synchronized (AC) and unsynchronized (DC) interconnections. Harmonized bilateral or multilateral trade via back-to-back interconnections can perform such functions, as is seen in the case of most of the analysed connectivity initiatives.

There are, however, factors that have proved to be major hindrances to successful implementation of regional connectivity initiatives, even in their earlier stages. The biggest obstacle, clearly demonstrated by lack of effective cross-border operations in WAPP, EAPP, CAPP and the Eight Country Interconnection Project in the Middle-East and North Africa region (EIJLLPST) is insufficient domestic power grid integration and capacity. In the latter case, nearly all activities of cross-border energy interconnections to date are limited to emergency operations instead of profit-based energy trade at normal system operations. Even in countries with more robust national power grids, lack of interconnectedness within national power systems can lead to the general reluctance of trading power across borders – as can be seen in case of GCCPG, where nominal power trade takes place yet far below the actual transmission capacity of the interconnector.

Weakness of domestic grids, and generally slower pace of grids deployment than that of deploying new power generation capacities, has proved to be a major obstacle to further integration within both nascent and mature connectivity spaces.

Table 2. Analysed power grid interconnections by their level of integration

Interconnection	Status
Western Interconnection	Interconnections in place, power market in place.
SGCE	Interconnections in place, power market in place.
Nord Pool	Interconnections in place, power market in place.
SIEPAC	Interconnections in place, power market in place albeit with low volumes due to outstanding regulatory/policy issues.
SAPP	Interconnection in place, power market nominally in place, power trade hindered.
SINEA	Interconnections in place, bilateral power trade partly via market mechanisms (TIEs), partly via bilateral agreements. Harmonization underway.
GCCPG	Interconnection in place, power exchange on a country-to-country basis. Plans to transition to a full-fledged power market based on the NordPool model.
EAEU	Interconnections in place, power market treaty signed, harmonization underway. Power trade via bilateral treaties, pilot spot trading took place.
CASA-1000	Interconnection under construction. Power trade to be carried out through bilateral PPAs.
APG/GMS	Six interconnections exist (SG-ML, Th-ML, Th-CM, LPDR-VN), nine in construction and 16 more planned. Power exchange- and trade based on bilateral agreements. Exception: the Lao People's Democratic Republic-Thailand-Malaysia trilateral agreement.
WAPP	Interconnection in place, no power market – major investments in strengthening power grid and solar generation flow in from IOs, NGOs.
EAPP	Interconnections only partly in place, several under construction. No power market, power trade via bilateral arrangements.
CAPP	Interconnections only partly in place, several under construction. No power market, power trade barely existing.
MERCOSUR	Interconnections partly in place, bilateral trade via existing interconnections.
Maghreb Int.	Interconnection in place, cross-border electricity exchange.
EIJLLPST	Interconnection in place, cross-border power exchange mostly limited to emergency operations.
SAARC ER	Interconnection partly in place, no power market, bilateral power trade via existing interconnections.

Table 3. Chronology of regional power grid integrations across different regions

Interconnection	First (bilateral) interconnections	Discussions on RPGI begin	Economic integration	First RPGI Agreement	First Relevant Institution	Implementation start (reg./ph.)
Western Interconnection	1906 US-MEX 1909 US-CAN	N.A. (ad hoc)	1994 (NAFTA)	1968 (NERC, WSCC)	1968 (NERC, WSCC)	1920s
SGCE	1906 DE-FR	1920s	1957	1951	1925	1920s
Nord Pool	1915 (DAN-SWE)	1920s	1952 (Nordic Council)	1963	1963 (Nordel)	1996
SIEPAC	1976 (HON-NIC)	1970s	1962	1979 (agr to establish CEAC)	1989 (CEAC)	2002
SAPP	1906	1980	1980 (SADCC)	1995	1990 (SADCC's electricity subcommittee)	1995
SINEA	2003 ECU-COL 2004 ECU-PER	90s	1969	2002 (Dec. 536)	2003 (Council of Andean Community Ministers of Energy, Electricity, Hydrocarbons and Mines) 2011 (SINEA)	2003
GCCPG	2006 UAE-OMAN	80s (1981)	1981	2001 (GCCIA)	2001 (GCCIA)	2004
EAEU	1980s (Siberia-KAZ)	early 90s	1995 (Customs Union)	2014 (EAEU)	1993 (Electric Power Council of CIS)	2015
CASA-1000	Construction began in 2021	late 90s	1997 (CAREC)	2005	2005 (CAREC's Energy Sector Coordinating Committee, ESCC)	2016
APG/GMS	1966 (Th-LPDR)	1980s	1967	1997 (APG)	1981 (HAPUA, under ASEAN)	N/A
WAPP	1960	1970s	1972 (OMVS)/ 1975 (ECOWAS)	1999 (WAPP)	1972 (OMVS)	2012
EAPP	1955 (KNY-UGN) 1960s (SINELAC)	N/A	1981 (PTA)	2005 (intergov. MoU on EAPP)	1973 (OMVS)	2010
CAPP	N/A	N/A	1964 (UDEAC)	2003 (MoUs on CAPP)	1974 (OMVS)	2009
MERCOSUR	1984 (Itaipu dam btw BRZ-PRG becomes operational).	1960s	1980 (LAIA)	1998	1975 (OMVS)	2005
Maghreb Int.	1952 (MOR-ALG)	1960s	1987 (Union of Maghreb Area)	1972 (COMELEC, by utilities)	1976 (OMVS)	1997
EIJLLPST	1998 (LYB-EGY)	1980s	N/A	1988 (EIJST)	1977 (OMVS)	2001
SAARC ER	1920s (IND-NEP)	2000s	1983 (SAARC)	2014 (Framework agreement)	1978 (OMVS)	N/A

For example, deepening connectivity with Mexico within the Western Interconnection has been delayed due to insufficient grid capacity and the fact that new transmission lines were deployed four times slower than new generation (Thornley, 2010) and remain quite fragmented to date (McNeece et al., 2022). In the European Union, only 16 out of 27 member States are on track to reach the 15% cross-border connectivity target by 2030 (EC, 2023).

Further hindrances to efficient operations of multilateral power trade and exchange include lack of regulatory framework harmonization and of price-making mechanisms.

Regulatory challenges include a wide array of issues, ranging from allocation of long-term transmission rights and guarantees of capacity in power trade contracts to general incompatibility of legal and regulatory systems of interconnected countries with each other. In the absence of a body to facilitate regulatory exchange and, ultimately, harmonization, getting past the stage of bilateral power exchange and trade proved to be very challenging.

Challenges related to price-making mechanisms include both the electricity pricing itself, often complicated by the various levels of national subsidization of electricity prices, and pricing for the regional transmission (wheeling charge), which, if non-transparent or lacking, makes it difficult for investors to know in advance how they will recoup their investment and what rate of return to expect.

3.2 New terrain for green power connectivity initiatives

While international cooperation on power grid connectivity can teach us a lot about drivers of successful initiatives and reasons for failure, the ongoing transformation of power systems around the world will challenge both existing power connectivity initiatives and emerging ones. The biggest challenge for established interconnection initiatives is adapting to the changing power mix of the interconnected countries. Renewables are gaining in prominence as a power generation source in many regions of the world – including North-East Asia. This, in turn, is increasing the need for the deployment of new transmission and distribution capacity, flexible storage solutions, smart demand management mechanisms and other modern energy system solutions. Some regions have already started to consider how to adapt their connectivity initiatives in order to enable the integration of increasing shares of renewable electricity. For example, the Central America Clean Energy Corridor (CECCA) has been proposed by the IRENA in cooperation with the Governments of the region, to promote the accelerated deployment and cross-border trade of renewable power in Central America, in the context of the regional electricity market and the regional transmission network (SIEPAC). Similarly, the European Union's Fitfor55 package and the most recent legislation, REpowerEU are designed to help the European power systems adjust to higher renewables targets, among others via accelerating grids deployment and making progress on some strategic interconnectors, Spain-France and the Baltic interconnections among them.

These challenges are not unique to cross-border interconnections but must be tackled system-wide. In fact, boosting power grid connectivity can partly address some of them, in particular by increasing the flexibility to the power systems of interconnected countries. In this context, regions where connectivity has yet to take off have a certain advantage as they design connectivity with their domestic power system transitions in mind from the very start, therefore optimizing the use of cross-border power grid infrastructure and generation capacities.

The other challenge for emerging power connectivity initiatives is the much shorter timeframe within which change needs to happen than it did in the previous decades. As the world is striving to achieve net-zero by mid-century, and is planning for a massive ramp-up of renewable power generation, adequate infrastructure must be put in place, most notably grids and interconnections, in order to enable a timely integration of new renewables capacity into the system. At least 3,000 gigawatts (GW) of renewable power projects, of which 1,500 GW are in advanced stages, are waiting in grid connection queues – equivalent to five times the amount of solar PV and wind capacity added in 2022 (IEA 2023b). At the same time, new solar and wind generation can be deployed two to three times faster than a transmission line, while the average lifetime of the grid infrastructure is up to twice as long as that for the renewable generation capacity. Long-term planning for both domestic grid expansion and cross-border interconnections that is aligned with countries' 2050-2060 renewables targets is therefore highly advisable in order to both enable smooth renewables uptake and maximal cost-effectiveness of the planned infrastructure. Lesson 1 from this chapter tells us that traditionally development of power systems connectivity has been an evolutionary process, and deployment of large-scale cross-border interconnectors is unlikely to take under a decade even under today's conditions. Therefore, in face of the need to decarbonise power systems by mid-century necessitate, planning of such cross-border infrastructure needs to begin as soon as possible, in order to maximise the potential of this infrastructure to contribute to countries' clean energy and climate targets – something which needs to be taken into account within the GPC in North-East Asia.

Chapter 4

The Roadmap for the Green Power Corridor in Northeast Asia

This chapter proposes a set of actionable priorities for the North-East Asian countries to consider in order to foster regional cooperation on a GPC. These priorities are aligned with the six GPC building blocks (figure 1). Each building block contains a set of principles which, in turn, suggest a set of relevant actions to support each building block's implementation.

The actions are proposed within a timeline that aligns with development of the GPC as suggested by the modelling presented in Chapter 2. The main focus is on the Sustainable Development Cases for multilateral interconnection models (ASG, NAPSI, NEAEI and the synthesis case), as these are most aligned with the GPC concept and the most cost-effective pathways. At the same time, these scenarios are the most ambitious in terms of climate commitments and they require a more complex cooperation framework for full and efficient implementation.

4.1. GPC building blocks: Principles, recommendations and plan of action

Political accord

GPC Principles:

- 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;

- Formalize political accord through joint statements, MoUs and other forms of intergovernmental agreements.

The essential role of political support by the national Governments in enabling cooperation on regional power grid connectivity has been highlighted in numerous studies and demonstrated by the past experience of connectivity initiatives in other regions of the world.

While involvement of relevant government agencies in planning is important at all stages of development, including on data sharing and emergency operations mechanisms, exchange (and, at later stages, coordination) of national grid plans etc., it is the initial phase of a connectivity initiative where political support is most crucial. Power grids are pieces of critical infrastructure for any economy. Therefore, governmental support for cross-border interconnections is needed to (a) boost the confidence of potential public and private investors in the feasibility of the initiative, and (b) create space for international organizations to facilitate the development of the needed institutional framework and dialogue mechanisms in a much more targeted and efficient manner.

There are certainly things that can be done by other stakeholders while political support has not yet been granted; some of them can even help consolidate political trust. Exchange and peer learning by the utilities to better understand national specificities of the to-be-interconnected power systems, expert working groups to discuss feasibility and benefits of connectivity, or early modelling exercises and feasibility studies – all this is possible and can contribute to a more open and trusted environment, while consolidating knowledge on the most efficient ways to proceed with cooperation on connectivity. In the case of the European power market, for example, the utility association UNIPEDE existed for around two decades as a precursor to the first intergovernmental discussions on power network building after the end of World War II.

While useful in their own right, these forms of cooperation have not been known to enable regional connectivity beyond bilateral power trade. In North-East Asia, a significant amount of preparation work has already been done by various academic communities, international financing institutions (e.g., ADB enabling NAPSI feasibility studies) as well as the meetings of ESCAP's Expert Working Group on Energy Connectivity. To move beyond the study stage, however, governmental support is key.

As a first step, countries of the region should recognize a common high-level vision of regional power grid connectivity – the GPC for North-East Asia suggested by this report can provide a first template for this. The agreement does not necessarily need to be signed at a formal/public high-level political event, but can be facilitated by one of the existing integration platforms.

Recognition of the GPC Roadmap would furthermore deliver the first important political signal of the countries' clean energy and climate ambition. Moreover, consideration of such an agreement is particularly timely as the focus of climate and energy diplomacy is on Asia this year, with several key moments taking place in the region, including the G7, the G20, the "Asian COP28" as well as the Asia-Pacific Energy Forum.

After the basic recognition of the GPC roadmap has been granted and the initial political support has been secured, institution building to set the groundwork of the GPC in North-East Asia can begin – including entities that involve government representatives on a regular basis, to ensure long-term buy-in and better cooperation.

Institution building

GPC Principles:

- Identify or, if necessary, establish inter-jurisdictional platforms for collaboration across all relevant areas.
- Develop a common methodology for feasibility studies (including the required modelling).
- Commit to data transparency wherever possible, and data sharing with selected partners for sensitive data.
- Update data on an agreed-upon schedule.

State of play in NEA

Existing institutional frameworks for regional cooperation in North-East Asia are fragmented, and there is no subregional organization for economic cooperation that includes all six countries. However, there are several multilateral organizations covering broader economic integration and cooperation issues with smaller, and largely overlapping, country membership. Among them is the Greater Tumen Initiative, established in 1995 by China, the Democratic People's Republic of Korea, Mongolia, the Republic of Korea, and the Russian Federation and originally aimed at promoting economic development of the Tumen River area, shared by these countries. At present, membership includes China, Mongolia, the Republic of Korea and the

Russian Federation, and the focus of cooperation has expanded since GTI's inception to cover economic development of the whole NEA region, including development of enabling infrastructure.

The trilateral China-Japan-Republic of Korea summit, held annually between 2008 and 2019, is another forum where cooperation issues including those on energy are being discussed on a head of state and ministerial level. Should it resume this year, it could prove useful as one of the platforms to start discussing connectivity issues. Furthermore, multilateral dialogue on broader economic issues is taking place within larger fora that go beyond the NEA region, including APEC and ASEAN+3.

There is a series of bilateral energy dialogues among the North-East Asia countries, including: ERINA's Japan-Russian Energy and Environmental Dialogue, focusing on Sakhalin oil and gas projects; Vladivostok LNG and Magadan II and III; China-Japan annual Energy Conservation Forum; China-Russian Federation energy dialogue, Russian Federation-Republic of Korea energy dialogue on the Democratic People's Republic of Korea, as well as the Mongolia-Russian Federation energy dialogue. However, these formats do not address power grid connectivity issues and focus largely on fossil fuel trade and environmental matters.

