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Sensitivity of Infrastructure Sectors to the Disruption of Commercial Electric Power

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ABSTRACT

Electric power is crucial to the function of other infrastructures, as well as to the stability of the economy and the social order. Disruption of commercial electric power service, even for brief periods of time, can create significant consequences to the function of other sectors, and make living in some environments untenable.

This analysis, conducted in 2017 for the United States Department of Energy (DOE) as part of the Grid Modernization Laboratory Consortium (GMLC) Initiative, focuses on describing the function of each of the other infrastructure sectors and subsectors, with an eye towards those elements of these sectors that depend on primary electric power service through the commercial electric power grid. It leverages the experience of Sandia analysts in analyzing historical disruptive events, and from the development of capabilities designed to identify the physical, logical, and geographic connectivity between infrastructures.

The analysis goes on to identify alternatives for the provision of primary electric power service, and the redundancy of said alternatives, to provide a picture of the sector's ability to withstand an extended disruption.

ACKNOWLEDGEMENTS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

As one of the core service infrastructures, electric power is critical to the function of other infrastructures as well as the stability of the economy and of social order. Disruption of electric power service, even for short periods of time, can lead to cascade failures in other infrastructures, and depending on seasonality effects, can make living in particular environments untenable. Thus, it is important to understand the consequences of disruptions of electric power service, so as to better understand the effects of disruptions on other sectors and on the general public that relies on regularly functioning infrastructure services.

This sensitivity analysis, conducted for the United States Department of Energy (DOE) as part of the Grid Modernization Laboratory Consortium (GMLC) Initiative, focuses on describing the function of each of the other infrastructure sectors and subsectors, with an eye towards those elements of these sectors that depend on primary electric power service through the commercial electric power grid. The analysis then moves on to identify alternatives for the provision of primary electric power service, and the redundancy of said alternatives, to provide a picture of the sector's ability to withstand an extended disruption.

Highlights of this analysis include the following:

Loss of commercial electric power will impact all sectors, with cascading impacts from the disruption of all aspects of the petroleum fuels supply chain creating the opportunity for severe transportation restrictions and impacts on the Water and Wastewater Sector impacting limited supplies of potable water in urbanized areas.

These indirect impacts to the transportation infrastructure will limit the ability of needed goods (especially food and fuel) to reach the affected area, limit the ability of merchants to sell said goods, and reduce the habitability of affected areas (warmer climates in the Summer, colder climates in the Winter).

This set of constraints on transportation and habitability will likely lead many to leave the affected area, if they can, at minimum until the outage is restored. In some cases, as was seen after Hurricane Katrina, if the disruption is long enough lived, departures will turn into migrations, with long-term net economic effects.

Backup generation, where available, will keep some services active in many infrastructures. These services, however, will be competing for the same scarce pool of fuel for their backup generators, placing increased value on the ability to move fuel for said generators – and for other transportation – from unaffected areas into the affected area. Prioritization at a local, State, and Regional level will be of value to the extent that it preserves vital services, serving as a bulwark against leaving the affected area, particularly among those necessary for restoration of disrupted critical infrastructure

This analysis is based on the experience Sandia analysts have in examining historical disruptive events, and from the development of capabilities designed to identify the physical, logical, and geographic connectivity between infrastructures. In so doing, this analysis will provide a basis for understanding each infrastructure sector's ability to withstand extended power disruption.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ARTCC	Air route traffic control center
ATM	Automated Teller Machine
DIB	Defense Industrial Base
DOE	United States Department of Energy
DHS	United States Department of Homeland Security
EPA	Environmental Protection Agency
GPS	Global Positioning System
GMLC	Grid Modernization Laboratory Consortium
kWh	Kilowatt hours
NISAC	National Infrastructure Simulation and Analysis Center
NPPD	National Protection and Programs Directorate
NG	Next generation
NRC	Nuclear Regulatory Commission
OCIA	Office of Cyber and Infrastructure Analysis
PSAP	Public Safety Answering Point
RORO	Roll-on, roll-off
SCADA	Supervisory Control and Data Acquisition

