Analytical Frameworks for Electricity Security

International Energy Agency

Electricity Security 2021

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Abstract

Given the salient role that electricity plays in modern economies, the task of ensuring electricity security is a top priority for policy makers. The process is an extensive and complicated one that involves careful consideration of costs and benefits. This chapter summarises the steps involved in developing a framework for electricity security. It defines outages, describes approaches to assessing how much they cost, and outlines the institutional responsibilities to prevent and/or react to them. In doing so, it lays out the existing approaches available to policy makers and the challenges they face in creating electricity security frameworks, including clarifying the costs and benefits, establishing reliability planning structures, and assigning institutional responsibility for various tasks. It then previews how policy makers and other stakeholders need to adapt frameworks for electricity security in the face of major trends affecting the sector – namely, the clean energy transition, cyberthreats and climate change.

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Executive summary

Aiming for reliability

Given the essential role that electricity plays in modern economies, the task of ensuring electricity security is a top priority for policy makers. Not only is electricity demand growing faster than overall energy demand globally, driven by increased electricity access and electrification, but electricity also has critical linkages with other parts of the energy sector, underpinning basic activities in the residential, commercial and industrial sectors.

This chapter defines outages, describes approaches to assessing how much they cost, and outlines the institutional responsibilities to prevent them. In doing so, it lays out the existing approaches that policy makers have available and the challenges they face in creating electricity security frameworks, including clarifying the costs and benefits, establishing reliability planning structures and assigning institutional responsibility for various tasks.

Electricity has a fundamental and intensifying role in our economy, implying that the impacts of an outage extend far beyond the power system. Power interruptions can trigger many incidents, ranging from the inconvenient to the life-threatening, for example people trapped in lifts, trains and underground transport, death and illness due to high temperatures from loss of air conditioning, and higher mortality in hospitals when backup supply fails. Moreover, the potential indirect impacts of electricity supply interruption are also enormous: transport disruption, food safety issues, crime and riots, and loss of economic activity, to name but a few.

It is important to establish a basic definition of electricity security and understand how the concept is evolving due to trends underway in the sector. The IEA defines electricity security as the electricity system's capability to ensure uninterrupted availability of electricity by withstanding and recovering from disturbances and contingencies. Many systems are seeing a growing share of variable renewables in the power supply as governments seek a cost-effective, low-carbon electricity mix, complemented by large potential for more demand response. All segments of the electricity system, from conventional plants to distributed PV, electric vehicles and aggregated demand response, face new challenges related to cybersecurity. And from the perspective of climate change and extreme weather events, all electricity infrastructure will become more vulnerable to disruption. These themes are rarely addressed through the same lens in an integrated manner.

The impacts of an outage depend on a range of factors, including timing, extent of damage, location, number of consumers and consumer segments affected, duration, and frequency of occurrence. At a basic level, outages can be categorised as: 1) cascading blackouts or black system events; 2) load-shedding; and 3) long rationing periods of electricity.

Policy makers can use different approaches to monetising these impacts. The economic value of a unit of electricity is linked to the welfare and benefits that households and firms derive from electricity consumption during a specific period of time. A useful metric is the value of lost load (VoLL), which assesses the economic impact of a power supply disruption by measuring the resulting lost economic output. The economic impact will depend on a number of factors such as the affected consumer group and the time, duration, frequency and season of the disruption. VoLL is useful to evaluate direct costs associated with limited amounts of energy not supplied, but is not fully reflective of all the costs of interruption, especially for high-impact events.

Various institutions are involved in providing electricity security and guiding the complex interactions between numerous stakeholders to maintain a well-functioning and reliable power system. The operation of the electricity system involves a diverse set of actors and varies considerably both within and between countries. Moreover, institutional roles increasingly need to shift in response to changing trends in the electricity sector, including the energy transition, cybersecurity and climate change.

Electricity becomes ever more crucial for our society

Globally, electricity demand has been growing faster than overall energy demand. The power sector accounted for around half of the growth in global energy demand in the past decade. In the IEA Stated Policies Scenario, electricity's share of final energy consumption is projected to rise from 19% today to 24% in 2040. Most of this growth comes from developing economies due to increasing income levels and growth in the industrial and service sectors. Growth in advanced economies due to electrification is partially tempered by improved energy efficiency. In the IEA's Sustainable Development Scenario, the role of electricity becomes even stronger, reaching 31% of final energy consumption by 2040. While the share of electricity in final consumption is less than half that of oil today, it overtakes oil by 2040 under the Sustainable Development Scenario.

The growing share of electricity in final energy demand does not even fully capture its importance. Electricity has critical linkages with other parts of the energy sector. It also underpins the basic activities of the residential, commercial and industrial sectors. As electricity commands growing shares of heating, cooling, transport and many digital sectors of communication, finance, healthcare and others, the need for adequate electricity security will intensify in the coming years.

Electricity security comprises many elements

Electricity security is often referred to by the term “security of supply”, or the more literal phrase, “keeping the lights on”. The eventual goal is to provide electricity to consumers reliably. There are many threats to meeting this objective, ranging from equipment failure, fuel supply shortages and operational planning failure, to human error and deliberate attacks.

The IEA applies the following definition:

“Electricity security is the electricity system’s capability to ensure uninterrupted availability of electricity by withstanding and recovering from disturbances and contingencies.”

This definition covers several properties, notably operational security, adequacy and resilience. While this is a broad definition covering many properties, it also excludes some elements. Electricity security does not directly include affordability or sustainability, although they should be explored alongside it.

Table 1. Key electricity security terms and definitions

Term	Definition
Operational security	The ability of the electricity system to retain a normal state or to return to a normal state after any type of event as soon as possible.
Adequacy	The ability of the electricity system to supply the aggregate electrical demand within an area at all times under normal operating conditions. The precise definition of what qualifies as normal conditions and understanding how the system copes with other situations is key in policy decisions.
Resilience	The ability of the system and its component parts to absorb, accommodate and recover from both short-term shocks and long-term changes. These shocks can go beyond conditions covered in standard adequacy assessments.

Term	Definition
Reliability	A metric for the historic or projected availability of electricity supply within a region under all conditions.
Robustness	The capability of the electricity system to avoid extreme adverse impact. Note: This is not the same as resilience. Robustness is about avoiding impact, but not necessarily by adapting. Resilience can refer to situations with substantial negative impact, but where the system could overcome this, possibly by adaptation.
Stability	The property of the electricity system to maintain the state of operational equilibrium and to recover from disturbances on very short time scales (a few seconds or less). Note: The difference with operational security is that stability always refers to pure electrical disturbances and a return to equilibrium. Security is more general and can cover equipment failure, and does not necessarily imply a return to equilibrium but to within acceptable limits.

Sources: European Commission JRC, CIGRE, IEA Electricity Security.