Cooperation on power grid connectivity is nascent, with cooperation agreements to date reached between non-governmental stakeholders, although some State-owned utilities have already been involved in various dialogues. Among these are the MoU signed by the SoftBank Group, State Grid Corporation of China (SGCC), Korea Electric Power Corporation (KEPCO), the operator of the Russian Federation's energy grid PJSC ROSSETI (ROSSETI) and the bilateral MoU between SGCC and KEPCO (for more details see Introduction). Finally there is an MoU on cooperation of electric power generation and promotion of interregional and cross-border cooperation between the Russian and Mongolian Governments – the only agreement on power grid connectivity at the government level.

The only multilateral platform to date that focuses on cross-border power grid connectivity in the region is the North-East Asia Power Interconnection and Cooperation (NEARPIC) Forum. The Forum serves as a multilateral platform for North-East Asian countries to share experiences, knowledge and expertise, and to forge strategic intergovernmental energy partnerships as well as promote regional power interconnection and advancement of the SDGs in the subregion (ESCAP, 2018).

As NEARPIC both covers all the member countries of the North-East Asian region and focuses specifically on promoting regional power grid connectivity, it can be a useful initial platform based on which institution-building for the GPC can take place.

Policy recommendations going forward

Based on the lessons learnt from other regions' connectivity initiatives and in alignment with the GPC principles, the following set of high-level policy guidelines can be offered to foster sustainable institution-building in the region:

- Focus on establishing an institutional framework enabling regular working-level exchange and coordination on key connectivity issues at the initial phase.

- Make use of the existing regional fora for economic cooperation as a springboard towards further institution-building and further consolidation of political will to support the GPC in North-East Asia.

- Create space for exchange and coordination platforms organized and run by utilities and regulatory bodies on a regular basis to enable faultless implementation of the connectivity initiative.

- Involve international and national PFIs in the institution-building and planning early on to secure financial support and the needed technical assistance.

- Make sure the core focus of the institutional work is optimizing the socio-economic and technical potential of cross-border connectivity (including stability of the grid, cheaper electricity price, demand-supply synergies and load sharing) and is aligned with the member countries' national energy and climate goals.

Phase I: Laying the groundwork

In the following years, the capacities of GTI and NEARPIC can be used to continue the working-group (WG) level dialogue to fine-tune the Roadmap and discuss the organizational aspects of institution-building, so that in 2025, the North-East Asia member States can launch an interim secretariat for NEA GPC – a working-level platform for regular exchange and data sharing. The Secretariat would, in turn, power up three main workstreams (either as WGs within the secretariat or stand-alone platforms):

- North-East Asia utilities platform launched (as a stand-alone or part of the NEA GPC IS) for exchange of knowledge and lessons learnt on bilateral trade (via existing interconnections) and coordination of future planning.
- Expert North-East Asia power grid connectivity WG created to enable mapping of the regulatory landscape and gaps across countries, investment needs to support the Roadmap, power up regional power sector database.
- Cross-stakeholder WG (IFIs, experts, utilities, public officers and other relevant entities) to test the outcomes of the studies and enable coordinated planning.

As the bilateral power trade within existing and newly planned (e.g., China-Republic of Korea) interconnectors grows, the WGs help to consolidate the experience from the region on power trade within existing bilateral arrangements, share knowledge and data, and map the regulatory and investment landscape to better understand the gaps for proceeding from bilateral to tri- and multilateral electricity trade.

The WGs are the key driver of cooperation on connectivity after the GPC Roadmap is agreed upon, as they facilitate regular exchange and peer learning among key stakeholders of the GPC and prepare the ground for a higher-level political agreement.

Based on the WG outputs, a Master Plan for GPC in North-East Asia is developed based on the GPC Roadmap – a document created in coordination with national power grids that formalizes the vision for regional power grid connectivity at the interstate level. The approval of this Master Plan by the member States is then followed by the first high-level political MoU on GPC in North-East Asia, paving the way to the implementation phase.

Phase II: Implementation

After the high-level political agreement is reached, the institutions needed for an efficient and faultless implementation phase can be put in place. These include, in particular, a formalized dialogue between the regulatory authorities (Regulatory Council) to coordinate and agree upon general rules for electricity trade in the region, including network access and congestion management, resource adequacy, network codes and guidelines for emergency operations and management. A formal association of national transmission system operators (an NEA ANTSO) can replace the utilities dialogue with a focus on ensuring secure and coordinated operation of the interconnected power systems and the optimal operations and development of the interconnected power markets.

One could furthermore consider formalizing the GPC Secretariat as a standalone organization, succeeding the Interim Secretariat under the auspices of ESCAP. Whether as a standalone institution or not, it would be advisable to keep the Secretariat in place as a key point of contact for investors, civil society organizations, other regional connectivity initiatives and Governments. While some WGs might be naturally phased out (as formal institutions, e.g. ANTSO, take their place), keeping the cross-stakeholder dialogue as a permanent format within the Secretariat would enable better coordination and continued trust building in the long term.

Phase III: Organic Development

In this phase all key institutions are already in place and running, and as potentially deeper integration of power systems in the region takes place these institutions will need to primarily focus on updating the regulations and guidelines in line with the progress on the GPC in North-East Asia vision and any relevant changes in national energy systems legislation; on ensuring consistency in the application of harmonized rules and regulations; and on providing platforms for transparent and secure data sharing.

<table>
<tr><th>Key Stakeholders</th><th>Key Formats</th></tr>
<tr><td>
• National utilities and private utility operators: Expert groups/leading think-tanks and research institutes from the region
• International organizations: energy agencies, existing regional integration institutions and platforms (e.g., GTI, NEARPIC)
• Governments: representatives from energy and environment ministries, officials responsible for national grid development plans
• Public financing institutions: MDBs, national banks, other PFIs national development agencies (e.g., Far East and Arctic Development Corporation (KRDV) in the Russian Federation, JICA in Japan, CIDCA in China etc.).
</td><td>
• Interim secretariat
• Utilities coordination forum
• Expert working groups
• Cross-stakeholder consultation group
• Regulatory Council
• Association of National Transmission System Operators (ANTSO)
</td></tr>
<tr><th colspan="2">Tentative timeline</th></tr>
<tr><th colspan="2">Phase I: Laying the groundwork</th></tr>
<tr><td colspan="2">
2023-2025
• Recognition of the GPC for NEA concept and the Roadmap reached by representatives of the member countries.

2025-2030
• Interim secretariat on NEA GPC (NEA GPC IS) created to provide a working-level platform for regular exchange and data sharing.
• NEA utilities dialogue launched (as a stand-alone or part of the NEA GPC IS) for exchange of knowledge and lessons learnt on bilateral trade (via existing interconnections) and coordination of future planning.
• Expert NEA power grid connectivity WG created to enable mapping of the regulatory landscape and gaps across countries, investment needs to support the Roadmap, power up regional power sector database.
• Cross-stakeholder WG launched (including IFIs, experts, utilities and public officers) to test the outcomes of the studies and enable coordinated planning
• A Master Plan for GPC in NEA based on the Roadmap is developed and approved by the member countries.
</td></tr>
<tr><th colspan="2">Phase II: Implementation</th></tr>
<tr><td colspan="2">
• MoU and intergovernmental agreement on multilateral cooperation on power grid connectivity, aiming at establishing multilateral power market by mid-century.
• Regional Regulatory Council created, bringing together regulatory authorities of NEA countries for exchange and joint planning for harmonized bilateral trade, and a long-term shift to multilateral power trade.
• NEA NTSO-E is formalized/ established (based on the utilities WG powered by the NEA GPC IS).
</td></tr>
<tr><th colspan="2">Phase III: Organic Development</th></tr>
</table>

Infrastructure

GPC Principles:

- Develop a common methodology for feasibility studies (including the required modelling).
- Least cost energy modelling approach including relevant sustainability parameters.
- Provide a transparent and open process for connecting renewable energy generation to the grid.
- Coordinate cross-border and intra-jurisdictional infrastructure planning.

State of play in NEA

As of 2022, cross-border power grid connectivity was at a preliminary stage with several grid interconnections in place for bilateral cross-border power trade. Current regional power grid interconnections are on the continental "triangle" between the Siberian grid and north-east China; Mongolia, and north- and north-east China, the Russian Federation and Mongolia (table 4).

The main electricity exporting countries in the region – China and the Russian Federation – export power to the Central Grid and the Western power system of Mongolia and import some of the electricity in periods of minimum loads in Mongolia. Russian Federation exports have been growing for several years and increased from 300 GWh in 2016 to 490 GWh in 2021 (Interfax, 2022). The Russian Federation also exports electricity to China via four cross-border lines. Since the bilateral trade agreement was signed in 2009, the Russian Federation's electricity exports have grown fourfold, from 854 GWh to 3.97 TWh in 2021 (Tass, 2023). China's power grid is connected to the mining facilities located in the southern Gobi Desert (Mongolia) by a 220 kV overhead transmission line, which was commissioned in 2013 and currently operates separately from the Mongolian grid. China's electricity exports to Mongolia amounted to 1,200 GWh in 2018, which accounted for about 15% of electricity supplied through Mongolia's Central Grid (Tumenjargal, 2018).

Cross-border power trade takes place between China and the Democratic People's Republic of Korea, which jointly operate four hydropower dams with installed capacity ranging from 190 MW to 630 MW, on the shared Yalu river. The total installed capacity of the jointly-operated hydropower plants is estimated to be about 2.4 GW. The Democratic People's Republic of Korea has been a net exporter of electricity to China for the past two decades, with exports amounting to ca. 280 GWh in 2020 (von Hippel and Hayes, 2021). An interconnection also exists between the Democratic People's Republic of Korea and the Republic of Korea, constructed as a part of the Kaesong Industrial Complex (KIC) project, aimed at strengthening economic cooperation and contributing to reconciliation between the Democratic People's Republic of Korea and the Republic of Korea. The industrial complex, which was built on the Democratic People's Republic of Korea territory and interconnected by infrastructure with the Republic of Korea, was supposed to enable Republic of Korea businesses to manufacture products in the DPRK as well as boost the Democratic People's Republic of Korea's economic development and ease tensions across the demilitarized zone. The power line interconnecting the KIC and the Republic of Korea power grid commenced operation in 2007, and was put out of commission in 2016 together with the KIC, which was shut down after the Democratic People's Republic of Korea nuclear test in 2016. Overall, the existing cross-border interconnections in North-East Asia are small in scale and, aside from the electricity mix in Mongolia, do not have any significant impact on the energy situation in the region.

Most interconnections in the region are in the mid-voltage range (100-220kV), with one high-voltage (500kV) HVDC interconnector in operation between the Russian Federation and China.

When it comes to the national grids in the region, the extent to which they are integrated and the way they are designed varies greatly – from the centralized power grid system in the Republic of Korea, through grids integrated at prefectural and provincial levels in Japan, China and Mongolia, to the poorly integrated grid in the Democratic People's Republic of Korea. The smaller scale of transmission capacity of the Mongolian and the Democratic People's Republic of Korea domestic grids makes them particularly

Table 4. Existing cross-border interconnections in North-East Asia

Russian Federation, Mongolia	Gusinoozerskaya TPP (RUS) - Darhkan (MNG)	2*220 kV	250
	Kharanorskay TPP (RES) - Choibalsan (MNG)	110 kV	n.a.
	Chadan (RUS) - Khandagaity-Ulanngom	110 kV	90
Russian Federation, China	Blagoveshensk (RUS) - Heihe (China)	110 kV	95
	Sivaki (RUS) - Sirius/Aigun (China)	110 kV	90
	Blagoveshensk (RUS) - Sirius/Aigun (China)	2*220 kV	300
	Amurskay (RUS) - Heihe (China)	500 kV	750
China, Mongolia	Oyu Tolgoi-Inner Mongolia	2*220 kV	300
China, DPRK	66kV	2*66kV	n.a.
DPRK-ROK interconnection	ROK-KIC	154kV	100

Note: Only interconnections of 110 kV and above were included in the modelling.

vulnerable to any fluctuations and disruptions in supply. In this context, an interconnection to the load centres in the neighbouring countries is required before solar and wind in Mongolia's Gobi Desert can be deployed at scale, as the domestic power system would not be able to integrate this amount of variable power in its current state. China's north-eastern, northern and eastern grids are therefore likely to play a central role in supporting the GPC in North-East Asia. China is actively developing ultra-high voltage domestic power to increase the power transmission capacity through three important transmission corridors in the north, mid and south. The first UHV was completed in 2009 and the system has since then grown to a network of 31 UHV lines, with another seven planned for construction over the next five years (Ye, Yuan, 2021).

The frequency of alternating current differs across the power systems of North-East Asian countries, While it is 50 Hz in the Russian Federation , Mongolia, China and northern Japan, it is 60Hz in the Republic of Korea and southern Japan. In the Democratic People's Republic of Korea the nominal frequency is 50Hz, but the actual operating frequency varies and is frequently below this level (von Hippel, 2001; Podkovalnikov, 2011). In addition, there are different approaches in maintaining power quality and control across the region, even within power systems with the same frequency.

Policy recommendations going forward

In a region with different levels of domestic power grid integration and a vast geographic area such as North-East Asia, a step-by-step approach based on expanding bilateral ties and gradually growing multilateral interconnections seems most fitting. There are examples of connectivity projects based on one transmission backbone (e.g., SIEPAC, GCCPG), which are technically and economically feasible and manageable due to a smaller geographic area and relatively few large demand centres. However, even in such cases, a backbone itself is not a guarantee for full-scale electricity trade – if the domestic power grids are not sufficiently interconnected (as is the case with the GCCPG) and lack strong institutional support, they might remain underused.

As the GPC in North-East Asia is meant not only to increase cross-border power trade, but enable integration of higher shares of renewables into the member countries' power systems or optimize the use of the already installed renewable generation capacities, it also requires very close coordination on generation and transmission infrastructure planning among member countries – at least at its later stages.

As international experience shows, synchronization is not necessarily a prerequisite for functioning cross-border power trade, and does not appear feasible in the region in the mid-term, given the variance in operating frequency across different national (and in the case of Japan – subnational) power systems. While full or partial synchronization of power systems in North-East Asia is by no means a foreclosed scenario, direct current interconnections and AC/DC/AC back-to-back converters seem to be the most immediate way forward towards boosting cross-border ties. This would also help to manage the difference in technical requirements and maintenance procedures across North-East Asian power systems while coordination on regulatory frameworks gradually takes off in the implementation phase of the GPC initiative.

