PNNL-32773

Electric Grid Blackstart: Trends, Challenges, and Opportunities

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Summary

Blackstart generation is defined as a generation plant being able to start up and produce power without the need for off-site power. Whether it is from emergency diesel generators, batteries, or smaller permanent magnet hydropower generators, the on-site power source is sufficient for the required load to start up and operate the generation facility. When recovering from a significant event that involves the loss of many generation units, non-blackstart units rely on off-site power to restart. This off-site power must be supplied either from blackstart generation facilities or available transmission capacity from other portions of the power system that may still be energized. Even though large-scale blackouts requiring blackstart generation as an essential element to restore the system are rare, the economic and societal consequences would be significant and therefore require system operators to be prepared to respond at any given time.

Depending on the regulatory structure at a specific location or region, grid operators and electric utilities may either own and operate blackstart resources or maintain contracts with different service providers for blackstart-capable power plants that can help with system restoration without requiring any off-site power supply. Traditionally, hydropower units and gas turbines have been the blackstart units of choice. Hydropower units can easily produce the station service power by simply opening a valve to flow water into the generator. Gas turbines have fast starting and ramping characteristics.

As renewable generation increases, a greater percentage of the load will be served by non-dispatchable generation. Traditional generation types (e.g., coal) are becoming less economical to run and are being retired. Changes in the overall generation profile favors cheaper, cleaner, and more sustainable resources. However, some renewable resources (e.g., wind and solar) are variable in nature and require additional balancing reserves. In addition, these changes in the power generation profile are affecting the blackstart readiness of the overall system.

The continued integration of distributed energy resources (DER) and ongoing efforts to modernize the power grid introduce new opportunities and risks associated with blackstart restoration. Specifically, grid operators and electric utilities must consider how DER can be used to aid in blackstart restoration and consider the increased communication and coordination that must take place between distribution and transmission system operators when performing restoration activities.

This report documents the study of the expected future state of the grid that will have an impact on blackstart restoration readiness and recommends actions that can be taken to increase grid resiliency, improve system modeling, perform more extensive studies, enhance training activities, and perform industry outreach to enhance power system blackstart capabilities. These recommendations include increasing overall grid resiliency, improving system modeling, performing more extensive technical studies, improving coordination of emergency response with the natural gas industry, enhancing training activities, performing outreach with affected stakeholders, and capturing and sharing industry best practices.

Acknowledgments

This work is supported by the U.S. Department of Energy (DOE), Office of Cybersecurity, Energy Security, and Emergency Response. Specifically, the authors thank John Ostrich at DOE for his vision and leadership associated with this activity. Additionally, the authors thank the many valuable conversations and input from key members of the industry that contributed valuable insights in support of this study.

Acronyms and Abbreviations

ADMS	Advanced Distribution Management System
BA	Balancing Authority
BES	Bulk Electric System
BPA	Bonneville Power Administration
DER	distributed energy resources
DOE	U.S. Department of Energy
EIA	Energy Information Administration
E-ISAC	Electricity Information Sharing and Analysis Center
EMP	electromagnetic pulse
EOP	Emergency Preparedness and Operations (Standards)
FERC	Federal Energy Regulatory Commission
GMD	geomagnetic disturbance
HVDC	high-voltage direct current
IID	Imperial Irrigation District
ISO	Independent System Operator
LLC	Limited Liability Company
MW/MVAR	megawatt/megavolt ampere of reactive power
NERC	North American Electric Reliability Corporation
NRC	U.S. Nuclear Regulatory Commission
ONG-ISAC	Oil and Natural Gas Information Sharing and Analysis Center
PJM	Pennsylvania New Jersey Maryland Interconnection, LLC
PMU	phasor measurement unit
PV	photovoltaic
RADICS	Rapid Attack Detection, Isolation, and Characterization System
RC	Reliability Coordinator
RFP	Request for Proposal
RTO	Regional Transmission Organization
SCADA	Supervisory Control and Data Acquisition
TO	Transmission Owner
TOP	Transmission Operator
TRS	Total Reliability Solutions LLC
VSC	voltage-source converter

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1.0 Introduction

Blackstart in power systems refers to restarting generation without off-site power as part of the system restoration process after a partial or complete shutdown has occurred. Even though such occurrences are rare, they have significant economic and societal consequences, thereby justifying the money and effort spent in planning for system restoration using blackstart resources. Some recent blackouts are listed in Table 1, which also includes the extent of damage caused by these outages (IEC 2014; Alhelou et al. 2019; FERC-NERC 2021).

Table 1. Major 21st century blackouts.

			Impact	
Date	Country/ Region	Cause of Outage	Affected People (millions)	Duration
February 2021	USA	Cold weather loss of generation	4.5	4 days
August 2019	Indonesia	Transmission fault affecting Jakarta	21.3	9 hr
June 2019	Uruguay	Bad weather led to cascading failures	3.4	4 hr
December 2018	Canada	Winds reached speeds of 100 km/hr	0.6	4 hr
July 2018	Azerbaijan	Unexpectedly high temperatures	8	8 hr
March 2018	Brazil	Transmission line failure	10	1 hr
January 2018	Sudan	Cascading failures	41.5	1 day
September 2017	USA	Hurricanes Maria & Irma	6.7	> 1 week
March 2017	USA	Winds reached speeds of 110 km/hr	1	>1 week
June 2016	Kenya	Animal shorted the transformer	10	4 hr
March 2016	Sri Lanka	A severe thunderstorm	10	16 hr
December 2015	Ukraine	Cyber-attack	0.2	6 hr
November 2015	Ukraine	Power system failure	1.2	6 hr
March 2015	Turkey	Power system failure	70	4 hr
January 2015	Pakistan	Plant technical fault	140	2 hr
November 2014	Bangladesh	High-voltage direct current station outage	150	1 day
August 2013	Philippines	Voltage collapse	8	12 hr
May 2013	Thailand	Lightning strike	8	10 hr
May 2013	Vietnam	Crane operator	10	10 hr
October 2012	USA	Hurricane Sandy	8	>1 week
July 2012	India	Cascading failure	620	12 hr
September 2011	USA	Cascading failure caused by the loss of a 500 kV line and subsequent operational error	2.7	12 hr
November 2008	Western Europe	Cascading failure caused by poor planning of power systems operations	15	2 hr
August 2005	Indonesia	Cascading failure caused by loss of a single line	100	7 hr
September 2003	Italy	Cascading failure caused by the loss of a single line due to a storm	56	12 hr
August 2003	USA, Canada	Series of faults caused by tree branches touching power lines and complicated by human error and software failure	55	Days
January 2001	India	Substation failure	226	12 hr

Most of the events listed in Table 1 did not result in a complete system collapse. However, the use of blackstart resources often assisted in the speed of recovery. The restoration process generally focuses on reconnecting the energized portion(s) of the system so that additional generation can be restarted. Then priority loads are restored as additional resources became available.

The reasons for blackout events are diverse, including weather, equipment failure, trees and foliage getting into power lines, and damage caused by accidents and vandalism.

A typical blackstart operation consists of three stages: preparation, system restoration, and load restoration (Fink et al. 1995). In the first stage, the system status is analyzed, and a strategy is developed to blackstart the system. In the second stage, blackstart-capable generators are started and then used to energize transmission lines and start other non-blackstart generators. In the final stage, the system load is restored. As more generation is restored, more load can be re-energized. Because of the complexity of power system transmission operations, a great deal of effort and careful planning are required to restore the system in the shortest possible time.

As described by Kirby and Hirst (1999), a blackstart operation requires the following resources:

- Blackstart generating units (often hydro and combustion turbine units) that require minimal power to start. Once these units start, the generated power is used to energize the rest of the transmission network and start other generators to pick up system load.
- Non-blackstart generating units that can be quickly started using power from blackstart generators.
- Transmission system equipment, controls, and communications and field personnel to monitor and restore the electrical system.
- System-control equipment and communications, and people for planning and directing the blackstart operation.

Entities registered to perform the Transmission Operator (TOP) function must maintain access to blackstart generation to meet the requirements found in *NERC Standard EOP-005-3 – System Restoration from Blackstart Resources* (NERC 2016). Specifically, TOPs must maintain sufficient blackstart resources capable of meeting the real and reactive power[1] requirements of cranking paths and the dynamic capability to supply initial loads must be available to recover shutdown areas of the electric system after a major event.

The *Glossary of Terms Used in the NERC Reliability Standards* defines a "blackstart resource" as:

> A generating unit(s) and its associated set of equipment which has the ability to be started without support from the system or is designed to remain energized without connection to the remainder of the system, with the ability to energize a bus, meeting the Transmission Operator's restoration plan needs for real and reactive power capability, frequency and voltage control, and that has been included in the Transmission Operator's restoration plan.

Traditionally, power system generation consisted of coal, natural gas, nuclear, and hydropower plants, and hydropower units and gas turbines have been the blackstart units of choice. These

[1] Reactive power regulation is critical for maintaining appropriate system bus voltages.

plants can be easily started on their own and are operated in a controlled manner such that any difference between power demand and supply is reduced in a short time through unit dispatch. In addition, the inertia associated with these conventional power plants makes the system more resilient to faults and, hence, system-wide outages have been rare events.

However, as the world continues to build more wind and solar generation, these conventional plants (primarily thermal plants) are slowly being replaced with renewable energy sources—in many states to meet the requirements set by various renewable portfolio standards. In addition, some legacy power-generation facilities, especially coal, are being phased out due to their uneconomic nature compared to cheaper natural gas and renewable power generation.

One of the main challenges of integrating renewable energy sources into the power grid is their non-dispatchable attribute. Also, while synchronous generation has natural inertia due to its spinning mass, most of modern wind and solar plants are interfaced to the grid through power electronics, and as such, have no inherent inertia. This decrease in system inertia could make the system more vulnerable to major disturbances that could result in system-wide blackouts. Thus, significant changes in power system operational practices are required to maintain system reliability.

In addition, the new generation profile consisting of higher penetration of renewable energy sources will also affect the blackstart capability of power systems. During the initial phase of system restoration, the system is relatively less stable, and therefore integrating wind and solar power with the system during this phase can destabilize the system due to the previously described nature of these sources. In addition, as the penetration of non-dispatchable renewable sources in the system continues to increase, it could become difficult to maintain enough conventional plants to blackstart the system in a traditional manner. Thus, it is necessary to carefully plan for system blackstart operation with non-dispatchable renewable energy sources by incorporating weather-forecast information and by using suitable instruments to control the intermittent nature of these sources to the maximum extent practicable.

Another consideration for electric grid blackstart in the future will be the continued integration of DER[1] and more sophisticated control systems resulting from grid modernization efforts. Grid operators and electric utilities must now consider how DER can be used to aid in blackstart restoration, and consider the increased communication and coordination needed between distribution and transmission system operators when performing restoration activities.

Furthermore, emerging threats to electric infrastructure and reliability such as geomagnetic disturbances (GMD), electromagnetic pulses (EMP), and coordinated cyber and physical attacks must be considered because of their potential to cause a “Black Sky” event that could damage the blackstart resources and significantly impact their ability to perform blackstart restoration.

[1] Distributed energy resources can include any combination of distributed generation, storage, or controllable/responsive load generally installed in the distribution system or within customer premises.

2.0 Blackstart Practices and Considerations

This section provides additional details about traditional blackstart practices that grid operators consider when preparing their blackstart plans.

2.1 Blackstart Resources Requirements

The availability of blackstart resources is the number one requirement for starting the system restoration process. Generating units must meet certain criteria to be considered blackstart resources. Not all power plants are equally capable of providing blackstart service. The following characteristics must be considered when determining if a unit can be a blackstart resource:

- station power requirements
- start-up time
- ramp rate
- size (real and reactive power capacity)
- on-site fuel supply
- frequency characteristics (response; ability to operate during frequency excursions)
- inertia (ability to stabilize system frequency)
- location.

The blackstart capability of power plants is highly dependent on power requirements for starting the plant. These power requirements are due to the auxiliary services needed to supply the plant during both start-up and steady-state operations. To start up the power plant, station service power is needed to drive the ancillary equipment, such as motors, pumps, and compressors. The differences in requirements for various kinds of generation are shown in Table 2. This informs the determination of which generators are preferred for the use in blackstart.

To give an example, a coal power plant has higher auxiliary power requirements due to the need to supply pulverized coal to the combustion chamber to provide steam and deal with scrubbing of the exhaust. A nuclear power plant has internal loads for all safety systems for monitoring the reactor, along with primary cooling pumps used for maintaining primary coolant flow through the reactor itself (loads which are of considerable size).

A hydro plant, however, only needs to have power for control of oil pumps (needed for moving gates and regulating turbine speed) and stator air cooling, which keeps the auxiliary power requirement for starting up and operating relatively low. Often, hydro plants will have smaller dedicated units to provide station service power which can provide this start-up power that can be brought online by simply opening a valve.

Additional considerations when building a new power plant may include the installation of an emergency power source (often diesel generators) to make it blackstart-capable. These capabilities will be factored into whether the generation plant will be deemed blackstart capable.

Table 2. Summary of the key characteristics of different power plants.

Type of Generator		Start-up Power (% of Generator Capacity)	Start-up Time	Fuel	Inertia
Hydro		0.5-1 %	< 1 hr (as fast as 10 min)	Almost always available; in case of pumped-storage hydropower availability is not guaranteed.	Medium
Gas Turbine	**Simple Cycle**	1.5-2%	<1 hr (30 min hot, 1 hr cold)	Depend upon having a (limited) supply of pressurized gas on-site and/or having the natural gas pipeline that supplies the combustion turbine plant pressurized and in service.	High
	Combined Cycle		Several hours (1-4 hr hot, 8-12 hr cold)	A gas pipeline supplying fuel is pressurized and in service.	
Thermal		7-8%	Coal/oil – 12 hr hot, 24 hr cold Geothermal – 6-12 hr Steam (drum type) – 4-6 hr hot, 8-10 hr cold Steam (once through) – 8-10 hr hot, 24 hr cold	On-site (but must be pulverized).	High
Nuclear		7-8%	Several days	On-site.	High

Some additional technical requirements of the power plants during blackstart operations include the following (NationalGrid 2018):

- the capability of generators to withstand magnetic inrush currents and transient voltages during network restoration phase and provide or absorb enough reactive power;[1]
- the capability to accept instantaneous loading of demand blocks, preferably in the range 35 to 50 MW, and to control frequency and voltage levels within acceptable limits during the block loading process; and
- the ability to blackstart multiple times to allow for possible unit tripping during the restoration process.

Plants can be configured to become blackstart-capable with a local on-site generator that is able to provide the necessary start-up power.

The following sections list the characteristics of different power plant types and their suitability to be blackstart resources.

[1] The size of inrush currents can be minimized by first energizing at a lower terminal voltage, and then slowly increasing power until a nominal voltage is reached (at which point the exciter is placed in automatic voltage regulator mode). This is typically known as a “soft energization” of generator step-up transformers.

2.1.1 Hydropower Units

Hydroelectric facilities require very little power during a blackstart, and the power is required only by the excitation system and valve operations for the turbine. Normally, a 50 MW hydro unit can be started using a 500 KVA diesel generator (Kurup and Ashok 2015). Additionally, most large hydro facilities have station service power sources (including hydro turbines), which are smaller, to provide power to the plant.