1. SCOPE

The Electric Power Subsector of the Energy Sector, discussed in detail within this document, is one part of the 16 infrastructure sectors "essential to the minimal operation of the economy and the government."[32] Since the mid-1990s, the U.S. Government has dedicated resources towards understanding the vulnerabilities faced by these Sectors and working with private infrastructure owners to limit the consequences of service interruptions. The National Infrastructure Simulation and Analysis Center (NISAC), a program of the U.S. Department of Homeland Security (DHS) National Protection and Programs Directorate (NPPD), Office of Cyber and Infrastructure Analysis (OCIA), with capabilities and expertise housed at Sandia National Laboratories, Los Alamos National Laboratory, and Pacific Northwest National Laboratory, regularly examines the consequence of disruption of infrastructure service from a range of threats, natural and manmade. Analysts at Sandia affiliated with the NISAC program have provided support to the assessment, including the development of this infrastructure-focused sensitivity analysis.

As one of the core service infrastructures, electric power is critical to the function of other infrastructures as well as the stability of the economy and of social order. Disruption of electric power service, even for short periods of time, can lead to cascade failures in other infrastructures, and depending on seasonality effects, can make living in particular environments untenable. Thus, it is important to understand the consequences of disruptions of electric power service, so as to better understand the effects of disruptions on other sectors and on the general public that relies on regularly functioning infrastructure services.

This sensitivity analysis, conducted for the United States Department of Energy (DOE) as part of the Grid Modernization Laboratory Consortium (GMLC) Initiative, focuses on describing the function of each of the other infrastructure sectors and subsectors, with an eye towards those elements of these sectors that depend on primary electric power service through the commercial electric power grid. The analysis then moves on to identify alternatives for the provision of primary electric power service, and the redundancy of said alternatives, to provide a picture of the sector's ability to withstand an extended disruption. The identification of potential "tipping points" for the function of each infrastructure is then performed. This analysis is based on the experience Sandia analysts have in examining historical disruptive events, and from the development of capabilities designed to identify the physical, logical, and geographic connectivity between infrastructures. In so doing, this analysis will provide a basis for understanding each infrastructure sector's ability to withstand extended power disruption. The document concludes with a summary of these "tipping points" that can serve practical uses to emergency managers, incident response specialists, and others faced with decisions in supporting the restoration of electric power service among competing sector resources.

2. CHEMICALS AND HAZARDOUS MATERIALS

2.1. Description of the Sector

The chemical sector manufactures and distributes chemicals that are used in many processes. Chemicals are key components for purifying the water we drink, creating lifesaving medicines, fertilizing and protecting crops from diseases and pests, and producing countless goods.

There are several activities within the chemical sector including: chemical production, storage, marketing and supply. There are two basic types of chemical production: commodity chemicals, produced in large quantities and widely used; and specialty chemicals produced in small quantities for specific, often singular, end uses.

Examples of the classes of chemicals produced include:

- Petrochemicals
- Chlorine
- Ammonia
- Industrial Acids
- Industrial Gases
- Inorganic Chemicals
- Pesticides, Insecticides, and Herbicides
- Agricultural Fertilizers
- Plastics and Plastics Precursors

Thousands of specific chemicals are produced in the US and globally. Each type of chemical asset has different dependencies on other infrastructures.

2.2. Dependencies on the Electric Power Subsector

2.2.1. Direct Impacts

Refineries generate their own power and they can be part of the grid; relying on the grid for backup power and selling power to grid operators. As was seen with cogeneration facilities at refineries in New Jersey following Superstorm Sandy, an undamaged refinery and cogeneration facility are rendered useless by any effect to a substation on the primary electric power grid to which the cogeneration facility is connected. Chemical manufacturing is reliant on electric power, and individual facilities may have onsite backup power to allow graceful shutdown and prevent expensive repairs in the event of a power outage.