Further general recommendations when approaching infrastructure deployment within the GPC include:

- Align regional modelling with national outlooks for future energy demand and renewable deployment plans;
- Enable and facilitate regular exchange between relevant agencies on national power grid development planning for better coordination;
- Accelerate the expansion and integration of domestic power grids, with particular focus on connectivity between sub-national power systems and adequate distribution networks;
- Conduct regular assessments of national power grids' flexibility, both current and projected in line with the existing power grid development plans. Analyse the potential of cross-border power grid connectivity to add the needed flexibility as the share of renewables-based generation grows;

- Provide a regularly updated overview of the curtailment rates of to-date installed renewable generation capacities and task national energy agencies or the expert working group within GPC in the North-East Asia Interim Secretariat with assessing the potential of cross-border interconnections to optimize the use of these renewables assets;
- Develop additionality criteria for connecting cross-border power interconnections to renewable generation capacities in North-East Asian countries to make sure the new cross-border power grid infrastructure planning either optimizes use of existing renewable assets (e.g., by reducing curtailing) or enables deployment of new renewables-based power generation capacity, without depriving local consumers of access to affordable clean electricity;
- Identify a set of bilateral projects of strategic importance as the initial step towards a GPC in NEA, focusing on regions with higher synergies. Based on common elements of the connectivity studies examined as well as the results of the modelled synthesis case, this includes: southern Mongolia-northern China; north-east China-Republic of Korea; Democratic People's Republic of Korea-Republic of Korea; northern China-Republic of Korea; and Republic of Korea-western Japan.

Phase I: Laying the groundwork.

In the initial phase of the GPC in North-East Asia, and building on the models suggested by this report, examination of the technical feasibility, implementation timelines and wider socio-economic effect of various options for interconnection needs to be conducted, guided by the GPC principle of aiming for the least average electricity cost while considering the sustainability criteria. The feasibility study or studies can be led by the Expert Working Group and curated by the Interim Secretariat of the GPC.

Consequently, a set of priority projects (at the initial stage, likely new bilateral interconnectors or enhancements of existing interconnections) is agreed upon to build the project portfolio to use when (a) seeking support with public finance institutions and private investors as well as (b) to plan the implementation timelines including any needed adjustments to national power systems. Ahead of the planning phase, the model of connecting the assets to national grids and generation facilities needs to be discussed and agreed upon by the TSOs and the utilities. Both the cross-stakeholder working group and the informal TSOs and utilities dialogues can be used for that.

In the next step, route planning, siting and permitting takes place. Cable routing, position of transmission towers, substations including converter stations as well as (if applicable) new renewable generation facilities are discussed, and environmental risks examined. When applicable, land use issues are discussed in coordination with local authorities and civil society. Making sure the permitting takes place as swiftly as possible is important to be able to secure the needed investments, as a protracted permitting process often impacts investors' willingness to reach FID on early-stage projects.

The same process needs to apply to the potential enhancements of the existing cross-border interconnectors, although it is expected to be less time-consuming as the route and location of the main transmission management and generation centres are already known.

Phase II: Implementation

As soon as the investment for proposed priority projects is secured, construction can begin. Depending on the length and route of the proposed lines, construction (including site preparation, tower foundation and tower assembly, and line stringing works) is expected to take two to five years, with the expectation for the first projects to begin operation by mid-2030s.

The construction timeline is not expected to significantly vary should priority projects include construction of and interconnection to new renewable generation facilities. It takes, on average 1.5 to 2 years to build a utility scale solar plant and about three to four years for an onshore wind farm IEA, 2023a). For offshore wind projects, more time is needed due to longer construction time.

Phase III: Organic Development

Given that the institutional base and regulatory framework are developed according to the Master

Key Stakeholders	Key Formats
• National TSOs, where applicable – regional TSOs (e.g., EPCOs in Japan, relevant EPS in Mongolia etc.). organizations for cross-regional coordination of TSOs (e.g., OCCTO), power generation companies, relevant ministries; expert WG(s); public and private investors.	• Early feasibility studies • Bilateral priority projects • Grid connection agreements • Shareholder agreement(s), • Regulatory arrangements for siting, permitting and procurement • Procurement, tender preparation, location surveys, permitting, engineering, components manufacturing , installation, commissioning and putting in operation;

Tentative timeline

Phase I: Laying the groundwork (2024-2030)

- Early feasibility studies (for bilateral/subnational interconnectors) suggested by the modelling exercise are conducted.
- Set of bilateral priority projects in alignment with national grid planning, North-East Asia countries' decarbonization goals and the GPC concept is agreed upon.
- Informal dialogue btw. national TSOs begins curated by the Interim Secretariat to exchange on national grid planning and discuss a joint mechanism for allowing new RES to connect to the grid.
- Grid connection agreement reached on the first batch of projects.
- Siting, permitting and procurement for key elements of (new) bilateral links of the GPC take place (renewables generation facilities, cable routing etc.).
- Existing bilateral interconnectors' capacity enhancement proceeds guided by the feasibility studies, the national grid planning and the electricity demand growth projections in main load centres.

Phase II: Implementation (2030-2040)

- Construction of newly-planned bilateral interconnections and renewables-based generation bases is underway.
- Power generation and transmission capacity enhancement for the newly constructed elements of GPC are considered and put forward based on the Master Plan for GPC in North-East Asia.
- New interconnectors and RES capacities begin operations.

Phase III: Organic Development (2040 onward)

- Potential benefits of full or partial regional power grid synchronization are studied.
- Feasibility studies on further, multilateral interconnectors in the region.
- Master Plan for GPC in North-East Asia is updated to include new planned grid infrastructure and the needed technical adjustments planning for regional power trade (e.g., synchronization).

Plan for GPC in North-East Asia, in this final stage the GPC project can be examined for the need for and potential benefits of regional power grid synchronization – either partial, within national power systems or across the borders, or a full one. As mentioned above, synchronization is not a prerequisite for functioning power trade in the region, but it would enable deeper integration and further optimization of the use of both power grid and renewable generation capacity, and so could be evaluated.

The Master Plan for GPC in North-East Asia, agreed upon in the implementation stage (see Institutional track), is regularly updated in alignment with changes to the national grid plans and planning for further connectivity infrastructure in the region.

Finance and Investment

GPC Principles:

- Infrastructure development requires sustainable financial frameworks.
- Leverage all forms of available financing to support the development of transmission infrastructure, both within and between jurisdictions.

State of play in NEA

The existing cross-border power grid interconnections (partly developed in the second half of the twentieth century) have been developed under bilateral arrangements and largely funded by the state-owned grid companies involved in the cross-border power trade.

International financing institutions (e.g., MDBs), Governments and private stakeholders (e.g., Softbank) have been increasingly providing financial support to the development of regional power grid connectivity studies and have been pivotal to the emergence of such connectivity concepts as the ASG, NAPSI, NEAEI and others (for full overview see ESCAP 2020). There has, however, been no investment case yet for a cross-border interconnection and/or adjacent power generation facility which involved financing institutions beyond state-owned enterprises or the national Governments of North-East Asian countries.

While some of the world's wealthiest countries are part of the region, the investment conditions are in general quite favourable and securing financing should not be a major problem, unlike in some other regions, particularly those in developing Africa. Nevertheless, international experience shows that the role of public finance is pivotal in the initial stages of planning. Securing support of international and national public finance institutions for capital intensive projects involving both large-scale transmission and power generation planning has proved to be key to attracting private investments. Moreover, these institutions have proved invaluable in providing technical assistance and capacity-building to countries who need it. Under one of the Sustainability scenarios (see modelling), large-scale renewable energy facilities are to be constructed and maintained by Mongolia, which creates both opportunities for green job growth as well as a challenge to ensure the skilled workforce is available by the time the project begins operations. As the GPC in North-East Asia enters its later phases and more extensive coordination of operations and planning across borders is needed, capacity-building will be needed also on the management level – both within governmental agencies and utility companies – and IFIs have a track record of offering such support.

As the case of SIEPAC has shown, a multi-donor arrangement can also be an important guarantee that helps to minimize financial and political risks. Enabling a dialogue between all relevant stakeholders to test possible financing arrangements would be important to make sure the implementation phase can begin without delays.

Policy recommendations going forward

- Ensure clarity over the financial burden for key national stakeholders (North-East Asia Governments, TSOs, utilities) including a mechanism for calculating the fair burden allocation for financing the operations of the GPC project (primarily the Interim Secretariat and the adjacent stakeholder groups).

- Develop transparent communication of investment return mechanisms (including price-setting for the wheeling charge, power trade) and timelines.

- Identify future electricity demand and needed renewables-based power generation and transmission capacity in the region (and in the subregions with planned interconnections) to better inform the investment decisions.

- Accompany feasibility studies on the new interconnections (see Infrastructure track) with an assessment of investment needs, investment risk assessment as well as an outline of the socio-economic rationale in order to establish a business case and secure the buy-in of investors.

- Utilize existing (national) support mechanisms for deployment and connection of renewables-based generation capacity to support the GPC investment case.

Phase I: Laying the groundwork

As an initial step, and before the larger investment decisions are taken, operations of the institutions that curate the preparation and implementation of the GPC in North-East Asia need to be secured and financed. A mechanism for financing the operations of the North-East Asia GPC Secretariat that is fair to all participating countries needs therefore to be developed and agreed upon by the North-East Asia member countries.

In order to enable peer learning and better understand the optimal financing arrangement for the GPC in North-East Asia the Interim Secretariat should curate a dialogue between the cross-stakeholder WG (the third sub-group organized by the Secretariat) and the international and key national financial institutions both from Asia-Pacific and other regions, who have enabled regional power grid connectivity projects in the past. This dialogue will also help to test the investment case for GPC in North-East Asia.

Parallel to this exercise, it is advisable to commission a study that analyses financing instruments available to support financing of the GPC or its elements, including loans, guarantees, tax incentives and other support mechanisms on the national level etc. The study can be carried out by the North-East Asia GPC expert WG or commissioned externally. A financing toolbox is then proposed for consideration to the North-East Asia Secretariat for each of the bilateral segments of the GPC cross-border interconnections and renewable-based generation facilities including risk mitigation instruments.

Phase II: Implementation

As soon as the siting and permitting process has been concluded (see Infrastructure track), the power purchase agreements (PPAs) between the participating utilities are signed, the wheeling charge and other relevant price-setting mechanisms are negotiated to ensure transparency on the return of investments and move the projects to the FID stage.

In the following step, the project agreements with the supporting financial institutions (or a consortium) are signed. It is unlikely that the whole GPC in a North-East Asia project can be signed off as one financing package, as the financing instruments are likely to vary depending on what North-East Asia countries are to be interconnected via priority projects, and in some cases additional arrangements to enable technical assistance and capacity-building might be needed.

As North-East Asia is in itself a mature market for renewable energy investments, it is expected that new renewable generation capacity (should such

Key Stakeholders	Key Formats
• Utilities, project developers and installers, IFIs, national financing institutions, development organizations (e.g., Far East and Arctic Development Corporation (KRDV) in the Russian Federation, JICA in Japan, CIDCA in China etc.), relevant ministries, Energy Charter Treaty, International Energy Charter.	• Procurement, tender preparation, location surveys, permitting, engineering, components manufacturing , installation, commissioning and putting in operation; shareholder agreement(s).

Tentative timeline

Phase I: Laying the groundwork (2024-2027)

- The mechanism for financing the operations of the North-East Asia GPC Secretariat is developed and agreed upon by the NEA member countries, ensuring fair distribution of annual contributions among member North-East Asian countries.
- A dialogue (or series of workshops) involving key financing institutions takes place to enable learning from international experience and test the GPC as an investment case.
- A study analysing financing instruments available to support financing of the GPC or its elements is carried out by the North-East Asia GPC expert WG.
- A set of most fitting financial instruments is proposed for consideration to the North-East Asia Secretariat.

Phase II: Implementation (2027-2035)

- A set of priority bilateral interconnection projects has been agreed upon and PPAs between the participating utilities have been signed.
- Project agreements with the supporting IFIs are signed (financing instruments varying depending on the participating parties and the need for concessional finance).
- Capacity-building programmes are developed with the support of IFIs, national financing institutions, where applicable – development agencies (see Capacity-Building Track).
- New generation facilities are co-financed by private investors.

Phase III: Organic Development (2035 onwards)

- Dialogue aimed at developing a transparent legal framework for GPC investments is launched to draw additional private investments.
- Follow-ups/capacity enhancements to newly constructed bilateral interconnectors and adjacent generation facilities entail 50-60% of private investments.
- Public financing institutions continue supporting GPC, focusing on technical assistance and capacity building.

be planned as part of the first batch of connectivity projects) can be co-financed by private investors.

Phase III: Organic Development

As the initial wave of projects begins operations and investors' confidence in the resilience and profitability of connectivity projects in the region is further strengthened, it is expected that the role of private investors in the follow-up projects, including further transmission capacity additions, possibly new multilateral interconnectors and new renewable generation will grow to carry ca. 50%-60% of the projects' finance.

Public finance institutions (MDBs in particular) will nevertheless continue playing a role also at the later stages of the GPC in North-East Asia, focusing more on technical assistance, capacity-building, and potentially enabling further feasibility studies and data collection.

So far there is no regional investment agreement or framework which would create transparent legal basis for energy investments. The existing international arrangements, e.g., the International Energy Transition Charter, focus primarily on fossil fuel assets and have not developed an investment regime adequate to cover clean energy so far. It is therefore advisable, as the GPC in North-East Asia project continues to grow, to establish a dialogue among relevant stakeholders aimed at developing such a framework that could both help draw additional private capital and mainstream the financing processes within the GPC initiative.

Regulatory framework and trading models

GPC Principles:

- Develop harmonized grid codes that enable secure and flexible operations.
- Enable bilateral cross-border power trading arrangements through harmonized and coordinated procedures.
- Establish multilateral trading arrangements that emphasize flexible and least-cost trading of electricity.
- Develop appropriate and consistent cost-sharing and cost-recovery mechanisms.

State of play in North-East Asia

National power markets in North-East Asia are in different phases of liberalization on the scale between regulated and fully liberalized markets. Until now, cross-border power trade in North-East Asia has been conducted via over-the-counter type of arrangements where two parties trade privately according to regulations that have been established on a case-by-case basis.

Existing contracts for cross-border electricity trade in North-East Asia are negotiated every year with a fixed price. As a rule, they do not include short- and long-term price formulae to adapt to market conditions. The inflexibility of some existing contracts has led to controversies in the past such as, for example, during the suspension of cross-border power trade between the Russian Federation and China in 2007. The existing contracts for cross-border power trade seem unfit for the purposes of the GPC. For example, Mongolia has long-term power purchase agreements with the Russian Federation, which leaves little room for integration of alternative forms of generation into the Mongolian grid in its current state. On the Russian Federation's side, strict provisions regarding variability and load-frequency control pose a challenge for integrating new renewables. Therefore, should the initial stages of GPC involve renewable power trade with the Russian Federation, specific agreements for potential variability will likely need to be negotiated.

