# Connecting the Global Power Grid

September - 2021


The Al-Attiyah Foundation

The Al-Attiyah Foundation is proudly supported by:

# INTRODUCTION

## CONNECTING THE GLOBAL POWER GRID

The transition to a more electrified society, and the greater dependence on variable renewable energy, raises the value of long-distance electricity interconnections. At the same time, advances in transmission and smart grids makes such links more feasible.

But developing a regionally interconnected and integrated electricity system involves a wide range of considerations, such as cooperation on system planning, grid synchronisation, and operational coordination.

What are the different modes of integration? How can system security ensure uninterrupted real time operations?

THE ABDULLAH BIN HAMAD AL ATTIYAH FOUNDATION

## Energy Industry Report

This research paper is part of a 12-month series published by The Al-Attiyah Foundation every year. Each in-depth research paper focuses on a prevalent energy topic that is of interest to The Foundation's members and partners. The 12 technical papers are distributed in hard copy to members, partners, and universities, as well as made available online to all Foundation members.

# EXECUTIVE SUMMARY

- The history of electricity systems is driven by expansion. The main driver of this expansion has been economics, specifically the reduction of overall investment and operational costs of the electricity system.
- New grid technologies, notably ultra-high voltage DC connections, are making long-distance connections more feasible. At the same time, factors including the desire for greater system reliability and the integration of higher shares of intermittent renewable generation, make electricity trade more important.
- Despite these drivers, international electricity trade has grown only very slowly. Commercial and regulatory factors have to be overcome to realise the full economic and environmental benefits of expanded interconnection.
- Connecting an electricity system involves a wide range of considerations, which include cooperation on system planning, grid synchronisation, coordination of system operations, integration of electricity markets, and the consolidation of regulatory plans and policies.
- Depending on the mode of integration, an interconnected electricity system should be administered by regulatory institutions and their supporting reliability institutions in regulating the exchange of electricity under a restructured or a fully integrated market structure.
- System security involves maintaining uninterrupted real time operations, dealing with system stress, and ensuring the necessary reliability protocols are in place to tackle them. The two main causes of systems of stress are coordinated dispatch, and loop and transit flow problem.
- Coordinated dispatch can be managed by multiple system operators sharing dispatch plans a day-ahead or agreeing to share changes closer to real time. And the loop and transit flow problem, involves managing bi-directional excess electricity flows that originate outside a respective transmission system operator's area of control.
- An important element of developing an interconnected electricity system is resource adequacy, which involves joint coordination and planning in expanding the generation, transmission, and distribution capacity to meet the long-term needs of the system.
- Planning for resource adequacy can occur through a voluntary or a formally mandated mechanism, which either way involves ensuring the equitable and efficient allocation of the interconnector capacity, and the exchange of electricity supply and / or electricity generating capacity.
- Policymakers and utilities should carefully deliberate governance, system security, resource adequacy, and use of new technologies, in order to realise the full benefits of an interconnected electricity system.

# INTRODUCTION

Cross-border electricity grids have played a crucial role in the historic development of electricity systems. Most pan-regional electricity transmission and distribution systems began as single isolated systems across a large city. As these systems expanded outside the urban areas, they became increasingly interconnected with neighbouring localities, with regional utilities devising electricity pools to trade electricity and generation capacity reserves.

The history of electricity systems is driven by expansion, which is primarily driven by their economic feasibility, the security and reliability of electricity supply, and, more recently, their integration with intermittent renewable energy sources.

In 1925, the first electricity pool was established in Connecticut, United States. As transmission and distribution systems evolved and technologies improved, this led to more long-distance interconnections, which at times crossed sovereign borders. In Europe, the first cross-border electricity grid was established in 1906, transmission links to neighbouring France and Italy.

The development of expansive electricity systems is driven by economies of scale, which capitalises on large and remote electricity generators, and transports electricity over long distances to an even larger section of consumers. As these electricity grids expand, they leap across different legal jurisdictions and take advantage of local economic benefits.

Another driver of integrating electricity grids is security and reliability of supply. This allows system planners, operators, and utilities to tap into a larger and/or a diverse set of resources,

which decreases the need to expand local reserve electricity generation and helps mitigate the potential impact of electricity outages.

And finally, the third main driver for cross-border grids, which is ever more relevant today, is the integration of intermittent renewable generation across different geographies. In interconnected electricity infrastructure, utility-scale renewable energy projects can achieve a higher degree of flexibility with the natural variations in resources, demand patterns, flexible generation, and demand-side technologies, which ultimately makes it easier to integrate an intermittent renewable resource such as solar PV, solar CSP, onshore and offshore wind, together with large-scale storage options, notably pumped hydropower.

Despite the benefits of an interconnected electricity infrastructure, international links are often exposed to different regulations from those that govern the domestic electricity sector. And in spite of the economic benefits achieved to extend the electricity system, they are rarely distributed equitably or equally between two or more different jurisdictions, which makes it difficult to agree on how to share the investment and operational cost of the interconnecting transmission and distribution system.

The security of electricity supply from an interconnected electricity infrastructure is often offset by various external risks, which are typically outside a respective planner, operator, or utility's control. A prominent example of this is interconnected alternating current (AC) systems, where a major disruption in one section of the electricity grid may disrupt the entire integrated grid[i].

Similarly, an uncoordinated deployment of intermittent renewable energy generation, which is not supported by the necessary investments in the electricity grid could lead to a spillover effects, such as "loop and transit" flows, which can at worse lead to electricity outages or increase the operations and maintenance cost for the interconnected system.

An effectively planned and implemented electricity grid could integrate electricity systems across various regulatory jurisdictions, maximise its benefits, and minimises its potential risks.

In order to achieve this, various elements of an interconnected electricity grid have to be considered. The various elements include:

- cooperation on electricity system planning,
- synchronisation of the electricity grid,
- coordination between system operations,
- integration of electricity markets,
- the collective harmonisation of policies and regulations, and
- Political and legal reliability and trust.

**Renewable Energy in Interconnected Electricity Systems**

As the share of renewables in the electricity mix increases around the world, the impact on the electricity system grows. The International Energy Agency (IEA) has identified various phases for the technological deployment of renewable energy technologies:

- Phase I: the impact of the variable renewable energy is small enough not to change system operations.
- Phase II: the share of renewable energy increases to a point where it impacts the overall electricity generation patterns of the existing fleet, but not significantly enough to require operational changes or system upgrades.
- Phase III: electricity generation patterns change significantly on a short enough timescale, and require increased system flexibility.
- Phase IV: the variability of electricity generation is high enough to create system stability problems for operator, hence, requiring significant technical investments and operational changes.

As electricity systems move up from phase I to phase IV, the share of intermittent renewable energy generation increases, which points to one reason why electricity system integration is an important tool in supporting the deployment of renewable generation.

The relative share of renewable energy in large, interconnected systems may be lower than the absolute share of renewable energy in an isolated electricity system, specifically if a country has deployed significantly larger capacity than its neighbours.

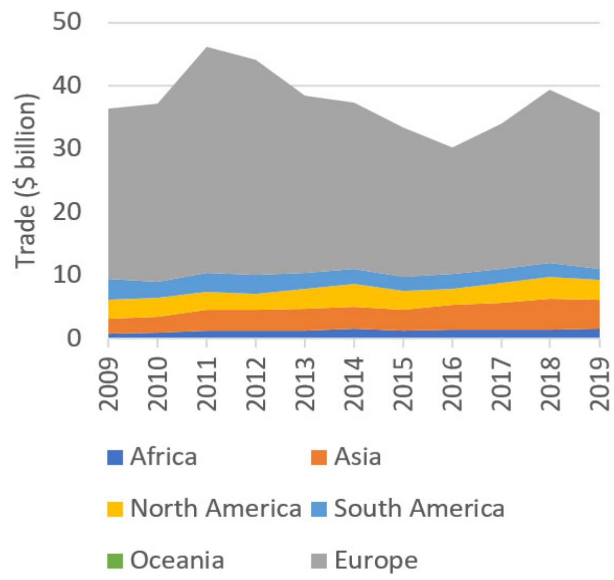
Denmark is an example of this, when in 2016, the country produced 12.8 TWh of wind energy, which accounted for 42% of total electricity generation. However, the country's share of wind generation relative to total EU electricity generation was relatively small. Wind generation in Denmark accounted for 3% of total generation of the Nord Pool (the Nordic and Baltic countries) in 2017.

Therefore, integrating electricity systems helps with the deployment of intermittent renewable energy in two different ways. Firstly, increasing the size of the total balancing area allows system operators to take advantage of the natural diversity in weather patterns across larger geographies. And secondly, electricity interconnections give system operators access to a larger set of diverse resources as well as additional pools of demand, hence making it easier to balance local renewable energy generation.

A careful consideration of these elements will ultimately determine an interconnected grid's structure; its governance in terms of policies, regulations, and institutions; the resource adequacy in terms of planning and investments; and systems security with regards to managing an integrated electricity system in real time.