However, some mini-hydro or micro-hydro plants (less than 1 MW capacity) cannot be used for a blackstart because they are dependent on the power network connection for frequency regulation and reactive power supply (Sun et al. 2011).

Pumped-storage hydropower units have most of the same advantages of conventional hydropower units. However, economic dispatch may deplete the ponds, so measures must be taken to hold water in reserve to ensure adequate energy remains available for a blackstart if units are designated for such (Gracia et al. 2018).

2.1.2 Simple and Combined-Cycle Gas Units

Aero-derivative gas turbines can be started using local battery power (similar to starting a jet engine). The time to restart them depends on how long the unit was offline (Sun et al. 2011).

Simple cycle combustion turbines do not have an associated steam system that needs to be warmed up. Combined-cycle plants, on the other hand, do require steam produced by a heat recovery boiler, and, therefore, will not be available until sufficient heat is provided to produce steam for the secondary turbine. Therefore, simple cycle gas turbines are well suited for use as blackstart resources (Walsh and Fletcher 1998; Abidi 1994).

2.1.3 Coal Units

The start-up of coal power plants relies upon natural gas or fuel oil to warm up the boiler. A warm-up time is associated with boiler and pipe seals expansion and power requirements for the complex cooling system that prevents overheating of equipment. Start-up time for the coal units can be categorized as follows:

- cold start – not available to be synchronized to the grid for more than 48 hours
- warm start – available between 8 and 48 hours
- hot start – available in less than 8 hours.

In case the coal plant is tripped off as a result of the blackout, it can be recovered as a blackstart unit (assuming station service is available). However, it is not advisable to include this type of unit in the restoration plan because of the uncertainties involved, which can result in an unsuccessful blackstart if the assumptions are incorrect in a particular event. Therefore, most coal units, particular larger facilities, are not assumed to be blackstart capable.

2.1.4 Diesel Units

Diesel generators can be started in a short time using only battery power, but they are generally small in size. Therefore, they cannot be used for blackstart operations that require a significant amount of power (Sun et al. 2011). However, diesel generators are key to starting coal, oil, and natural gas units that can then be used to aid in system restoration.

2.1.5 Nuclear Units

The U.S. Nuclear Regulatory Commission (NRC) regulates the maintenance and operation of the nuclear power industry. In doing so, they specify what is required for starting up, and providing backup power supply for maintaining station service power (primary and backup). NRC regulations prevent the operation of the power plant without two separate power sources being available for station service. As such, a nuclear power plant cannot be used in any blackstart capability (PJM 2019).

In addition, after a nuclear facility is shut down, a considerable amount of time is involved for the regulatory authorities to conduct the necessary inspections and permit facility restart. Thus, nuclear generation is often not available for several days following a major disturbance. In the case of the August 14, 2003 blackout, multiple nuclear power facilities were offline for several days following the event (Eto 2004).

In the future, new certified designs, about to be field tested, might be capable of serving as blackstart resources. For example, the NuScale modulator reactors are advanced small modular reactors, whose inherently different design principles allow them to be manufactured and assembled on-site, with a design that can provide significant flexibility and dispatchability.[1]

2.1.6 Wind and Photovoltaic Generation

Because of the unpredictability wind and solar power and the variability of wind and solar plants, it is difficult to plan for the use of renewable energy sources, either as blackstart resources or to aid in the restoration process. Furthermore, during the initial phase of system restoration, the system is relatively weak and, hence, a totally controlled environment is required for successful system restoration. Because the wind and solar output vary, the system can undergo another blackout during the restoration process if uncontrolled power sources are added during the initial phase of restoration (Zhu and Liu 2012).

2.1.7 Battery Storage Systems

Battery storage systems have been proven to provide power to start up large power plants, as in the U.S. case of the Imperial Irrigation District (IID) using a 33 MW/20 MWh lithium-ion storage system to start a 44 MW combined-cycle plant (Colthorpe 2017).

However, using batteries dedicated only for blackstart operations can be an expensive option compared to using the traditional diesel generator (Burns & McDonnell Eng. Co. 2017). Also, these batteries would remain under-utilized (Burns & McDonnell Eng. Co. 2017).

2.1.8 Summary of Blackstart Units Deployed in North America

The current approximate mix of the blackstart units registered with the North American Electric Reliability Corporation (NERC) is given in Table 3.

[1] https://www.nuscalepower.com/about-us/doe-partnership

Table 3. Blackstart units registered with NERC.

Blackstart Resources Type	%
Hydropower turbine generators	37
Gas turbines	60
Fossil	1
Combined cycle	1
Diesel	1
Wind & solar	0

A recent joint study conducted by the Federal Energy Regulatory Commission (FERC) and NERC found that several units recognized to have blackstart capability are not listed in restoration plans (and are thus not registered with NERC). While such units are not planned for use if a blackout occurs, they could serve as a source of backup power when the designated units are not available (FERC-NERC 2018). The study concluded that grid operators currently have sufficient blackstart resources and included recommendations for enhancing the practices employed to ensure readiness.

2.2 Transmission Requirements

2.2.1 Cranking Paths

In accordance with *NERC Standard EOP-005-3 – System Restoration from Blackstart Resources*, each TOP system restoration plan must include identification of cranking paths and initial switching requirements between each blackstart resource and the unit(s) to be started.

The *Glossary of Terms Used in the NERC Reliability Standards* defines a “Cranking Path” as “A portion of the electric system that can be isolated and then energized to deliver electric power from a generation source to enable the start-up of one or more other generating units.”

Cranking paths are usually determined by the location and capability of blackstart resources and the location of the generating stations and loads that are critical to system restoration.

In most instances, TOPs will identify multiple cranking paths that can be used to facilitate system restoration based on available resources and the nature of the event (e.g., partial vs. total system shutdown).

2.2.2 Frequency and Voltage Control

In accordance with *NERC Standard EOP-005-3 – System Restoration from Blackstart Resources,* each TOP must verify that its restoration plan accomplishes its intended function. This verification can be done through analysis of actual events, a combination of steady-state and dynamic simulations, or testing.

TOPs must verify the following:

- the capability of blackstart resources to meet the real and reactive power requirements of the cranking paths and the dynamic capability to supply initial loads,
- the location and magnitude of loads required to control voltages and frequency within acceptable operating limits, and

- the capability of generating resources required to control voltages and frequency within acceptable operating limits.

The primary objectives of the verification process are to ensure blackstart restoration plans can be executed as designed and that the TOP has the resources (e.g., generator control mechanisms, reactive devices) required to maintain voltage and frequency within acceptable operating limits throughout the restoration process.

2.3 Functional Entity Roles and Responsibilities

In accordance with mandatory NERC standards, certain functional entities must be prepared to enable system restoration from blackstart resources to assure reliability is maintained during restoration and priority is placed on restoring the interconnection.

Most requirements related to system restoration can be found in the NERC standards described in the following sections.

2.3.1 NERC Standard EOP-005-3 – System Restoration from Blackstart Resources

The purpose of this standard is to ensure plans, facilities, and personnel are prepared to enable system restoration from blackstart resources to ensure reliability is maintained during restoration and priority is placed on restoring the interconnection.

Most of the requirements in this standard are applicable to the TOP function, although some requirements are applicable to Distribution Providers, Generator Operators, and Transmission Owners (TO) that are identified in TOP restoration plans.

This standard requires each TOP to have a restoration plan that allows for restoration of the TOP's system following a disturbance in which one or more areas of the Bulk Electric System (BES) shuts down and the use of blackstart resources is required to restore the shutdown area to service.

These restoration plans must be approved by a Reliability Coordinator (RC) and include the following:

- strategies for system restoration that are coordinated with the RC's high-level strategy for restoring the interconnection, and
- operating processes for restoring loads required to restore the system and re-establish connections and for transferring operations back to the Balancing Authority (BA).

The restoration plans must also identify the following:

- each blackstart resource and its characteristics (e.g., unit type, real and reactive power capacity),
- cranking paths and initial switching requirements between each blackstart resource and the units to be started, and
- acceptable operating voltage and frequency limits to be applied during restoration.

This standard also includes requirements for verifying that the restoration plan accomplishes its intended function, testing to verify the capability of blackstart resources, and performing annual system restoration training for staff.

2.3.2 NERC Standard EOP-006-3 – System Restoration Coordination

The purpose of this standard is to ensure plans are established and personnel are prepared to enable effective coordination of the system restoration process to ensure reliability is maintained during restoration and priority is placed on restoring the interconnection.

This standard is applicable to the RC function only and requires each RC to have a restoration plan that starts when one or more of the following situations occurs:

- Blackstart resources must be used to re-energize a shutdown area of the BES.
- Separation has occurred between neighboring RCs.
- An energized island has been formed on the BES within the RC area.

The scope of the RC's restoration plan ends when its TOPs are interconnected, and its RC area is connected to its neighboring RC areas.

This standard also includes requirements for reviewing each of its TOPs' restoration plans to determine capabilities relative to the RC area restoration plan and other TOP restoration plans and provides system restoration training for staff.

2.3.3 Reliability through Markets

Approximately two-thirds of the U.S. population represent areas where organized wholesale electricity markets are coordinated by an Independent System Operator (ISO) or a Regional Transmission Organization (RTO). While the details may vary, the ISO or RTO operates the transmission system, prepares regional transmission plans for the market footprint, and conducts competitive product markets (covering energy, capacity, and/or ancillary services markets). Ancillary markets provide compensation for blackstart services.

Currently, seven ISOs and RTOs operate in the United States, and all of them are registered with NERC to perform the RC function (see NERC 2019). As of 2015, these seven entities serve 213.5 million of the total estimated U.S. population of 321 million(NASEM 2017). (See Figure 1.)

NERC holds the highest level of authority for grid operations and reliability and directs eight regional reliability entities—Northeast Power Coordinating Council, Reliability First, Midwest Reliability Organization, Southeast Reliability Corporation, Florida Reliability Coordinating Council, Texas Reliability Entity, Southwest Power Pool and Western Electricity Coordinating Council—as depicted in Figure 2. Table 4 and Figure 3 shows the current RCs that are registered with NERC.

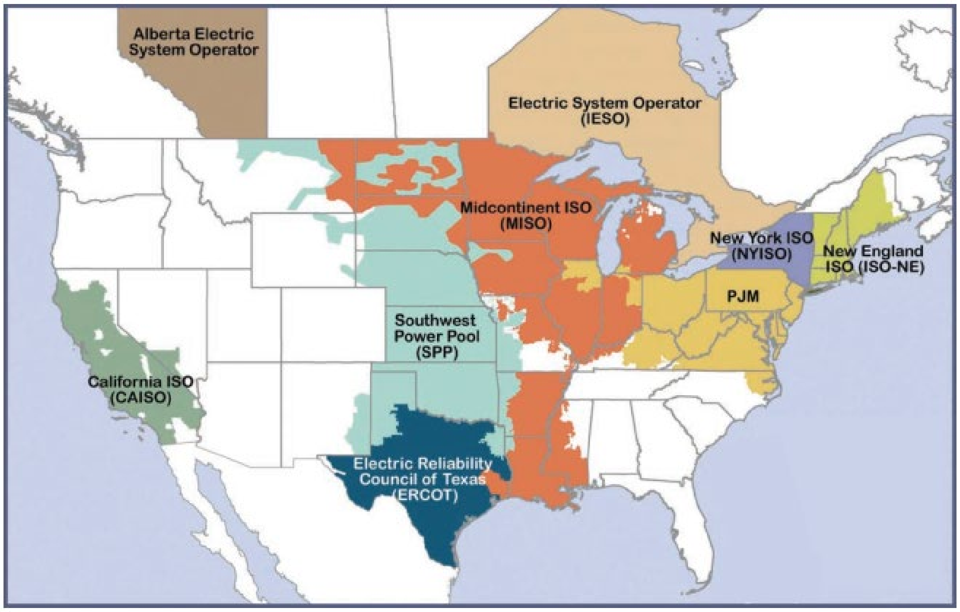

Figure 1. Map of RTO and ISO service areas in the United States and Canada (NASEM 2017).

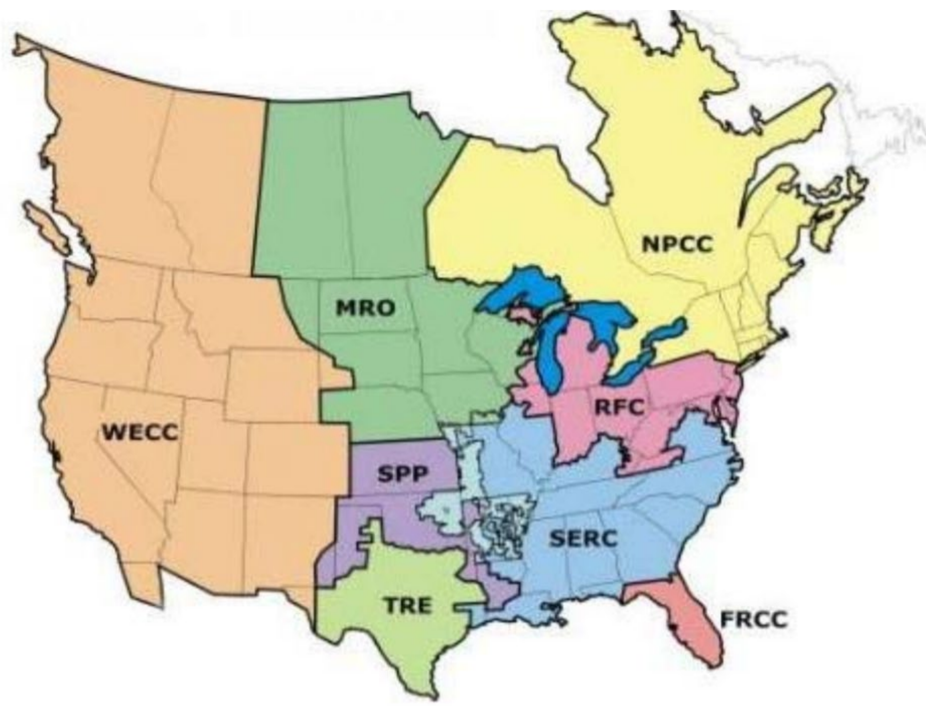

Figure 2. NERC regional entities (NERC 2019a).

Table 4. Reliability coordinator footprints in the United States.

NERC Reliability Coordinator	Regional Entity	State[a,b]
ISO New England (ISO-NE)	NPCC	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont
New York ISO (NYISO)	NPCC	New York
Pennsylvania New Jersey Maryland (PJM)	RF	Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia
Midcontinent ISO (MISO)	MRO, RF, SERC, SPP	Montana, North Dakota, South Dakota, Minnesota, Michigan, Wisconsin, Iowa, Illinois, Indiana, Missouri, Kentucky, Arkansas, Mississippi, Louisiana, Texas
Southwest Power Pool (SPP)	SPP	Arkansas, Iowa, Kansas, Louisiana, Minnesota, Missouri, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming
Tennessee Valley Authority (TVA)	SERC	Tennessee, and parts of Alabama, Mississippi, Kentucky, Georgia, North Carolina, and Virginia
Florida Reliability Coordinating Council (FRCC)	FRCC	Florida
Southern Company Services (SOCO)	SERC	Alabama, Georgia, Mississippi, North Carolina
VACAR-South (VACAR-S)	SERC	Georgia, North Carolina, South Carolina, Virginia
Electric Reliability Council of Texas (ERCOT)	TRE	Texas
RC West (RCW)	WECC	Western portions of the WECC, including California, Oregon, Washington, Idaho, portions of Montana, Wyoming, Nevada, Utah, Arizona, New Mexico
Southwest Power Pool West (SPPW)	WECC	Eastern portions of the WECC, including Colorado and portions of Montana, Wyoming, Utah, Arizona, and New Mexico

FRCC = Florida Reliability Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RE = Reliability Entity Inc; RF = Reliability First; SERC = Southeast Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Reliability Entity; WECC = Western Electricity Coordinating Council.