Cooperation on common regulatory frameworks can be a gradual process as regional cross-border power trade – if run primarily bilaterally at the initial stage – does not necessarily require immediate harmonization of standards and operations. Even among the connectivity initiatives that have been in operation for some time now, only four are operating within a common regulatory framework and in a fully or predominantly harmonized environment – the Western Interconnection, SGCE/NordPool, SIEPAC and SAPP. The emerging common power market of the EAEU is a further interesting case where a common regulatory framework is currently being negotiated and which is yet to cover only the cross-border power trade while national regulations and power markets continue to function separately.

The remaining multilateral trading arrangements, e.g., the LTSM model, operate in a standalone mode akin to bilateral power trade and exchange arrangements.

At later stages when the regional power grid connectivity within GPC moves on to multilateral trade in renewable electricity, the contracts' structure and the regulatory framework will need to be adjusted accordingly, and ideally harmonized across the region. While complete harmonization of national rules and standards does not need to take place on the initial stages of the GPC in North-East Asia, there is a lot that can be done in advance to prepare this process and ensure the smooth transition from bilateral to multilateral trade.

Policy recommendations going forward

- Involve national regulatory authorities and transmission system operators early on in planning of the GPC in North-East Asia to ensure buy-in into the initiative and prepare the ground for the development of a regional regulatory framework.

- Develop a contract template and an initial set of standards and requirements essential for bilateral power trade and exchange to provide basic regulatory alignment across different bilateral links in the initial stage of the GPC in North-East Asia.

- Ensure clarity over price-making mechanisms for traded electricity and transmission and test the economic rationale of power trade under agreed conditions in the context of national pricing instruments (e.g., electricity subsidies for industry, households).

- Make sure price-making mechanisms are aligned with renewables trade and – at least in the initial stage of the GPC in the North-East Asia initiative – are not linked to or affected by the pricing of peaking (fossil fuel) capacity to avoid price distortions and reflect the investment structure of interconnectors and RES generation (high CAPEX, low OPEX).

- Consider using existing national power exchange platforms as the power trade starts to evolve from 100% PPA-based towards a liberalized one.

- Facilitate the development of the regulatory framework parallel to the development of an infrastructure backbone to ensure alignment of all key tracks of the GPC.

- In exchange with relevant energy sector stakeholders and international organizations, work out a way reflect the value of the GPC in North-East Asia, not only the cost of the projects (e.g., environmental and health benefits, jobs creation etc.).

- Enable regular peer-to-peer exchange with regulatory institutions involved in connectivity initiatives in other regions to make sure the GPC in North-East Asia avoids undesirable path-dependencies as it pursues an increasingly renewables-based regional power system (e.g., common European market can offer lessons learnt on risks of linking electricity price to peaking/most expensive generation units – in the European Union's case, wholesale gas-based electricity).

Phase I: Laying the groundwork

As the region is home to a wide variety of regulatory frameworks and power trade models, the first step advised at the initial phase of the GPC in North-East Asia is to commission a comprehensive mapping of the national regulatory frameworks in the region to identify overlaps, potential synergies and gaps. The task can be performed by the Expert WG or outsourced to a consortium of regional research institutes.

Based on the results of the mapping, a basic template for bilateral power trade and a set of core standards and requirements is then developed in close consultation with the region's- utilities and regulatory authorities. While the application of this core set of rules can be voluntary for the already existing power trade arrangements (or alternatively, the transition can be mandated within a certain timeline), it is advisable to align new power trade contracts and operations with these rules in order streamline member countries' approach to bilateral power trade and enable faster and easier harmonization later on.

During this phase the informal peer-to-peer exchange among national regulatory authorities starts to take place to create the buy-in of this key stakeholder group in the GPC in the North-East Asia initiative and pave the way for institutionalized cooperation in the later phases (see Institutions track). The regulatory authorities dialogue can be curated by the Interim Secretariat or by one of the international organizations, e.g., IEA's Regulatory Authorities Transition Accelerator (RETA). Similarly, a dialogue among the region's key utilities and TSOs is launched as one of the WGs of the Interim Secretariat (see Institutions track).

Phase II: Implementation

As the construction of new interconnectors and generation capacities takes place, the informal exchange formats between regulatory authorities and TSOs are consolidated to form a regional Regulatory Council and a network of transmission system operators (NTSO). With a formal mandate, these organizations develop mechanisms to enable faultless operation of the interconnectors and to prepare the needed regulatory framework for future multilateral trade. Among others, these mechanisms need to cover coordination of ancillary services and emergency responses as well as to enable transparent and regular data sharing.

Phase III: Organic Development

The last phase of the GPC in North-East Asia envisages harmonization of national regulatory frameworks in a way that is aligned with national energy policy priorities, and enables the optimal use of national power markets and grids while avoiding overregulation of the multilateral power trade. As the harmonization efforts proceed, and a truly regional framework for multilateral power trade and grid operations begins to take shape, it is advisable to launch one or a series of multilateral power trade pilots to test the functionality of the framework and the responsiveness of all the relevant stakeholders within GPC to the proposed changes.

After several successful runs, regional power trade rules and regulations are confirmed by the Regulatory Council and revised and updated on a regular basis while bilateral arrangements are slowly phased out.

Key Stakeholders	Key Formats
• National regulatory bodies (e.g., NRDC, OCCTO, KOREC etc.), where applicable – regional regulatory bodies (in later stages), national power exchange platforms (e.g., JPEX).	• Network codes, technical standards, environment standards, additionality requirements, guidelines on cross-border interconnector operations, cost recovery guidelines, template for bilateral power trade.

Tentative timeline

Phase I: Laying the groundwork (2024-2030)

- Expert WG (part of the NEA GPC IS) is conducting a mapping of the national NEA regulatory frameworks to identify overlaps/synergies and gaps.
- A template and a core set of standards and requirements is proposed for new bilateral power trade agreements.
- Peer-to-peer dialogue between national regulatory authorities is initiated, either under the auspices of the Interim Secretariat or curated by a relevant international organization (e.g. , RETA).

Phase II: Implementation (2030-2040)

- North-East Asia utilities platform is formalized and grows into a regional Regulatory Council. The North-East Asia NTSO-E is formalized (based on the utilities WG powered by the NEA GPC IS).
- Mechanisms to coordinate ancillary services within bilateral trade arrangements are established. Joint emergency response mechanisms are developed; data-sharing mechanisms to enable faultless operation are mapped

Phase III: Organic Development (2040 onward)

- Harmonization of national regulatory frameworks takes off, paving the way to a regional power trading platform, and to harmonization of grid codes.
- (Optional) a regulatory framework for multilateral power trade is proposed, a pilot multilateral power trade project is launched in parallel to the existing bilateral arrangements.
- Regional power trade rules and regulations developed and confirmed, bilateral arrangements slowly phased out.

Capacity building and social inclusion

GPC Principles:

- Establish inclusive stakeholder consultations processes.
- Develop targeted capacity-building and other forms of training programmes for all impacted social groups.
- Measure and make public the social benefits of increased connectivity.

State of play in North-East Asia

Given the overall preliminary state of cross-border power grid interconnections in North-East Asia, no known capacity-building programmes have taken place in direct connection to the already established interconnections. Due to the fact that the existing interconnections have been constructed and are operating in less populated areas, and are largely decoupled from national grid and power generation planning – largely linked to existing fossil fuel-based power generation, power trade on smaller scale (aside from RUS-MNG case) – social aspects of cross-border power grid connectivity have not been prioritized by the involved stakeholders so far.

Policy recommendations going forward

Capacity-building and social inclusion have not been an explicit part of regional power grid connectivity initiatives so far, and are therefore among the "new" issues as cross-border power trade increasingly involves installment of large-scale renewables-based power generation and large-scale power transmission infrastructure. The projects therefore increasingly affect the local communities. On the other hand, they create opportunities for local economic growth and value creation. In order to secure the latter in an equitable, sustainable and gender-balanced way, capacity-building needs to be streamlined and made available to all relevant stakeholder groups involved in the GPC in North-East Asia initiative – from construction workers and RES generation facility operators to utility managers and transmission system operators.

Awareness-raising and an open and continuous dialogue with the communities affected by the construction of transmission and power generation facilities (e.g., nomadic populations in Mongolia's Gobi desert) must take place together with the inception of informal working groups and dialogues (see Institutions track). This is necessary to both secure the buy-in of the local population and provide for better understanding of socio-economic benefits of GPC in North-East Asia as well as to avoid frictions with the civil society later on that might impede construction or any other part of the implementation phase. Potential environmental and socio-economic risks of the GPC need to be mapped out together with the local authorities and representatives of civil society, and social and environmental safeguards must be developed.

CASA-1000 is one of the few regional connectivity projects that has embedded social safeguards for the affected population groups and has provided a general assessment of possible social benefits in the early development stage (World Bank, 2014). Otherwise, international experience does not offer many lessons learnt on this particular track so far.

The countries of North-East Asia, however, have themselves substantial experience that they can apply from other areas of engagement, among others their development policy in third countries; therefore it is worth exploring what lessons learnt can be adjusted to the purposes of the GPC. Some further recommendations on this track include:

- Make sure local jobs and value creation in exporting countries is being fostered (e.g., RES manufacturing, in future – industrial growth using domestic H2 production etc.), focusing on local communities and border regions as well as communities dependent on to-be-retired fossil fuel-based infrastructure (e.g., coal communities);
- Ensure gender equity when training new skilled workers for developing and maintaining the projects;
- Enable cross-regional skill learning and exchange. Invite experts from regions already working with highly digitalized, flexible cross-border power trade and exchange, and from regions trading in high shares of renewables-based electricity, to offer training within capacity building programmes.

- Enable studies exploring and explaining environmental risks and benefits of renewables-based power generation facilities in NEA (e.g., wind farms might be suitable for preserving vast sections of steppe habitat in the Gobi desert) to feed into public awareness campaigns and educational programmes.

- Explore the potential of establishing a regional education program on green grids for staff and management levels, including representatives of national utilities, local regulatory authorities and investment bodies, with priority access and financial support enabling participation in the programme by local communities.

- Engage the local NGOs in the planning process to enable civil society buy-in.

Phase I: Laying the groundwork

Although the international experience on the matter (specifically in cross-border power connectivity) is scarce, it is advisable to bring together stakeholders engaged in securing social and environmental checks within connectivity projects in other regions for a series of dialogues to enable peer learning, and arrive at a set of priority areas to cover with the capacity-building/social track.

As soon as the first set of bilateral priority projects is agreed upon, a regional dialogue to map the capacity-building needs as well as social and environmental criteria to ensure efficient, equitable and sustainable implementation of the GPC in North-East Asia can take place. The key focus of the dialogue and its outputs (e.g., studies) needs to be on local communities affected by siting transmission lines and renewable generation facilities.

After the capacity-building needs and key population groups to target have been identified, the cross-stakeholder coordination WG can embark on developing a set of education and training programmes. The education programmes can be offered both to students of relevant disciplines (e.g., engineering, energy infrastructure planning, energy policy etc.) as well as to junior and mid-management or the utilities and other relevant stakeholder groups. The training programmes need to cover staff involved in all stages of the implementation phase of the GPC in North-East Asia, including preparation of the construction sites and the construction of both transmission lines and renewables generation capacity as well as operation and maintenance of the infrastructure. In the meantime, the Interim Secretariat can begin discussing the needed funding and provision of education facilities with key educational institutions and training facilities (in case use of existing institutes is preferred to creating new ones) and with financing institutions.

Phase II: Implementation

The implementation phase for this track begins earlier than for most others as staff need to be trained ahead of the GPC construction. Education and training programmes are launched in this phase, aiming for a first wave of graduates before the end of the decade.

As planning of the GPC priority projects proceeds, public information and awareness-raising campaigns need to be developed by the relevant ministries and communication agencies in close cooperation with local civil society organizations. It is furthermore advisable to involve local authorities of the regions affected by the interconnectors, representatives of civil society as well as labour organizations to accompany the GPC planning and implementation process by providing peer assessments of its social inclusiveness, environmental sustainability and gender equity.

Phase III: Organic Development

As the pool of skilled workforce and graduates from the GPC education programms grows, the construction process can begin. In order to ensure accountability and transparency of the implementation phase (of the Infrastructure track), developing a monitoring mechanism to assess alignment of the projects with social and environmental requirements is advisable.

Finally, public information and awareness-raising campaigns, which have started to take place in the previous phase, are best kept ongoing as they can provide regular updates on the development progress of the GPC and maintain social buy-in to the initiative.

Key Stakeholders	Key Formats
• Local communities in border regions and regions with to-be-deployed renewable generation capacities, capacity-building organizations/ educational institutions, IFIs, relevant ministries, labour organizations (unions), ILO, development organizations, IFIs, national financial institutions with experience of supporting capacity-building at home and in partner countries (e.g., JICA, ADB, WB etc.).	• Capacity-building programmes for staff operating renewables-based power generation capacities, power grid operations, installers, construction workers etc.; public awareness campaigns; regional youth and young professionals' dialogues; joint green grids education programmes (technical college or university level); gender diversity training; gender diversity criteria; sustainability criteria.

Tentative timeline

Phase I: Laying the groundwork (2023-2025)

- International workshops sharing lessons learnt on capacity-building and education programmes for renewables-based power grids are organized.
- Cross-country dialogues and studies mapping the capacity-building needs to enable planned connectivity projects are organized, focusing on capacity-building among local communities and communities of the border regions.
- Cross-stakeholder coordination WG is engaged to discuss and design a set of GPC education programmes for students of relevant disciplines; project implementation staff and mid-management.
- An agreement on the funding and provision of education facilities with the key financing and educational institutions is reached at the Secretariat level.

Phase II: Implementation (2025-2030)

- Education and training programmes are launched.
- Public information and awareness-raising campaigns are developed by the relevant ministries in close cooperation with local civil society communities.
- Local CSO communities and labour organizations are invited to accompany the GPC planning and implementation process by providing peer assessments of its social inclusiveness, environmental sustainability and gender equity.

Phase III: Organic Development (2030 onwards)

- Graduates from the GPC education and training programmes become the growing skilled labour-force supporting and driving the implementation of the GPC in NEA.
- Ongoing public information and awareness-raising campaigns offer regular updates on the progress regarding the implementation of the GPC.

4.2. Conclusion

The case for enhanced power grid connectivity in North-East Asia has never been stronger. As the modelling exercise in this report has shown, cooperation on a Green Power Corridor in North-East Asia can facilitate development of cost-effective low-carbon power sources in the region, providing access to cheaper and sustainable electricity for all participating countries. Furthermore, it can accelerate decarbonization and limit the region's GHG emissions, thus contributing to countries' climate targets.