## PROGRESS OR STAGNATION IN INTERNATIONAL ELECTRICITY TRADE?

Figure 1 Value of cross-border electricity trade over time by exporting country region[ii]

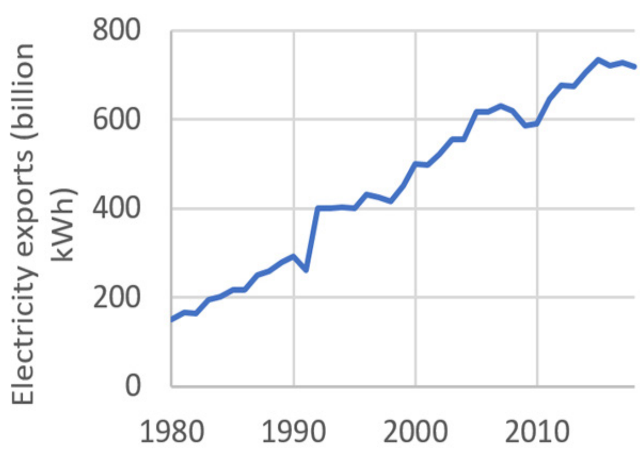



Despite these drivers, the value of electricity trade has actually remained flat over the last decade (Figure 1). Europe dominates the trade, but the amount fell sharply from 2011 to 2016 before partly recovering. This is mostly driven by a drop in exports by Switzerland, Germany and Austria, which may be related to the phase-out of nuclear plants and to hydropower conditions. Asian and African trade has grown around 7% per year on average but remains relatively small, while trade within South America has fallen. Since these figures are expressed in terms of value, they are also affected by fluctuating electricity prices, themselves driven by global and regional natural gas prices and other factors – the value of trade may fall with falling prices even if the quantity of transferred electricity rises.

Nevertheless, it is clear that the value of electricity exports is very small compared to other energy markets. In 2019, $35.7 billion of electricity was traded internationally, compared to $986 billion of crude oil, $688 billion of refined petroleum, $143 billion of liquefied natural gas (LNG), $99.5 billion of non-LNG natural gas and $128 billion of coal.

Taking a longer-term view, global electricity exports expressed in energy terms (kilowatt hours) have grown at 4.3% annually during 1980-2018, while generation expanded 3.1% per year. The share of exports in total generation has thus risen only from 1.9% to a high of 3.6% in 2005 before falling back to 2.8% in 2018. And the rise in exports is partly driven by the breakup of the Soviet Union in 1991, which turned sizeable internal flows into exports (global exports of 261 billion kWh in 1991 jumped to 401 billion kWh in 1992).

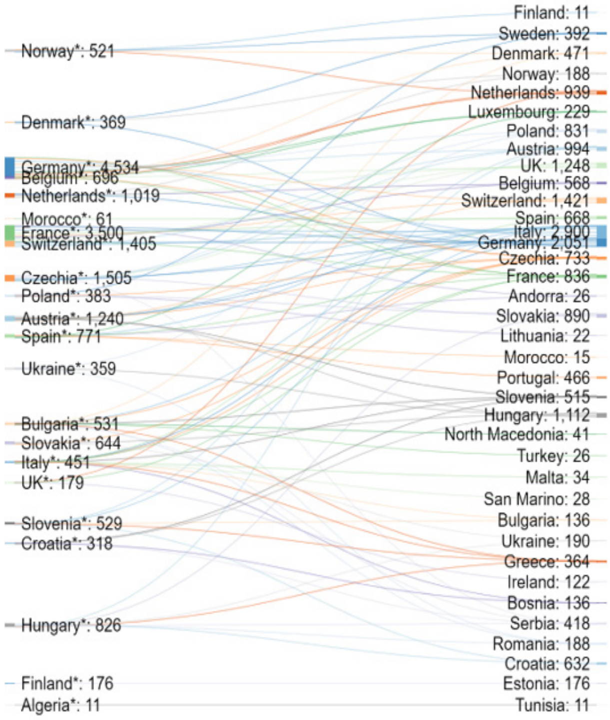
Figure 2 World electricity exports 1980-2018, in energy units[iii]



Europe's position is anomalous due to its small geographic size, large number of countries, high income, well-developed infrastructure, energy market and regulatory integration, political and legal stability, and diversity of generating resources, all of which favour electricity trade. Long-distance electricity movement also occurs within, for instance, the USA and China, but of course does not register as international trade.

Figure 3 shows the complexity of trade within Europe, including the connections to Morocco and thereby to Algeria and Tunisia. Note that Europe is also connected to Turkey and Russia, which themselves trade electricity with neighbours in West, Central and East Asia. Also note that some minor imports are excluded for clarity. It can be seen that some 22 European and connected North African countries could be considered as significant electricity exporters and 37 as significant importers. Many countries, including Germany, the Netherlands, Slovakia and Hungary, are both important exporters and importers (or transit countries).

Figure 3 Electricity trade by value within Europe, 2019 (million $), exporters shown with *[iv]




Also, several trade flows are between countries that do not share a border, for instance between Czechia and Italy, Czechia and the UK, Spain and Austria, Bulgaria and Cyprus, and Bulgaria and the UK. In these cases, the physical flow of electricity must obviously traverse one or more intervening countries. And some relatively small countries, such as Hungary, Slovakia and Bulgaria, are key hubs because of geographic connectivity.

The situation within Asia is simpler (Figure 4). Total trade is much less than in Europe, and centres primarily on Russia and its Caucasus/Central Asian neighbours; and China. Laos is a major exporter but nearly all to Thailand. Much of China's 'trade' in fact goes to its special administrative regions of Hong Kong and Macau. India is connected to Bangladesh, Nepal and Bhutan but otherwise isolated.

Figure 4 Electricity trade by value within Asia, 2019 (million $), exporters shown with *

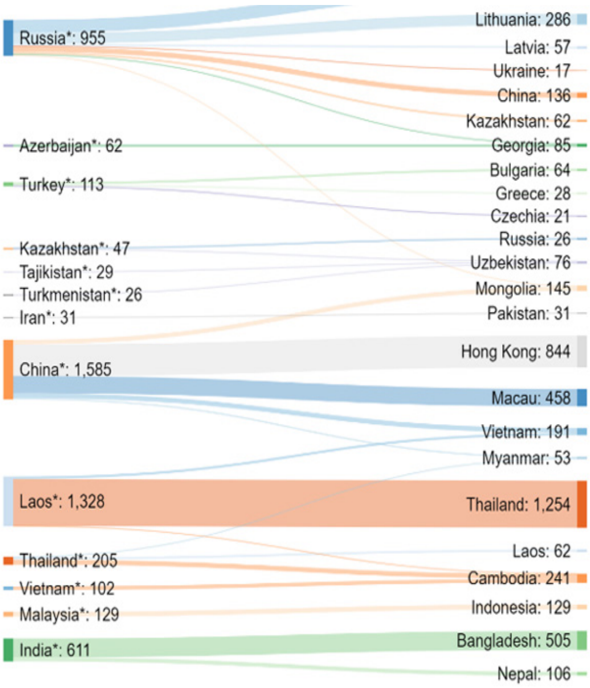
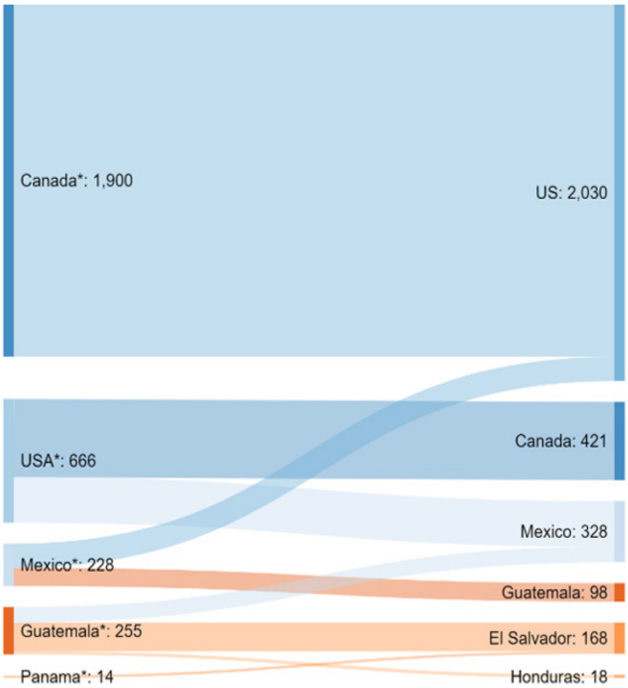



Figure 5 Electricity trade by value within North and Central America, 2019 (million $), exporters shown with *




The situation in the Americas is even simpler (Figure 4). There is quite large trade between Canada, the US and Mexico, and some in Central America mostly involving Guatemala. Central America is not linked to South America at all, and South American trade (not shown) is nearly all hydropower from Paraguay to Brazil and Argentina.

Finally in sub-Saharan Africa, there are two main clusters of interconnections, in southern Africa (South Africa, Mozambique and neighbours) and West Africa (mostly Benin, Togo, Côte d'Ivoire, Nigeria, Niger, Ghana and Burkina Faso), with some very limited links in east Africa.

It would therefore appear that the potential for enhanced international electricity trade, and its contribution to economic and environmental progress, is not being fully realised and indeed has not made substantial aggregate progress over the last decade.

## TECHNOLOGY

In the 20th century, alternating current (AC) was the most preferred mechanism for transmission and distribution grids, despite being limited by transmission capacities and distance constraints, and the inability to connect and synchronise two AC electricity networks with different frequencies.

In future, the needs of the electricity systems will determine the role of grid interconnections and large-scale transmission and distribution technologies. New technologies for transmitting and distributing electricity over longer distances and between different electricity grids are expected to increase beyond the current levels of deployment; driven by an increase in access to electricity, variable renewable energy generation, electrification of new products and services across various industries, and the need to build smarter electricity grids.