Assets impacted by power outage are likely to cause downstream impacts due to connectedness of processes and products. The magnitude and extent of the effects within the chemical sector depends on supply network structure, duration of disruption and the amount of the chemical available from other sources (other producers or stock) or the ability to substitute for the impacted chemicals).

Some chemical storage and transfer are reliant on electric power for pumping (pipelines) and climate control (e.g., heating or cooling).

It is possible for refineries to continue to function on their own power using fuels from storage; but Grid function may be necessary for dumping excess power.

2.2.2. *Secondary Impacts*

In the event of a long-term power outage over a large region, there could be labor shortage due to uninhabitable conditions, which could shut down asset operations.

The Chemical Sector is highly dependent on multiple infrastructures which if impacted could reduce or stop production.

- Natural gas and Petroleum products are feedstocks for petrochemicals (alternative feedstocks exist)
- Water, Rail and Road Transportation are essential for the delivery of some feedstocks and chemicals to intermediate and end users
- Water is used for cooling and in chemical production
- Communications systems are used in monitoring and control of chemical production and for transactions

If the Chemical Sector's end users are shut down because of the power outage, demand will drop. Supply networks include all the producers, transportation systems and end users of the chemicals in the supply chain. In order to estimate and understand how a long-duration power outage would impact this Sector and the Sectors that depend on the chemicals impacted, an analysis using the geographic boundary of the power outage area, and the expected duration of the outage, would need to be used as a starting point. It is likely that disruptions to the Chemicals Sector will extend well beyond the area inclusive of the power outage area, due to supply chain effects.

The ethylene supply chain shown in Figure 2-1 provides a partial view of the structure of chemical supply networks and how disruptions in production or demand can propagate through the chain.