The Roadmap suggested by this report shows that, while the establishment of a full-fledged multilateral power grid interconnection and power trade mechanisms will be a gradual process, incremental steps in the short-term, such as setting up first working-level institutions and dialogue formats can go a long way towards building trust among key stakeholders and driving the implementation of the Green Power Corridor.

There are already existing elements upon which North-East Asian countries can draw to drive the development of Green Power Corridor. First, there is a wealth of international experience derived from successfully launched connectivity initiatives in other regions that can provide North-East Asian countries with a well-tested set of tools for institutions building, securing financing, establishing regulatory frameworks etc., many of which can be adjusted to regional specificities. Second, there are various international and regional institutions, ADB, IRENA, GTI, ESCAP and many others, which can help get the work started on the six pillars of the Green Power Corridor building blocks. Finally, North-East Asia can thrive on homegrown research and innovation potential, as well as on its own low-carbon technology supply and value chains, which are second to no other region, when moving on to the implementation of the Green Power Corridor.

Now it is up to North-East Asian member countries to take the first practical steps in laying the groundwork for the Green Power Corridor, starting with political signals of support and a basic coordination mechanism (as suggested by this report, the Interim Secretariat). Once these building blocks are in place, the rest will follow.

Appendix
Detailed description of GPC Model

The GPC Model is a simulation model of the electricity systems of Northeast Asia, designed to support the preparation of the Green Power Corridor Roadmap. This appendix provides a detailed description of the Model's set-up, inputs, and assumptions. The Model itself can be requested from ESCAP for further inspection and use.

Model structure

Geographic

As outlined in Chapter 2 above, the GPC Model covers six countries in Northeast Asia: China, DPRK, Japan, Mongolia, ROK, and Russia. These countries are disaggregated into subnational regions corresponding to independent power systems or dispatch zones (Figure 2). China is divided into six regions that map to its major grid zones (excluding Tibet), while Mongolia's five independent power systems are represented. Japan is separated into two regions for its Eastern and Western grids, and DPRK and ROK are modeled with one region apiece. For Russia, the Model includes the two grid zones that adjoin other countries in Northeast Asia (Siberia and Far East). Due to data limitations, however, it was not possible to model the Russian regions fully, and they are not discussed further in this appendix.

Temporal

The Model simulates electricity demand and supply in its various regions between 2010 and 2060. In general, it includes historical data for 2010-2021 and makes projections for 2022 and later. Each year of the modeling period is divided into 96 time slices that represent a typical 24-hour day in each of four seasons (spring, summer, fall, and winter). Electricity demand and supply are modeled in each time slice, ensuring that hourly, seasonal, and annual variations are represented.

Sectoral and technological

On the demand side of the Model, final electricity consumption is divided by major sector, including the following:

- Agriculture, forestry, and fishing
- Commercial and public services
- Industry
- Residential
- Transport
- Other

Within each sector, demand is represented in a top-down fashion – that is, as total demand by sector. The Model does not include an explicit representation of subsectors, electricity end uses, or electricity-using technologies. This design was selected to be compatible with the GPC project's scope and overall approach. As explained further below, electricity demand projections for most regions are an exogenous input to the Model and are taken from pre-existing studies.

The electricity supply modelling covers generation, storage, transmission, and distribution. These components of the electricity supply system are represented in each modeled region. Except in Mongolia, electricity generation and storage capacity is aggregated by technology, including both currently used and potential future technologies. The following technologies are considered:

- Biogas
- Coal integrated gasification combined cycle (IGCC)
- Coal steam subcritical
- Coal steam subcritical combined heat and power (CHP)
- Coal steam super and ultracritical
- Coal steam super and ultracritical CHP
- Coal steam super and ultracritical CCS
- CSP
- Geothermal
- Hydro large
- Hydro small
- Hydrogen fuel cell
- Liquid biofuel
- Lithium ion batteries
- Natural gas combined cycle
- Natural gas combined cycle CCS
- Natural gas combined cycle CHP
- Natural gas internal combustion
- Natural gas internal combustion CHP
- Natural gas steam
- Natural gas steam CHP
- Natural gas turbine
- Natural gas turbine CHP
- Nuclear generation 1 and 2
- Nuclear generation 3
- Oil combined cycle
- Oil internal combustion
- Oil open cycle
- Oil open cycle CHP
- Oil steam subcritical
- Oil steam supercritical
- Pumped hydro storage
- Solar PV
- Solid biomass
- Solid biomass CHP
- Tidal or wave
- Waste incineration
- Wind offshore
- Wind onshore

In the case of Mongolia, project stakeholders requested a finer-grained representation of generation and storage capacity that separately simulates major existing and potential plants. These include the following:

- Altai Soum PV
- Amgalan CHP
- Baganuur Power Plant (PP)
- Booroljuut PP
- Bukhug PV
- CHP2
- CHP3
- CHP4
- CHP Choibalsan
- CHP Dalanzadgad
- CHP Darkhan
- CHP Erdenet
- Darkhan PV
- Dornod Nuclear
- Durgun HPP
- Egiin Gol HPP
- Erdeneburen HPP
- Erdenet Factory CHP
- Esenbulag PV
- Gegeen PV
- Govi Sumber Wind Park
- Khovd Myngad PV
- Khovd Nuclear
- Monnaran PV
- Murun PV
- Oyu Tolgoi Wind Park
- Sainshand PV
- Salhit Wind Park
- Shand Wind Park
- Shuren HPP
- Sumber PV
- Taishir HPP
- Tavan Tolgoi PP
- Tenuun Gerel PV
- Tsetsii Wind Park
- Uhaa Hudag PP
- Uvs Umnugovi PV
- Uvs Wind Park
- Zavkhan Telmen PV
- Zavkhan Uliastai PV
- Zavkhan Wind Park

Other generation and storage capacity beyond these plants is aggregated by technology; this includes new capacity that is constructed if the existing and potential plants are insufficient to meet electricity production requirements.

The GPC Model represents electricity transmission and distribution in two primary ways. High-voltage transmission between regions (i.e., connections ≥ 110 kV) is modeled explicitly, with power flow on the transmission lines simulated. The Model covers all existing high-voltage lines that link one of its regions to another, as well as potential inter-regional high-voltage lines from a variety of plans, policies, and analyses. Within each region, by contrast, transmission and distribution lines networks not modeled explicitly. Instead, the Model assumes perfect intra-regional connectivity while accounting for average transmission and distribution losses. The costs of extending intra-regional grids to accommodate new generation and storage are factored into the Model via the capital costs of generation and storage technologies.

Modelling platform

The GPC Model was built with two software tools: the Low Emissions Analysis Platform (LEAP) and the Next Energy Modeling system for Optimization (NEMO). LEAP and NEMO are designed to work together and provide an integrated system for electricity modeling. LEAP supplies the user interface for the GPC Model, including data entry and results reporting functionality. It is also used to calculate electricity demand, transmission and distribution losses, and GHG emissions from electricity production, as well as to define and manage modeling scenarios. NEMO performs the Model's simulation of electricity generation, storage, and inter-regional transmission. When the Model is run, LEAP provides electricity production requirements to NEMO, and NEMO returns generation, storage, and transmission results to LEAP.

Both LEAP and NEMO are developed by the Stockholm Environment Institute with a goal of enhancing the transparency and accessibility of modeling analyses. LEAP is open-access software, and NEMO is open-source and open-access. The tools can be downloaded from their respective websites, which also contain documentation, links to training exercises, and a user support forum.

- **LEAP website:** https://leap.sei.org/
- **NEMO website:** https://www.sei.org/tools/nemo-the-next-energy-modeling-system-for-optimization/

To carry out its calculations, NEMO uses a specialized mathematical solver program. NEMO is compatible with multiple solvers, including open-source and proprietary options.[3] For the GPC project, the Gurobi Optimizer solver[4] was used; however, the GPC Model can also be calculated with the open-source HiGHS solver, which is installed with NEMO.

Scenarios

As indicated in Chapter 2, the Model evaluates a number of future scenarios that are defined by permuting sustainability and connectivity cases. Two sustainability cases and six connectivity cases are considered, leading to 12 modeled scenarios in total. The different cases are described in depth in Chapter 2, so they are characterized only briefly here.

The sustainability cases include a **Baseline** case and a **Sustainable Development** case. The first assumes that Northeast Asia's power systems develop in a business-as-usual way, in which unconditional NDCs are implemented but national energy and climate policies otherwise remain the same. In the second case, Sustainable Development, conditional NDCs, national net-zero GHG emission commitments, and SDG 7 are implemented, as are associated measures in national energy and climate plans (e.g., coal phase-outs, zero-carbon power targets, deployment of emerging technologies).

The six connectivity cases explore different levels of inter-regional transmission connectivity. They include the following:

1. **Baseline** – existing inter-regional transmission only

3 https://sei-international.github.io/NemoMod.jl/stable/installation/#solver_compatibility
4 https://www.gurobi.com/

2. **National and Bilateral Plans** – Baseline connectivity + firm planned inter-regional transmission lines in Mongolia and between China and ROK

3. **Asian Super Grid (ASG)** – Baseline connectivity + inter-regional transmission and renewable power development plans in ASG study (Asian Development Bank 2014)

4. **North-East Asian Power System Interconnection (NAPSI)** – Baseline connectivity + inter-regional transmission and renewable power development plans in NAPSI study (Asian Development Bank 2020)

5. **North-East Asian Energy Interconnection (NEAEI)** – Baseline connectivity + inter-regional transmission plans in NEAEI study (Huang 2018)

6. **Synthesis** – Baseline connectivity + commonalities among inter-regional transmission plans in cases 2-5

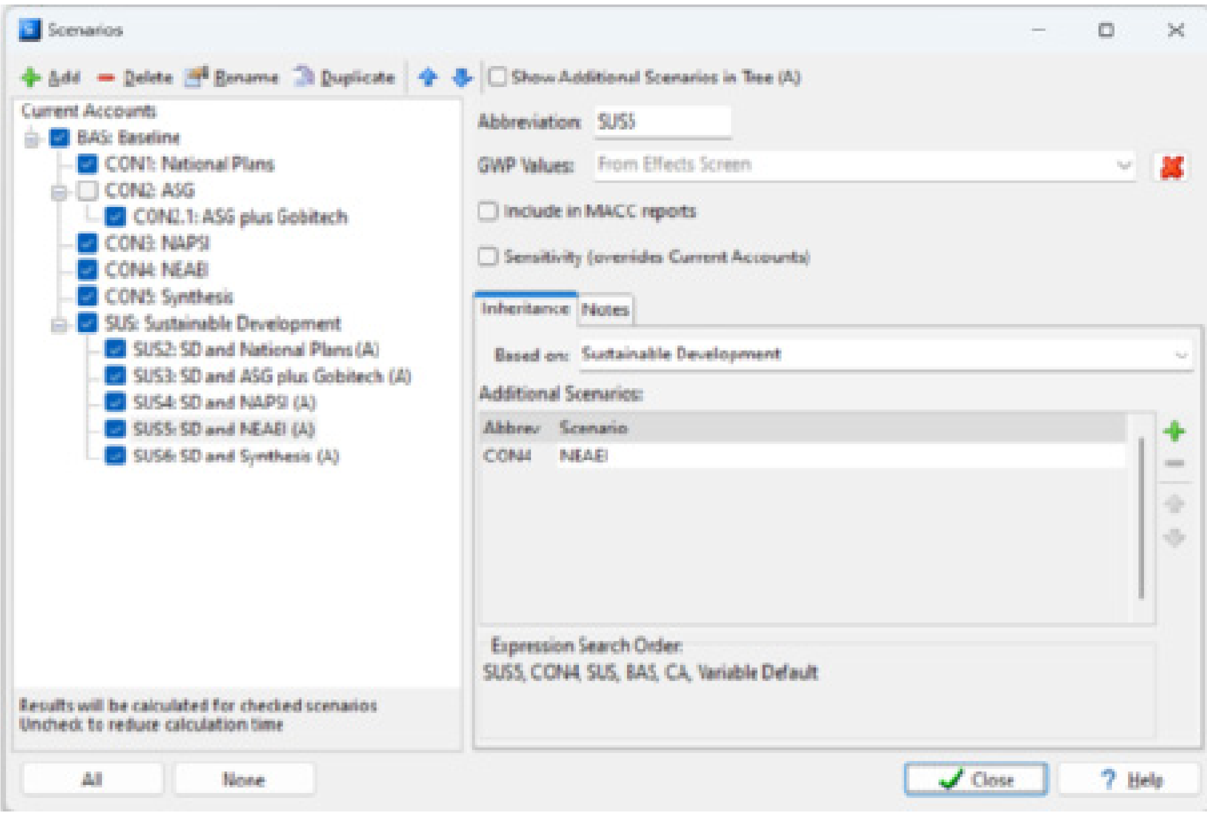
Each combination of a sustainability case and a connectivity case is specified as a scenario in the Model and can be separately simulated (Figure 11).

Simulation methods and inputs

Electricity demand

Projected electricity demand in the GPC Model is primarily based on previously published analyses, selected for their coherence with the Model's sustainability cases. The specific sources used, and the approach to integrating them in the Model, are described in Table 5.

Figure 11. GPC scenarios in the LEAP scenario manager



The "Baseline" scenario models the Baseline sustainability and connectivity cases, while the scenarios whose abbreviations begin with "CON" represent Baseline sustainability and other connectivity cases. The "Sustainable Development" scenario simulates the Sustainable Development sustainability case and Baseline connectivity. The scenarios beneath "Sustainable Development" model the Sustainable Development sustainability case and non-baseline connectivity. The scenarios abbreviated as "CON2" and "CON2.1" are different variants of the ASG connectivity case. The first comprises ASG's inter-regional transmission plans only, while the second includes the study's transmission and renewable power development plans. The second was used in the GPC Roadmap analysis.
Source: SEI

The supplemental data file distributed with this appendix provides electricity demand data and projections for both sustainability cases.