These trends will change the future prospects of new and existing cross-border electricity grids and will factor in national policies in terms of 1) cost of interconnections over long distances, 2) connecting asynchronous grids, 3) connecting remote energy resources through off-grids and mini-grids, and 4) accommodating variable renewable energy generation.

The cost of interconnection over longer distance is lower for high-voltage direct current (HVDC) systems in comparison to AC systems. HVDC reduces line losses by a figure of 4, and the amount of cable required is also considerably less. Despite the fixed costs of developing terminals at both ends being higher for HVDC, the cost of the link per unit of electricity produced is much lower. Therefore, the longer the link, the lower the relative cost.

# TECHNOLOGY

The high cost of converters and breakers means that HVDC will be cheaper than AC only over long distances[v]. Given the current technology, it is estimated that the break-even distance is ~600 km – 800 km.

Moreover, there are no technological limitations to the length of an HVDC cable, in comparison to high voltage alternating current (HVAC) systems which are limited to the maximum possible transmission distance and the reactive flow of electricity due to large cable capacitance.

In the future, superconducting lines would halve losses again, and require smaller rights-of-way.

Currently, the longest grid interconnection is the HVDC undersea link between the Netherlands and Norway, called the NorNed, which spans 600 km and transmits 700 MW. Globally, there are ~10,000 km of interconnectors with each connection measuring ~250 km.

A number of interconnection projects operating on HDVC systems have been envisioned as demand for long-distance interconnections increase. An example of such is the North Sea Link, a 1,400 MW subsea HVDC transmission and distribution system between the United Kingdom and Norway. The link is expected to commence operations in 4Q, 2021 and will be the longest subsea interconnector in the world spanning 720 km[vi]. The estimated cost of the project is US$ 2.3 bn[vii].

Another advantage of HVDC systems is their ability to connect to asynchronous grids and can adapt to any rated voltage and frequency they receive, which in contrast to AC or HVAC systems can be difficult to achieve as they must be synchronised. There are currently 13 GW of interconnected asynchronous grids globally. In terms of frequency, these asynchronous grids can be mechanical hazards, for example in the case of Japan, where 1,200 MW connect its Western and Eastern regions; and in terms of voltage, such as between the 500 kV Russia and China interconnection.

In the case of the former, plans are in place to increase in the electricity exchange capacity between the Western and Eastern regions of Japan to 2,500 MW to help speed up expansion of renewable energy generation[viii]. Actual plans are expected to be finalised in 2022 with construction expected to begin in 2023.

Increasing the voltage level in transmission grids improves the economic feasibility for remote resources and loads. The race to increase voltages and transmission distance is encouraging grids to transmit power at 800 kV and 1,000 kV, which significantly reduces losses over longer distances. An example is the 2,375 km Rio Madeira HVDC link built to export electricity from hydropower projects on the Madeira River in the Amazon Basin to major load centres of Southeastern Brazil.

At the same, ultra-high voltage systems (UHV) that are known to connect vast amounts of extremely remote resources are increasingly being deployed. In 2019, State Grid Corporation of China completed the 1.1-million-volt transmission line, which covers 3,300 km and transports 12 GW of electricity between Xinjiang to Anhui[ix].

One of the key drivers of HVDC lines and interconnectors is the ability to transport variable renewable energy to areas of high demand, which could otherwise increase curtailment. A range of transmission technologies can be deployed to increase their capacity, such as flexible AC transmission systems (FACTS) in HVAC lines and flexible HVDCs. A key component of the latter is a voltage-source converter, which converts DC electricity to AC allowing greater freedom and flexibility.

The Skagerrak 4 interconnector in Denmark, a joint venture between Norwegian and Danish transmission system operators, Statnett and Energinet, is specifically designed for variable wind generation[x]. The interconnector has a full transmission capacity of 1.4 GW. In the medium-term, voltage source converters (VSC) are expected to grow, particularly across emerging markets, as ~80% of new interconnections and high voltage transmission lines rely on flexible technologies.

Therefore, as the deployment of new technologies for transmitting and distributing electricity over longer distances and between different electricity grids increases, there will be greater emphasis on investments directed towards improving their flexibility and interconnections.

# CONNECTING THE GLOBAL ELECTRICITY GRID

As noted, HVDC technology improvements have made continental-scale transmission increasingly feasible and cost-effective.

Figure 6 Future global electricity grid (speculative)[xi]

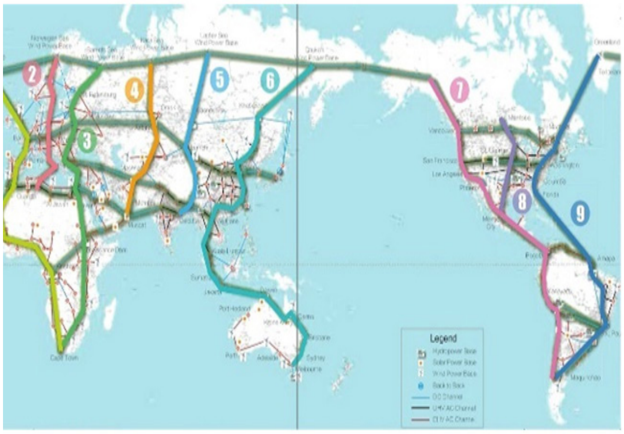


Figure 6 shows a speculative picture of how such a grid could develop by 2070. Components of it include:

1. China's supergrid, connecting inland solar, wind and hydropower to the east coast, already well-developed;
2. A Nordic and North Sea grid connecting hydropower and offshore wind (already partly in existence);
3. A Brazilian supergrid for inland hydropower;
4. Atlantic Wind Connection down the USA's east coast;
5. CASA-1000, connecting hydroelectric power in Kyrgyzstan, Tajikistan, Afghanistan and Pakistan;
6. Egypt-Cyprus-Greece, with an agreement for a 2 GW subsea cable signed in October 2021[xii];
7. IceLink carrying geothermal and hydroelectric power from Iceland to Europe;
8. XLinks' plan to bring 10.5 GW of solar and wind from Morocco via a subsea cable to Spain, Portugal, France and the UK[xiii] ;
9. A supergrid from Australia to southeast Asia and China, possibly beginning with an Australia-Singapore link bringing wind and solar power[xiv];
10. Asian supergrid, linking Japan, Korea, China, Mongolia and possibly Russia, propounded by Softbank's Masayoshi Son;
11. Desertec, bringing Saharan solar and wind power to Europe;
12. Gobitec, connecting Gobi Desert solar and wind to China and Russia;

China has pushed the Global Electricity Interconnection, which would rely heavily on Chinese HVDC and other technology and could include components of XI Jinping's Belt-and-Road Initiative. State Grid Corporation of China, one of the world's largest companies, launched the Global Energy Interconnection Development and Cooperation Organisation to facilitate this vision[xv].

However, many of these connections are of dubious economic or political feasibility. Even relatively limited ones, such as CASA-1000, have struggled to take off. The very limited existing electricity trade even between neighbours such as North Africa and southern Europe may cast doubt on the practicality of long-distance international and multinational lines. Clean energy trade as hydrogen carried by ship may prove to be more modular, scalable, flexible and secure.


## INTEGRATION: THE PRACTICAL REALITIES

Moving ahead, international power connection demands a clear attention to practical details and organisation.

The modes of integration for an interconnected cross-border electricity systems can range from a limited, through a bilateral – unidirectional power trading system, to completely integrated electricity systems. The greater the degree of integration, the greater the opportunity to maximise its benefits, which typically also results in greater operational complexity.

**Table 1. Hierarchy of Integration**

| Limited to Complete Integration | Example |
|---|---|
| Bilateral, Unidirectional Electricity Trade | Electricity Exports from Thailand to Lao PDR |
| Bilateral, Bidirectional Electricity Trade | Bidirectional Electricity Flow between California, US and Baja California, Mexico |
| Multilateral, Multidirectional Electricity between Differentiated Markets | Southern African Power Pool |
| Multilateral, Multidirectional Electricity between Harmonised Markets | European Union Internal Energy Market |
| Unified Market Structure, Differentiated Operations | Nord Pool |
| Unified Market and Operations | Pennsylvania, New Jersey, and Maryland (PJM) Power Pool |

# INTEGRATION: THE PRACTICAL REALITIES

However, in order to choose an appropriate mode of integration, several basic technical and economic issues must be addressed in the early planning process for an electricity grid integration. These technical issues include:

- how the electricity system will operate in a synchronous or asynchronous environment,
- defining the magnitude and direction of the anticipated electricity flow,
- determining the length and span of the electricity system in terms of physical distance and terrain,
- and identifying the key technical and operational differences between the systems to be interconnected.

In addition to the technical considerations, electricity grid interconnections require a careful calculation of costs, benefits, and risks. Interconnection offers both direct and indirect economic costs and benefits.

An example of direct economic benefits to one or all of the countries participating in the interconnection are its opportunity costs, the direct costs avoided by the use of the interconnection.

These avoided costs include the cost of input fuels used in electricity generation, the cost of producing these fuels, capital expenditure on the construction of the electricity generation facilities and their operations and maintenance costs, and the capital and operating costs for any transmission facilities avoided by the interconnection. These benefits accrue to the importer of electricity.