(a) Intrastate organizations (cooperatives, city utilities, county utilities, rural electric associations, etc.) are governed by the state public utility commissions unless a contract exists across state boundaries. The operation of each state is dependent on the required market organization and procurement of ancillary services, including blackstart and restoration, by state law (see Figure 4 in Section 2.5.3).

(b) The impact of multiple regulations across federal and state commissions hinders development and implementation a consistent set of restart procedures. Local operating conditions are inconsistent because equipment is unique to each region. The Pacific Northwest, Tennessee, and Colorado regions have significant hydro resources. The central Rocky Mountain area has significant high-voltage direct current (HVDC) links with possible operation to restart the interchanges. The Midwest has significant HVDC in the northern zone with significant pumped hydro in Missouri and Michigan. The location of wind generation in the states of Montana, Texas, Iowa, and Minnesota require unique operating procedures for energy balancing as well as restarting.

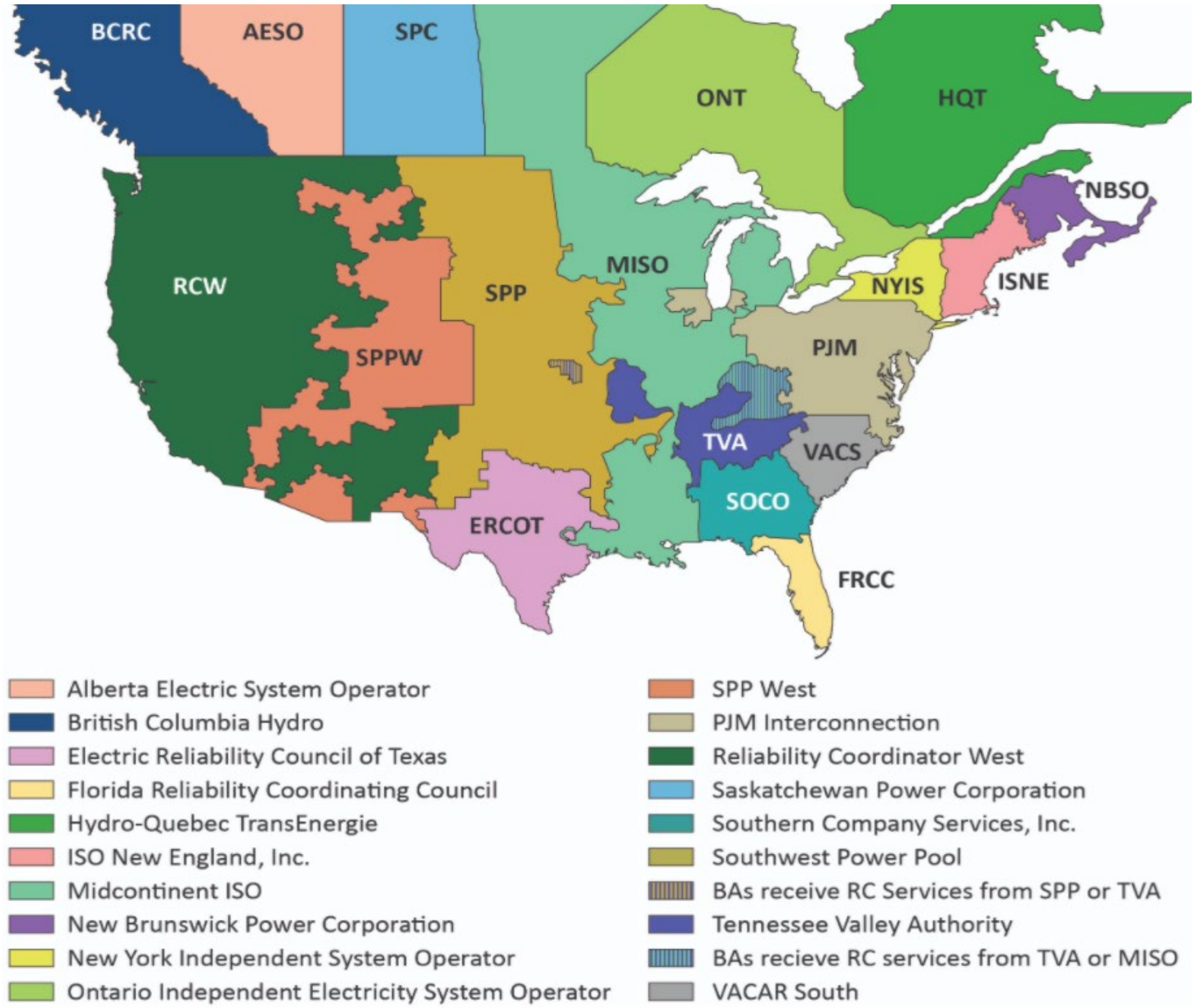

Figure 3. NERC Reliability Coordinators (NERC 2019b).

2.4 Blackstart Restoration Strategies and Approach

The specific strategies applied for system restoration from blackstart resources vary depending on the operating characteristics of the power system and an entity's restoration priorities and objectives.

It is nearly impossible to predict all possible combinations of problems that may occur after a major electric system failure. Therefore, restoration plans are typically designed to provide general strategies and guidelines for performing restoration activities to meet the stated goals and objectives.

A general strategy for system restoration is to do the following:

- Analyze – Conduct an initial assessment to determine system conditions.
- Stabilize – Determine the actions necessary to stabilize any portions of the system that remain operable.

- Restore – Perform restoration activities to re-energize shutdown areas of the power system.
- Return to normal operation – Restore the power system to a point that allows for normal operation.

General restoration priorities are to do the following:

- Energize transmission facilities to facilitate system restoration activities (e.g., cranking paths).
- Provide off-site power to nuclear power plants.
- Provide start-up power to generating stations that can aid in system restoration.
- Restore loads that are critical for substations to support infrastructure.
- Return the system to normal operations or a state whereby the choice of the next load to be restored is not driven by the need to control frequency or voltage.

2.5 Blackstart Restoration Phases

Upon experiencing a complete loss of all power, the main objective of the restoration process is to return the BES to the normal operating state safely and as fast as possible.

A typical blackstart restoration consists of three distinct phases described in the following sections.

2.5.1 System Preparation

The primary objective of this phase is to assess the state of the power system to determine its status and the proper approach to its restoration. An initial assessment must be performed first to determine if restoration conditions exist, and then a more detailed assessment is conducted to identify the resources that are available for use.

Prior to beginning the restoration process, the operator must determine the status of the generating units, neighboring systems and tie-lines, and whether any portions of the system are islanded and operational. In addition, the operator must gather information that might help determine the cause of the disturbance, which could prove instrumental in avoiding potential recurrences during the restoration process (e.g., not reenergizing faulted equipment).

2.5.2 System Restoration

Once the operator has determined the system status to the best of his or her abilities, system restoration can begin. It is during this stage that blackstart resources may be used to energize cranking paths and provide start-up power to other generators that can aid in system restoration.

A significant amount of communication and coordination must take place during this phase to ensure all involved remain aware of the actions taking place to facilitate restoration and avoid potential pitfalls.

Operating the power system in restoration conditions presents unique challenges that are not present during normal operations (EPRI 2002). The most important issues to address are as follows:

- Voltage control – Energizing transmission lines and operating reactive devices can cause runaway voltage conditions, which can result in equipment damage or system shutdown. Operators must take great care in controlling voltage during the restoration process and remain within the operating parameters defined in the TOP restoration plan.
- Frequency control – Maintaining frequency during the restoration process can be extremely difficult because changes in generation and load are more impactful on a smaller system. Cold-load pickup[1] can have a significant effect on the frequency and energizing a single distribution circuit can result in unacceptable deviations. In addition, sufficient operating reserve must be maintained throughout the restoration process to provide dynamic response to load and generation changes and to avoid a potential system collapse.
- Equipment issues – Some equipment may have been damaged during the initial disturbance. Other equipment may be inoperable due to a loss of stored energy, failed control systems, etc. Reduced fault current and abnormal system configurations could lead to protective relaying issues and some protection schemes may not be appropriate for restoration conditions. The operation of backup systems and equipment may require dispatching personnel to remote sites and should be planned to avoid delays in restoration.
- System dynamics and stability issues – The power system has increased exposure to system dynamics issues during the restoration process. Maintaining dynamic stability when operating a weak system can be difficult, and care must be given to limiting the amount of transfer across lines and controlling voltage to avoid potential stability issues.

2.5.3 Load Restoration

For successful restoration, the critical loads must first be understood and identified. Critical loads are defined as the loads needed to perform restoration and are essential for sustained operation of the BES. They also may be critical based on the service they provide. Critical loads include (but are not limited to) the following:

- nuclear power plants (maintain service even if shutdown)
  - critical for powering coolant circulation pumps for removing decay heat
  - need two independent off-site feeds to operate or restart
- loads that may be critical for restoration priority or to support critical infrastructure
  - pumping plants for both water and wastewater lift stations
  - emergency services (police, hospital, airports)
- station service power to key utility assets, including substations, generation facilities
- critical communication facilities
- command and control facilities.

Some utilities may also include gas compressors as a critical load (FERC-NERC 2018).

[1] Cold-load pickup is a term used in the electric utility industry to refer to the challenge of restoring load that has been off for a while, because all the thermostats are turned on thereby disrupting the normal load diversity. The power consumption will be greater for several minutes to a few hours immediately after restoration than it would have been otherwise without the disruption. While the term implies the effect is magnified during colder weather, the same principle applies during hot weather associated with simultaneous air-conditioning demand.

Operators must determine which loads to energize first to aid in system restoration. As previously stated, loads that are critical for substations and infrastructure support will be prioritized, but other loads may be picked up to help control the frequency and voltage.

Because power systems are highly capacitive when lightly loaded, voltage control must adapt to keep system voltages from rising excessively. Therefore, the sequence of how much load is restored and where it can first be restored based on proximity to generation and/or suitable transmission capacity is critical. The general concept is that the rules provide a means to energize zones that contain critical demand first, such as emergency rooms of medical facilities. Traditionally, distribution to life-supporting medical equipment is given priority for restoration. For example, given the failure rates and fuel availability for diesel generators, hospitals and other critical facilities are given priority even though they may have on-site backup generation.

At the beginning of a restoration event, operators must be careful not to pick up large chunks of load too soon; general guidelines recommend that load blocks be limited to no more than 5% of the total synchronized generation. Operators will be able to restore load more rapidly during the later stages of restoration as the non-blackstart generation is recovered. This is necessary for maintaining the adequate operating reserve needed for large amounts of cold-load pickup. Some utilities that have flexible generation (such as hydro) may elect to bring up substantial generation reserves before adding load in larger blocks.

Further complicating the process is the fact that following a large blackout, several entities will be simultaneously involved in the restoration, and their collective actions must be carefully orchestrated.

The system restoration process will end when the system is returned to a state in which the choice of the next load to be restored is not driven by the need to control frequency or voltage and operations are transferred back to normal operations. Figure 4 shows the different phases of the restoration process over time.

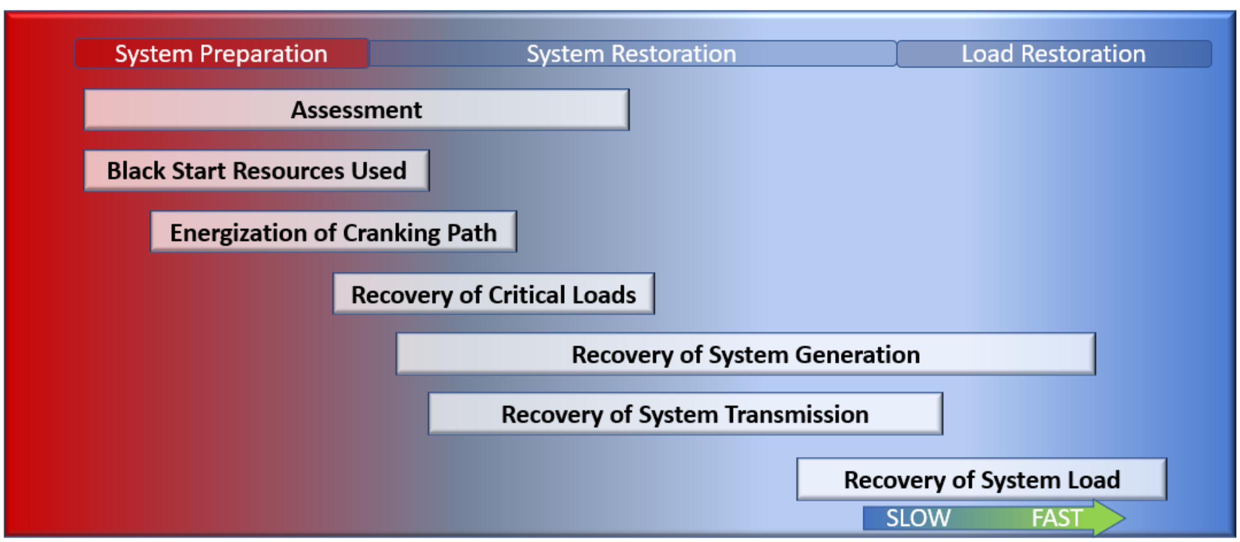

Figure 4. Restoration process over time.

2.6 Blackstart as a Service

Ancillary services are defined as services that support the reliable operation of the power system, which can include voltage support, frequency regulation operating reserves, and blackstart capabilities. As of July 1, 2013, blackstart became a mandatory service, and the specific requirements are defined by NERC standards (EOP-005-3 and EOP-006-3).

For participants operating in an organized market, compensations for blackstart services are outlined in the ISO or RTO tariffs (blackstart resources are compensated via the Open Access Transmission Tariff of some market areas [e.g., PJM, New York ISO, ISO – New England]). Compensation typically factors in the blackstart service provider's fixed, variable, training, and fuel storage costs, plus an incentive for participation. In addition, some markets provide some degree of compensation for blackstart resource feasibility studies and for the installation of equipment needed to support blackstart capability. Payments for those resources are collected via the transmission tariff. In non-market areas, regulated generator owners are compensated via retail rates charged to utility customers (FERC-NERC 2018).

According to NERC, blackstart resources are compensated as additional reliability services in most electric wholesale markets. The compensation for these plants includes being compensated for the following:

- rated power (at the market rate) during the annual blackstart testing, in which the generator is connected to a dead bus;
- training costs associated with maintaining staff with the capability to perform a blackstart;
- fuel storage costs (as associated with fuel type); and
- the blackstart capacity of the generator.

Table 5 lists the compensation specification given in different markets in the United States.

Table 5. Summary of black start compensation in different markets (Gracia et al. 2018).