Electricity supply

The core method in the GPC Model's electricity supply modeling is least-cost optimization, which is carried

Table 5. Sources and methods for electricity demand projections in the GPC Model

Country	Sustainability Case	
	Baseline	Sustainable Development
China	• Historical data from National Bureau of Statistics (2021) • Projected demand from *China Energy Transformation Outlook 2022*, BLS1 (baseline) scenario (Energy Research Institute of Chinese Academy of Macroeconomic Research 2022) • Projected sectoral demand disaggregated to regions using data from National Bureau of Statistics	• Projected demand from *China Energy Transformation Outlook 2022*, CNS1 (carbon neutrality) scenario • Projected sectoral demand disaggregated to regions using data from National Bureau of Statistics
DPRK	• Historical data and projected demand from energy system modeling of DPRK by Nautilus Institute, Reference scenario (von Hippel 2022) • Projections extended from 2050 to 2060 using average growth rates during 2041-2050	• Projected demand from Nautilus Institute modeling, Sustainable Development scenario • Projections extended from 2050 to 2060 using average growth rates during 2041-2050
Japan	• Historical demand from International Energy Agency (2021), disaggregated to regions using Agency for Natural Resources and Energy (2021b) • Projected demand from *APEC Energy Demand and Supply Outlook 8th Edition*, Reference scenario (Asia Pacific Energy Research Centre 2022) • Projected sectoral demand disaggregated to regions using data from Agency for Natural Resources and Energy	• Projected demand from *APEC Energy Demand and Supply Outlook 8th Edition*, Carbon Neutrality scenario • Projected sectoral demand disaggregated to regions using data from Agency for Natural Resources and Energy
Mongolia	• Historical demand from Mongolia National Statistical Commission (2022a) and Energy Regulatory Commission (2019a) • Projected demand includes both secular demand growth and discontinuous demand growth • Secular demand growth simulated using econometric models based on gross domestic product, sectoral value added, population, and access to clean cooking technologies » Data sources for estimating models include Mongolia National Statistical Commission(2022b; 2022c), World Health Organization(2022) » Econometric methods follow those used in Intelligent Energy Systems (2021) • Discontinuous demand growth from Intelligent Energy Systems (2021) – includes new industrial demands and new demands for electric heating	• Projected demand based on Baseline demand and percent changes in sectoral demand under Mongolia's full NDC (Ovgor 2021)
ROK	• Historical data from International Energy Agency (2021) and Electric Power Statistics Information System (2021b) • Projected demand through the 2034 based on total target demand in *9th Basic Plan for Electricity Supply and Demand* (Ministry of Trade, Industry and Energy 2020) and sectoral demand shares in *APEC Energy Demand and Supply Outlook 8th Edition*, Reference scenario • Projected demand after 2034 based on sectoral demand growth rates in *APEC Energy Demand and Supply Outlook 8th Edition*, Reference scenario	• Projected demand through the 2034 based on total target demand in *9th Basic Plan for Electricity Supply and Demand* and sectoral demand shares in *APEC Energy Demand and Supply Outlook 8th Edition*, Carbon Neutrality scenario • Projected demand after 2034 based on sectoral demand growth rates in *APEC Energy Demand and Supply Outlook 8th Edition*, Carbon Neutrality scenario

out in the NEMO software. With perfect foresight, the Model minimizes the total discounted costs of electricity generation, storage, and high-voltage, inter-regional transmission. All costs are expressed in real terms in the Model, and a 3% real discount rate was used to calculate results for this report. The modeled costs comprise capital and operation and maintenance (O&M) costs of equipment as well as the cost of fuels consumed for electricity generation.

In each year, hour, and region of the Model, NEMO ensures sufficient supply is mobilized to meet demands for electrical energy and power while respecting technical and operational limits. Two main decisions are made in this context:

1. How much electricity generation, storage, and transmission capacity to add if existing capacity is inadequate (capacity expansion)

2. How to utilize available capacity to meet power and energy requirements (capacity dispatch)

The cost minimization objective controls both of these decisions.

With respect to capacity expansion, the Model is constrained not only by how much capacity is needed for electrical energy and power, but also by a reserve margin requirement. A key resource adequacy criterion, this input specifies how much surplus generation and storage capacity must be available when a region's electricity system is at peak load. A single set of reserve margin requirements is used in all of the Model's scenarios, and was developed from the sources in Table 6.

Reserve margin data and targets for China were not available, so the Model uses values from ROK in Chinese regions. For DPRK, the Model does not include its own reserve margin requirement because it incorporates generation and storage capacity projections from von Hippel (2022); these are based on reserve margin targets in the underlying source. The specific reserve margin requirements incorporated in the Model are reported in the supplemental data file.

When calculating whether reserve margin requirements are satisfied, the Model pro-rates installed capacity with technology (or, in Mongolia, plant) specific capacity credits. These indicate the percentage of installed capacity that counts toward the reserve margin. The capacity credits in the Model are based on average capacity factors for wind, hydro, and tidal/wave generation technologies, and on technical availability factors in other cases (except for solar PV, whose capacity credit is zero).

The electricity demands that must be satisfied at each modeled time step depend on final electricity demands, described in the previous section, and transmission and distribution losses. The Model computes transmission and distribution losses using region-specific average loss rates. In the Baseline sustainability case, these are taken from the sources in Table 7.

Loss rates improve in the Sustainable Development case in Mongolia and DPRK, following Ovgor (2021) and von Hippel (2022). The supplemental data file presents the values used for each sustainability case.

The combination of final electricity demands and transmission and distribution losses determines electricity production requirements, which must be met by modeled generation, storage, and transmission. Production requirements are

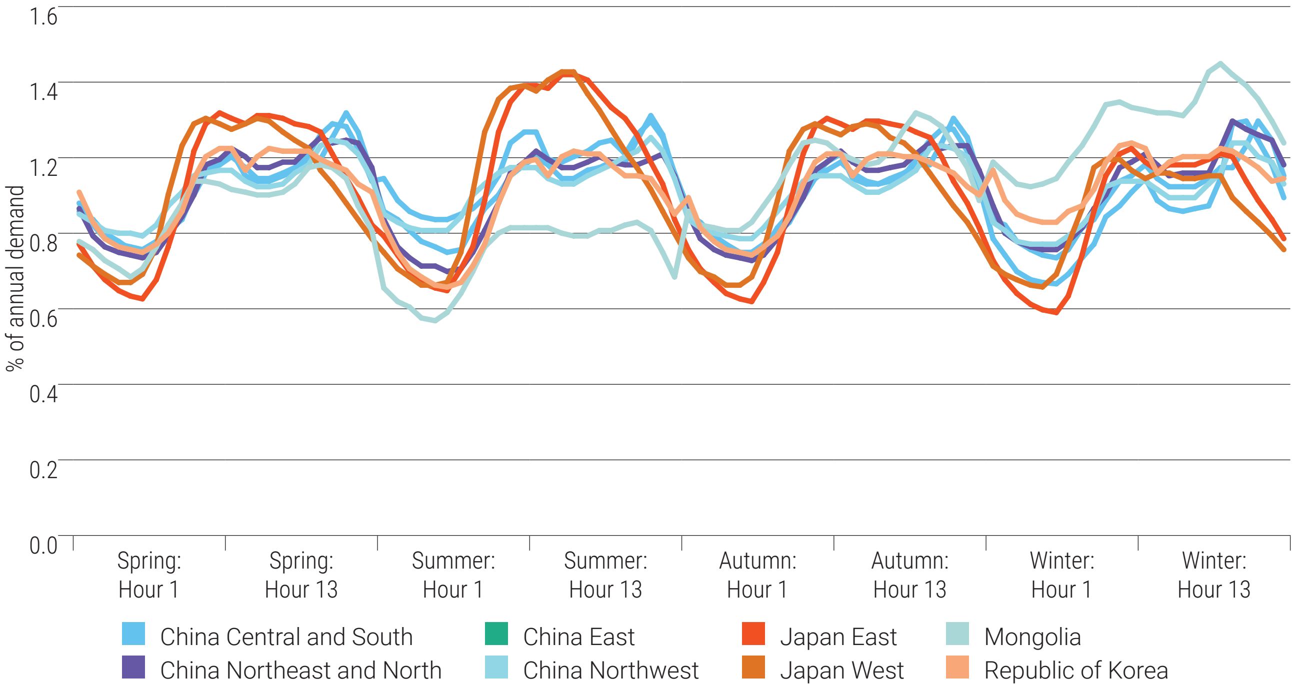
Table 6. Sources of reserve margin requirements data used in the GPC Model

Country	Sources
Japan	Japan Electric Power Information Center (2022)
Mongolia	Intelligent Energy Systems (2021)
ROK	Ministry of Trade, Industry and Energy (2020)

Table 7. Sources of transmission and distribution loss rate data used in the GPC Model's Baseline sustainability case

Country	Sources
DPRK	von Hippel (2022)
Mongolia	Energy Regulatory Commission (2019b), Mongolia Energy Governance Project (2023)
All others	International Energy Agency (2021)

Figure 13. Grid-level load curves in the GPC Model



Source: SEI

distributed over the hourly time slices in each year using grid-level load curves that were derived from Intelligent Energy Systems (2021) for Mongolia and from Otsuki (2017) for other countries (Figure 16). Since no better data were available, the same curves are used in all of the Model's scenarios.

In both the Baseline and Sustainable Development sustainability cases, the Model includes data on currently installed electricity generation and storage capacity, and it projects future capacity consistent with national plans, policies, and the definition of each case. Table 8 lists sources used for exogenously specified generation and storage capacity in the Model (including historical data and projections where appropriate). The Model assumes this capacity is built without exception.

After accounting for exogenously specified capacity, the Model is allowed to make endogenous decisions to build new generation and storage. These decisions are conditioned by which technologies are eligible for construction in each region. In the Baseline sustainability case, all technologies currently existing in a region are eligible for endogenous construction, with the exception of hydropower, nuclear generations 1 and 2, waste incineration, and pumped hydro storage. Additionally, in DPRK, endogenous expansion of generation capacity is disallowed before 2051 to be consistent with the projections in von Hippel (2022). In the Sustainable Development case, several technologies are enabled to support deep decarbonization and to align with national plans: gas CCS and hydrogen fuel cells in ROK; coal and gas CCS in China; and coal CCS, gas CCS, and hydrogen fuel cells in Japan.

The construction of eligible technologies is limited by resource potentials (for renewable energy and CCS) and by national plans and policies. Table 9 outlines the sources used to establish these limits.

The supplemental data file provides data on historical and projected generation and storage capacity in each GPC scenario.

Turning to transmission capacity, as noted above, the Model represents high-voltage transmission lines that connect the modeled regions. The Baseline connectivity case includes existing lines, and the other connectivity cases add proposed or potential lines to the existing grid. The NAPSI and NEAEI cases are predicated on studies that report expected deployment dates for their proposed lines; these

Table 8. Sources of exogenously specified electricity generation and storage capacity in the GPC Model

Country	Sustainability Case	
	Baseline	Sustainable Development
China	• Historical data from Platts (2021), bias corrected using data from China Electricity Council (2022) • Projected growth in pumped hydro from National Energy Administration (2021) • Projected growth in hydropower from Energy Research Institute of Chinese Academy of Macroeconomic Research (2022)	No additional assumptions (Baseline assumptions inherited)
DPRK	• Historical data and projected capacity from von Hippel (2022), Reference scenario	• Projected capacity from von Hippel (2022), Sustainable Development scenario
Japan	• Historical data from Platts (2021), bias corrected using data from Japan Electric Power Information Center (2022) • Data for nuclear plants from Federation of Electric Power Companies of Japan (2023) and Chugoku Electric Power Co. (2023) • Deployment targets for biogas and biomass, geothermal, hydropower, solar, waste incineration, and wind from Agency for Natural Resources and Energy (2021a)	No additional assumptions (Baseline assumptions inherited)
Mongolia	• Historical data and projected capacity from Ovgor (2021)	• Projected capacity from Ovgor (2021)
ROK	• Historical data from Platts (2021), bias corrected using data from Electric Power Statistics Information System (2021a)	No additional assumptions (Baseline assumptions inherited)

Table 9. Sources used to establish limits on endogenous capacity expansion in the GPC Model, including limits due to resource potentials and national plans and policies

Country	Sustainability Case	
	Baseline	Sustainable Development
China	• Solar and wind potentials from China National Energy Administration (2013), allocated to regions using World Bank (2022b) • Geothermal potential from Energy Research Institute of Chinese Academy of Macroeconomic Research (2022), allocated to regions using Zhang et al. (2019) • Biomass potential from Kang et al. (2020) • Tidal/wave potential and gas CCS potential from Energy Research Institute of Chinese Academy of Macroeconomic Research (2022) • Coal CCS potential from Wei et al. (2021) • Nuclear deployment limits from Energy Research Institute of Chinese Academy of Macroeconomic Research (2022)	No additional assumptions (Baseline assumptions inherited)
DPRK	• Solar and wind potentials from World Bank (2022b) and von Hippel (2022)	No additional assumptions (Baseline assumptions inherited)
Japan	• Solar and wind potentials from Japan Ministry of Environment (2011), allocated to regions using World Bank (2022b) • Geothermal potential from Japan Ministry of Environment (2011) • Biomass potential from Wu et al. (2020)	No additional assumptions (Baseline assumptions inherited)
Mongolia	• Solar and wind potentials from Mongolian Ministry of Energy and IRENA (2016), allocated to regions using World Bank (2022b) • Geothermal potential from Mongolian Ministry of Energy and IRENA (2016)	No additional assumptions (Baseline assumptions inherited)
ROK	• Solar, wind, geothermal, and biomass potentials from Hong et al. (2019)	No additional assumptions (Baseline assumptions inherited)

are reflected in the Model as exogenously specified construction dates. The National and Bilateral Plans connectivity case also comprises exogenous construction dates for its new lines, taken from its underlying data sources (Gazryn Zurag Co., Ltd 2023; UNESCAP 2020). By contrast, the ASG plan does not prescribe construction dates for its proposed transmission lines, so in this case the Model is allowed to choose endogenously whether/when the lines are built. The new transmission lines in the Synthesis case are also constructed endogenously since this case is a composite of the other connectivity cases.

Table 10 provides a summary of the transmission lines represented in each connectivity case, including their capacity and when they are constructed.