Accruing to the exporter are the direct economic benefits: the revenue generated from electricity sales and the payments received in hard currencies for the export of electricity to other countries. These benefits can be substantial when the cost of generation in the exporter is lower, at least at certain times, or when the country is able to utilise its generation assets at higher levels of capacity. Of course, when interconnected countries are exporting at some points and importing at others, the primary benefit is a lower overall system cost.

The indirect benefits can also include macroeconomic benefits to the national and local economies through the employment of labour that is needed for the construction and operation of the interconnected system. In addition to this, an integrated electricity system may lead to improved electricity supplies, which fosters the development of the local industrial sector, as well as improvements in services such as education and healthcare. This will lead to a "re-spending" effect where an interconnection reduces the prices that end consumers pay for electricity and/or improve its reliability, leaving more disposable income for other consumption, savings, and investment activities.

An interconnected electricity system may boost markets for electricity in one or more of the interconnected countries by further reducing electricity prices. Depending on the mode of integration and how the local institutions are selling the electricity, pricing arrangements are needed to specify what the buyers and sellers will pay and receive for electricity and electric system services that are offered through the interconnection.

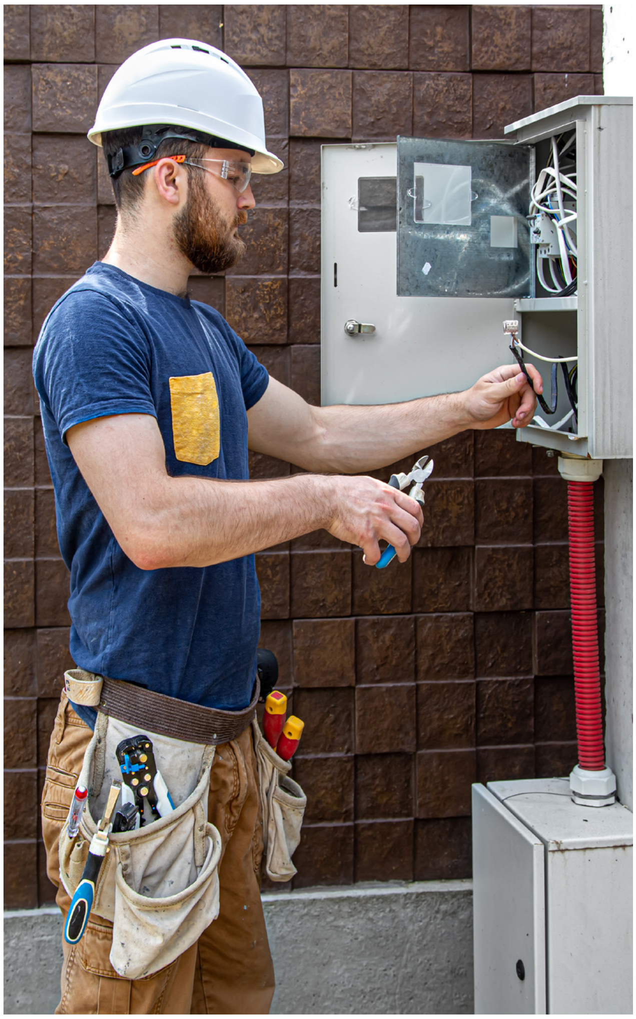
These prices can be based on production costs or avoided costs, or through negotiation, or a market-based pricing mechanism if there are enough buyers and sellers to provide for structured and fair competition.

In the case of long-term sales agreements, pricing arrangements may have escalation provisions to protect sellers from the risks of increases in input fuel costs, and / or assure that the price they receive for the electricity are in line with the price of the competing fuels.

Therefore, to ensure that the economic benefits of an integrated electricity systems are fairly distributed, one of the key considerations is to make sure that the direct costs and the avoided costs of the interconnections is specified as accurately as possible, under the appropriate mode of integration and its overall planning. The degrees of integration for an interconnected electricity system can be categorised as: bilateral, multilateral, and unified.

A bilaterally integrated electricity grid infrastructure allows the trade of electricity across two regulatory jurisdictions, which at times can be unidirectional. An example of this is the exports of hydropower-produced electricity from Lao PDR (Laos) to Thailand. In some cases, the bilateral trade involves an intermediary transit point, such as electricity exports from Laos to Malaysia that transit through Thailand. However, across most regions a bilateral flow of electricity tends to be bidirectional, for example between California and Baja California in Mexico; and between the United States and Canada.

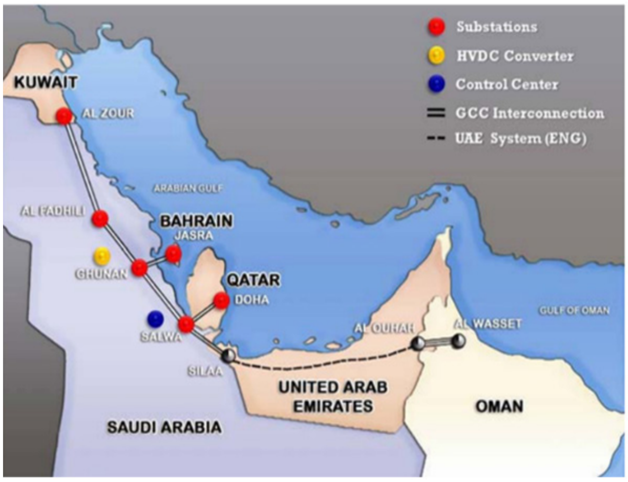
In contrast to a bilateral system, a multilaterally integrated electricity grid infrastructure involves three or more countries that trade electricity among themselves. An example of this is the European Internal Energy Market (EIEM) that operates under a harmonised market and regulatory structure. In contrast to the EIEM, the Southern African Power Pool (SAPP) and the Central American Electrical Interconnection System (SIEPAC) facilitates the trade of electricity between the respective systems under different market structure that are regulated by different jurisdictions. In both cases, the integration is regulated by regional institutions that support the coordination between local institutions, rather than replacing them.



# INTEGRATION: THE PRACTICAL REALITIES

Another example of a multilaterally integrated electricity grid is the GCC Interconnection Grid (GCC-IG) that connects the national grids of six GCC member countries with a total capacity of 2.4 GW. The GCC-IG achieved commercial operations in 2009 with Bahrain, Kuwait, Qatar, and Saudi Arabia initially linking their electricity grids, followed by the UAE and Oman's linking their infrastructure by 2013.

Figure 7 Geographic route of the GCC grid[xvi]

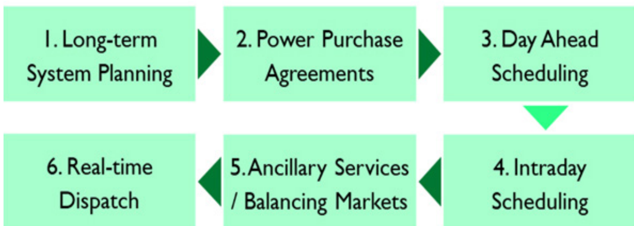



The GCC-IG's primary purpose is to serve as a security mechanism that shares spinning reserve capacity  and the occasional ad-hoc transfer of electricity. In addition to this, there has been a considerable interest in utilising the grid for commercial trade through a regional electricity pool or a spot market. In 2017, a six-month trial period for spot trading began with the aim of developing a commercial platform.

However, a unified electricity grid infrastructure differs from a multilateral model as it allows regional institutions a greater degree of flexibility in managing the electricity system across multiple regulatory jurisdictions. In the United States, the Pennsylvania – New Jersey – Maryland Power Pool (PJM) is the single largest regional electricity system in the world, where system and market operations are managed by a single institution. Comparably, the Nord Pool in Europe is an electricity exchange owned and operated by Euronext and the transmission systems operators of Nordic and Baltic countries. The Nord Pool operates across multiple countries, where each operator maintains full control over its system of operations[xvii].

Besides the degree of integration across various interconnected electricity grids, the level of integration can also extend to ancillary services (such as frequency regulation, contingency reserves, and black-start regulation) and real-time electricity dispatch, or over longer time horizons through long-term system planning through power purchase agreements (PPA). In between these time horizons are elements that may be regulated by market arrangements or inter-regional arrangements, such as the sharing of short-term forecasts or scheduling for the day, week, or month ahead.

Figure 8 Levels of electricity grid integration[xviii]




Most interconnected electricity grids began with increased collaboration on long-term planning, which ultimately led to short-term information sharing for real time planning.

However, the simplest mode of integration is one that allows for collaboration over longer time horizons, which includes harmonising long-term electricity development / expansion plans. The United States' Western Interconnection is a long-term electricity trading system that is managed through PPAs, in contrast to the Western Energy Imbalance Market (EIM) that functions in real time.

Therefore, there isn't a single pathway to achieve an interconnected electricity system. Many models exist but it is difficult to identify a framework of principles that could integrate efforts. Whichever model is adopted, it needs to satisfy the requirements of governance, resource adequacy, and system security.

## GOVERNANCE

Interconnected and integrated electricity grids that operate across multiple regulatory jurisdictions require a governance framework to regulate the process and regulatory institutions that will establish and enforce the rules for the exchange of electricity. Political and governance considerations typically include 1) the dependency on the neighbouring country's regulatory structure, 2) whether the economic benefit from the export of electricity or its input resources present a cost to local economic development, and 3) a desire to develop new resources such as renewable energy generation locally in order to capture its full economic value.

Political institutions enable the cross-border integration of electricity grids across two different segments. Firstly, they support the integration between different external regulatory jurisdictions. Secondly, they support integration efforts within their own territories.