Market	Tariff Type	Unit Size Classification	Technology Differentiation	Initial Term of Commitment
ISO-NE	Standard payment	7 +2 classes	Fossil, hydro	>1 year or unit age based
NYISO	Standard payment	7 classes	Not mentioned	3 years
PJM	Cost Recovery	Not mentioned	Combustion turbine, hydro	>2 years
MISO	Cost recovery	Not mentioned	Not mentioned	>3 years
CAISO	Cost recovery	Not mentioned	Not mentioned	Not mentioned
ERCOT	Economic payment	Not mentioned	Not mentioned	2 years

ISO-NE = ISO New England; NYISO = New York ISO; PJM = Pennsylvania New Jersey Maryland Interconnection, LLC; MISO = Midcontinent ISO; CAISO = California ISO; ERCOT = Electric Reliability Council of Texas.

PJM currently puts out an RTO-wide Request for Proposal (RFP) for new blackstart resources every 5 years. This first process started in 2013, which allowed for time to address units that were scheduled to be decommissioned in 2015. The second RFP process was initiated in 2018.

Once a generation plant is considered a blackstart resource, PJM continues to make that assumption until the generator owner/generator operator provides notice that they will no longer participate in the service. For security reasons, the details of which facilities provide this service are not publicly disclosed.

As stated in the RFP, the following must be demonstrated to meet the requirements for what may be considered a blackstart:

1. A blackstart unit must have the ability to start without an outside electrical supply.
2. A blackstart unit must be able to close its output circuit breaker to a dead (de-energized) bus within 180 minutes (or less based on the characteristics of the specific critical load) of a request from the TO or PJM.
3. A blackstart unit must be capable of maintaining frequency (isochronous mode) and voltage under varying loads.
4. A blackstart unit must be able to maintain rated output for a period of time identified by each TO's system restoration requirements (typically 16 hours).

2.7 An Illustrative Example of System Restoration Using Blackstart Resources

To provide a detailed illustration of the principles described in this section, the following example of the system restoration steps is taken from PJM's operating documentation (PJM 2019):

1. Perform a system assessment to determine extent of the outage.
2. Start blackstart units to form islands.
3. Build cranking paths to other generating units, nuclear stations, and critical gas facilities.
4. Restore critical load.
5. Synchronize and interconnect islands to form larger islands.
6. Connect to outside areas.
7. Return to normal operations.

Each TOP is responsible for restoring its zonal customer loads. However, requests from neighboring entities for cranking power are a higher priority than restoring any additional customer load of the supplying area.

Moreover, during the restoration process, there are additional concerns that are put upon the type of generation that is brought online. PJM mandates the amount of reserves that need to be available for each online generator to ensure there is a reduced probability of frequency declining below safe operating levels as new loads are picked up. This is key in determining how fast the load is restored. The amount of load that each unit can pick up in terms of the percentage of the capacity rating of the generator units are as follows:

- 5% for fossil steam
- 15% for hydro
- 25% for combustion turbines.

A sample step-by-step restoration process on the Institute of Electrical and Electronics Engineers (IEEE) 39-bus system is depicted in Figure 5. The red-colored segments represent the energized section of the grid and the black segments the parts of the grid that are offline. The process (from t=1 through t=9) shows this small system being restored.

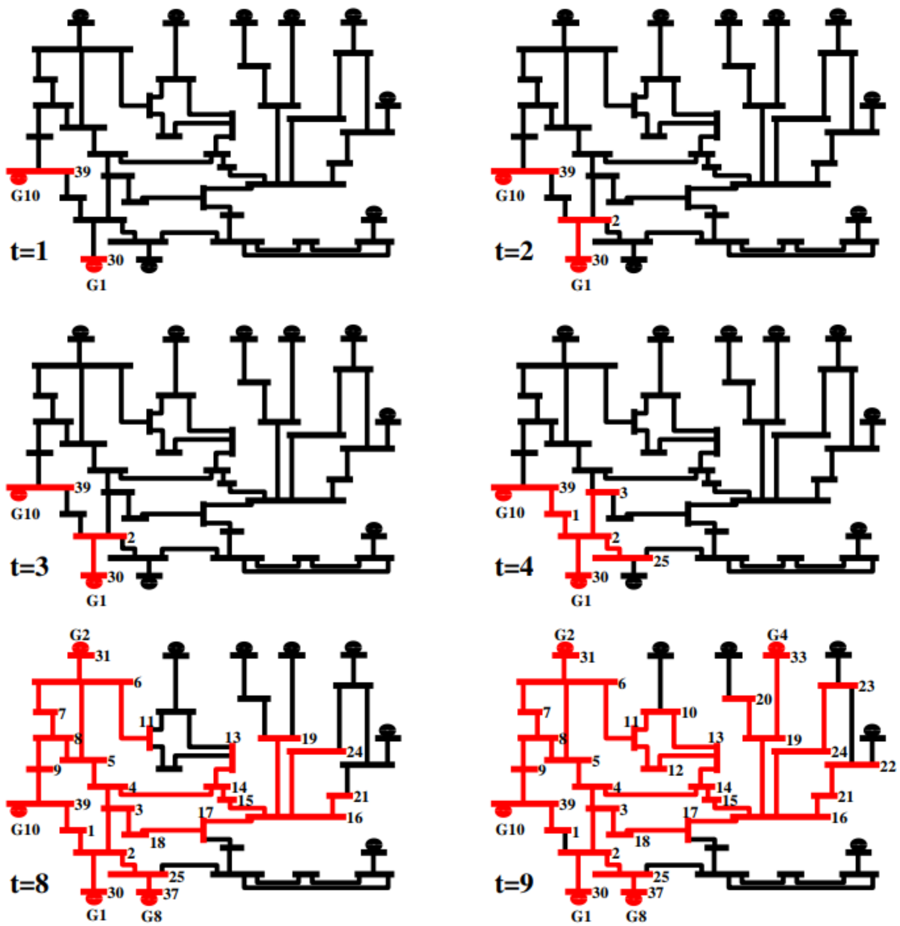

Figure 5. Example of blackstart restoration on a smaller system (Patsakis et al. 2018)

In case the large region lost the power, a parallel restoration approach is being designed to bring the grid back in service. In this case, multiple blackstart units should be powered up simultaneously, thereby creating several electrically isolated islands across the affected region. After the islands are stable and large enough, they are synchronized and reconnected to form a complete and recovered grid. In the particular example shown in Figure 5, the entire restoration was accomplished using blackstart-capable units in the bottom left of this fictitious system. Had there been another blackstart unit on the other side of the system, the simultaneous restoration could have been accomplished with fewer steps.

3.0 Opportunities and Challenges

The nation's electric grid is experiencing unprecedented changes in generation portfolio, transmission and distribution system, and in the way it is operated. The grid is transforming to accommodate the implementation of new smart grid technologies, continued technological advances, and the development of new business models. The operation of the electric system is becoming more complex with the integration of a range of new end uses that are both being developed and/or have been commercialized. These include intelligent buildings, electric vehicles, hydrogen production stations, and small-scale distributed generation systems (e.g., combined heat and power, photovoltaic [PV], and fuel cell systems).

3.1 Renewable Generation

Renewable-based electricity generation includes hydroelectricity, wind, solar (PV and concentrated "thermal" solar power), biomass, and waste. Today in the United States, 21% of the total electricity demand is supplied by renewable resources. With the goal of reducing the greenhouse gas emission, a target date for achieving the carbon pollution-free electricity sector is no later than 2035 (Lawson 2021). In February 2021, the U.S. Energy Information Administration projected that the share of total electricity generation that will be coming from renewable sources in 2050 might vary from 33% to 57% (more than double what it is today), depending on factors such as future energy prices and economic growth, where the highest growth of renewables is predicted for solar and wind generation.[1]

Increased penetration of renewable resources is driven by the environmental, economic, and social challenges of the future. Among all three categories, certainly the greatest driving force for the integration of renewables is the worldwide environmental movement.

This shift in generation portfolios will have profound effects on the operation of the grid, which will, in turn, affect the operation of renewable resources themselves as well as the operation of other resources and equipment connected to the grid (CN-NREL 2012). Wind and solar generation both experience inherent intermittency. Different from conventional electricity sources, they are characterized by *non-controllable variability*, *partial unpredictability*, and are *location-dependent* (Perez-Arriaga 2011).

Variability of the generation output results in the need for:

- additional energy to balance supply and demand on the grid on an instantaneous basis (balancing reserves), as well as
- ancillary services, such as frequency regulation and voltage support.

Partial unpredictability calls for:

- improved weather and generation forecasting technologies,
- the maintenance of reserves that stand ready to provide additional power when renewable generation produces less energy than predicted, and
- the availability of dispatchable load to "soak up" excess power when renewable generation produces more energy than predicted.

[1] Wind and solar generation are increasing throughout the country, with significant adoption occurring in in California and Northwest Texas.

And finally, location dependency may require additional transmission capacity.

Renewable generation types (PV and wind) do not have the ability to function as blackstart units without significant incremental investment in *grid-forming inverters*[1], a nascent technology receiving research and development support. As a result, the displacement of traditional generation by wind and solar generators could introduce concern not just to the system normal operation, but also to future power systems related to their ability to provide blackstart capability.

While the generation mix is changing, the NERC blackstart requirements are not. The larger-scale introduction of a market solution will allow another method to add value and contribute to the decision about the type of generation installed. Hopefully, industry planning and market-based processes will continue to provide a solid basis for ensuring that blackstart adequacy is being met.

Concerns about this change from traditional resources, particularly replacing natural gas with renewable generation are often brought up by various experts. For example, former Chief Executive Officer of PJM Andy Ott testified before Congress in 2018 that natural gas combustion turbines are currently the technology of choice for blackstart.[2]

Nevertheless, as the generation portfolio continues to change (as explained earlier), there will be a need to continue to assess blackstart strategies.

3.2 Distributed Energy Resources and Energy Storage

In addition to large-scale facilities, an increasing portion of generation will be from small and distributed resources, often located on customer premises. Their controllability and dispatchability can be challenging from a system restoration perspective. As the amount of DER penetration continues to increase, the aggregate effect on the bulk power grid also becomes greater.

For example, the California Energy Commission estimates nearly 75,000 new homes would be built in 2020, which would add an additional 222 MW of solar power to the grid that year alone (Wolf 2019). With this high penetration of renewables (especially DER), the net load curve starts to be greatly affected, to the point where there are over-generation risks, as shown in Figure 6. Furthermore, the large differences seen in net load during the peak solar production compared to the time the solar is off, impose great risk to grid stability and require large amounts of fast-starting units to make up for the ramp caused by the sharp decrease in output toward the evening.

[1] https://www.energy.gov/eere/solar/articles/powering-grid-forming-inverters

[2] https://www.pjm.com/-/media/library/reports-notices/special-reports/2018/20181011-ott-written-senate-testimony-on-system-restoration.ashx

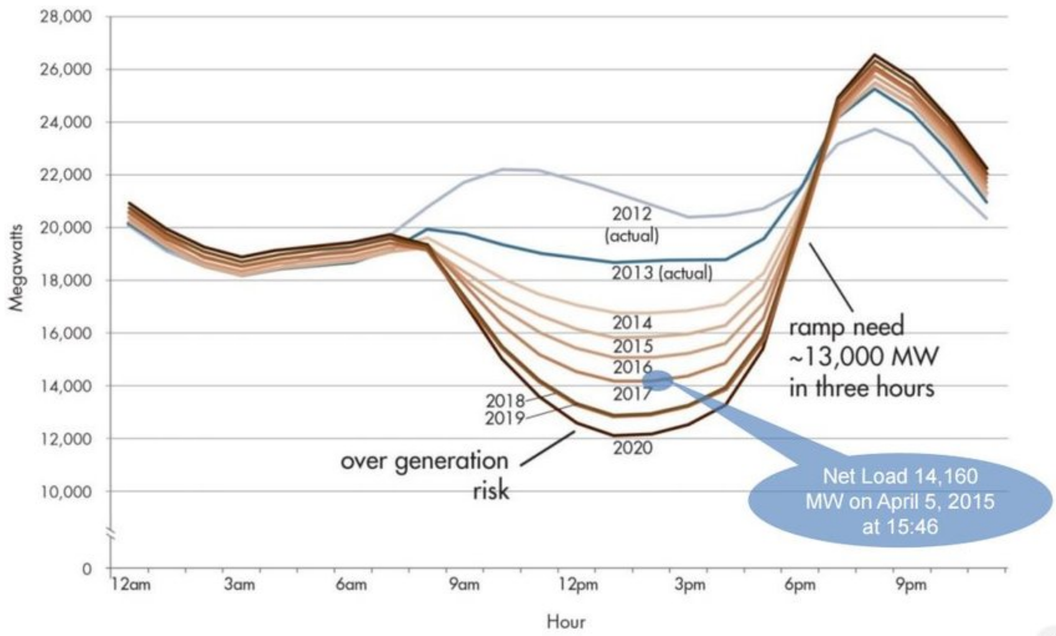

Figure 6. Historical and projected net load in California during a typical spring day (Anderson et al. 2017).

A possible means of reducing the impact of non-dispatched DER on the transmission system would be to use distributed energy storage systems. Electricity storage makes it possible to shift the net load seen by the grid and distribute it more evenly during the day. While the net load during the day would be higher in this case, with the ability to discharge the stored electricity in the evening the net load peak would decrease, lowering the overall ramp rate. This would help minimize the impact of DER on bulk grid generation and transmission by lowering the need for fast-start resources (like gas-fired turbines).

Energy storage on the bulk transmission grid is also necessary to provide the balancing resources needed for renewable generation and be available as a source of energy for times of peak loads (lowering even more the need for potentially expensive fast-start resources). The size needed for utility-scale storage allows for a larger selection and flexibility in the choice of methods that would not necessarily make monetary sense on a smaller scale. Various methods of storing this energy range from traditional methods to new and innovative technologies; examples include, but are not limited to, the following:

- batteries
- super capacitors
- pumped hydro
- concrete gravity
- flywheels
- compressed air.

In addition, energy storage units could be used to reduce the variability of renewable generation and allow large renewable plants to be considered as blackstart resources in the future. For example, the Tehachapi pumped-storage hydropower unit was initially investigated to complement wind generation as a virtual power plant. The pairing of energy storage with renewable energy resources is expected to continue as each distributed generation is augmented with a distribution system as a virtual power plant.

3.3 Synchrophasor Technology

Cost and component reductions in electronic sensors, computer controllers, and standardized communication systems have enabled many smart grid technology deployments. Advances in digital relay software and hardware have opened new avenues for monitoring, control, and protection of critical infrastructures.

A synchrophasor is a time-synchronized measurement of a quantity described by a phasor. Phasor measurements include both magnitude and phase information. Devices called phasor measurement units (PMUs) measure voltage and current, and with these measurements, derive parameters such as frequency and phase angle. Data reporting rates are typically 30 to 60 records per second. In contrast, current Supervisory Control and Data Acquisition (SCADA) systems often report data every 4 to 6 seconds—more than a hundred times slower than PMUs. The accurate time resolution of synchrophasor measurements allows unprecedented visibility into system conditions, including rapid identification of details such as oscillations and voltage instability that cannot be seen from SCADA measurements.