The data in Table 10 for lines in all connectivity cases and in the National and Bilateral Plans case were gathered from Government of Mongolia, Ministry of Energy (2015), Oyu Tolgoi LLC (2020), Organisation

Table 10. High-voltage transmission lines simulated in the GPC Model

Connectivity Case	Connected Regions		Maximum Power Flow [MW]	Construction Year
All	China Central	China East	41000	Existing
All	China Central	China North	11000	Existing
All	China Central	China Northwest	26000	Existing
All	China Central	China South	22500	Existing
All	China East	China North	12000	Existing
All	China East	China Northwest	6000	Existing
All	China North	China Northeast	24500	Existing
All	China North	China Northwest	43500	Existing
All	China North	Mongolia South	300	Existing
All	DPRK	ROK	100	Existing
All	Japan West	Japan East	2100	Existing
All	Mongolia Altai-Uliastai	Mongolia Central	90	Existing
All	Mongolia Central	Mongolia South	250	Existing
All	Mongolia East	Mongolia Central	90	Existing
All	Mongolia Central	Mongolia South	250	2022
All	Japan West	Japan East	900	2027
National Plans	Mongolia Altai-Uliastai	Mongolia Central	250	2028
National Plans	Mongolia Altai-Uliastai	Mongolia Central	90	2028
National Plans	Mongolia East	Mongolia Central	250	2028
National Plans	Mongolia West	Mongolia Altai-Uliastai	250	2028
National Plans	China North	ROK	2000	2025
ASG	Mongolia Central	China Northeast	8000	Model-determined
ASG	Mongolia Central	China North	8000	Model-determined
ASG	China North	China East	8000	Model-determined
ASG	China North	ROK	8000	Model-determined
ASG	ROK	DPRK	8000	Model-determined
ASG	ROK	Japan West	8000	Model-determined
ASG	Japan East	Japan West	8000	Model-determined
ASG	China Northeast	DPRK	8000	Model-determined
ASG	China Northeast	China North	8000	Model-determined

Continued next page

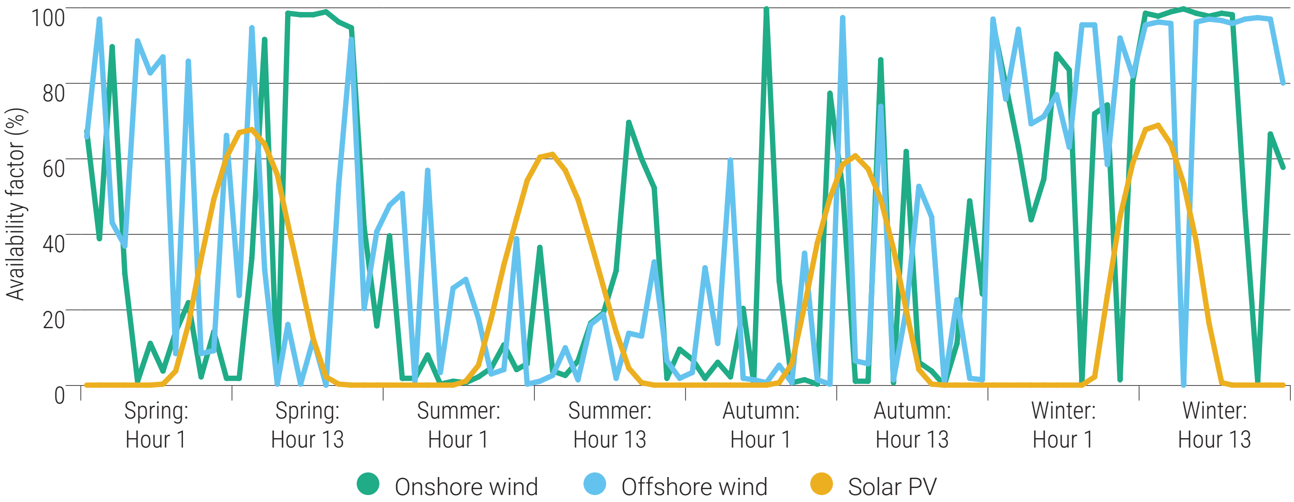
Table 10 continued

Connectivity Case	Connected Regions		Maximum Power Flow [MW]	Construction Year
NAPSI	China North	ROK	4000	2036
NAPSI	ROK	Japan West	2000	2036
NAPSI	Mongolia South	China North	4000	2036
NAPSI	China North	Mongolia South	2000	2036
NAPSI	Mongolia South	Mongolia Central	2000	2036
NAPSI	Mongolia Central	Mongolia Altai-Uliastai	1000	2036
NAPSI	Mongolia Altai-Uliastai	Mongolia West	1000	2036
NEAEI	Mongolia Central	China North	4000	2025
NEAEI	DPRK	ROK	3000	2025
NEAEI	China North	ROK	2000	2025
NEAEI	ROK	Japan West	2000	2025
NEAEI	Mongolia South	China North	8000	2035
NEAEI	China Northeast	DPRK	3000	2025
NEAEI	China North	ROK	8000	2035
NEAEI	China Northeast	DPRK	750	2025
NEAEI	ROK	Japan West	8000	2035
NEAEI	China Northeast	ROK	8000	2035
NEAEI	DPRK	ROK	8000	2035
NEAEI	Mongolia South	China North	8000	2050
NEAEI	China North	Japan West	8000	2050
NEAEI	China Northeast	DPRK	8000	2050
NEAEI	DPRK	ROK	8000	2050
NEAEI	China Northeast	Japan West	8000	2050
Synthesis	Mongolia South	Mongolia Central	8000	Model-determined
Synthesis	Mongolia South	China North	8000	Model-determined
Synthesis	China Northeast	DPRK	8000	Model-determined
Synthesis	DPRK	ROK	8000	Model-determined
Synthesis	China North	ROK	2000	Model-determined
Synthesis	ROK	Japan West	8000	Model-determined

of Cross-regional Coordination of Transmission Operators (OCCTO) (2021), Japan Electric Power Information Center (2020), UNESCAP (2020), and Gazryn Zurag Co., Ltd (2023). For the ASG, NAPSI, and NEAEI cases, the data were taken from the sources noted in the section on Scenarios above. The data in the Synthesis case were drawn from the other connectivity cases.

The dispatch of generation and storage capacity in the Model is bounded by availability factors and minimum utilization factors, which place a ceiling and floor respectively on the percent of installed capacity that is dispatched. Both types of factors are specific to technologies (or plants in Mongolia). The availability factors take into account planned and unplanned downtime for equipment as well as the variability of wind and solar resources. Minimum utilization factors are used to calibrate the Model to historical dispatch and, where data were available, to ensure that the dispatch of CHP capacity follows demands for heat. With limited exceptions, described below, the same availability and minimum utilization factors are used in every scenario. Their values are summarized in the supplemental data file.

Figure 14. Availability curves for wind and solar power in the GPC Model's China North region



Source: SEI

The availability factors for solar and wind technologies/plants vary over the course of the year depending on the availability of the underlying renewable resource. To develop intra-annual availability curves for solar and wind, resource potential estimates from the World Bank's REZoning tool were combined with hourly simulations conducted with the Renewable Energy Simulation toolkit for Python (RESKit) (World Bank 2022b; Institute of Energy and Climate Research: Techno-economic Systems Analysis 2022). Separate curves were created for each region and for onshore versus offshore wind – examples for the China North region are illustrated in Figure 15.

Across the modeled regions, the availability curves for solar show regular diurnal and seasonal patterns. The curves for wind are more unpredictable when viewed in chronological (hourly) order, as wind speed can vary sharply from one hour to another. However, when the wind curves are sorted by value to give duration curves (showing the number of hours the availability factor is at or above a certain level), clearer patterns emerge (Figure 16). The sorted curves have long tails for periods of very high and very low wind production, and steep transitions between the upper and lower tails.

A variety of data sources were used to develop the availability and minimum utilization factors in the GPC Model. Table 7 provides a summary of the principal sources consulted.

Availability factors for the Model's liquid biofuel, oil combined cycle, oil internal combustion, oil open cycle, and oil open cycle CHP technologies are based on values for similar technologies in the foregoing sources.

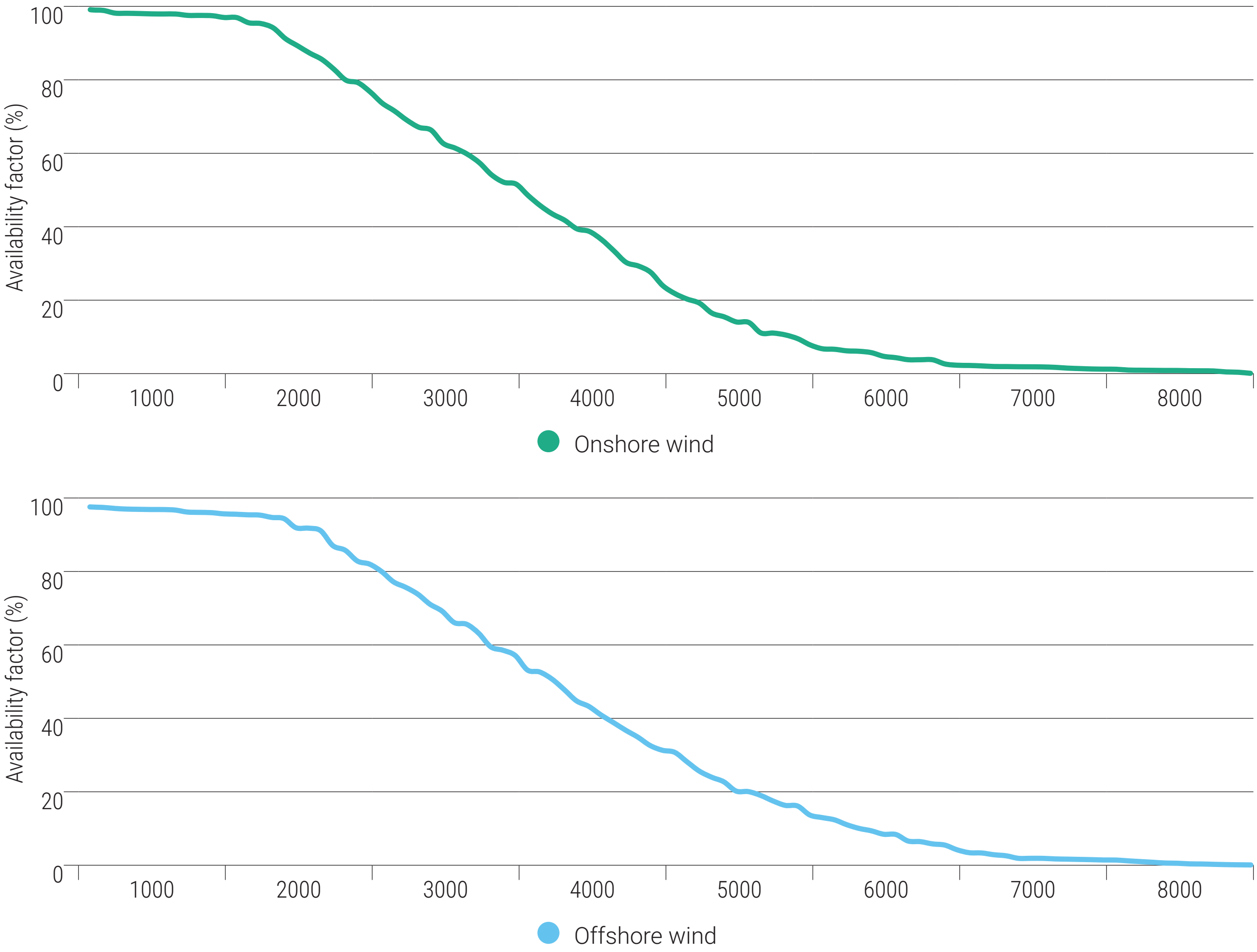
As part of its dispatch calculations, the Model determines how power flows through the high-voltage transmission network. Given the transmission data available, it uses a transshipment method to simulate power flow, in which it can choose the flow on each line provided that the line's maximum flow limit is respected (Krishnan et al. 2016). Power flow is separately decided for each line, year, and time slice.

As alluded to earlier, a key step in constructing the GPC Model was calibrating modeled dispatch to historical electricity production data. These data were taken from the sources listed in Table 8.

For sources that are not disaggregated by the detailed technologies in the Model, the historical production was distributed among technologies in proportion to their available capacity.

In addition to the inputs already mentioned, the Model incorporates several other generation, storage,

Figure 15. Wind availability duration curves in the GPC Model's China North region



Source: SEI

and transmission parameters that have a significant influence on results. These include parameters for costs, efficiency, technical lifetimes, storage full load hours, and emission factors. The main sources of these inputs are summarized below, and values used in the Model are presented in the supplemental data file. Unless otherwise noted, these inputs do not vary across scenarios.

The projected prices of fuels used to generate electricity also play an important role in the GPC Model's cost-minimization calculations. The Model comprises two different fuel price projections – one for the Baseline sustainability case and one for the Sustainable Development case. The basis for each projection is outlined in Table 14, and the projections themselves are reported in the supplemental data file.

Finally, for the Sustainable Development case, the Model includes a few additional assumptions and constraints to ensure the attainment of national decarbonization goals. Specifically:

- In China, at least 1200 GW of wind and solar capacity must be built by 2030, and 99% of electricity generation must be from zero-carbon sources by 2060 (Energy Research Institute of Chinese Academy of Macroeconomic Research 2022).

- In Japan, 99% of electricity generation must be from zero-carbon sources by 2050 (Agency for Natural Resources and Energy 2021c).

- In ROK, electricity generation from coal is phased out by 2050, at least 1.4% of generation must come from hydrogen fuel cells by 2050, and a limit on carbon dioxide emissions from electricity generation is imposed. The Model was calibrated to ensure that electricity

Table 11. Sources of data used to develop availability and minimum utilization factors in the GPC Model

Category	Sources
China	Availability factors for hydropower: China Electricity Council (2022)
DPRK	Availability factors for technologies other than solar PV and wind: von Hippel (2022)
Japan	Availability factors for nuclear technologies: Federation of Electric Power Companies of Japan (2023), Agency for Natural Resources and Energy (2021a) Availability factors for hydropower: Japan Electric Power Information Center (2022)
Mongolia	Availability factors for technologies other than solar PV, wind, oil internal combustion, coal steam subcritical, and coal steam subcritical CHP: Ovgor (2021) Minimum utilization of CHP plants: Namkhainyam et al. (2019)
ROK	Availability factors for hydropower: Electric Power Statistics Information System (2021a)
All other countries and technologies not covered above	Availability factors for biogas, natural gas internal combustion, natural gas internal combustion CHP, tidal or wave, waste incineration, hydrogen fuel cell, and lithium ion batteries technologies: Danish Energy Agency (2022) Availability factors for coal IGCC, coal steam subcritical, coal steam subcritical CHP, coal steam super and ultracritical, coal steam super and ultracritical CHP, geothermal, natural gas combined cycle, natural gas combined cycle CHP, natural gas turbine, natural gas turbine CHP, nuclear generation 3, CSP, solid biomass, solid biomass CHP, natural gas combined cycle CCS, and coal steam super and ultracritical CCS technologies: National Renewable Energy Laboratory (2022) Availability factors for natural gas steam, natural gas steam CHP, nuclear generation 1 and 2, oil steam subcritical, and oil steam supercritical technologies: Schröder et al. (2013) Availability factors for solar and wind: World Bank (2022b), Institute of Energy and Climate Research: Techno-economic Systems Analysis (2022) Availability factors for pumped hydro storage: China Electricity Council (2022)

Table 12. Sources of historical electricity production data used in the GPC Model

Country	Sources
China	China Electricity Council (2022)
DPRK	von Hippel (2022)
Japan	Japan Electric Power Information Center (2022)
Mongolia	Ovgor (2021)
ROK	Electric Power Statistics Information System (2021b)