Ongoing changes to electricity systems will have far-reaching implications for all elements of electricity security. Many systems are seeing increasing shares of variable renewable supply as governments seek a cost-effective low-carbon electricity mix, complemented with large potential for more demand response. This has implications for operational security, future capacity and the flexibility investment needs of the system. All segments of the electricity system, from conventional plants to growing shares of distributed PV, electric vehicles and aggregated demand response, face new challenges related to cybersecurity. From the perspective of climate change and extreme weather events, all electricity infrastructure will become more vulnerable to disruption, although solar PV and wind may actually be the most resilient elements compared to thermal plants and grid assets. As such, electricity security in the future will bring together actions taken at the technical, economic and political levels to maximise the degree of short- and long-term security in a simultaneous context of the energy transition, cyber events and climate impacts.

The themes covered in this report are rarely addressed through the same lens in an integrated manner. From a detailed technical perspective, issues such as market design, system stability, cybersecurity or physical resilience may be addressed as separate disciplines. For policy makers, however, they do cover similar questions, including how reliability is defined as a measurable objective, which organisations carry which responsibilities, and how appropriate incentives are given to the sector to ensure adequacy with a diverse generation mix and sufficient transmission and distribution networks.

Large-scale outages can have substantial societal and political impacts

Unsurprisingly, given the central role of electricity globally, even rare, isolated power outages can have far-reaching effects. Power interruptions can prompt many incidents, ranging from the inconvenient to the life-threatening, such as people trapped in lifts, trains and underground transport, death and illness due to high temperatures from loss of air conditioning, and higher mortality in hospitals when backup supply fails.

The potential indirect impacts of electricity supply interruption are also enormous and include transport disruption, food safety issues, crime and riots, and loss of economic activity. This can lead to health and safety problems as well as substantial financial losses. In extreme cases where power outages relate to extreme natural events, loss of electricity supply exacerbates other recovery challenges, making restoration of the power system one of the earliest priorities.

As electricity is a regulated good and most often designated as critical infrastructure, governments are generally held accountable for the reliability of power supply. A large-scale blackout or generally low reliability (or the perceived risk of it) can have strong political implications. Frequent and ongoing blackouts have also been connected with social and political unrest in some regions. This adds complexity to questions around how reliability is valued in planning, as governments and responsible organisations may have an incentive to maximise reliability beyond the point of pure economic efficiency or take a very risk-averse position.

The political sensitivity of electricity supply risks can also complicate the energy transition agenda. Perceptions of security concerns linked to higher contributions from variable renewables, higher levels of demand response and wider digitalisation can lead to pushback on clean energy solutions. This is highlighted by several blackouts such as those in South Australia in 2016 or the United Kingdom in 2019, when renewables plants were involved and triggered a fundamental review of how the system is operated. Even though the underlying technology or variability of infeed was proven not to be the main cause, they were presented in the media as supposedly illustrating the unreliability of renewables.

This underlines the challenges of formulating a balanced policy on electricity security – the topic is fundamentally complex and touches on many highly technical aspects, but at the same time is commonly politicised and communicated in the public sphere in an overly-simplified way, at times misrepresenting reality. This only emphasises the need for rigorous analysis to underpin decision-making to ensure reliability.

Defining electricity outages

Electricity outages vary in their characteristics and impacts

Electricity supply disruptions have varying economic impacts depending on their magnitude, duration and number of consumers affected. As electricity consumption is directly related to the productive activity of households and companies, the amount of unsatisfied electricity demand has to be taken into account to fully assess the economic impact of a disruption.

It is important for policy makers to differentiate between different types of outages, as they have different causes and affect society in different ways. Enhancing electricity security requires an understanding of the different causes and the magnitude of impact of power supply interruptions. The following is a categorisation based on the causes and magnitudes of the events.

1) Cascading blackouts or black system events occur when an initial outage causes the system to collapse from an increasing series of line overloads. These events affect all customers on the network, except those with backup generation, during a period from hours to days before full restoration. Social damage is significant as a black system event affects many essential services, such as payment systems, telecommunications and traffic lights. These events are mostly due to equipment failure and simultaneous contingencies, and are very rarely related to lack of installed generation capacity. The Hokkaido blackout in Japan in 2018 due to an earthquake and the South Australian blackout in 2016 due to a mix of severe storms and flawed interconnection standards are recent examples.

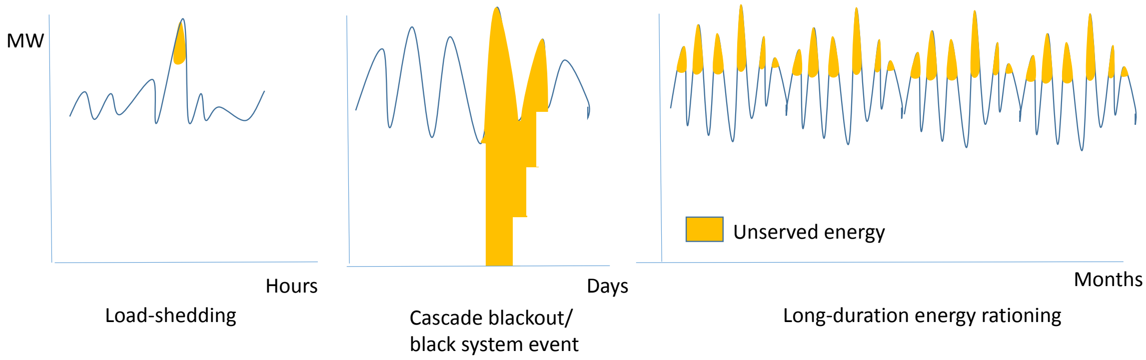
The potential indirect health, safety and financial impacts of blackouts are also enormous and include: transport disruption (the unavailability of trains and charging stations for electric vehicles); food safety issues (risks to refrigeration); problems related to public order (crime and riots); and loss of economic activity. In cases where power outages relate to extreme natural events, loss of electricity supply exacerbates other recovery challenges, making restoration of the power system one of the earliest priorities.

2) Load-shedding is the deliberate disconnection of electrical power in part of a power system. It is a preventive measure taken by system operators to maintain system balance when supply is currently or expected to be short of the amount needed to serve load plus reserves, after exhausting other options like tapping demand response, emergency supplies and imports. These are short-duration events lasting from minutes to a few hours, where small amounts of energy are rationed to segments of consumers (1-2% of the unserved energy during a cascading blackout), while allowing loads that provide essential services to continue to be served. They are, from a consumer point of view, indistinguishable from other interruptions on the distribution grid. The anticipated, controlled and limited use of this extreme measure should be seen as an instrument to maintain security of supply.

Most current reliability standards target a level of supply that would expect a small amount of acceptable load-shedding as a way to balance security of supply and economic considerations. For example, the Alberta system operator in Canada has needed to apply this type of interruption in three events between 2006 and 2013, with a total duration of 5.9 hours and an amount of energy well within the regulatory (reliability) standard. Even if load-shedding results only in small amounts of energy not being served, it completely cuts power supply to certain groups of customers, creating an array of inconveniences. To share the damage and minimise the inconvenience, the power cuts are often "rolled", switching from one customer block to the next. In the near future, digitalisation should allow power systems to phase out this small but drastic and inefficient way of rationing energy. This would cut energy only to non-essential appliances or storage-enabled devices, and maintain it for other uses where interruption would create more inconvenience, such as lifts.