Although SCADA is the primary tool used by system operators for monitoring and controlling the BES, few grid operators and electric utilities maintain wholly redundant data collection and communication systems that can replace SCADA if it fails or is compromised. However, a standalone synchrophasor network with extensive PMU deployment essentially creates a separate system to collect grid condition information and deliver it to the control room. For this reason, many utilities elect to keep their synchrophasor data network independent of their Energy Management System and SCADA system so it can serve as a backup when needed (NASPI 2015, 30). This use of synchrophasor data is particularly relevant from a system restoration perspective given the possibility of a cyber-physical sabotage or “Black Sky” event resulting in the loss of critical systems and a partial or total shutdown of the power system.

The many ways synchrophasor-based applications can provide value when performing system restoration include, but are not limited to, the following (NASPI CRSTT 2015):

- Detecting system islanding events – Synchrophasor-based measurements may be used to identify conditions where frequency and voltage angle changes are not in synchronism across the system, indicating that an islanding event has occurred.
- Analyzing cause and resulting system conditions – Synchrophasor data may be used to determine the sequence of events and identify possible causes of the disturbance that resulted in a blackout condition. These data can be extremely useful when developing a restoration strategy and, depending on the nature and severity of the event, may allow the operator to identify failed facilities that must be isolated before restoration activities begin.
- Returning the system to within acceptable parameters – After a major disturbance, system operators must assess the status of generation and transmission facilities that remain energized to determine if unacceptable operating conditions exist. Failing to stabilize portions of the system that remain operational may result in significant equipment damage and widespread outages. Synchrophasor data can be used to quickly assess post-disturbance conditions and identify unacceptable system performance that must be addressed.
- Determining restoration activities – When an RC and its affected TOPs implement their respective restoration plans, they must ensure their activities to restore shutdown areas to service and parallel electrical islands to the main grid are coordinated and do not jeopardize the overall objective of returning the system to a reliable state. Synchrophasor data can be

used to assess the impact such actions more accurately may have on system voltage and frequency. The use of these data to detect power system oscillations and potential voltage stability issues is particularly valuable when performing system restoration.

Entergy's use of PMU data and analytical tools after Hurricane Gustav struck the Gulf Coast in 2008 provides an excellent example of how synchrophasor technology can be used during islanding events and system restoration. After the hurricane struck the area, so many of Entergy's transmission lines were damaged that an electrical island was formed within the heart of the service territory. Entergy's SCADA system did not detect this island, but its phasor data system revealed its existence by showing two distinct frequency plots.

Once they recognized that their planned service restoration activities would compromise the operational integrity of the island, Entergy reevaluated and redesigned its restoration plan. The utility then used its phasor system to observe both the island and the rest of its service territory, watching the two frequency lines (as shown in Figure 7), as it executed a new restoration and synchronization plan that successfully resynchronized the island 33 hours later.

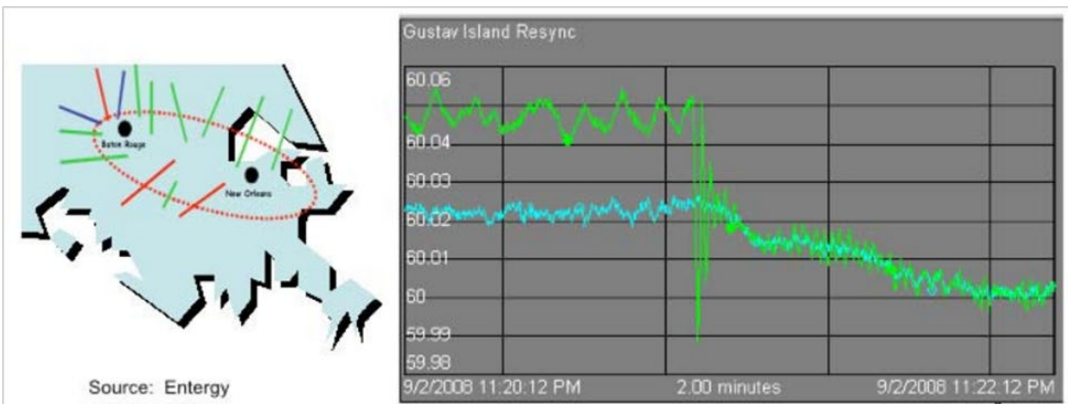

Figure 7. Entergy system islanding after Hurricane Gustav, 2008 (NERC 2010).

Many reliability entities have included synchrophasor-based applications in their blackstart exercises, using phase angle monitoring for generator resynchronization, line reclosing, and frequency monitoring for generation and load balancing (NASPI 2015).

3.4 Advanced Distribution Management System

Distributed resources are also being investigated to handle energization of the local grid, such that the cold-load pickup is not an issue when the distribution system is being re-synched to the transmission system. However, the technical challenges of coordinating and controlling the distribution system require more advanced control systems. To be able to properly control the amount of DER that are being placed online, Advanced Distribution Management Systems (ADMSs) are being implemented.

An ADMS is a software platform that integrates numerous utility systems and provides automated outage restoration and optimization of distribution grid performance. ADMS functions can include automated fault location, isolation, and service restoration, conservation voltage reduction, peak demand management, and volt/volt-ampere reactive (volt/VAR) optimization. In effect, an ADMS transitions utilities from paperwork, manual processes, and siloed software systems to systems with real-time and near-real-time data, automated processes, and integrated systems (DOE 2015).

As grid operators and electric utilities consider how DER can be used to increase system resiliency and aid in restoration activities, they also must determine how monitoring and control systems such as ADMSs may be incorporated into their respective restoration plans.

3.5 Transactive Controls

The advent of low-cost computer-based sensors, micro-controllers, switches, and motor controllers with wireless communications devices is enabling the evolving development of new business forms, such as transactive energy, advanced demand response technologies, and distributed control of smart charging resources for electric vehicles.

When talking about the future of power grid reliability, it is imperative to consider the role that transactive energy and controls could play in a blackstart situation. Transactive energy is an emerging energy management approach based on balancing supply and demand collaboratively instead through a centralized command and control approach, driven particularly by a market-price–based approach. This method of control requires communication between generation and load in the form of smart devices and metering, and it allows the consumer to be selective about when they are willing to pay higher amounts during peak grid usage times or pay lower amounts to use off-peak energy. Customers could be incentivized to pay less to use power during off-peak times to help utilities better manage their generation resources during peak demand. The key to success with transactive controls is communication between the smart devices and the utility that is managing the supply and demand.

If there were a need for a blackstart restoration, transactive controls could be used to help curtail load during generation ramp-up. In current scenarios without transactive controls, the power gets turned back on in limited stages. With more load curtailment mechanisms in place for lower priority customers, a faster pace of restoration is envisioned. This largely ameliorates the "cold-load pickup" phenomenon, where customer demand is immediately high due to reduced diversity (i.e., all thermostats are simultaneously demanding electricity the moment power is restored to that distribution feeder). Before the power is disrupted, there is a certain degree of load diversity, with individual thermostats controlling individual heating, ventilation, and air-conditioning units. After a prolonged interruption, every thermostat in the system will be turned on, and the initial load will be greater than it was before the disruption. This is a well-known phenomenon that places constraints on how quickly load can be recovered. Smart devices that could be programmed to look for a blackstart signal after being powered up from a sustained outage could be used to help balance load during the ramp-up and restoration process.

Similarly, transactive controls could be used to manage generation and load if there were a need to provide power rationing during a lengthy blackstart restoration effort. Ratepayers could "opt-in" or "opt-out" of their rationing, or even pool rations together for the greater good of their community or neighborhood. Price-based schemes, such as real-time pricing, would also provide a natural mechanism for rationing power during the restoration process.

Transactive energy and control and smart metering/devices provide the opportunity to build a smart blackstart restoration, and these cutting-edge technologies should be considered when updating energy assurance or incident management plans, and any future blackstart procedures. Demand response, such as that offered by transactive residential contracts, has been shown to provide frequency control equivalent to a traditional generation.

3.6 Electric – Natural Gas Coordination

The natural gas and electricity industries provide a service that is critical to national health and safety. Recent events have illustrated why the interdependence of these industries merits careful attention. FERC has stressed the importance of ensuring that a lack of coordination between the two industries will not result in outages and reliability problems.

Over the last few years, natural gas has been used much more heavily in electricity generation. This trend will likely accelerate as coal-powered generation is retired, renewable energy resources require more backup by natural gas plants, and low natural gas prices encourage more use of gas (FERC 2019).

Events such as the Southwest outage in February 2011 and the Texas event in 2021 suggest that more resources must be allocated to planning for the increased use of natural gas to generate electricity (FERC-NERC 2011, FERC-NERC 2021). These planning efforts should consider how natural gas availability can affect electric grid blackstart capability and actions that can be taken to proactively address potential electrical–natural gas coordination issues before they occur.

As mentioned earlier, natural gas generation as a blackstart resource depends upon having a supply of pressurized gas on-site and/or having the natural gas pipeline that supplies the facility pressurized and in service. To reduce the risk of this dependency, many blackstart generating units have dual fuel capabilities (using either natural gas, fuel oil, or both). This capability is intended to address instances in which the primary source of fuel is disrupted, so the generation facility will be able to switch over to its secondary fuel, which is stored on-site.

In addition to improving electric–natural gas coordination to address interoperability concerns, it is important to recognize how coordinated cyber and physical attacks could affect the industry sector as a whole. For that reason, NERC's Electricity Information Sharing and Analysis Center (E-ISAC) and the Oil and Natural Gas Information Sharing and Analysis Center (ONG-ISAC) recently agreed to improve information sharing between the organizations and their members to enhance the cybersecurity of North America.

Using a variety of tools, the E-ISAC and the ONG-ISAC analyze potential physical and cybersecurity threats and, using their respective secure platforms, alert and advise members about how to mitigate threats (E-ISAC 2019).

3.7 Emerging Threats

3.7.1 Cyber Threats

In the age of the automation and the ever-increasing connectivity and ease of low-cost communication, there has been greater visibility and control of electricity assets even with a reduction in utility staffing. And as the distinctions between information technology and operational technology become blurred, cyber exposure of the critical industrial control systems, which were previously completely disconnected from the outside world, becomes greater. This increased exposure has resulted in increased vulnerabilities in the power grid to cyber-attacks. These vulnerabilities are imposing high risk not just to the grid operation but also related to the possibility of not being able to restore the system after an intrusion. Critical control systems need to be carefully considered when planning for the blackstart strategy to minimize the impacts of these cyber threats.

3.7.2 Climate Change

Climate change is also posing a greater threat to the nation's infrastructure as more severe, natural disasters start to become the norm. Hurricanes over the last decades have completely devastated parts of the power grid, from Hurricane Sandy's impact on the Northeast to Hurricane Maria's effects on Puerto Rico. The subsequent recovery from these events is extremely expensive, time-consuming, and requires specialized approaches for addressing each disaster. Figure 8 shows the power dissipation index trends associated with the North Atlantic Ocean. The power dissipation index is a means of quantifying the hurricane magnitude and their number of occurrences over a year (i.e., the total combined energy of hurricanes).

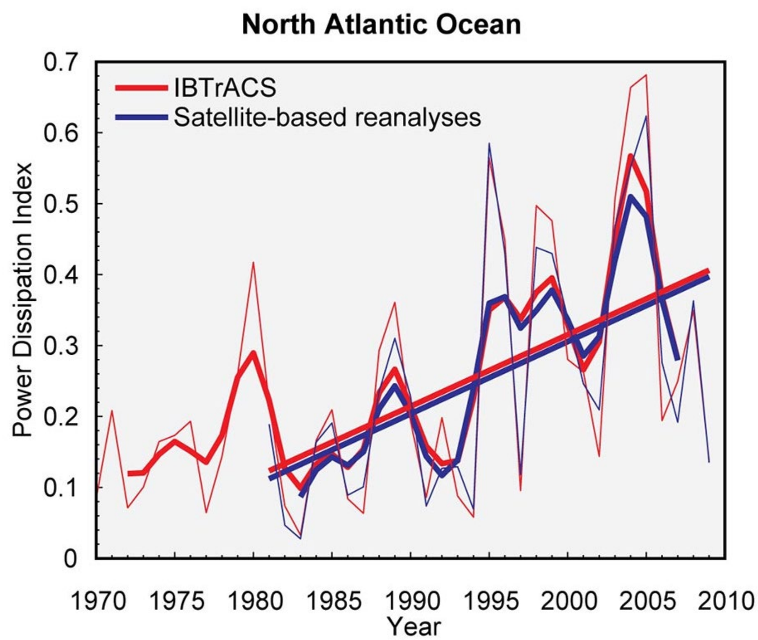

Figure 8. Observed trends in hurricane power dissipation (Kossin et al. 2007).

3.7.3 Other Emerging Threats

Events like geomagnetic disturbances (GMDs or solar weather) have also been known to have an impact on the power transmission system through the induction of geomagnetically induced current causing saturation on transformers. This is especially prevalent in the grids that are near the magnetic north and south. The auroral zones in Figure 9 are due to the magnetic fields of the Earth coming together, which make these areas less capable of providing protection from solar weather (think of the Northern Lights). This combined with high-resistant soil types (namely igneous rock) makes an area even more susceptible to GMD. This condition exists in Quebec, and it caused an outage of Quebec's system on March 13, 1989. Figure 9 shows the normal auroral location zone, with the extreme zonal event that occurred and caused the system collapse (Odenwalder 2009).

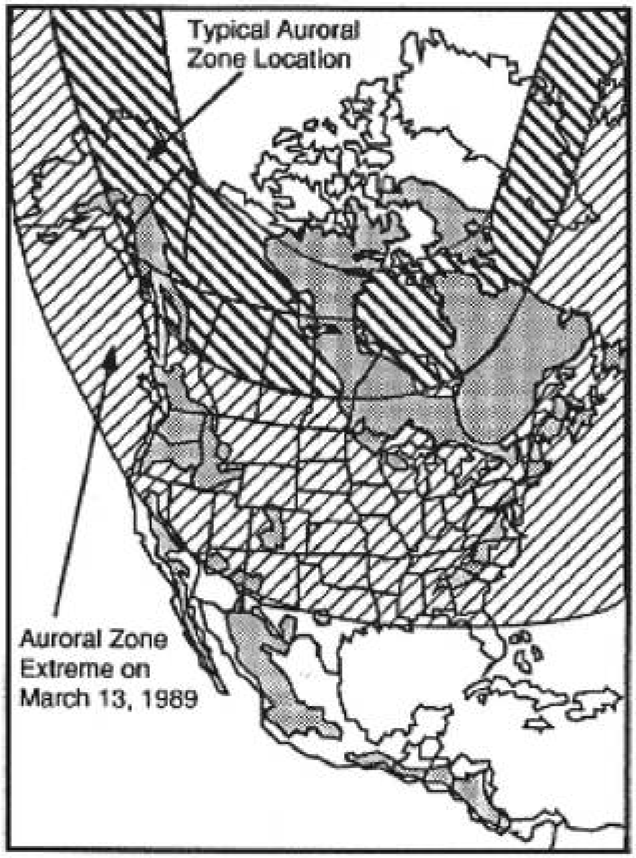

Figure 9. GMD event on March 13, 1989 (Credit: American Geophysical Union).