In some cases, a political institution provides explicit approvals. The 35-electricity transmission and distribution interconnections between the United States and Canada are an important component of the North American Power Grid and the United States. The United States Department of Energy (DOE) issued permits for construction, operation, maintenance, and their connection to the transmission and distributions facilities that operate within US borders. These permits are deemed to be of public interest and are a result of recommendations from the Departments of State and Defense.

In order to determine whether the issuance of a presidential permit is in the public interest, the DOE assesses the prospective impact of the project based on the reliability of the electricity supply and its environmental impact. Throughout the process the activities of the DOE are provisioned by the United States Federal Power Act.

Equally, the National Energy Board of Canada operates on the same scope as the DOE, and grants authorisation for the cross-border transmission and distribution of electricity. Currently, 142 presidential permits have been issued of which 100 are for transmission and distribution lines to Canada and 42 are for lines to Mexico[xix].

In contrast to the interconnections and integrations between the United States and its neighbouring countries, the proposed Association of Southeast Asian Countries (ASEAN) Power Grid (APG) Initiative is more of an exercise in demonstrating the bloc's soft power.

There isn't a unilateral governing institution among ASEAN countries that has the authority to develop the distribution and transmission lines, implement the harmonisation of market demand and regulatory framework, or increase cross-border collaboration. However, under the ASEAN Interconnection Masterplan Studies, AIMS Phase I and Phase II, member countries can jointly establish aspirational targets and demonstrate the feasibility of the integration.

Political reasoning for these projects extends beyond the integration of cross-border electricity systems. For example, Thailand does not have to worry about electricity exports from Laos, as the hydropower projects were developed by Thailand's utility company, Electricity Generating Authority of Thailand (EGAT), which also fully owns and operates them. EGAT is a fully owned by the Government of Thailand. Even though Laos earns revenues from these hydropower projects, the country receives a very limited amount of electricity from them and does not have the ability to influence their operations.

Although the arrangement allows Thailand an additional degree of security, for Laos the arrangement is suboptimal, as there are electricity generating assets within its own country that use the local water resource, from which Laos derives a partial benefit.

In recent times, the Government of Laos has emphasised its right to repossess assets on its territory. At the same time, Thailand is also exploring the role of electricity imports in its mix, mainly driven by the need to diversify sources[xx]. It is expected that the governments of Thailand and Laos will agree on moving to a utility trading model over the coming years.

As new energy sources and infrastructure change the balance of power between countries, it will also reconfigure alliances, trade flows, and create new interdependencies between countries. The control of grid infrastructure will become a vital component of the national security consideration and an important component of projecting regional influence and power. Countries that dominate electricity grid infrastructure may exercise undue control over their neighbours, and regional electricity cut-offs could become a strategic foreign policy tool, in a way similar to oil and gas sanctions. Countries that might engage in such cut-offs will be seen as unreliable partners. Multilateral institutions and legal remedies will often be required to encourage vulnerable countries to entrust their energy security to a neighbour in this way.

Furthermore, regulatory institutions play an important role in the cross-border integration of electricity systems. These institutions set the rules for cost sharing and recovery of the infrastructure assets. They define and regulate the market frameworks across various regulatory jurisdictions. And they monitor market participants to prevent anti-competitive behaviour. However, their scope is dependent on whether the electricity system integration occur within the regulator's own jurisdictions or involves multiple regulated jurisdictions.

In the United States, the Federal Energy Regulatory Commission (FERC) is the sole federal regulator whose authority is limited to the transmission system in states where there is a significant interconnection with other states. The states of Texas, Hawaii, and Alaska are excluded from the FERC's regulatory oversight. In addition to the FERC, state-level regulators regulate the distribution systems and the retail markets.

In the EU, despite the existence of the Agency for Cooperation of Energy Regulators (ACER), it is not a formal regulator. The ACER's primary purpose is to encourage and support cooperation among the various regulatory authorities, specifically in areas that are governed under the EU legislation. In the electricity sector, its oversight involves, 1) the preparation and implementation of framework principles and network codes, 2) encouraging the development of regional initiatives, infrastructure, and network development, and 3) implementing and monitoring the Regulation on Wholesale Energy Market Integrity and Transparency.

# GOVERNANCE

The Energy Charter Treaty, which entered into force in 1998, is not an EU institution but it includes every EU member except Italy; it has 53 signatories, therefore including several non-EU countries (Japan, the UK, Ukraine and Russia, for example). It provides a framework for the security of cross-border energy investments, and therefore adds some security to electricity trade between signatories (though it does not apply to trade between two or more EU members).

Moreover, various regions have established reliability institutions that specifically regulate and oversee system security. These institutions play a complementary role to regulatory authorities, mainly in introducing and monitoring the implementation of reliability standards and assessing the overall reliability of supply for the electricity systems.

In the United States, the enforcement of reliability standards is overseen by the North American Electric Reliability Corporation (NERC), which sets the standards for the United States, Canada, and Baja California in Mexico. In contrast to this, the Government of Canada has not established a federal authority to mandate compliance with NERC, which in effect is mandated by each individual provincial government.

In the EU, the European Network of Transmission System Operators for Electricity (ENTSO-E) is responsible for assessing the reliability of the bloc's electricity system. ENTSO-E is mandated to performs periodic resource adequacy assessments and it develops the necessary network codes.
In addition to this, Regional Security Collaborators (RSC) are primarily responsible

for collecting, processing, and sharing information between member transmission and distribution system operators.

It is possible for regions to trade electricity without a long-term bilateral PPA or by simply exchanging electricity. However, electricity trade is best enabled through a market framework, which can occur in a restructured market or a fully integrated regulated market.

Implementing a restructured market structure involves allowing external electricity producers to participate in a local market or a regional market. The EU is a great example of how to develop an advanced multilateral electricity market framework by aggregating varying electricity market structures. The bloc's market restructuring reforms began at the national level and over time evolved to incorporate increased regionalisation and harmonisation, through a process of market coupling that is based on the development of the Nord Pool market. Functionally, these electricity exchanges are distinct but aggregated over time into a common wholesale market. An example of such an exchange is the European Power Exchange (EpexSpot), which is a France-based electricity exchange operating in the UK, Scandinavian and Benelux countries, and Poland[xxi].

In contrast to a restructured market, a regulated market structure involves assessing how the market frameworks can be utilised to enable electricity trading between various utilities, and whether to allow independent power producers (IPP) to operate separately or through various utilities, in a vertically integrated market. An example of a regulated market is SAPP, which consist of 16 member countries, 12 public and vertically integrated utilities, two IPPs, and two private transmission and distribution operators[xxii]. SAPP operates under a market framework where only surplus electricity produced by a member country is traded with the SAPP regional members. In addition to this, electricity can also be traded on short-term emergency basis, in case of unexpected shortfalls.

The SAPP consists of several markets that oversees different aspects of the electricity system. A forward market facilitates the weekly and monthly trade of electricity, the intra-day market allows for participants to auction in real-time, and the day-ahead market enables participants to trade electricity on an hourly-basis for delivery the following day. All three markets are physical markets that ensure the actual delivery of electricity at an agreed time. The day-ahead market is the most critical one since it provides the reference price for the other markets.

Nonetheless, how market frameworks are implemented in practice are dependent on the underlying market structure of the integrated regulatory jurisdictions. These frameworks can be as simple as a bilateral contract or as complex as a regional electricity market that facilitates multilateral electricity exchange.

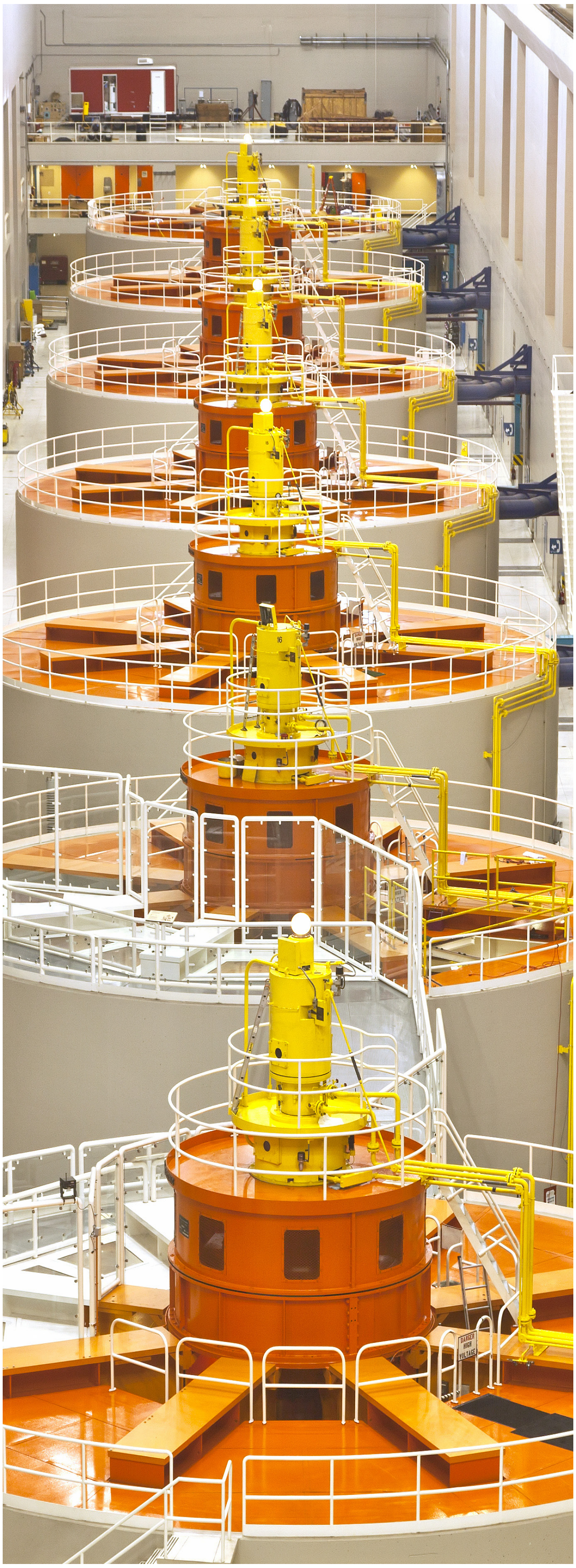
Establishing an interconnected and integrated electricity system is best enabled through the establishment of regional institutions. Despite the varying roles these institutions might be entrusted with, their scope must ensure a simple and predictable supply of electricity, which facilitates short-term flexibility and an optimal use of regional resources.