3) Long rationing periods of electricity occur when system operators and governments have to limit power supplies on a planned basis because of large deficits of electricity supply to meet demand. This is possibly the most harmful type of power sector event that a society can face. Some long-duration rationing events have entailed rationing as much as 4-10% of annual electricity consumption, creating large social and macroeconomic impacts. They include the event in Brazil in 2001 caused by drought and an unfavourable investment framework. The large supply shock in Japan following the Great East Japan Earthquake also falls under this category, when the government responded with a nationwide electricity conservation campaign that forced industry to make massive electricity demand shifts.

Figure 1. Depiction of different types of outages by duration and energy unserved



Many emerging economies such as Iraq and South Africa see their economic and social welfare severely impacted by recurrent periods of electricity rationing that can last many months. Although developed economies have solved this type of event due to sound investment frameworks, it remains a challenge for many developing economies, even as some countries such as India have made great strides in overcoming such events. Nonetheless, this is not a dimension that developed economies should take for granted, and investment frameworks need to be updated and responsive to new trends.

Examples of past outages highlight the range of outcomes

A set of examples of interruptions, ranging from small, preventive and exceptional load-shedding events to large-scale incidents with an impact for many months, illustrates the range of incidents and outcomes that are possible. A longer, more detailed list of large-scale outages is provided in the Appendix.

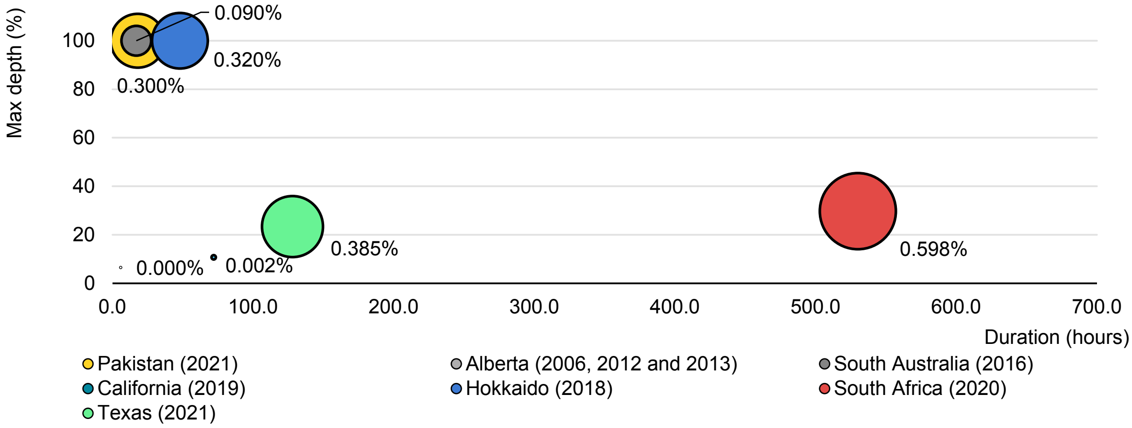
Table 2. Selected electricity supply interruptions and their impact in duration and energy not supplied

Location and type of interruption	Scale	Duration	Energy not supplied	Economic impact	Types of policies to be considered
Alberta, Canada (events in 2006, 2012 and 2013) **Short-term load-shedding – exceptional preventive interruptions to avoid cascade blackout**	Small area automatically isolated; affecting ~6.5% of load, usually not including essential facilities and services	5.9 hours (over three events)	972 MWh (over three events) 0.00001% of energy consumption	USD 9 720 000 (over three events)	Operational reserve procurement
South Australia (2016) **Cascade outage and black system event**	State-wide outage	Full blackout for 3 hours. After 7.5 hours over 80% of load was reconnected. Full reconnection of all load took about a day	10-13 GWh (estimated) 0.09% of annual state energy consumption	USD 271 million	Grid code review, in practice also triggered full electricity market review
California, United States (2019) **Preventive disconnections – transmission lines shut down to prevent wildfires**	Affecting ~10.7% of PG&E customers, including several essential services (e.g. traffic lights)	3 days	0.0016 % of PG&E annual delivered energy 102 000 MWh	USD 1 billion	Vegetation management, undergrounding lines, distributed resources as backup
Hokkaido, Japan (2018) **Cascade blackout and black system event**	Whole interconnected system in Hokkaido, affecting 100% of customers, including several essential services	48 hours for 99% restoration	100 GWh (estimated) 0.30-0.35% of Hokkaido's annual energy consumption	USD 1.4 billion	Stronger interconnection, grid code review, operating reserves procurement, improved black start and system restoration procedures

Location and type of interruption	Scale	Duration	Energy not supplied	Economic impact	Types of policies to be considered
South Africa (since 2007, including estimates for 2020) **Recurring rolling black-outs**	Load-shedding implemented in 6 stages depending on the shortfall; 1 000 MW per stage 2019 saw the worst impact, shedding 30 GWh during the implementation of stage 6	Since 2014 total duration of load-shedding events amounts to 1 710 hours 2015 saw 852 hours, spanning stages 1 to 3 2019 saw 530 hours, with half of load shed in stages 4 to 6	3 867 GWh (estimated). Of which: 1 325 GWh in 2015 1 352 GWh in 2019	USD 10-20 billion	Improved investment framework
Brazil (2001) **Extended period of energy rationing caused by drought**	Countrywide 100% of customers affected either through increased prices or direct rationing	Not known	7-10% of annual electricity consumption (20% of energy consumption over 6 months)		Review of investment and market frameworks
Pakistan (2021) **Tripping of two 500-kV transmission lines**	Countrywide	18 hours	443 GWh (estimated)	451 million USD	Grid code review, operatin g reserves review Management systems to implement operations and maintenance properly
Texas (2021) **Short-term load-shedding – exceptional preventive interruptions to avoid cascade blackout**	State-wide	5 days	1.85 TWh (estimated)	16.7 billion USD	Gas-electric security coordination Incentives for weatherization Improve interconnections

Sources: Jardini et al. (2002), CSIR (2020), Wolfram (2019); IEA analysis based on Australia and Hokkaido electricity data.

Figure 2. Maximum depth, duration and total unserved energy as a percentage of annual demand for different outages



Sources: Data in this IEA analysis include: AESO 2017, South Africa, Australia and Hokkaido electricity data.

Assessing the costs of an outage

Introducing the VoLL

The first step towards developing a framework for electricity security is to define the scope of the challenge. Notably, policy makers need to take into account the social and economic impacts of interruptions to electricity supply when making balanced decisions to foster electricity security. Impacts can be quantified so that they can be weighed against the costs of increasing reliability, for example by investing in infrastructure. This is not straightforward as the deep integration of electricity into our societies and economies means that outages have far-reaching impacts.

The economic value of a unit of electricity is linked to the welfare and benefits that households and firms derive from electricity consumption during a specific period of time. In most markets, the price of a commodity is directly linked to the value that consumers place on it. In the case of electricity, this link is much less clear. A similar challenge exists for other commodities that depend on a shared, capital-intensive infrastructure, such as water supply or waste management. Still, policy makers and system planners need an objective metric to assess the potential economic impact of supply disruptions to effectively price reliability and steer decision-making processes.