EMPs, which are short bursts of magnetic energy, are transient phenomena, compared to the more steady-state GMDs. These events can be natural (e.g., lighting strikes), man-made (e.g., voltage transients due to motors starting), or caused by military-grade weapons (high-altitude nuclear blasts). Protecting against these effects can be accomplished in a variety of ways, including by shielding, grounding, hardening, and blocking; hardening electronics; and installing surge protection and/or transformer neutral blockers.

3.8 Unconventional Blackstart Examples

Innovative blackstart and grid restoration methods significantly reduce the risk of damage caused by blackouts. Technologies and capabilities are constantly changing, which enables new approaches relative to more traditional methods. As such, there are examples of unconventional blackstart methods that differ from more common practices but have proven successful in field testing and real-life events.

3.8.1 Grid-Level Battery for Blackstart

Developed by the Berlin-based storage pioneer Younicos, in 2017, the WEMAG battery power station blackstart test took place in the city of Schwerin in northern Germany. In this test, the battery station successfully restored a previously disconnected power grid.

> It shows that batteries can be used to restore the grid — this time we used a combined-cycle turbine generator, but the next phase will use renewable energy. The battery itself is too small to provide energy for any length of time — but that's not what it's designed to do. It's designed to keep the grid stable — while renewable energies provide the energy. The blackstart takes this one (logical) step further: It basically shows, or aims to show, that we can not only keep the grid stable just with renewables (and the batteries), but also restore it quickly (Hales 2017).

In the United States, a 33 MW/20 MWh lithium-ion battery energy storage system, which in its everyday use provides grid stability and helps smooth the output from local renewable power sources, was used on May 10, 2019, to kick-start an IID 44MW combined-cycle natural gas turbine (located at El Centro Generating Station in Imperial Valley, California). "The battery energy storage system did not only provide start-up power, but converted it, allowing the generator to achieve synchronization" (Colthorpe 2017).

The ability of batteries to provide this much-needed grid function has long been discussed. Improving the efficiency of existing thermal generators could be a quick way to deploy batteries and make power networks more flexible.

3.8.2 High-Voltage Direct Current

Controlling flows, reactive power supplies, or demand can render high-voltage direct current (HVDC) links difficult to use for the integration. Traditional means of using a Line-Current Converter require a large amount of reactive support and cannot operate into a "dead" system because they require commutation power from the system at the load end.

Recent advances in Voltage-Source Converter (VSC) technology include a Pulse-Width Modulation (PWM)-based VSC HVDC scheme, which has no such restriction. Another advantage of VSC HVDC is that it has the capability to ride through voltage transients, while improving the system performance with the reactive support that it can provide; VSCs can provide real and reactive power separately. Being able to maintain reactive power support, while still being able to reverse the real power flow, makes these uniquely capable during blackstart events.

VSCs do need to be configured for a blackstart. Doing so begins with station service power that can either be provided by a battery or diesel backup, but they are often chosen when available due to their relatively low power requirements and capabilities in quickly coming online.

3.8.3 Distributed Batteries for Blackstart

The U.S. DOE continues to conduct research on using DER on the distribution system to aid in blackstart operations. DOE's Office of Electricity has investigated using local diesel and renewable generation sources in microgrids to aid in the blackstart of nearby transmission resources. The projects investigated reconfiguring distribution systems and using community microgrids to provide power via local subtransmission and transmission networks to start up a hypothetical thermal plant (Schneider et al. 2017). The research area included a field demonstration of using local, backup diesel generators to energize a subtransmission transformer. The local diesel generators were able to successfully handle the inrush from the energized transformer and could theoretically provide the start-up power needed for a nearby thermal plant.

More recently, DOE has conducted several projects investigating how inverter-based DER can be used to blackstart and backup power operations. Leveraging a prior Defense Advanced Research Projects Agency project called Rapid Attack Detection, Isolation, and Characterization System (RADICS), and beginning in 2018 DOE has been conducting field tests on a microgrid located on Plum Island, New York ("Validation, Restoration and Black Start Testing of Sensing, Controls and DER Technologies at Plum Island" 2020). The tests have focused on the cyber-resilience and physical capabilities of grid-forming, inverter-based DER, and microgrids to provide backup power during electrical outages. Investigations of how inverter-based energy storage devices react to cold-load pickup and distribution service restoration have been key aspects to help evaluate the future of these resources in power grid blackstart and restoration activities.

4.0 Recommendations

This report provides the following recommendations related to grid resiliency, system modeling, additional areas of study, coordinated emergency response, enhanced training, outreach, and industry best practices are listed in the following sections.

4.1 Increase Grid Resiliency

Identify critical power system components to determine optimal locations where hardening of components could improve system reliability and blackstart capability.

Steps that can be taken may include the following:

- Establish redundancy in blackstart resources and cranking paths.
- Increase the robustness of structural design and materials of identified critical transmission towers.
- Increase the power capacity rating of cranking paths through circuit construction and increased required clearance underneath the towers.
- Fortify critical substations (to provide further protection from external natural elements).
- Maintain an independent and isolated SCADA system for separate control of the blackstart resources and cranking paths.
- Deploy synchrophasors to provide added visibility, situational awareness, and redundancy of critical monitoring infrastructure.
- Take measures to further protect transformers because of the potential that geomagnetically induced current that could drive them into saturation.
- Harden electronic power system protection and control devices against EMP and GMD damage.
- Develop processes for ensuring DC power supplies at critical substations will be sufficient during extreme restoration scenarios.

4.2 Improve System Modeling

Determine how system models can be improved to perform more extensive studies of blackstart capability and system restoration plans.

Emphasis should be placed on improving models to more accurately test the ability to:

- Start blackstart resources and energize cranking paths to deliver power to targeted units.
- Provide start-up power to inverter-based generation sources (which requires accurate modeling of load commutated inverters).
- Control voltage while providing power to inverter-based generation resources aiding in system restoration.
- Manipulate DER to aid in system restoration (for energization purposes or other).

4.3 Perform More Extensive Studies

Perform additional studies to determine the best approaches to system restoration given more complex scenarios (e.g., use of DER to increase system resiliency and aid in restoration).

The studies should address the following needs:

- Determine how the changing generation mix will affect the use of generators for voltage control during blackstart and system restoration and whether additional reactive devices may be required for voltage control.
- Determine how changes in load characteristics (and location) may affect blackstart capability and system restoration activities.
- Identify potential fault current and ground return concerns when leveraging DER to aid in restoration.
- Improve methods for energizing transformers and performing cold-load pickup.
- Determine strategic placement of reactive resources for voltage control to aid in distribution-based restoration activities.
- Establish different methods for synchronization of electric islands (including islanded portions of the distribution system).
- Coordinate DER to transfer or pick up critical loads to aid in system restoration.
- Determine the power requirements to maintain DER operability during restoration events.

4.4 Coordinate Emergency Response with Natural Gas Industry

Consider dependencies on natural gas for blackstart capability and system restoration, and determine the degree to which restoration plans should be coordinated with gas industry counterparts.

Steps that can be taken may include the following:

- Identify electric–natural gas interdependencies that can affect blackstart capability or the ability to perform system restoration.
- Conduct joint studies or analyses of events and scenarios that could significantly affect both industries.
- Establish processes to communicate specific information and coordinate certain actions during major events.

4.5 Enhance Training Activities

Consider how electric industry training activities can be improved upon to provide a deeper knowledge of how power system operating characteristics are changing and how the changes may affect blackstart capability and system restoration.

Emphasize creating a realistic training environment to simulate blackstart scenarios and facilitate interaction with the people, processes, and tools that may be relied upon in an actual restoration event.

Topics that could be addressed might include the following:

- Operation of renewable resources and DER during extended restoration events (aiding in recovery and limiting exposure).
- Operation of distributed resource control systems (e.g., ADMS) during restoration events.
- Operation of generation-load-interchange balancing mechanisms during restoration events.
- Operation of distribution-oriented automatic schemes during certain restoration scenarios (not allowing separation of load for local good to hinder recovery).
- Expected communication and coordination with affected parties (may include third-party generator operators, natural gas industry representatives, etc.).
- Expected communication and coordination with regulatory bodies and governmental agencies to waive restrictions and aid in recovery (to be coordinated with existing processes for declaring emergencies, suspending markets and standards of conduct).
- Performing system restoration from blackstart resources with the loss, degradation, or compromise of a critical system.

4.6 Perform Outreach

Consider establishing programs to work with other parties that own or operate generation, transmission, or distribution facilities that could be involved in system restoration activities to establish a common understanding of the communication and coordination that will take place during a restoration event.

Emphasis should be placed on identifying and addressing concerns or issues that could impede restoration activities, which may include developing processes or establishing agreements to avoid potential disagreements when restoration events occur.

4.7 Capture Industry Best Practices

Establish a method for identifying and capturing industry best practices, including establishing requirements for qualifying blackstart resources. Curating, enhancing, and disseminating these best practices to key North American stakeholders would be a good role for DOE.

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Appendix A – Current State and Future Trends of Power System Operations

A.1 Power Grid Operations

Power systems are traditionally operated as a one-way delivery system, in which electricity is generated at large power plants, transported to load centers via a transmission network, and delivered to customers through distribution systems.

Grid operators and electric utilities continually assess and evaluate projected system conditions to ensure acceptable system performance. These assessments are performed in an iterative fashion, starting with seasonal planning studies conducted up to a year in advance, outage coordination studies performed weeks ahead of time, operational planning analyses for next-day operations, and finally, real-time assessments performed at least once every 30 minutes.

Power system state assessments are necessary to know the state of the electric grid to identify and address unacceptable system performance. This work identifies the following characteristic taxonomies of power system operating states. The five operating states are categorized under the following definitions as extensions to Dr. Tom Dy-Liacco's original presentation (Liacco 1978):

- Normal state – A state characterized by the satisfaction of all the equality and inequality constraints and by a sufficient level of stability margins in transmission and generation so that the system can withstand a single contingency, be it a loss of a transmission line, a transformer, or a generator. In that case the system state is deemed to be secure; consequently, no action is taken.
- Alert state – A state typified by the satisfaction of all the equality and inequality constraints and by an insufficient level of stability margins, which is an indication that the system is dangerously vulnerable to failures. This means that in the event of a contingency, at least one inequality constraint will be violated, for example, due to the overload of a transmission line or a transformer. To bring the system to a normal state, *preventive actions* must be taken, typically by increasing the structural redundancy in the transmission system. It is important for the operators to know the alert state if the system is about to enter a partial blackout, islanded condition, or total system blackout.
- Emergency state – A state in which all the equality constraints are satisfied and at least one inequality constraint is violated, indicating that the system is experiencing overloads. Obviously, the system calls for the immediate implementation of *corrective actions* to remove the overloads, prevent the damage of equipment, and mitigate the risk of cascading failure that may result in a blackout. These actions consist of load shedding, transmission line tripping, transformer outages, or generating unit disconnections.
- In extremis state – A state characterized by the violation of both equality and inequality constraints that stem from the chain of actions taken during a previous emergency state while the transmission network remains interconnected. At this stage, *heroic actions* are implemented to either reconnect the disconnected load and generation if this is at all possible or to perform additional outages to protect the overloaded equipment, which may result in the breakup of the network.
- Restorative state – A state in which the equality and inequality constraints are violated while the system is breaking up into pieces, resulting in the formation of islands that may be

energized or not. Here, restorative actions need to be implemented to bring the system to a normal or alert state.

Evaluations of projected system conditions and assessments of real-time operating states must reflect applicable inputs, including but not limited to load, generation output levels, known protection system and special protection system status or degradation, transmission outages, generator outages, interchange, facility ratings, and identified phase angle and equipment limitations. The operating states and potential transitions between states are shown in Figure A.1. Note that the transition time between states can occur very rapidly, particularly when the situation is deteriorating.

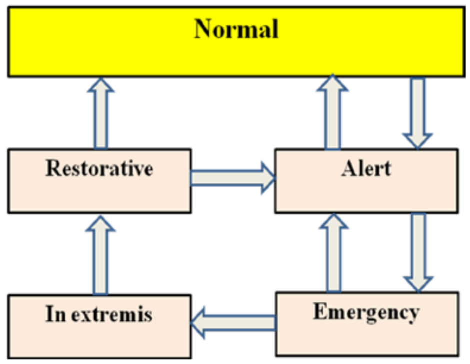


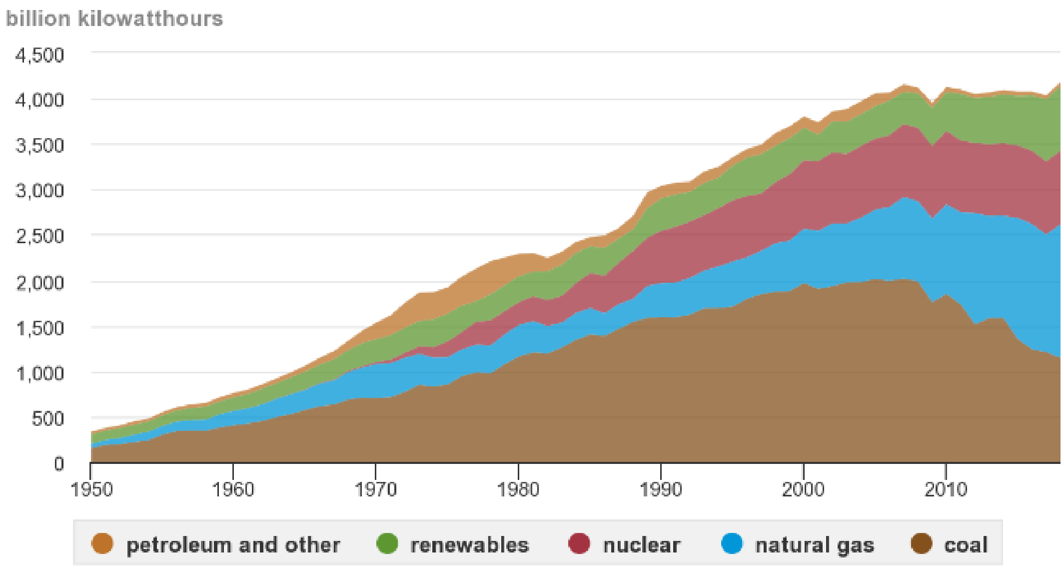
Figure A.1. Five operating states of an electric power system and their transitions (Fink and Carlsen 1978).

The function of an electric power system is to deliver electric energy at regulated voltage magnitudes and frequencies within specified ranges. Thus, the above categories are refined based on the concepts of robustness and resilience. The robustness of a system to a defined set of perturbations is stated as the system ability to maintain function. Such perturbations include changes in structure (topology). The system resilience to a defined class of *unexpected* extreme perturbations is the system ability to (1) gracefully degrade its function by altering its parameters or structure and (2) quickly recover it once the perturbations have been removed or mitigated.