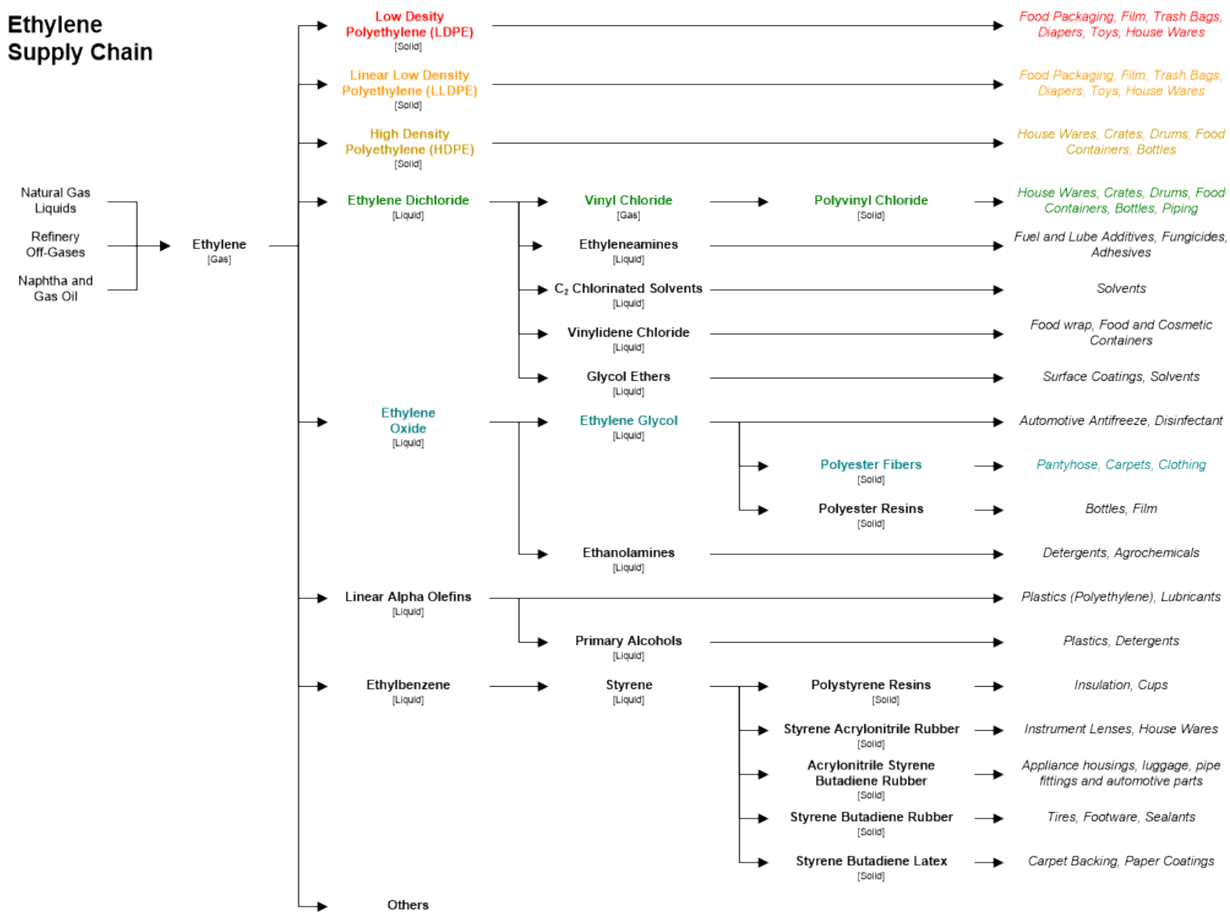

Figure 2-1. Ethylene supply chain [9]

2.3. Mitigations and "Tipping Points"

There are several ways to mitigate the direct impacts of power grid outage. At an asset level, the ability to automatically and instantaneously isolate the facility from the grid and generate power to support operations, might prevent long-term disruption to the operation of that facility. This may not be enough to maintain operations if the conditions outside the plant boundary cause displacement of the population. Providing suitable living conditions for staff and their dependents may also be required. None of the asset-level mitigations will matter if end users are impacted by the power outage. At a network level, having sufficient production, stored product and transportation capacity to offset the disrupted capacity would reduce the supply disruption impacts outside the disrupted region.

3. COMMUNICATIONS

3.1. Description of the Sector

The communications sector includes the assets and networks that provide voice and data communications services including wireline and cellular telephones, and the Internet. From the economic activity it supports to the reliance on the sector for life saving communications in an emergency, it is an integral part of modern life and provides enabling functions across critical infrastructure sectors. Communications assets are critical to natural disaster response and recovery efforts from individuals placing 9-1-1 calls to the coordination functions of emergency dispatch services for restoration and recovery operations. The Internet supports communications and data services for individuals, businesses, and other critical infrastructure sectors.

The emergency services sector is closely coupled to the communications sector: current basic and E9-1-1 systems are heavily integrated into the existing voice communications network, while next generation (NG) 9-1-1 systems rely on Internet protocol technologies.

3.2. Dependencies on the Electric Power Subsector

From an asset standpoint, the voice network consists of central offices (mobile switching centers in relation to cellular service) that house the switches that provide the connectivity for the network and cellular tower sites and associated base stations that provide connectivity from a cellular phone into the network. The Internet consists of data centers and hosting facilities, points of presence (in many cases co-located with central offices) and Internet exchange points designed for providers to exchange traffic with one another, and undersea cables and their associated cable landing stations. It is worth noting that many of these facilities carry and house both voice and data traffic and switching equipment. For example, undersea cables are used for both voice and data traffic as are many central offices. Similar to convergence in access technologies, such as cell phones used for both phone calls and web browsing, the facilities that house these services are also converging.

For voice communications, backup technologies are regulated by the Federal Communications Commission. The minimum FCC requirement for central offices to maintain at least 24 hours of backup power and sites that are not in central offices to maintain at least 8 hours of backup power. Central offices that are directly connected to Public Safety Answering Points (PSAPs) or house databases that serve 9-1-1 are required to certify annually that they meet the 24 hour backup requirement under full load, to include network monitoring equipment. For central offices that house 9-1-1 routing equipment, the annual certification is for 72 hours of backup power under full load.