A useful metric is the value of lost load (VoLL), which assesses the economic impact of a power supply disruption by measuring the resulting lost economic output. The economic impact will depend on a number of factors such as the affected consumer group and the time, duration, frequency and season of the disruption. In the United States a countrywide assessment of the value of reliability found differences in the economic impact of supply disruptions for various consumer groups.

Table 3. Relative impact of an outage on various economic sectors by duration of interruption

Interruption cost (USD)	Momentary	30 minutes	16 hours
Medium-sized and large commercial and industrial			
Cost per event	12 592.00	15 241.00	165 482.00
Cost per average kW	15.90	18.70	203.00
Cost per unserved kWh	190.70	37.40	12.70
Small commercial and industrial			
Cost per event	412.00	520.00	9 055.00
Cost per average kW	187.90	237.00	4 128.30
Cost per unserved kWh	2 254.60	474.10	258.00
Residential			
Cost per event	3.90	4.50	32.40
Cost per average kW	2.60	2.90	21.20
Cost per unserved kWh	30.90	5.90	1.30

Source: Sullivan, Schellenberg and Blundell (2015).

The study shows that the cost per outage event is greater for medium-sized and large commercial and industrial consumers. However, when normalised to a kW or kWh of electricity demand, the cost of an outage is higher for small commercial and industrial consumers. While longer outages impose higher total costs, as expected, the cost per unit of energy not supplied is lower for longer outages across all sectors.

Beyond variations across customer groups, the economic impact of power outages varies across regions and will depend on the time of occurrence. A 2013 assessment of the economic cost of electricity supply interruptions in Germany estimated that, on a national level, average total hourly costs amount to around EUR 430 million, but reach a peak between 13.00 and 14.00 on a typical December Monday at EUR 750 million. In this assessment, regional disaggregation showed that the greatest impact was concentrated in the states of Baden-Württemberg, North Rhine-Westphalia and Bavaria, which have larger populations and greater economic activity compared to the rest of the country.

In addition to the difference in economic impact per region, power outages can have different impacts across consumer groups depending on whether they happen in the summer or winter, expressed as the share of economic losses.

Table 4. Relative impact of an outage on various economic sectors, depending on the time of year

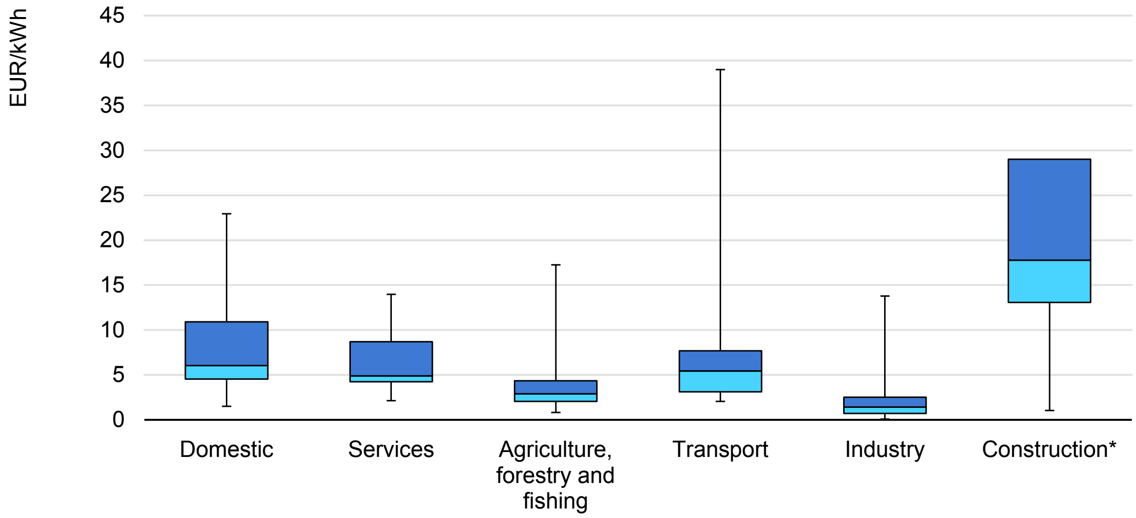
Sector	Maximum		Minimum		Average share (%)
	Share (%)	Time of year	Share (%)	Time of year	
Residential	74	Dec/Sun/11.00	31	Sep/Sat/04.00	46
Agriculture	2	Nov/Thu/08.00	0	Jan/Sat/14.00	1
Manufacturing	23	Jul/Sun/05.00	8	Jan/Sun/11.00	15
Commercial and public services	53	Nov/Fri/11.00	18	Jan/Sun/11.00	39

Source: Growitsch et al. (2013).

Many VoLL studies provide strongly different views. These can be related to actual differences across geographies in terms of economic impact and differences in customer classification, but also differences seen between actual macroeconomic impact and the stated willingness of users to accept outages. Especially for non-household customers, dedicated attention is needed on the actual macroeconomic impact of an outage versus companies' perceived loss or risk profile.

A study on VoLL frequency distribution in the EU found that residential loads show a higher average VoLL than most other segments, while some industries had high outliers. As the methodology has a significant impact on the VoLL assessment, wide variances in observations across sources complicates the task of setting an economic reliability target

Figure 3. VoLL frequency distribution in the European Union for various types of customers



*Construction values are restricted to observations under the 75th percentile. It should be noted that while the associated loss for the construction industry is higher, this particular value is seen as an outlier or an overestimation due to a number of factors in how VoLL is calculated and potential inconsistencies in data collection. One of the potential explanations for the construction sector's high associated VoLL stems from the way the metric is constructed. As an industry with very high value added but comparatively low electricity intensity, proportionally much more economic impact will be divided by less electricity consumption.

Source: ACER and CEPA (2018).

Still, VoLL approaches, such as those adopted in the United States and most European countries, can be useful for policy makers to better understand the varying impacts of supply disruptions on different consumers at different times. VoLL potentially allows them to identify targeted measures to manage reliability through, for example, demand response programmes, operational practices and infrastructure investment.

As redundancy in the electricity system increases, so the probability of outages decreases, but the utilisation rate of infrastructure also drops. Is it worth building an additional power plant or interconnector that might only be needed to avoid a small amount of energy not being supplied once in ten years and otherwise sits idle most of the time? The VoLL allows this question to be evaluated directly in economic terms.

Thus the VoLL is integral in very specific applications. These include cost-benefit analysis of grid investment, at the transmission level for interconnectors and for distribution (undergrounding, faster fault detection, etc.). VoLL can also be used to determine an appropriate target level of loss of load expectation (LOLE) for the reliability standards that are used in adequacy assessments to determine capacity requirements, and to set targets for specific cost-reflective market designs, both discussed in Chapter 3.

The VoLL is meant to capture the marginal cost of a small amount of electricity not supplied, derived for each customer, be it a household or commercial and industrial customer. It does not evaluate broader impacts on the entire economy from large-scale events, long-term supply shortfall or lack of electricity access.