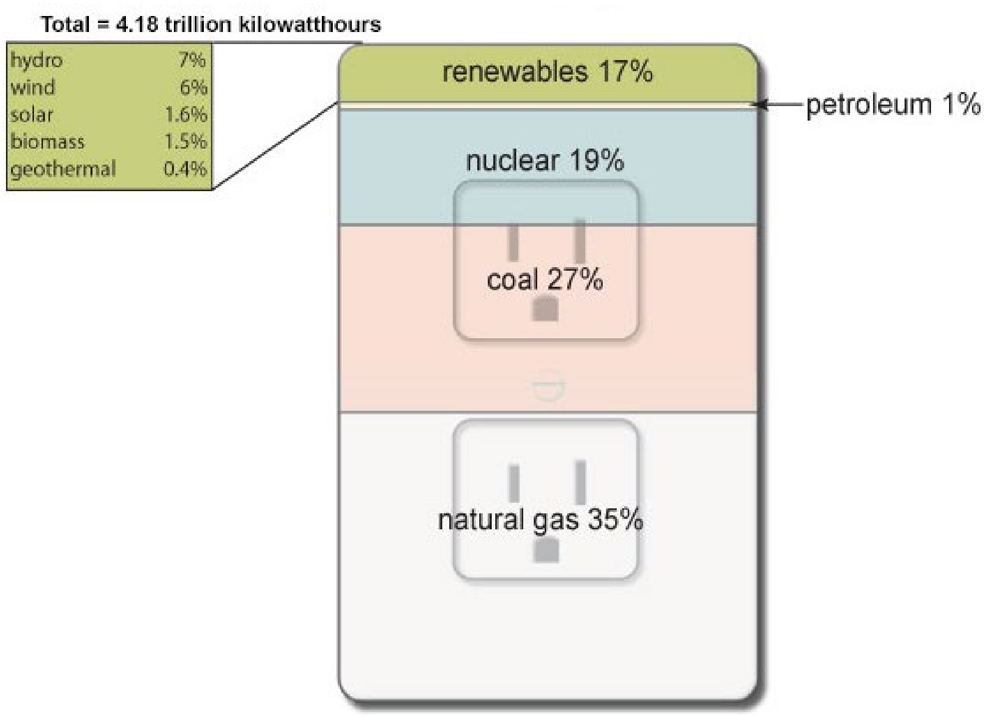
Robustness applies to the normal and alert states and the transitions between states, whereas resilience applies to the emergency and in extremis states and those transitions. The restorative state and transitions to other states advance into definitions of more advanced properties—*self-reconfiguration* and *self-sustainability*. These properties are outside the realm of resilience or robustness because the system needs to self-restore its integrity. From the given definitions it is clear that robustness and resilience are not general properties of a system but are relative to specific perturbations.

A.1.1 Generation

Primary energy sources in the United States include fossil fuels (petroleum, natural gas, and coal), nuclear energy, and renewable sources. Figure A.2(a) shows the historical energy source mix used for electricity production from 1950 through 2018, and the current energy generation is shown in Figure A.2(b).



(a)



(b)

Figure A.2. U.S. electricity generation by energy sources (EIA 2019).

Most electricity is generated by steam turbines (fossil fuels, nuclear, biomass, geothermal, and solar thermal energy). Other major technologies include gas turbines, hydro, wind, and solar photovoltaic. Figure A.3 shows the trends in renewable energy sources in United States for the last 60 years.

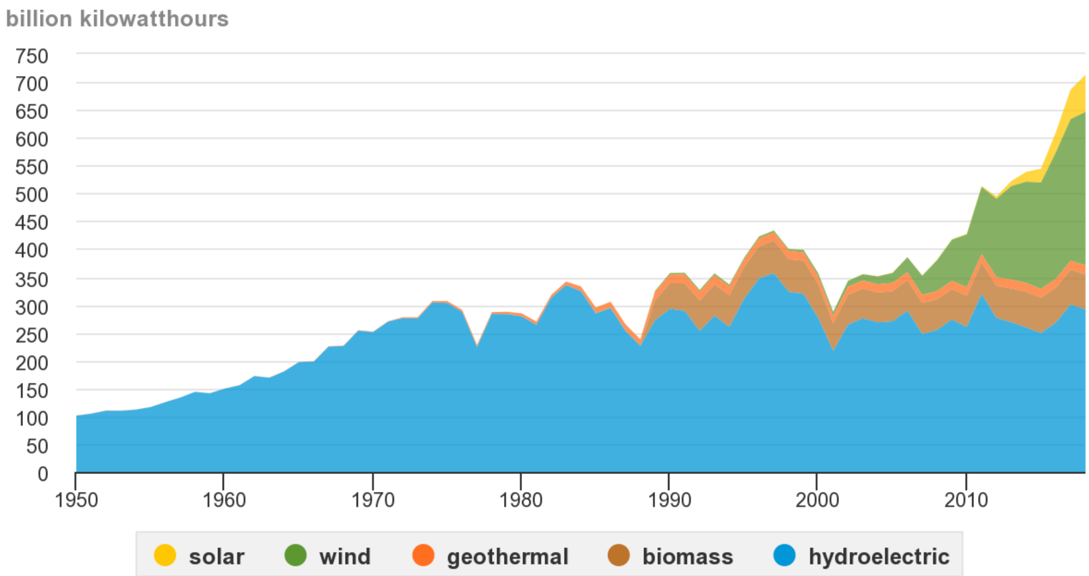


Figure A.3. U.S. electricity generation from renewable energy sources 1950–2018(EIA 2019).

A.1.2 Transmission

A transmission system is made up of high-voltage equipment that transfers electricity from one location to another. The traditional grid architecture is based on large-scale generation located remotely from consumers, hence the need to transmit power from the generating source to the customer.

As shown in Figure A.4, electricity is typically produced at lower voltages (25 kV or less) then "stepped up" for transportation over lines that operate at higher voltages (i.e., 230 kV to 765 kV).

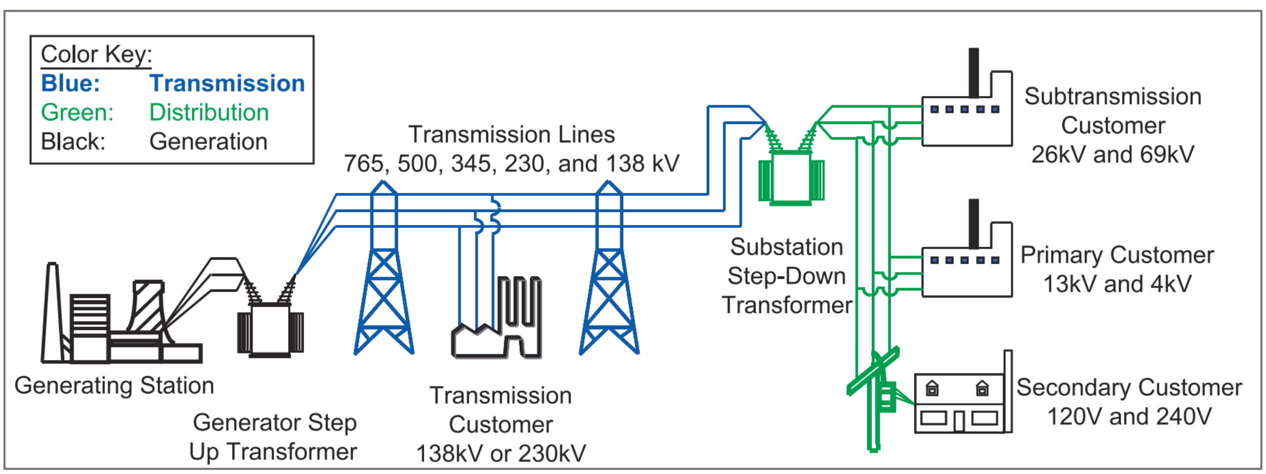


Figure A.4. Basic structure of the electric system (Eto 2004).

There are several benefits to transporting electricity over a transmission system, such as:

- Reduced power losses – Operating at a higher voltage reduces electricity losses from conductor heating, which results in cost savings.

- Interconnected system operations – Transmission lines are interconnected at switching stations to form a network or “grid” that electrically connects utilities so that power can be exchanged over long distances when necessary or desirable. Operating an interconnected system provides reliability and economic benefits in that it forms a “stronger” system that is less susceptible to major disturbances and allows for the operation of electrical markets so that power can be bought, sold, and traded as a commodity.
- System redundancy – Transmission systems are typically designed to have multiple feeds so that the loss of a single piece of equipment does not eliminate a utility’s ability to serve customer load or exchange power with other utilities.
- Desirable generation locations – Hydroelectric plants require a swift-running stream or river and elevation change for effective operation. Large fossil fuel and nuclear steam generators require a large cooling resource, which is typically provided by a body of water such as an ocean, lake, or river. Wind and geothermal generation must be located where these forces are available. Such conditions are not typically found in heavily populated areas, therefore generating stations are often located several miles from customers.

Maintaining safe and reliable operation of an interconnected power system is a complex task that requires careful planning, sophisticated tools, and trained personnel. The NERC Reliability Standards define requirements for planning and operating the North American BES and focus on performance, risk management, and entity capabilities. The Reliability Functional Model defines the functions that need to be performed to ensure the BES operates reliably and is the foundation upon which the reliability standards are based.

A.1.3 Distribution

Distribution systems are the final step in delivering power to end-use consumers. Distribution systems are like transmission systems in that they employ transformers, circuit breakers, and protection systems, but different in that they operate at a lower voltage (2.4 to 34.5 kV) and are typically radial (power coming from one source) in nature.

In most cases, distribution substations supply power to the primary distribution circuits, which are often referred to as “feeders.” Overhead wires supported by utility poles are the most common means of supporting distribution circuits, but underground cables are also used.

Distribution transformers are mounted on pole tops or located in underground vaults. These transformers “step-down” to secondary voltages that can be used by the customers.

While the number of end-use customers that maintain the means to generate their own electricity continues to grow, the majority rely on their service provider to meet their demand.

No single organization is responsible for establishing or enforcing reliability standards in distribution systems, although state utility regulators and boards of publicly or customer-owned utilities often assess performance using quantitative reliability metrics and set goals for the allowable frequency and duration of system and customer outages (NASEM 2017).

A.2 Future Trends

Future trends in generation, forecasting, transmission, roles and responsibilities, operational tool complexity, distributed energy resources, bi-directional power flow, and functional entity coordination are addressed in the following sections.

A.2.1 Trends in Generation

Though renewable subsidies have decreased in the past years (see Figure A.5), renewable production has continued to increase. The economic justification for this is a direct result of the improved manufacturing processes and technologies that have reduced the capital cost and operation and maintenance of these forms of generation, resulting in renewables being integrated due to economics as well as the necessity for meeting renewable portfolio standards.

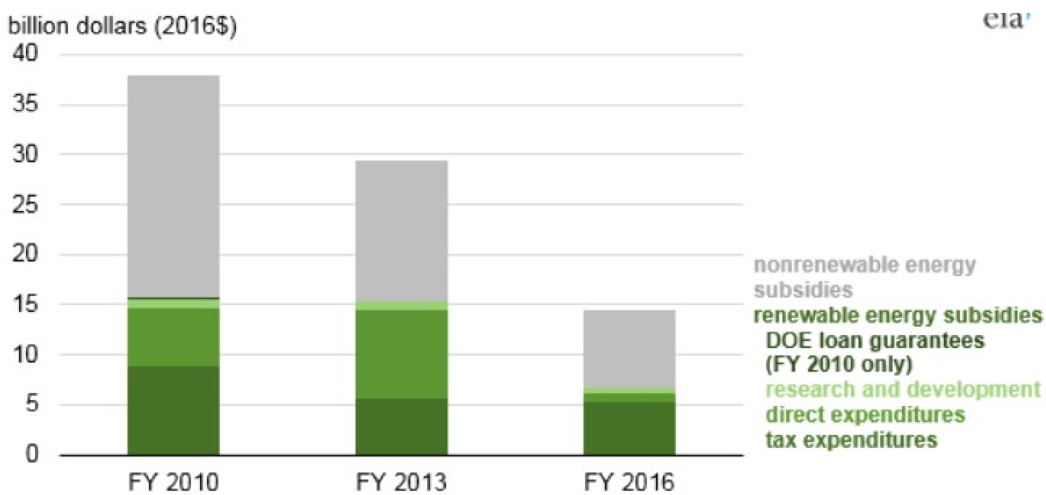


Figure A.5. Federal energy-related subsidies by category (EIA 2018).

Recent advances in manufacturing have made PV panels much more palatable in terms of cost. The change in the availability of PV-type resources has in return driven down the cost of electricity. As a result, solar installations have become more appealing as a generation source for both residential consumer and bulk generation providers.

However, as more renewable resources are integrated into the BES, more balancing reserve sources from traditional sources of generation must also be in place to provide the needed balance for real power in the grid. This then creates a “reserve market,” which is another method that conventional generation plants can use for a source of revenue.

Recent advancements in technological abilities are a large driving force for the type of generation being installed. The use of “fracking” as a method of extracting natural gas has resulted in an abundance of supply and therefore has kept the costs relatively low.

Consequently, current natural gas prices are pushing energy toward a higher percentage of load being served by it, while traditional coal-fired power plants (all built before 1971) are being retired. Reasons for shutting down the coal-fired plants are threefold: (1) cost of the upgrading dated facilities, (2) price of the fuel, and (3) impact on the environment.

When siting new generation plants, there is more to be considered than the type of fuel used. Beyond simple power output, there are ancillary services that will add to the financial return.

The maximum efficiency that can be achieved by a single cycle plant is only ~34% (Peaker combustion turbines). On the other hand, combined-cycle plants can reach efficiencies of up to 60% with the use of a heat recovery steam generator. While efficiency seems like it could be the main driver for the type of plants to be installed, the addition of the heat recovery steam generator involves a large capital cost related to the requirements of an entire steam plant.

The current gas prices, size of the unit,[1] and ancillary requirements (e.g., providing frequency responsive reserves) all come into play. Combined-cycle turbine generators are typically base-loaded units with no governor response available, whereas the combustion turbine generators have these ancillary services that are monetizable outside of the plant megawatt output.

Figure A.6 shows the average construction cost for the selected power plants. Note that cost does not include public opinion, environmental impacts, or availability of resources (especially true for hydro power).

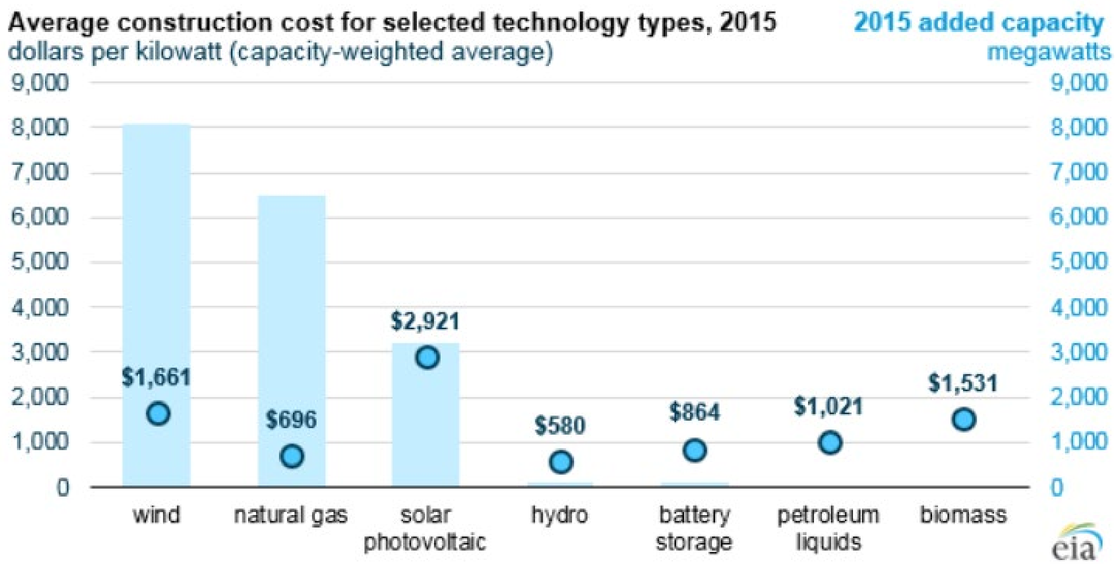


Figure A.6. Average construction cost for selected technology types (EIA 2017).