Generally, at communications facilities that house switching equipment (central offices, data centers, points of presence, Internet exchange points, cable landing stations) both backup batteries and generators are present. The batteries are designed to provide power until the generators can start, and provide additional power after those generators have run out of fuel, along with providing power for long enough that a technician can be brought on site to diagnose and repair a generator if it fails to start, typically several hours. Communications carriers typically keep two to three days' worth of fuel on site, though large data centers, large central offices, and cable landing stations will typically operate for a longer period of time, up to a week or more, depending on the policy of the provider. Undersea cables can be powered from landing stations at either end of the cable, but for traffic exchange to happen, the switching equipment at the landing station will also need power. In some facilities, generators are set up in an N+1 configuration to allow for longer continuous operation in the event of an extended power outage.

Cellular towers are required to have a minimum of eight hours of backup under nominal loading in the event commercial power fails. This backup power used to be supplied by batteries, but increasingly carriers have turned to backup generators which can operate for 12 to 24 hours before needing to be refueled. Communications facilities will continue to operate for days to weeks on backup generators until they run out of fuel or until commercial power is restored. Generators are routinely tested and maintained, so a low number that fail to start and switch over is expected.

In addition to electric power, communications facilities also require cooling. In many cases cooling is provided by chillers that are served by municipal water systems. These water systems may also require electric power to operate. In areas where chillers are ineffective, air conditioning units will be used and the facility will not be reliant on the municipal water supply.

Electric power may rely on commercial communications services for both day to day operations and for recovery. Supervisory Control and Data Acquisition systems (SCADA) to various locations may run over lines leased from commercial communications providers. Any of these links that are down due to commercial power being out and generators at the communications facilities being out of fuel will cause a delay in the ability to restore commercial electric power.

3.3. Mitigations and "Tipping Points"

The primary mitigation for communications facilities will be access to and prioritization of fuel for generators. Additional mitigation could be provided by serving these facilities off of multiple electric power circuits or prioritizing restoration of critical communications facilities such that they will not run out of generator fuel before they are restored. For infrastructures that use cellular or land mobile radio capabilities for voice communications, especially restoration and recovery operations, satellite phones could be a mitigation option. Radio towers are also dependent on commercial electric power and backup generation for their operation, so land mobile radio systems are also likely to not be operational.

4. COMMERCIAL FACILITIES

4.1. Description of the Sector

Commercial facilities encompass a range of physical locations that are characterized by open public access and "large crowds of people for shopping, business, entertainment, or lodging." [49] These include offices, retail locations, areas, hotels and lodging facilities, and other areas were people gather inside or outside. Commercial facilities are geographically diverse but are directly correlated to population centers. Retail alone accounts for one fifth of the U.S. economy and provides 25% of the jobs. One in four jobs in the private sector are in the retail industry for approximately 42 million positions. [43]

Few commercial facilities are equipped with large emergency generators capable of supporting the infrastructure entirely until power is restored. Most facilities have smaller generators and small amounts of fuel. Generators are intended to support the facility while customers or workers are evacuated. Generally, the generators provide power for emergency lighting, access to exits (occasionally provide short term power to elevators), and short access to point of sale systems. Some home improvement stores (Home Depot and Lowes) in Florida do have full backup generators that allow the stores to function fully following loss of power. [17] This is due to the store's experiences following Hurricane Andrew in 1993 and is not followed nationally.

4.2. Dependencies on the Electric Power Subsector

Commercial facilities are dependent upon electrical power to operate.

This sector includes office buildings that provide offices for other infrastructure sectors to operate. Generally, these facilities may be better prepared to weather long term power outages but are still dependent upon the individuals that keep the buildings operational. In past power outages, emergency response departments noted that problems in facilities management negatively impacted their ability to do their job. [6] Additionally, this sector provides employment for an extensive percentage of the U.S. population. If this sector is without power for a significant period, it will remove a substantial part of the U.S. economy and produce extreme financial hardships for many. This will impact other sectors as individuals either relocate or are forced to consume social services (if available) for basic needs.