High-impact, low-probability events have broader economic repercussions

The economic cost of interruptions, measured through the VoLL, captures the impact of outages where these only affect individual consumers and firms, and when the outages are of short duration. However, in other cases the usefulness of the VoLL decreases, for instance for events causing substantial physical infrastructure damage, such as natural disasters, where interruptions last for longer periods and disrupt essential services. Irrespective of the actual cause, traditional VoLL assessments fail to reflect the economic damage caused by long-duration and large-scale supply interruptions.

Even in a small community, the VoLL based on an individual's value of energy will largely underestimate the damage to that individuals' welfare when multiple infrastructure-related services are not provided. A household with a backup generator living in a community affected by a blackout will also be affected by the lack of other services and activities that rely on power. Electricity disruptions affecting infrastructure and essential services such as traffic lights, airports, public transport, payment services, telecommunications and health services are more costly to society as a whole. In this sense, VoLL should be seen as a minimum estimate of the damage created by an electricity shortage.

Even if many of these services are typically not subject to rationing or load-shedding, or are expected to have backup power supply, they can still be put out of service in cases of devastating events. As economies become increasingly reliant on electricity, it will become difficult to isolate the economic impact to individual sectors. A power outage in the United Kingdom during August 2019, triggered by a lightning strike, is an example of how even very short-duration supply disruptions (less than one hour, in this case) that fall within reliability standards can extend into other critical sectors, such as public rail transport, and magnify the economic and societal impact.

Interruptions can entail risks to safety and property. Extreme weather events could trigger higher demand, making interruptions more threatening. For example, households depending on electric heating during an extreme cold snap could be at risk under a long supply interruption.

Some predictable interruptions, or series of interruptions, are substantial in length, frequency and geographical coverage such that it cripples general economic activity. In South Africa, for example, research by the Council for Scientific and Industrial Research (CSIR) estimates that persistent load-shedding between 2007 and 2019 has led to an economic impact ranging between EUR 8 billion and EUR 17 billion. In 2019 alone, the worst year on record for load-shedding, the impact on the economy is estimated between EUR 3 billion and EUR 6 billion.

Policy makers should approach electricity security matters recognising that low-probability events, capable of causing simultaneous damage to multiple power sector elements, can cause damage larger than that strictly proportional to the suspension of private consumption, as is the case for short-duration outages limited to a small part of the distribution system.

Even when the probability is low in absolute numbers, but there is a trend of multiple outages or a high perception of risk, policy makers need to respond to the overall damage to economic activities.

Institutional responsibilities for preventing outages

The next step is institutional delegation

Once policy makers define the scope of the challenge, assess the costs and benefits of electricity security, and establish a reliability planning framework, the implementation of such a framework requires institutional delegation from within the government and throughout the electricity supply chain.

The operation of the electricity system involves a diverse set of actors and varies considerably both within and between countries. At the same time, the range of responsibilities that needs to be fulfilled to maintain electricity security is similarly varied and can be spread across multiple actors, making the clear delegation of roles and co-ordination among participants a crucial element of maintaining security of supply.

Electricity systems are based on a web of actors with roles and responsibilities in security

Electricity systems in various jurisdictions operate in different ways, with the ultimate task being to ensure that supply can meet demand at various timescales. The systems in place have generally operated well for today's systems. Below is a list of institutions that can play a role in electricity security, although their specific responsibilities can vary across markets.

Governments: The basic tenets of electricity security and reliability are dictated by government policy as defined in law. In this regard, legislators have an important role to play in establishing the parameters of electricity security in their jurisdiction, along with government ministries that have oversight over the energy and electricity sectors. The task of emergency preparedness and response is also often handled by government, which assigns responsibilities to regulators, system operators and industry, as needed.

Regulators: While government policy sets electricity security frameworks, it often delegates the task of developing standards and enforcing them to regulators, which operate independently in most IEA member countries. In this capacity, regulators are usually tasked with reviewing resource adequacy, undertaking market design and standard setting to meet security parameters, and setting technical connection and operational requirements.

Balancing authorities: Within a given interconnection area, a designated balancing authority ensures that supply is equal to demand at all times. In many countries, transmission system operators serve as balancing authorities. In some jurisdictions, integrated utilities serve this role. Balancing authorities are required to maintain levels of reliability within their systems, as set out by laws and regulations, by directing grid users to change their infeed profile or by procuring balancing services competitively. In advanced markets, balancing responsibility lies with market parties to mitigate deviations from a committed infeed profile; the balancing authority then maintains oversight of this process and corrects residual imbalances. Power pools have been created in several jurisdictions so utilities can undertake balancing functions over a larger and more diverse area.

System operators: System operators play a crucial role in maintaining electricity security as the entities responsible for the bulk transmission of electricity on high-voltage networks. In doing so, they serve as the intersection between generation and distribution system operators and have system-wide visibility over critical elements of the electricity system. They are often tasked by regulators with acting as the balancing authority and monitoring adequacy within the regions they cover. The owners and operators of the transmission grid, or transmission operators, are responsible for the technical performance of transmission infrastructure and follow instructions given by system operators. Although every power system has only one transmission grid, ownership can be divided among many transmission asset owners. In several markets, transmission system operators (TSOs) are established as entities that oversee both system operation and the operation of transmission assets.

Generation owners and operators: Generation assets are essential to support adequacy and operational security. Their timely response to the system operator's instructions allow for large systems with multiple actors to maintain a secure operation. This includes responding to calls from balancing authorities to ramp up or down generation to meet load needs, offering ancillary services or taking responsibility themselves for adhering to a projected infeed profile.

Distribution companies: Distribution companies ensure the safe delivery of power from the high-voltage transmission system to the end users of electricity. In this capacity they are responsible for the operation, maintenance and development of their distribution networks. Depending on the country, they may be limited to managing the network – like conventional distribution network operators in Europe – or be bundled with retail services to regulated consumers within their jurisdiction – like distribution utilities in Latin America, India and the United States. Their geographical coverage may also range from a single city to the whole national territory, depending on the country.

As the main interface between customers and the rest of the electricity system, distribution companies have responsibility for managing and reporting outages or issues on their networks, and following the schedule set by the system operator. Currently, discussions are ongoing as to whether distribution companies should evolve to take on a more active role in operating the system locally, co-ordinating the dispatch of distributed generation and storage, or running local flexibility services. While no generalised view on this is evident, the emergence of such models in specific jurisdictions poses important questions for policy makers and regulators on new options for the cost-effective and secure operation of modern power systems.

Vertically integrated utilities: For most of the 20th century the dominant entities for generating, transmitting and distributing bulk power were vertically integrated electric utilities. In regions with a vertically integrated structure, these utilities control all the activities needed to serve their service territories, and are responsible for ensuring sufficient supply to meet load, effectively serving as the balancing authority. They either maintain their own generation infrastructure, or can purchase electricity through contracts with other suppliers.

Market operators/exchanges: Market operators oversee the financial settlement of wholesale electricity markets. The time periods for settlement include intraday, day-ahead and forward/futures markets, all of which are closely co-ordinated with system operators to ensure reliability.