While nuclear power is considered a source of carbon-free energy production, the hazards of storing the spent fuel, and the impact of several high-profile accidents and disasters over the past 50 years, have resulted in mixed public views regarding the use of nuclear power.[2] Figure A.7 shows the 40-year projection of the nuclear reactors startups and closures around the world.

[1] Typical combustion turbine generators could be 100 MW, while a typical combined-cycle turbine generator is 450 MW.
[2] http://world-nuclear-news.org/Articles/US-public-opinion-evenly-split-on-nuclear

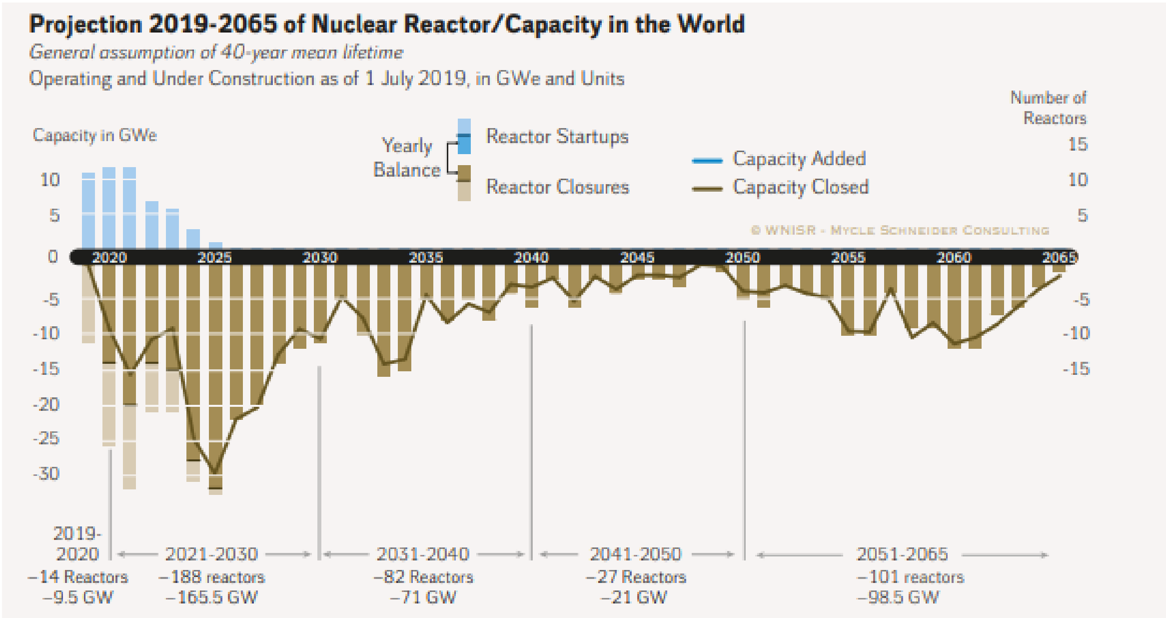


Figure A.7. Nuclear power plant retirement projection through 2065 (Schneider and Froggatt 2019).

A.2.2 Forecasts

The U.S. DOE projects that coal and nuclear generation will significantly decline due to governmental regulation and economics, whereas generation from natural gas will increase primarily due to the decline of natural gas prices, as well as the need for the higher balancing reserves capacity.

Renewable generation is projected to increase at an even faster rate than natural gas due to the declining installation cost of wind turbines and solar photovoltaic, and the increased availability of renewable tax credits. Based on the 2020 U.S. Energy Information Administration (EIA) database, about 21% of total electricity generation is provided by renewable energy sources, and by 2050 the total electricity generation from renewables is projected to double (~42%). Figure A.8 depicts the predicted electricity generation from selected fuels (left) and breakdown of the total percentage of different renewable generation types (right).

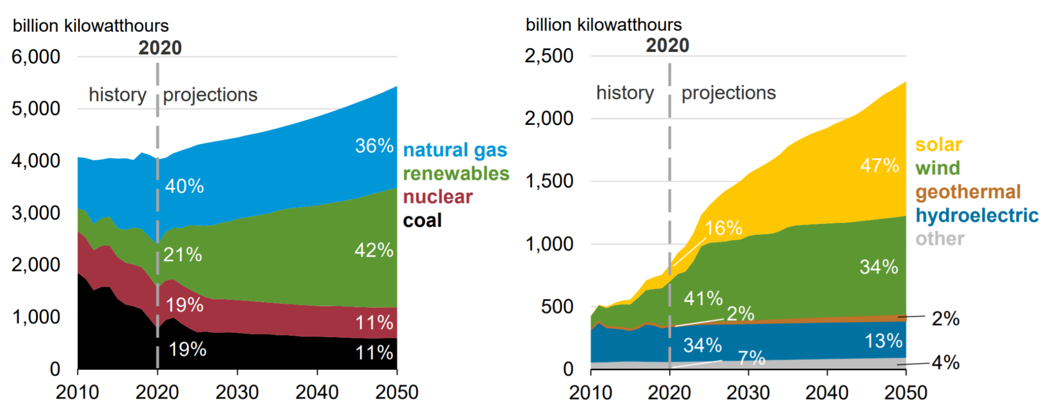


Figure A.8. Electricity generation from selected fuels (Reference case) (AEO 2021)

The current trend in the retirement of fuel sources (see Figure A.9) is also almost exclusively aimed at coal, where the cost of upgrading or maintaining the generation facilities outweighs the possible revenue provided.

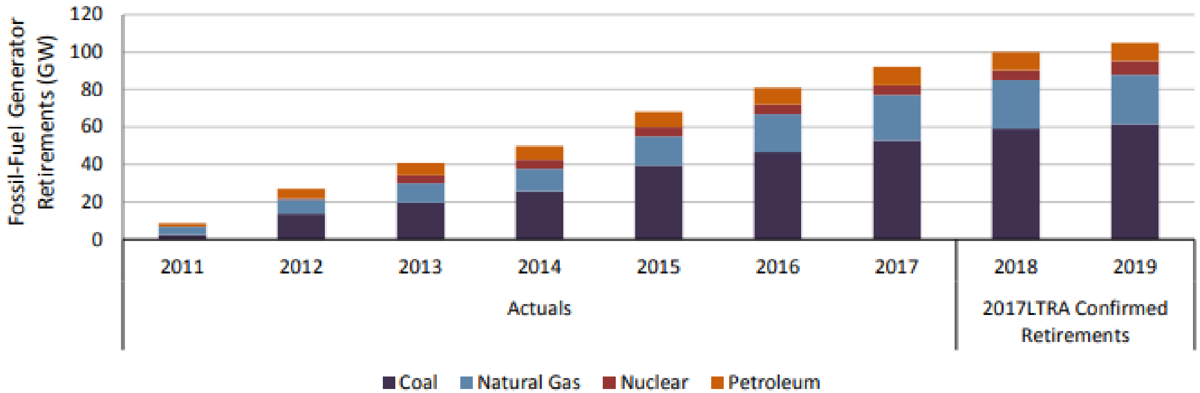


Figure A.9. Annual generation retirement by fuel type.

A.2.3 Trends in Transmission

Today's transmission system faces many persistent and new challenges, including aging infrastructure, difficulties siting and constructing new transmission assets, and changing regulatory policies.

The last 40 years have seen limited investment in the North American transmission grid. Figures provided by DOE show that 70 percent of transmission lines and power transformers are 25 years or older, and 60 percent of circuit breakers are 30 years or older. Catastrophic failures of transmission assets threaten system reliability and changing system dynamics may increase the likelihood of such events (DOE 2015).

Historically, reliability has been achieved through redundancy and reserve margins. When a utility company needed to upgrade or replace infrastructure due to aging equipment or increased demand, it would initiate projects to build new lines and substations at a regulated rate of return. However, regulations to build large-scale transmission lines have become more onerous and utilities often have difficulty attaining the local and state permits required to build new lines.

The impact of such difficulties is illustrated by the Bonneville Power Administration's (BPA's) May 2017 decision to forego an initiative to build a new $1 billion, 80-mile transmission line along Interstate 5 in Oregon. The former BPA Chief Executive Officer Elliott Mainzer stated that BPA chose to take a "new approach to managing congestion on our transmission grid" and the decision reflected "a shift for BPA—from the traditional approach of primarily relying on new construction to meet changing transmission needs, to embracing a more flexible, scalable and economically and operationally efficient approach to managing our transmission system" (Feldman 2017).

While maintaining a robust BES remains critical to operating a reliable power system, decisions such as the one BPA made are becoming the norm as grid operators and electric utilities recognize the opportunities that exist to harvest advanced technologies and find "non-wires alternatives" to address infrastructure needs and operate the electric system in a more efficient manner.

A.2.4 Evolving Roles and Responsibilities

Since the 1930s in the United States, most electric service has been provided by investor-owned or publicly owned utilities responsible for all elements of electric supply: generation, transmission at high voltage, and local distribution of power at low voltage.

Several decades ago, most electric utilities were vertically integrated, meaning that the utility owned the power plants and/or contracts for power, owned or had rights to use high-voltage transmission lines that carry power from remote power plants to their local systems, and owned and operated the low-voltage distribution system to deliver power to consumers. But nearly 20 years ago, several states and federal regulators began to move aggressively toward breaking up vertically integrated utilities to separate ownership of generation, transmission, and distribution systems (NASEM 2017).

Today, there is a patchwork of restructured and vertically integrated utilities across the United States. According to the EIA, there are more than 3,000 utilities that own and/or operate some part of the generation, transmission, or distribution infrastructure in the United States.

As the industry trends away from business models where a single party has responsibility for operating both generation and the transmission system, whether through deregulation or the introduction of DER and other non-centrally dispatched resources, the need to coordinate among multiple parties to control generation for frequency and voltage support increases. This increased need for communication and coordination adds another level of complexity to operating the power system during emergency conditions.

A.2.5 Increased Complexity of Operational Tools

The set of tools used by system operations staff to monitor and control the grid continues to improve at a substantial pace. As grid modernization efforts progress, new architectural concepts, tools, and technologies will be used to measure, analyze, predict, protect, and control power systems.

Introducing more sophisticated tools with enhanced analytical and predictive capabilities will improve the operators' ability to proactively identify and address issues that could adversely affect grid safety, reliability, and resiliency. However, significant training will be required to ensure that operators know how the tools function and can analyze and validate their outputs to address potential failures and degradations. In addition, electric companies must consider how much visibility and control of distribution system operations will be required by transmission system operators to perform their assigned roles and responsibilities (e.g., controlling load for system restoration purposes) (SCE 2016).

A.2.6 Distributed Energy Resources

Tremendous change is taking place in consumers' adoption of DER to supply a portion of their energy needs. DER displace energy that was traditionally supplied by the BES, contributing to declining load on the grid, but adding complexity to operations, market design efforts, and system planning needs.

Solar cells are distributed and augmented more often with residential batteries. Residential batteries are also used to provide the peak-shaving capability of the demand cycle. Microgrids are another approach to increasing the resilience of the grid to disturbances. Such distributed resources are potentially key resources for reintegrating or blackstarting the power grid.

A.2.7 Bi-Directional Power Flow

As previously stated, the traditional distribution system design has minimal generation injection points and is radial in nature. The key changes in distribution system operating characteristics will stem from the fact that a continued integration of DER will cause power to flow in both directions.

The bi-directional power flow that will result from increased power sources, accompanied by a variety of energy efficiency and demand response programs that drive customers to manage power consumption on a more local level, will require improved situational awareness and deeper insight into distribution system conditions and performance.

A.2.8 Functional Entity Coordination

The distribution provider function is responsible for operating the distribution system and will be most affected by the continued integration of DER. When analyzing how the grid modernization efforts will affect the distribution provider function, one must consider how the level of coordination with the RC, BA, and TOP functions, which are collectively responsible for maintaining BES reliability, may change (see Figure A.10).

BA and TOP system operators currently coordinate with distribution providers as required to address load-generation-interchange balancing issues and unacceptable system performance. Communications between the distribution provider and other organizations providing transmission functions typically pertain to the distribution provider’s ability to act as required to maintain bulk system reliability. The distribution provider’s capacity for firm load shedding to address operating emergencies is of most interest to system operations organizations, including reliability coordinators, balancing authorities, and transmission operators.

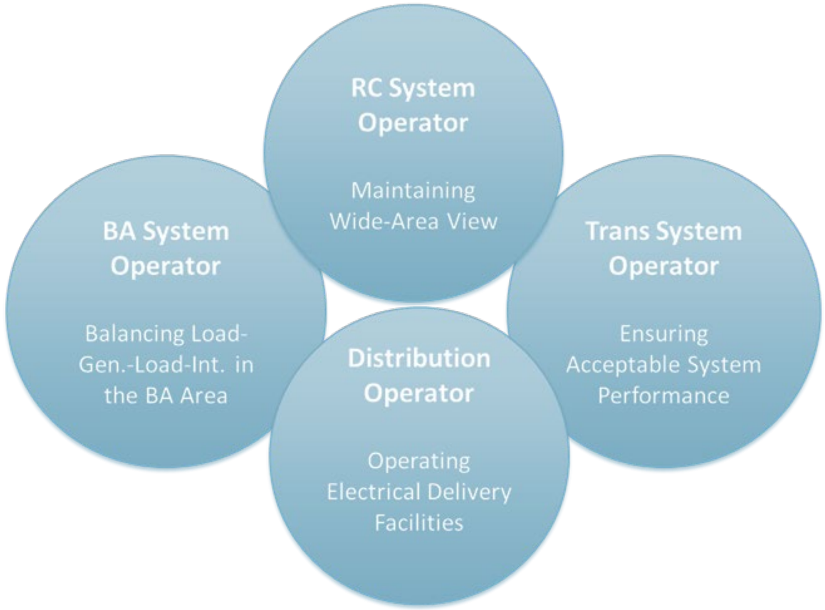


Figure A.10. Functional entity coordination.

The distribution provider function seldom communicates directly with an RC. Instead, the RC works with the BAs and TOPs, for which it provides reliability coordination services, who in turn coordinate with distribution providers as required to perform mitigation.

In most cases, distribution providers are called upon to help mitigate abnormal conditions or unacceptable system performance that originated on the transmission system. In other words, it is highly uncommon for balancing or local area transmission issues to originate from distribution systems given that the majority are radially fed.

However, the impact that distribution system operations will have on a BA's ability to balance its area and a transmission operator's ability to maintain acceptable system performance will change as more DER are integrated into the distribution system. Balancing authorities and transmission operators will need to monitor the status of distribution assets more closely as part of their generation and load profiles. In turn, distribution operators will need to coordinate with balancing authorities and transmission system operators more frequently and will require the knowledge and skills needed to understand how events on the distribution system affect BES operations. This increased need for communication and coordination will be especially relevant when addressing emergency conditions, such as system islanding and blackstart restoration.

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