Table 13. Sources of electricity generation, storage, and transmission cost data used in the GPC Model

Category	Sources
	Generation and storage capital costs
DPRK	von Hippel (2022)
China	Solar and wind technologies: International Energy Agency (2019)
All other countries and technologies not covered above	Coal steam subcritical (CHP and non-CHP), natural gas combined cycle (CHP and non-CHP), natural gas internal combustion (CHP and non-CHP), natural gas turbine (CHP and non-CHP), oil combined cycle (CHP and non-CHP), solar PV, waste incineration, wind onshore and offshore, and hydrogen fuel cell technologies: Danish Energy Agency (2022) Coal IGCC, nuclear generation 1,2, and 3, CSP, solid biomass (CHP and non-CHP), natural gas combined cycle CCS, coal steam super and ultracritical CCS, lithium ion batteries, and pumped hydro storage technologies: National Renewable Energy Laboratory (2022) Coal steam subcritical (CHP and non-CHP), geothermal, hydro small and large, oil open cycle (CHP and non-CHP), oil steam subcritical, oil steam supercritical, and tidal or wave technologies: Schröder et al. (2013)

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Table 13 continued

Category	Sources
Weighted costs of capital for generation and storage	
DPRK and Mongolia	Coal technologies: Stakeholder consultations in 14 December 2022 NEARPIC workshop.
All other countries and technologies not covered above	International Renewable Energy Agency (2022)
Generation and storage variable O&M costs	
DPRK	von Hippel (2022)
Mongolia	Coal steam subcritical technologies (CHP and non-CHP): Intelligent Energy Systems (2021)
All other countries and technologies not covered above	Biogas, coal steam subcritical (CHP and non-CHP), natural gas combined cycle (CHP and non-CHP), natural gas internal combustion (CHP and non-CHP), natural gas turbine (CHP and non-CHP), oil combined cycle (CHP and non-CHP), solar PV, waste incineration, wind onshore and offshore, and hydrogen fuel cell technologies: Danish Energy Agency (2022) Coal IGCC, nuclear generations 1, 2, and 3, CSP, and solid biomass (CHP and non-CHP), lithium ion batteries, and pumped hydro storage technologies: National Renewable Energy Laboratory (2022) Coal and gas CCS technologies: National Renewable Energy Laboratory (2022), Wei et al. (2021) Coal steam subcritical (CHP and non-CHP), geothermal, hydro small and large, oil open cycle (CHP and non-CHP), oil steam subcritical, and oil steam supercritical technologies: Schröder et al. (2013) Tidal or wave technology: Danish Energy Agency (2023)
Generation and storage fixed O&M costs	
DPRK	von Hippel (2022)
Mongolia	Subcritical coal steam (CHP and non-CHP), hydro large and small, solar PV, and wind onshore technologies: Intelligent Energy Systems (2021)
All other countries and technologies not covered above	Biogas, coal steam subcritical (CHP and non-CHP), natural gas combined cycle (CHP and non-CHP), natural gas internal combustion (CHP and non-CHP), natural gas turbine (CHP and non-CHP), oil combined cycle (CHP and non-CHP), solar PV, waste incineration, wind onshore and offshore, and hydrogen fuel cell technologies: Danish Energy Agency (2022) Coal IGCC, nuclear generations 1, 2, and 3, CSP, and solid biomass (CHP and non-CHP), coal and gas CCS, lithium ion batteries, and pumped hydro storage technologies: National Renewable Energy Laboratory (2022) Coal steam subcritical (CHP and non-CHP), geothermal, hydro small and large, oil open cycle (CHP and non-CHP), oil steam subcritical, oil steam supercritical, and tidal or wave technologies: Schröder et al. (2013)
Transmission costs[a]	
National Plans case	EDF (2020), Huang (2018)
ASG case	Mano et al. (2014)
NAPSI case	EDF (2019)
NEAEI case	EDF (2020), Huang (2018)
Synthesis case	EDF (2020), Huang (2018)

[a] When reporting transmission costs by region, the Model follows a few allocation rules. Costs that are specific to a transmission line are split evenly between the regions connected by the line. When a connectivity case includes costs that are not allocable to particular transmission lines but are assigned to a country, the costs are divided evenly among the regions in the country that are involved in the connectivity case. For connectivity cases with costs that are not allocable to transmission lines and are not assigned to countries, the costs are split evenly among all regions involved in the connectivity case.

Table 14. Sources of electricity generation and storage efficiency data used in the GPC Model

Category	Sources
DPRK	von Hippel (2022) (includes efficiency improvements in the Sustainable Development case)
Mongolia	Ovgor (2021) (includes efficiency improvements in the Sustainable Development case)
All other countries and technologies not covered above	Biogas, natural gas internal combustion, and hydrogen fuel cell technologies, efficiency adjustments for CHP technologies: Danish Energy Agency (2022) Coal IGCC, solid biomass, natural gas turbine, natural gas combined cycle, nuclear generation 1 and 2, natural gas combined cycle CCS, coal steam super and ultracritical CCS, lithium ion batteries, and pumped hydro storage technologies: National Renewable Energy Laboratory (2022) Nuclear generation 3: World Nuclear Association (2021) Waste incineration: Yang et al. (2018) Other coal and gas steam technologies: Schröder et al. (2013)

Table 15. Sources of technical lifetimes for electricity generation and storage in the GPC Model

Category	Sources
All countries	Coal IGCC: Basile et al. (2015) CSP, nuclear generation 3, hydropower, lithium ion batteries, and pumped hydro storage technologies: National Renewable Energy Laboratory (2022) Nuclear generation 1 and 2: Goldberg and Rosner (2011) Other technologies: Danish Energy Agency (2022)

Table 16. Sources of storage full load hours in the GPC Model

Category	Sources
All countries	Lithium ion batteries and pumped hydro storage technologies: National Renewable Energy Laboratory (2022)

Table 17. Sources of emission factors for electricity generation in the GPC Model

Category	Sources
All countries and technologies	Intergovernmental Panel on Climate Change (2022)

Table 18. Sources and methods for fuel price projections in the GPC Model

Country	Sustainability Case	
	Baseline	Sustainable Development
China	• Current coal prices from Energy Research Institute of Chinese Academy of Macroeconomic Research (2022) • Current natural gas prices from World Bank (2022a) • Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Stated Policies case	• Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Announced Pledges case
DPRK	• Current coal prices from Energy Research Institute of Chinese Academy of Macroeconomic Research (2022) • Current natural gas prices from World Bank (2022a) • Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Stated Policies case	• Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Announced Pledges case

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Table 18 continued

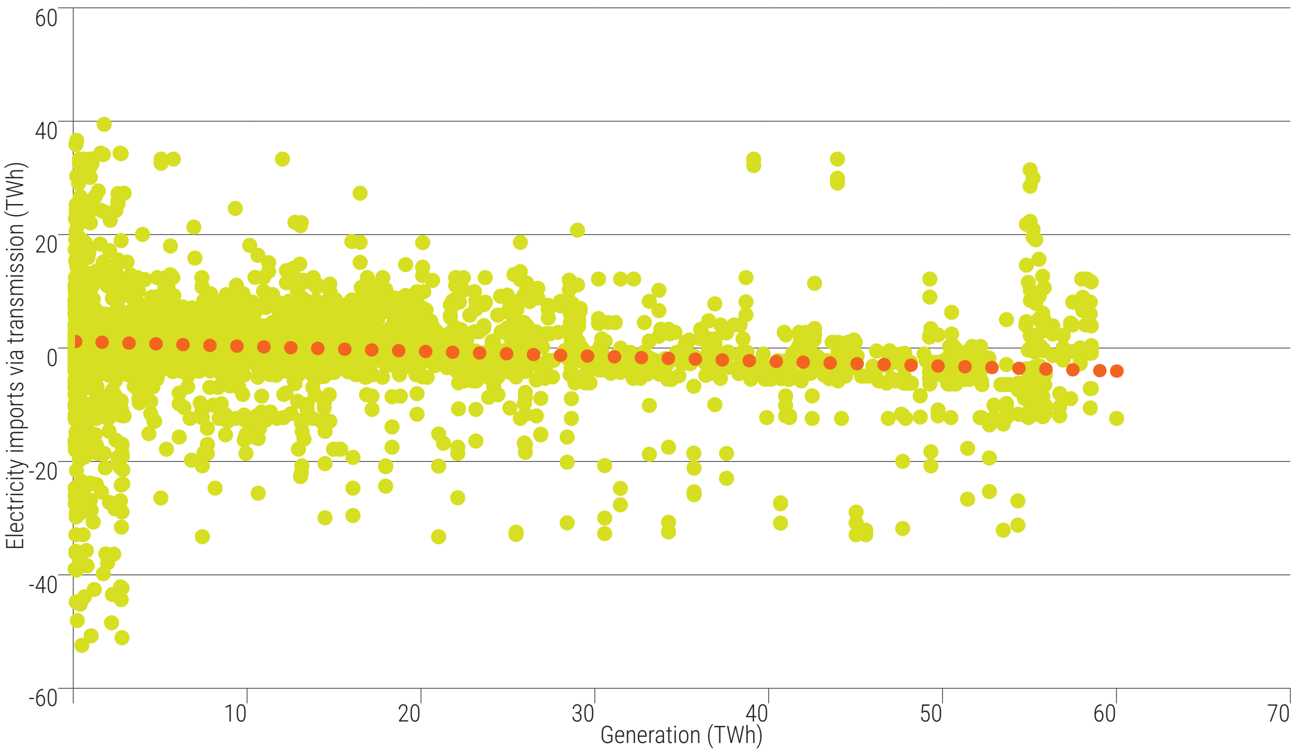
Country	Baseline	Sustainable Development
Japan	• Current coal and natural gas prices from World Bank (2022a) • Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Stated Policies case	• Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Announced Pledges case
Mongolia	• Current coal and natural gas prices from Intelligent Energy Systems (2021) • Projected coal, natural gas, and oil prices until 2030 from Intelligent Energy Systems (2021); after 2030 based on International Energy Agency (2022b), Stated Policies case	• Projected coal, natural gas, and oil prices until 2030 from Intelligent Energy Systems (2021); after 2030 based on International Energy Agency (2022b), Announced Pledges case
ROK	• Current coal and natural gas prices from World Bank (2022a) • Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Stated Policies case	• Projected biogas, coal, ethanol, natural gas, and oil prices based on International Energy Agency (2022b), Announced Pledges case
All	• Current prices: • Biogas and biomass: Energy Research Institute of Chinese Academy of Macroeconomic Research (2022) • Ethanol: Agency for Natural Resources and Energy (2022) • Oil: Intelligent Energy Systems (2021) • Current and projected nuclear fuel prices from National Renewable Energy Laboratory (2022) • Current and projected hydrogen prices from International Energy Agency (2022a)	

generation from natural gas, renewables, and fuel cells comports with targets in the government's 2050 Net-Zero Scenario policy, assuming Baseline connectivity (2050 Carbon Neutrality Committee 2021)

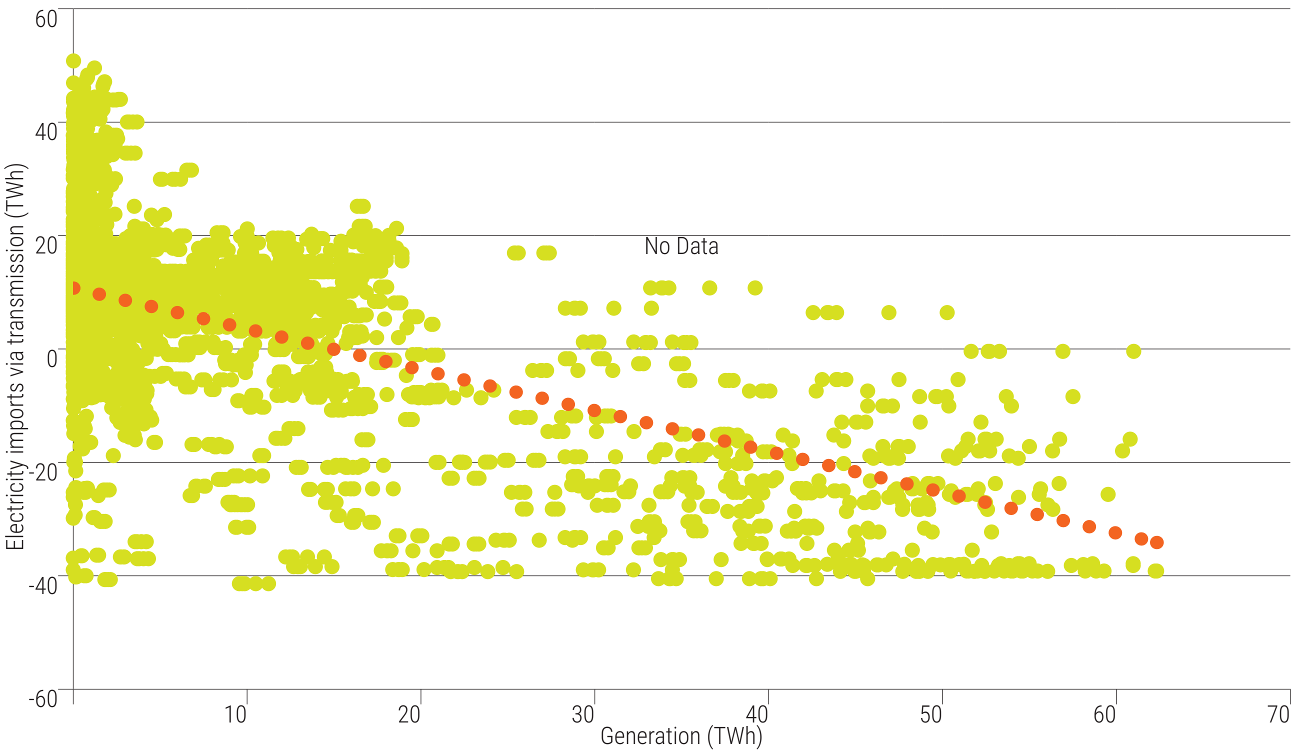
Results from the GPC Model are discussed at length in the main body of this report. However, the supplemental data file also provides key results in spreadsheet format. These include final electricity demand and generation and storage capacity, mentioned earlier, as well as electricity generation, GHG emissions from generation, electricity trade via the modeled transmission network, and transmission costs.

Supplemental Charts

Figure 17. Relationship between offshore wind/solar PV generation and electricity imports via transmission



y = 0.08704x + 1.1353; R^2 = 0.0167



y = 0.08398x + 2.8669; R^2 = 0.2152

Each dot represents a modeled region in a year, season, and hour of the day. Results are shown for the six transmission connectivity cases with Sustainable Development sustainability.
Source: SEI

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