Consumers: While policy makers rightfully put consumers and society at the centre of policy objectives, the electricity sector historically comes from a perspective where load was inflexible and seen as a passive element. In modern systems, end users (industrial, commercial, households) shape the load profile in the electricity system in an increasingly active way. From an electricity security perspective, they can provide important demand response services during periods of supply tightness and become active consumers.

The advent of distributed generation can blur the line between consumer and generation. Increased uptake of distributed solar PV is one often-raised example of small consumers becoming producers as well. Embedded generation is not an entirely new trend as many facilities have had emergency generators for decades, which can support reliability of the individual facility and also resilience of the wider system. Developments in behind-the-meter storage, electric vehicle charging, digitalisation and efficiency all make the grid edge less passive. A clearer willingness-to-pay expressed by individual consumers, or a better view on the actual value of lost load, can also change how markets and system operators specify reliability.

Example: Institutional responsibilities in the United States

The Federal Energy Regulatory Commission (FERC) is the primary electricity sector regulator at the federal level in the United States, with broad authority over bulk power system operations, including system reliability. Under the comprehensive Energy Policy Act of 2005, Congress required FERC to set and enforce reliability standards for the entire transmission network. Specifically, the electricity chapter of the 2005 act called for the establishment of an electric reliability organisation across North America to set reliability standards, under the purview of FERC within the United States.

The North American Electric Reliability Corporation (NERC) is a non-profit organisation, originally formed by the electric utility industry, which ensures the reliability of the North American bulk power system. In 2006 FERC designated NERC as the government's electrical reliability organisation for the United States. On this basis, NERC has the authority to develop and enforce reliability standards and assess the forward-looking reliability, adequacy and related risks (both seasonal and ten-year outlook) of the physical grid, which it does on an annual basis. There are six regional reliability entities spanning the United States, Canada and Baja California in Mexico that fall under NERC's jurisdiction to ensure reliability. Failure to comply with NERC reliability standards can carry hefty penalties. NERC plays a similar role in Canada, where its standards are mandatory and enforceable at the provincial level, while Mexico's Grid Code includes ten NERC reliability standards.

Given the federal system of government, state governments also have an important role to play in maintaining electricity security in the United States. State public service commissions or state public utility commissions regulate the electricity distribution system, including overseeing reliability of supply to end users of electricity, within their respective jurisdictions. In particular, they set standards for voltage, frequency and other technical areas on the distribution network based on industry standards.

In California in 2015, for example, electricity reliability was placed at risk when the fuel supply of gas generators was threatened due to the leak at the Aliso Canyon natural gas storage facility. In response to the subsequent closure of the facility that limited gas supplies to generators, the state legislature in 2016 passed a law requiring that utilities procure an additional 500 MW of electricity storage capacity to bolster reliability and flexibility in the state's bulk power system.

In another case, the California Public Utility Commission modified market rules to ensure that battery storage options are valued more accurately in the wholesale power market. This was separate from a FERC order in 2018 that required grid operators to adjust rate structures to facilitate the participation of energy storage resources in regional wholesale power markets.

Since the late 1990s utilities in most US regions have opted to join independent system operators (ISOs) and regional transmission organisations (RTOs), organisations that ensure reliability by co-ordinating generation and transmission operations in their service areas, which often span several states.

Within each US interconnection area, balancing authorities ensure that supply is sufficient to meet demand. ISOs and RTOs take the role of balancing authority where they are active. In other areas the active utility takes this role.

Federal and state reliability obligations require utilities to ensure that they have sufficient resources to meet projected demand, as well as an additional reserve margin that covers unexpected demand spikes or supply disruptions. Utilities are asked to compile integrated resource plans (IRPs), covering a period of 10 to 20 years, which outline customer needs and investment plans and which are approved by the regulator.

Capacity markets – where generators are paid to maintain generating capacity – are used in some markets to ensure adequate supply, upon discretion of the RTO or ISO, subject to FERC approval and oversight. In the United States, regional system operators ISO-NE, MISO, NYISO and PJM administer capacity markets in their areas. In recent years, grid operators in PJM and ISO-NE had to redesign capacity market rules to adjust for the sizeable growth in subsidised generation sources (renewables, gas and, in some cases, nuclear power). In these cases, policy support for clean generation technologies is dictated at the state government level in the form of renewable portfolio standards or emissions credits to nuclear, while adequacy responses are determined at the grid operator level, creating institutional co-ordination challenges. Meanwhile, in other regions also experiencing substantial shifts in their electricity mixes, the ISO did not opt for capacity mechanisms and operates an energy-only market.

Beyond operational security and adequacy, government agencies at all levels and across multiple disciplines are involved in emergency response. Primarily, in most emergencies the federal government's role is centred on co-ordination and communication among the various stakeholders. Electric utilities play a crucial role, as they are responsible for repairing damage to infrastructure and restoring services to customers. Power providers conduct year-round planning and preparation, including exercises and drills, for various types of emergencies, including weather, cyberattacks and physical attacks on infrastructure. In severe emergencies the government also provides logistical support, including equipment, skilled repair staff, damage assessment expertise and security forces.

The United States also has a sophisticated threat assessment network that gathers and disseminates information to relevant stakeholders even before an event takes place. Reciprocally, power providers are responsible for reporting significant events to the Department of Energy, NERC and their respective regional organisations, while ISOs and RTOs are also required to report incidents to NERC and the Department of Energy. During and after an emergency incident, electric utilities take the lead in restoring services to customers, often prioritising service to critical emergency facilities such as hospitals before restoring wider service.

As the US electricity system has evolved, so too have the policy and regulatory structures underpinning electricity security. Notably, the growth of digitalisation in the sector has led to an increased focus on cyber protection, initiated either by FERC or NERC-led changes to regulatory rules or by changes passed into law by the US Congress. For example, the Energy Independence and Security Act of 2007 directed FERC and the National Institute of Standards and Technology (NIST) to develop smart-grid standards based on concerns about cyberattacks stemming from the growth of smart grids.

From a regulatory perspective, FERC is tasked with developing cybersecurity standards for the bulk electricity system. Under FERC's direction, NERC developed critical infrastructure protection cybersecurity reliability standards that went into effect in 2008. In 2018 FERC further directed NERC to develop modifications to these reliability standards to update reporting of cyber incidents. This increased the reporting obligations so that in addition to reporting incidents where reliability had been compromised, it would also be required to report any incident that could pose a future threat to the system. NERC in March 2019 also proposed standardised reporting requirements that will require cybersecurity incident reports to be sent to centralised databases of the Electricity Information Sharing and Analysis Center (E-ISAC) and the United States National

Cybersecurity and Communications Integration Center (NCCIC). The updated standards have been approved by FERC and will take effect on 1 January 2021.

With respect to climate resilience, the US Climate Resilience Toolkit was launched in November 2014 and is managed by the National Oceanic and Atmospheric Administration Climate Program Office and hosted by the administration's National Centers for Environmental Information. The tool is a result of co-ordination and initiative between several agencies across the US government, with guidance from the US Global Change Research Program. As part of the US federal climate data-sharing initiative, the toolkit is a website designed to help people and institutions find and use tools, information and expertise to promote climate resilience.