# SYSTEM SECURITY

In an interconnected electricity infrastructure, the decisions made by its stakeholders could have unavoidable spillover effects in a real time environment, especially when there is no ability to provide advance warning or systems change. In contrast to resource adequacy, system security ensures uninterrupted real time operations, dealing with system stress that is beyond normal operating conditions, and ensuring the necessary reliability protocols are in place.

Even in isolated, standalone electricity systems, uncertainty is a common phenomenon. Operators and utilities have developed a number of tools and protocols for managing it. An example of such a tool is an electricity grid code that define the way electricity generators respond to system changes. However, in an interconnected electricity system, operational responsibilities are divided among multiple operators, which require coordination to ensure reliable operations in real time. Among many aspects of coordination, two are of particular importance; coordinated dispatch, and loop and transit flows. Coordinated dispatch involves multiple system operators sharing dispatch plans a day-ahead, or agreeing to share changes closer to real time. Baltic and Nordic transmission system operators that operate in the Nord Pool are a good example of coordinated dispatch.

In order to improve system efficiency and security, Nordic transmission system operators coordinate the balancing of their reserves through a common resource list and a merit order curve. The information is distributed between all of the transmission service operators, and the use of any specific balancing resource remains completely under the control of the respective operator for the country where the resource is located.



For example, if Norway realises that an electricity generator in Demark is better placed to help a short-term spike in electricity demand compared to a local generator, then Norway's system operator will contact its counterpart in Denmark, who in response will activate the supply / resource. However, despite the coordinated dispatch mechanism helping improve the balancing requirements for the Nord Pool, it still falls short of a common balancing market.

Another important element of system security is loop and transit flows, which involves managing bi-directional electricity flows that originate outside a respective transmission system operator's area of control. Without some degree of real time dispatch coordination, the operator can only respond to the electricity flows requests through their local resources or infrastructure. With the rapid increase in intermittent renewable energy generation, the problem of loop and transit flows has become even more apparent due to increasing renewable energy deployment in some EU countries. During periods of high renewable energy generation, which often has priority access to the grid and close-to-zero marginal operating costs (indeed, often negative operating costs due to subsidies and incentives), surplus electricity is diverted to neighbouring countries.

The problem of loop and transit flows is typically addressed unilaterally either by the operator of the source country or by the utility operator of the impacted system. Operators of the source country have little incentive to tackle the problem, whereas local utilities of the impacted system mainly respond by to re-dispatching generation to other neighbouring countries. In the long term, these utilities are forced to expand their internal network capacity, which involves associated capital costs that must be borne by local electricity producers and consumers. However, when electricity flows are large and cannot be re-directed, such a scenario forces the local utility to curtail local electricity production, therefore allowing for an unscheduled import of electricity.

Another method of tackling the loop and transit problem is by restricting the cross-border flow of electricity through phase shifters or by increasing local transmission capacity. In case of the former, a phase shifter allows the system operator the choice to restrict or allow the flow of electricity through an interconnector. In doing so, the burden of the loop and transit flow problem is pushed back onto the system of origin operator, forcing it to take operational measures to balance its own system. However, by increasing the local transmission capacity allows for continued absorption of loop and transit flows without curtailing local generation. This also shifts the cost burden from the source country to the recipient country, where the former receives the benefit but does not share the cost.

Furthermore, all electricity systems are susceptible to various degrees of stress levels that are beyond normal operating conditions. These periods of stress can last for an extended period, for example, through an unexpected breakdown in the electricity generating capacity; or can be short in duration but significant, such as because of an extreme heatwave or snowstorm. In either case, inter-regional coordination is essential for ensuring stable operations. In some cases, direct intervention may be required.

# SYSTEM SECURITY

The winter of 2017 / 2018 in Japan is an example of how central institutions play an important role in ensuring system stability during periods of stress. Although the day-to-day balances of the electricity system is the responsibility of the local utility across the respective prefecture in Japan, the Organisation for Cross-Regional Coordination of Transmission Operators (OCCTO) is authorised to coordinate system operations between interconnected electricity systems.

In early January 2018, parts of Japan experienced heavy snowfall particularly in areas covered by the Tokyo Electric Power Company (TEPCO). This led to a temporary halt in generation from 1.7 GW of solar PV. Towards the end of the month temperatures further decreased, which led to demand increasing to 56 GWh per day. As result of this event, TEPCO responded by activating its available reserves and acquired an additional 10 GWh of available resource from neighbouring prefectures that operated in a different regulatory jurisdiction, in coordination with the Organisation for Cross-Regional Coordination of Transmission Operators (OCCTO)[xxiii]. When the 10 GWh remained insufficient, OCCTO reintervened to deliver an additional 12 GWh.

Recently, in September 2021, the 2 GW Interconnexion France-Angleterre (IFA) interconnector between the United Kingdom and France went offline as result of a fire at a converter station on the UK side of the link, which led to a partial outage. To ensure system stability and meet the evening demand peak, the UK National Grid ESO responded by activating a 645 MW bioenergy generator and a 450 MW coal fired generator.

The outage contributed to electricity prices reaching a record high, with the day-ahead market delivering at £ 2,500 / MWh for some hours.

Although establishing a common reliability framework is not a fundamental requirement of an interconnected electricity system; at the very least, a common understanding of protocols and when they must be followed in a synchronised electricity system is very important.

**Table 2. Selected Outages in Interconnected Electricity Systems**

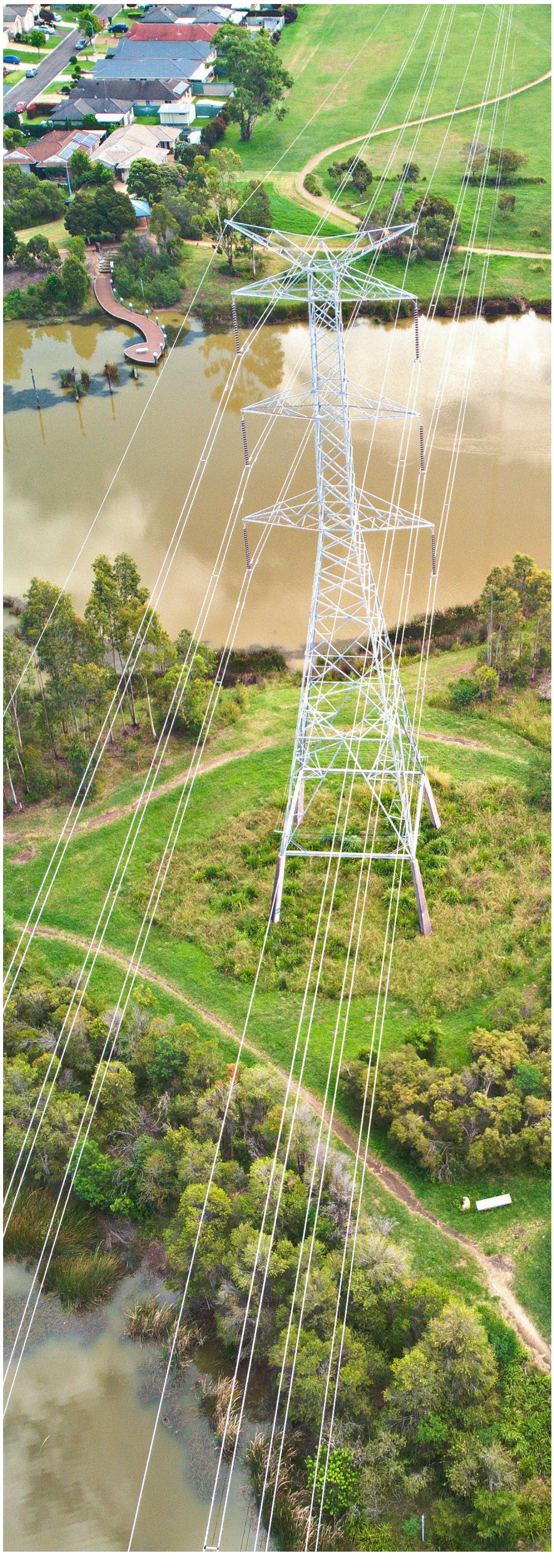
| Year | Affected System (number and regions) | Population Affected (million) | Cause of Outage |
|---|---|---|---|
| 2001 | Seven (Indian states) | 230 | Failure of a substation in Uttar Pradesh |
| 2003 | Five (United States and Canada): Ontario, MISO, PJM, NYISO, ISO-NE) | 50 | Plant outage, line failure in Ohio |
| | Three (Western Europe): France, Italy, Switzerland | 56 | Transmission line failure in Switzerland |
| 2006 | Seven (Western Europe): France, Germany, Netherlands, Belgium, Italy, Spain, Portugal | 15 | Human error at a substation |
| 2009 | Two (Brazil and Paraguay) | 87 | Loss of key high-voltage transmission lines in Brazil |
| 2012 | Nine (Indian states): | 620 | Circuit breaker trip, line failure and relay problem |

Source: International Energy Agency (IEA)

In 1965, an electricity outage on the interconnected system between Canada and the United States led to the establishment of the North American Electric Reliability Council (NAERC), which developed a framework of reliability protocols for its member utilities. At the time, these protocols were voluntary and lacked an enforcement mechanism. Over the following decades, the United States experienced a number of multiregional blackouts.