As power systems evolve to address shifting generation profiles, climate change and cyberthreats, the institutional approach to electricity security will also need to evolve. This includes adjusting market designs to provide appropriate investment signals for flexibility resources, increased investment in infrastructure resilience, adopting new tools and technologies, and greater co-ordination among market participants and stakeholders across the electricity system.

Example: Institutional responsibilities in India

Policy as it relates to electricity in India is primarily conducted from the Ministry of Power. The Central Electricity Authority is the main advisor to the ministry and is responsible for the technical co-ordination and supervision of programmes and data collection and dissemination. Under the Electricity Act 2003 the Central Energy Regulatory Commission is the central regulator and is responsible for a number of areas, including grid security (grid code, deviation settlement mechanism, ancillary services). The State Electricity Regulatory Commissions collaborate through the Forum of Regulators.

The electricity system in India is operated by the Power System Operation Corporation (POSOCO), a state-owned company under the Ministry of Power. Since 2017 the corporation has been fully responsible for ensuring the integrated operation of the grid in a reliable, efficient and secure manner through its five Regional Load Despatch Centres and the National Load Despatch Centre. It is fully independent from transmission activities.

India has achieved the integration of the five unsynchronised regional state grids, a process which started in the 1990s and was completed in December 2013. In 1991 the north-eastern and eastern grids were connected. In March 2003 the western region was interconnected, and in 2006 the northern grid was interconnected. This created four synchronously connected regional grids: northern, eastern, western and north-eastern, forming a central grid operating at one frequency. On 31 December 2013 the southern region was connected to the central grid in synchronous mode, thereby achieving "one nation–one grid–one frequency".

The world's largest synchronous power system is operated via the National Load Despatch Centre, the five Regional Load Despatch Centres and 33 State Load Dispatch Centres. Central-level power dispatch is divided into five regions: northern, western, southern, eastern, and north-eastern. Power distribution companies work with the State Load Dispatch Centres or have their own load dispatch departments.

Reforms undertaken in the past decade have bolstered India's electricity security. For example, to maintain grid discipline amid large power outages and frequency dips, the Central Energy Regulatory Commission introduced unscheduled interchange charges in 2009, which were subsequently replaced by the deviation settlement mechanism in 2014. Further, the ancillary services mechanism was introduced in 2016 to reduce congestion, increase power trading and stabilise grid frequency.

The main framework for adequacy planning in India is the ten-year National Electricity Plan, which is prepared by the Central Electricity Authority under the Ministry of Power every year for two five-year periods (in total ten years). The long-term demand projections are carried out by the Central Electricity Authority in the Electric Power Survey.

Regulatory responsibilities need to be updated

As the electricity system continues to evolve in response to the energy transition and emerging trends such as cyberthreats and climate change, governments and regulators need to continue to update the legal and regulatory requirements placed on system operators to ensure that electricity security is maintained.

In some cases this will require legislative changes to redefine frameworks, roles and responsibilities for various institutional actors in the electricity system so that they adapt to ongoing transformations in the power sector. In this regard, the European Union's passage of the so-called Clean Energy Package (see below) is an attempt to restructure the institutional framework for electricity markets, including electricity security. This in the face of ongoing changes to the fuel mix as well as increasing interconnectivity across electricity systems. It is a gradual evolution from earlier European legislative initiatives, or packages, for the electricity system published in 1996, 2003 and 2009. These started from an unbundling and market perspective, but increasingly cover security-related provisions.

Regulators, in particular, will have an important role to play in ensuring electricity security amid the energy transition. Either based on changes to law or stemming from existing statutory authority, they will need to adjust market designs and standards to reflect greater variability of supply and demand. New threats such as cybersecurity and climate change will also need to be accounted for. For example, in the United States FERC issued Order 842 in February 2018 to support the secure integration of renewables into the grid and manage risks stemming from the retirement of baseload generation and lower utilisation of other plants. The order requires all new generators (regardless of size or technology) to be capable of providing primary frequency response as a precondition for grid interconnection. Similarly, Europe established a legally binding grid code in 2016 across all its member states that requires all new connections to have essential ancillary service capabilities, to pave the way for future operational rules and balancing markets with ever higher shares of VRE and distributed resources.

Australia provides an example of how the energy transition is shifting the institutional responsibilities for ensuring electricity security in a federally structured government. Following the system-wide blackout in South Australia on 28 September 2016 after severe storms and heat waves, the Council of Australian Governments' Energy Council, which comprises state governments, commissioned an independent review into the future security of the national electricity market, also known as the Finkel Review. The black system event prompted a wider assessment of energy market design and security amid the rise of renewable energy and the exit of thermal power capacity.

Key reform actions identified by the Finkel Review included strengthening the governance of the national electricity market through the creation of a new Energy Security Board to co-ordinate electricity security and reliability across the market. The board, created in 2017, includes representation from regulators, market operators and system operators. It provides assessments of the national electricity market to the Energy Council, including risks and opportunities in its operation and recommendations for addressing them, although it does not have the authority to change rules or laws directly.

Smart policies and regulations can also help strengthen the contributions of other actors to electricity security. Owners and operators of generation, storage and other assets will need to ensure a balanced and optimised portfolio, including anticipating future trends to determine appropriate timing for investment in new capacity and to avoid stranded assets. To this end, transparent and efficient market design is crucial to ensuring supply adequacy. Service providers will be called upon to adopt and adapt services to meet new market needs.

Many jurisdictions are discussing the need to create a new figure that assumes responsibility for co-ordinating distribution-level assets, in effect a distribution system operator that can procure flexibility services from its network users, for example voltage support and congestion management. Distribution operators would also be tasked with administering distributed energy programmes and accommodating a growing share of distributed assets into their networks. Moreover, as the intersection of load, demand response and smart grids occurs on distribution networks, distribution system operators could play a crucial role at the grid edge to ensure smooth integration of new technologies and secure digital connectivity. Co-ordination between transmission and distribution operators will intensify as distributed flexibility sources are able to address both local system issues and take part in system-wide wholesale and ancillary service markets.

Consumers will also become smarter with better data to adjust their demand based on price signals and system needs. A growing number of electric vehicles will increase demand, and consumers will participate in electricity markets as both producers and storage providers, giving them a role not only in lowering system costs but ultimately also in ensuring electricity security. Electrification of other sectors will also increase the pool of consumers that can play a role in providing crucial flexibility resources.

Lastly, the R&D community (including publicly funded R&D) is at the forefront of technological development and system modelling and analysis, and its collaboration with system operators and other institutions in electricity security applications should be fostered.

Responsibilities for electricity security can conflict between regulators, market participants and policy makers

Overseeing the front lines of the electricity system, balancing authorities and transmission system operators are often in the best position to identify beneficial changes in market design and specifications to improve reliability. These changes would typically need to be proposed to the regulator and require approval before implementation. For example, following the 2014 polar vortex that brought extreme cold across a broad area of the middle and eastern parts of the United

States, grid operators developed new winter performance standards for generators to better ensure adequacy under these conditions (building upon improvements made after a 2011 cold snap). These standards were approved by FERC.