In 2003, following a major blackout that affected 50 million people in Canada and the United States, the efficacy of these protocols was revisited. And a government legislation was passed that led to the establishment of a national electricity reliability corporation, the NERC, that enforced mandatory standards.

Therefore, system security of an integrated electricity system ensures stable real time and short-term operations, and is best managed by a reliability institution that enforces the necessary protocols and standards under a customised framework in dealing with coordinated dispatch, the loop and transit problem, and system stress.



# RESOURCE ADEQUACY

An important element of developing an interconnected electricity grid connection is resource adequacy, which involves sufficient investments in expanding the generation, transmission, and distribution capacity to meet the long-term needs of the system, which falls under the purview of the local jurisdiction.

Planning for resource adequacy has significant implications that are similar to system security and require careful thought in terms of collaboration and coordination on regional planning, allocation of interconnector capacity, and the exchange of electricity across borders.

Electricity system planning can occur through a voluntary or a formally mandated mechanism. For instance, the Regional Power Grid Consultative Committee (RPGCC) of the Greater Mekong region is a good example of an ad-hoc voluntary process. RPGCC's membership consists of 5 ASEAN member countries and Southern China, and the committee is supported by the Asian Development Bank (ADB). Some of the RPGCC's plan are ambitious, which notably include the establishment of a regional control centre.

However, most of the committee's meetings are focused on the integration of the electricity system, and specifically the construction of the connecting transmission and distribution infrastructure. Also, the information shared between the RPGCC member countries is high-level and the group lacks a framework to aggregate these plans and incorporate them into a local strategy. Despite the significant levels of collaboration, the absence of a regional electricity market means there is little incentive for collaborative planning on a multilateral basis.

In contrast to the RPGCC, the SAPP follows a formally mandated process and is responsible for collecting and aggregating federal electricity development plans of each member country, through which it compiles a list of projects that are categorised based on priority. That list is eventually shared with the Southern African Development Community (SADC) Secretariat, which takes into consideration the priorities highlighted by SAPP and formulates the Regional Infrastructure Development Master Plan[xxiv].

Similar to SAPP, in the EU, regional planning is conducted by ENTSO-E through a Network Development Plan (NDP), which is outlined every ten years. The NDP process begins with member countries submitting their national plans to the ENTSO-E, which aggregates them

and develops a single strategy. A key function of NDP's strategy is the identification of Projects of Common Interest (PCI) that are identified twice every year and are eligible to receive additional financing from the European Commission.

Moreover, another component of resource adequacy planning is the equitable and efficient allocation of the interconnector capacity. The most common method to measure the interconnecting capacity is Net Transfer Capacity (NTC), which is the surplus transfer capacity between two interconnected areas for further commercial activity beyond the committed utilisation of the transmission and distribution networks[xxv].

However, the actual transmission capacity available in real time depends on the system conditions, which is why some regions are moving towards a flow-based approach. This approach takes into account actual potential and modelled system conditions, and the topology of the grid on both sides of the interconnector when estimating the available capacity.

Regardless of the approach, the interconnector capacity calculated can be on a non-firm or firm basis. In case of the latter, the access to the capacity is capped to the allocated amount, whereas if it is on a non-firm basis, the transmission and distribution access is not guaranteed.

Non-firm access makes it difficult to exchange electricity as the access to market is dependent on sufficient real time transmission capacity. In such a scenario, producers minimise their risks by exchanging electricity during off-peak hours when the interconnecting capacity is less restricted, prices are low, and the risk of additional generation may be diminished.

In Japan, interconnector capacity has typically been allocated on a first-come-first-served basis, where local utilities were able to reserve transmission and distribution capacity for up to ten years, thus restricting access for other utilities. However, in order to encourage market access, interconnector allocation moved to an implicit auction system. Under this system, utilities are awarded transmission and distribution capacity based on the order in which they clear the spot market, which is capped to the available amount of capacity at the time.

Explicit auction systems, in contrast to an implicit system, consist of auctions that are conducted on monthly or annual basis, in order to ensure long-term access to the transmission and distribution capacity. However, explicit systems are known to create inflexibilities, specifically by allocating capacity that could potentially be utilised in real-time.

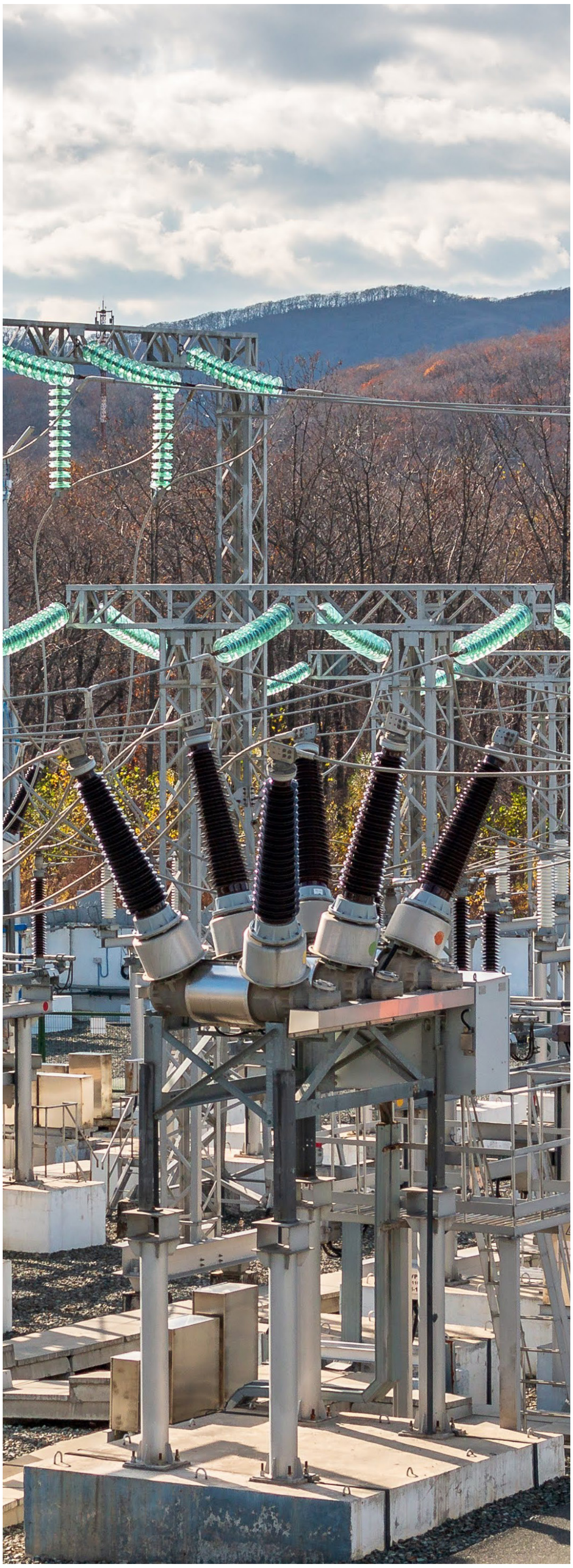
Trading of electricity generating capacity is another way of contributing to the resource adequacy requirements of another regulatory jurisdiction, in addition to the actual exchange of electricity. Usually, the dispatching country has control of the electricity generating capacity, as in the case between Thailand and Laos. However, for capacities that are outside the actual ownership of the receiving country, the exchange of generating capacity is limited to the lack of visibility and lack of operational control.

These constraints can be tackled through a long-term bilateral PPA that allocates capacity and ownership of the transmission and distribution infrastructure. For instance, in the PJM Power Pool, if an external utility wishes to sell its capacity to PJM, it must 1) demonstrate its ability to supply network capacity in the local regulatory jurisdiction, 2) meet all the tests for capacity testing, 3) have a letter of non-recallability, and 4) must agree to be treated as having electronically moved to PJM's service territory.

The letter of non-recallability ensures that the electricity supply will not be curtailed by the capacity operator. The last two criteria allow the utility to remove itself from the control of the local system operator and pass operational control to PJM.

Nonetheless, regional electricity planning should look at the overall resource adequacy of the interconnected system. And once the interconnectors are constructed, it is important to agree on how to measure and allocate interconnector capacity.

In an ideal scenario, all utilities should agree on a common interconnector calculation approach, which should be allocated across multiple time frames and regulatory jurisdictions to ensure a reliable supply of electricity, and also enables the optimal utilisation of the interconnector capacity in real time. This will determine an effective allocation of the interconnector capacity for utilities that wish to exchange electricity generating capacity across multiple regulatory jurisdictions.



## IMPLICATIONS

There are various examples of integrated and interconnected electricity systems around the world. However, the fundamental question is not whether regulatory jurisdictions should integrate their electricity systems, but how can an effectively planned and implemented integrated electricity system maximise its benefits and minimise its potential risks.

Cross-border integration of electricity systems has various implications in terms of economic growth, security, and environmental impact of the electricity system. In most cases, these implications are positive: reduced electricity tariffs, an increase in security, and a reduction in the environmental impact. However, integration also brings with it economic and security challenges, some of which relate directly to the environmental benefits.

For some stakeholders, the interconnectivity of the electricity system can be challenging as some entities will benefit more than others. The wider challenge of the interconnected system is to how best to allocate the benefits across market participants, specifically in terms of investment and operational costs related to the cross-border transmission and distribution infrastructure.

In terms of system security, the main challenges include managing expectations in achieving self-sufficiency or energy independence, that is to say individual participants should not fully rely on electricity from their neighbours. Secondly, the coupling of the electricity systems across different regulatory jurisdictions increases the risk of a major power outage that could have a spillover effect in other interconnected areas. And thirdly, synchronised electricity systems must develop the capability to deal with unexpected electricity flow, i.e. the loop and transit flows problem, which is expected to be a greater challenge as electricity mixes increasingly incorporate intermittent renewable energy.

Therefore, policymakers and utilities should deliberate cross-border collaboration across a wide range of areas that extend beyond governance, system security, resource adequacy, and use of technologies. In any case, the role of regulatory institutions will be important, specifically in integrating systems across borders without compromising on local autonomy, through a balance between regional and local priorities. These considerations will be absolutely necessary in realising the full benefits of an integrated and interconnected electricity system.

# CONCLUSION

The history of electricity systems is driven by expansion. The main driver of this expansion has been economics, specifically the reduction of overall investment and operational costs of the system. Interconnected electricity systems can also bring with them security and environmental benefits in terms of integrating their shares of intermittent renewable energy sources.

Economic growth, environmental imperatives, and improvements in long-distance transmission technology, have created the potential for greatly expanded international energy trade. Yet this potential has still to be realised, with growth in electricity exports running only slightly ahead of consumption growth since 1980, and trade effectively flat since 2011. A step change in international and, especially, intercontinental energy trade will require much more effective governance, with attention to security, political, commercial and legal concerns.

The practical job of connecting an electricity system involves a wide range of considerations, which include cooperation on system planning, grid synchronisation, coordination of system operations, integration of electricity markets, and the consolidation of regulatory plans and policies. These considerations have implications in terms of system security, resource adequacy, and governance.

Depending on the mode of integration, an interconnected electricity system must be administered by a governance framework that directs regulatory institutions and their supporting reliability institutions in regulating exchange of electricity in a restructured or a fully integrated market structure. The scope of these directives ensures system security and their long-term resource adequacy needs.

System security involves maintaining uninterrupted real time operations, dealing with system stress beyond normal operating conditions, and ensuring the necessary reliability protocols are in place to tackle them. Among many aspects that threaten system security, the two that are of particular importance are coordinated dispatch, and the loop and transit flow problem.

Coordinated dispatch can be managed by system operators sharing dispatch plans a day-ahead or agreeing to share changes closer to real time. And loop and transit flow involve managing bi-directional excess electricity flows that originate outside a respective transmission system operator's area of control.

In addition to system security, an important element of developing an interconnected electricity system is resource adequacy, which

involves joint coordination and planning in expanding the generation, transmission, and distribution capacity to meet the long-term needs of the system.

Electricity system planning can occur through a voluntary or a formally mandated mechanism and involves ensuring the equitable and efficient allocation of the interconnector capacity, and the exchange of electricity supply and / or electricity generating capacity.

Another key factor in determining the success of an interconnected electricity system is the role of new technologies in transmitting and distributing electricity over longer distances and between different electricity grids. These technologies are likely to factor in national policies and system governance in terms of the cost of interconnections over long distances, connecting asynchronous grids, connecting remote resources, and accommodating variable renewable energy generation.

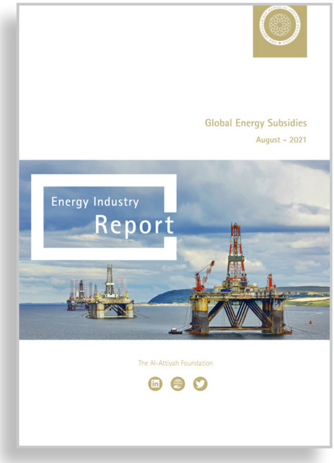
Therefore, policymakers and utilities should carefully deliberate cross-border collaboration across a wide range of areas, including governance, system security, resource adequacy, and use of new technologies in order to realise the full benefits of an interconnected electricity system.

## APPENDIX

**i. International Energy Agency, Learning from the Blackouts: Transmission Systems Security in Competitive Electricity Markets, 2005**
**ii. Data from https://oec.world/en/profile/hs92/electricity**
**iii. Data from https://www.eia.gov/international/data/world/electricity/electricity-imports**
**iv. Data from https://oec.world/en/profile/hs92/electricity**
**v. https://spectrum.ieee.org/lets-build-a-global-power-grid**
**vi. National Grid, North Sea Link: Connecting the UK (Blyth) to Norway (Kvilldal)**
**vii. National Grid, The World's Longest Interconnector gets Underway, March, 2015**
**viii. Reuters, Japan Considers Doubling Inter-regional Power Grid to Boost Renewable Energy, April, 2021**
**ix. Power Technology, China's Mega Transmission Lines, March, 2019**
**x. Nexans, Subsea Interconnectors, (https://www.nexans.com/business/power-generation-transmission/subsea-interconnectors)**
**xi. https://chinadialogue.net/en/energy/10722-the-risks-of-a-global-supergrid/**
**xii. https://www.bloomberg.com/news/articles/2021-10-13/egypt-set-to-agree-on-electricity-link-up-with-greece?sref=IUPsko0S**
**xiii. https://www.ft.com/content/d3b8947a-bdb1-445e-80f7-a19b51dd977d**
**xiv. https://www.bloomberg.com/news/articles/2021-09-23/outback-to-singapore-solar-power-bid-clears-indonesia-hurdle?sref=IUPsko0S**
**xv. https://chinadialogue.net/en/energy/10722-the-risks-of-a-global-supergrid/**
**xvi. Hassan K. Al Assad, GCC: The Backbone of Power Reform (www.gccia.com.sa)**
**xvii. The Nord Pool, (https://www.nordpoolgroup.com/)**
**xviii. Internal research and analysis**
**xix. United States Department of Energy, Presidential Permits, (www.energy.gov/oe/services/electricity-policy-coordination-and-implementation/international-electricity-regulatio-3)**
**i. Electricity Generating Authority of Thailand (EGAT), Thailand Power Development Plan 2015 – 2036, Energy Policy and Planning Office**
**xx. EPEX SPOT, (https://www.epexspot.com/en)**
**xxi. Southern African Power Pool, (http://www.sapp.co.zw/)**
**xxii. ISEP – Energy Chart, Heavy Snow in TEPCO Area on 22nd January 2018, January, 2018**
**xxiii. Southern African Development Community (SADC), Regional Infrastructure Development Plan, August, 2012**
**xiv. ETSO-E, Net Transfer Capacities and Available Transfer Capacities in the Internal Market of Electricity in Europe (EIM), User Guide (https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/ntc/entsoe_NTCusersInformation.pdf**

# PAST ISSUES

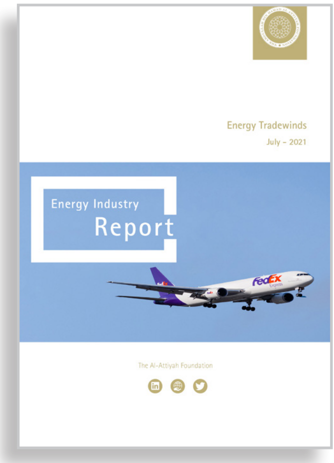
Have you missed a previous issue? All past issues of The Al-Attiyah Foundation's Research Series, both Energy and Sustainability Development, can be found on the Foundation's website at **www.abhafoundation.org/publications**




## August – 2021
### Global Energy Subsidies

Energy products are commonly subsidised in both industrialised and developing countries for a host of reasons, even as governments face increasing pressure for energy policy to converge around efficiency, sustainability, affordability, and access.

(QRCO.DE)




## July – 2021
### Energy Tradewinds

The aviation and shipping industries are widely considered to be hard-to-abate sectors. Some technological solutions, and fuel sources to decarbonise these sectors have been developed but require urgent implementation if emission targets are to be met.

(QRCO.DE)


## June – 2021
### New Strategic Commodities

The rise of new energy systems and progressing transition to low-carbon energy sources draws attention to emerging strategic resources. These resources include critical minerals lithium, copper and rare earths required in renewable energy systems.

(QRCO.DE)

# OUR PARTNERS

**The Al-Attiyah Foundation collaborates with its partners on various projects and research within the themes of energy and sustainable development.**

Barzan Tower, 4th Floor, West Bay, PO Box 1916 - Doha, Qatar

Tel:  +(974) 4042 8000, Fax: +(974) 4042 8099
www.abhafoundation.org

AlAttiyahFndn
The Al-Attiyah Foundation