The main policy decisions and implementation actions for electricity security are undertaken by government and regulators. Looking at different countries, it is clear that governments have taken different positions on how much power to give to an impartial regulator. Rule change proposals highlight different perspectives on addressing electricity security amid the energy transition. In another example from the United States, in response to growing concerns about the reliability impacts of the closure of coal and nuclear generation, in September 2017 the Department of Energy issued a notice of proposed rulemaking that urged FERC to develop cost recovery mechanisms for baseload power generators that support grid reliability and resiliency. The proposal specifically called for ISOs and RTOs, under the direction of FERC, to develop compensation mechanisms for baseload plants that have 90 days of fuel supply on-site, which primarily include coal and nuclear plants. In January 2018 FERC unanimously rejected the department's notice on the grounds that it did not provide sufficient evidence of supply risks to the grid. Instead, FERC opened a study on grid resilience that is still underway.

In addition to differing views between policy makers and regulators, different priorities or actual conflicts of interest can also emerge. This is the case in some regions where capacity markets have been implemented. Such mechanisms can be driven by policy makers seeking to ensure reliability without extreme scarcity pricing. Detailed specifications are often delegated to the system operator, which may take a risk-averse position and overestimate the volumes needed. A regulator tasked with supervision can push back based on the argument of keeping consumer prices low, but faces information asymmetry. Another area where the energy transition may expose conflicts that policy makers need to address is in distribution systems, where a policy push for more distributed generation, efficiency measures and local flexibility measures needs to align with prevailing regulatory incentives.

Federally structured states or regional blocs such as the European Union also have the unique challenge of ensuring reliability across a broader range of states or nations. In these cases, the states or countries have their own prerogative to set energy policy, such as renewable electricity or CO_2 reduction targets. However, balancing and reliability are co-ordinated across a larger geographical footprint, which can result in overlapping or conflicting priorities for guaranteeing electricity security. EU member states reached a new compromise on bringing security policies to a wider regional level with several provisions in the 2019 Clean Energy Package, including the Risk Preparedness Regulation and the establishment of regional co-ordination centres (see below).

Responsibilities are shared with or allocated to new levels of governance

There are many models of inter-jurisdictional governance arrangements, which may be thought of as existing across a spectrum. This ranges from systems with bi- or multilateral arrangements to those with fully harmonised rules. Moving to the latter, independence is sacrificed in order to increase overall efficiency of trading and system operations.

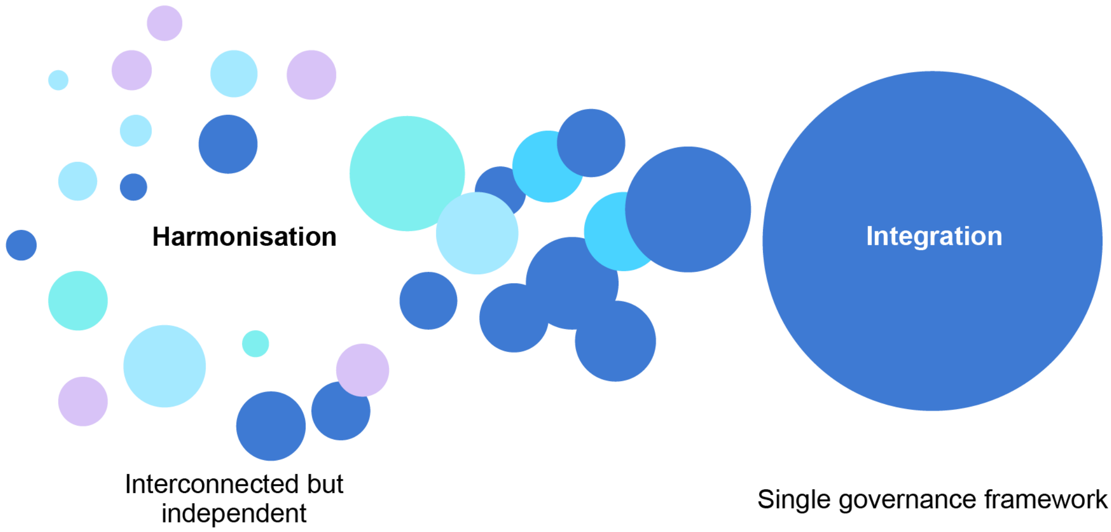
Developments in the European Union provide a clear case of how the stronger harmonisation of rules and schemes for international governance can emerge in strongly interconnected systems.

In practice, EU member states tend to exercise their prerogative to ensure security of electricity supply, decide on their level of reliability and their national electricity mix at the country level. However, crises may affect several member states at the same time, as illustrated by several examples summarised in the past incidents section below – including a blackout in Italy and Switzerland in 2003, and the November 2006 incident that triggered load-shedding across 11 countries due to a badly executed disconnection of an electricity line to allow the passing of a cruise ship. These events illustrated the potential for a clear disconnect and friction between national, EU and regional reliability considerations. In a positive recognition of this tendency, a more encompassing, cross-regional concept of electricity security has been emerging in the European Union.

The most recent step in a series of legislative actions is when the European Union adopted a new electricity market design under the so-called Clean Energy Package, which entered into force in July 2019. Its provisions target a number of critical improvements: fostering scarcity pricing and rewarding flexibility provided by generation, demand response and storage; avoiding overcapacity by co-ordinating national resource adequacy assessments, taking a regional and European perspective; and encouraging explicit cross-border participation in capacity remuneration mechanisms.

The package also establishes common rules for crisis prevention and reinforcement of regional TSO co-operation through the mandatory establishment of regional co-ordination centres. These will be operational as of 1 July 2022 and will replace existing voluntary regional security co-ordinators. The new centres will perform operational security analyses of the region and recommend to TSOs the most effective and economically efficient remedial actions.

Figure 4. Models of cross-border integration: From harmonisation to unification



Source: IEA (2019).

One important platform for co-operation is the Electricity Coordination Group, created in 2012, which allows for discussion between member states, national regulators, the Agency for the Cooperation of Energy Regulators (ACER), ENTSO-E and the European Commission on electricity policy. Cross-border initiatives such as ENTSO-E, ACER and the regional security co-ordinators play an important role in the European security of supply architecture.

The new Regulation (EU) 2019/941 on risk preparedness in the electricity sector provides a new legal and policy framework for security of electricity supply in the European Union. It requires national risk preparedness using measures to prepare for and mitigate electricity crises as identified in regional and national electricity crisis scenarios. Such scenarios will be identified using a common methodology developed by ENTSO-E and approved by ACER. The plans will be assessed by the European Commission, in consultation with the Electricity Coordination Group, which will provide recommendations under certain circumstances – for example where measures to address electricity crises are identified as ineffective or in cases of non-compliance with the regulation.

In addition to designing risk preparedness plans, ENTSO-E carries out seasonal adequacy assessments (winter and summer) and the regional co-ordination centres will carry out the week-ahead to at least day-ahead adequacy assessments. These assessments have been done for many years already, but will now receive a stronger legislative basis and will be prepared according to a methodology developed by ENTSO-E and approved by ACER. Chapter 3 explores developments in adequacy assessments, such as those conducted across Europe.

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