4.3. Mitigations and "Tipping Points"

It is impractical to equip all commercial facilities with large generators or with enough fuel to allow for continuous operations in the case of a long-term power outage. Additionally, many retailers and other commercial facilities operators are likely to resist requirements for large generators and stockpiling fuel. The cost for this can be substantial and is likely to be beyond what many retailers are willing to do.

5. CRITICAL MANUFACTURING

5.1. Description of the Sector

The critical manufacturing sector is defined as industries that are "crucial to the economic prosperity and continuity of the United States." [50] This includes a variety of industries including primary metal production, machinery manufacturing, electrical equipment manufacturing (including transformers), and transportation manufacturing facilities. Many of these industries are required for other industries to operate and provide the backbone for industrial and commercial operations. It also includes production for defense and supports the Defense Industrial Base Sector. It is highly dependent upon large amount of uninterrupted electricity and cannot be run by generator. These facilities tend to be concentrated around major U.S. coastal cities and ports. Most facilities are owned and operated by the private sector. [44]

5.2. Dependencies on the Electric Power Subsector

The critical manufacturing sector is dependent upon large amounts of uninterrupted power, continuous waters, global communications networks, all modes of transportation, and a constant supply of base materials (largely metals, raw ore and chemicals).

There is no sector not dependent upon critical manufacturing. Any large-scale disruption will cause immediate and long-term disruption is every facet of life both domestically and internationally. Immediately, other sectors will face material shortages and lose access to replacement machinery. [44] Over time, this will consume backup machine parts and any stockpiled materials. Long-term power loss for these facilities will lead other factories or service providers to be unable to cope with damaged goods or equipment.

During the 2003 Northeast Blackout, many critical manufacturing facilities were shut down. A study completed by the Ohio Manufacturing Association estimated the direct cost to be approximately 1.08 billion dollars (1.39 billion adjusted for inflation) to Ohio manufacturing facilities. 55% of the manufacturers were impacted for an average of 36 hours.

Nationally, over 100,000 auto workers were idled, and 70 auto and plant parts were shutdown. Additionally, several plants reported damage to furnaces or damage to products currently in production. Plant damage required additional time offline to repair.

Several steel production facilities were in the impacted region and most lost four days of production. Again, several facilities reported damage to the plant or to existing products including an explosion and fire at a facility in Lorain, Ohio, which was a contributing factor to the company's bankruptcy filed several months later. Several facilities near the blackout were requested to reduce power consumption and operated at lower production rates. Other metal production facilities were similarly shut down. [10]

Regarding the production of large voltage transformers, there are two major components that are filled by this sector. Cold-rolled grain oriented laminated steel (also referred to as electrical steel) is a core component to voltage transformers. Transformers rated between 300-500 MVA require 170,000 – 220,000 pounds of electrical steel. As of 2007, there were only 11 manufacturers in the world including two in the United States. AK Steel and Allegheny USA both produce electrical steel and have facilities throughout the eastern United States – largely focused around the Midwest and Ohio Valley. Additionally, large amount of copper is required for the production.

As of 2012 there were only a few facilities in the United States that could produce large power transformers. These are clustered on the Eastern Interconnection.

5.3. Mitigations and "Tipping Points"

There is little that can be done in short term to protect critical manufacturing sectors. Many of the facilities consume more power than can be produced by backup generators. Depending upon what is needed to recovery from a large power failure, some of the facilities will need to be equipped with power supplies and have their raw goods transported to them. Finished products will also have to be transported to the facilities that need them. Determining the exact set of goods and power requirements will be dependent upon why the power grid failed and what replacement parts are required.

6. DAMS

6.1. Description of the Sector

The Dams Sector provides water retention and control services in the United States. This includes hydroelectric power generation, the supply of water for municipal, industrial, and agricultural uses, flood control, river navigation, and recreation, among other uses. These services support multiple critical infrastructure sectors and industries. More than 10 percent of cropland in the United States is irrigated by water retained by the Dams Sector. Approximately 60 percent of power produced in the Pacific Northwest is from hydroelectric dams. [45] Figure 6-1 below shows the locations and principal functions of dams in the continental U.S.

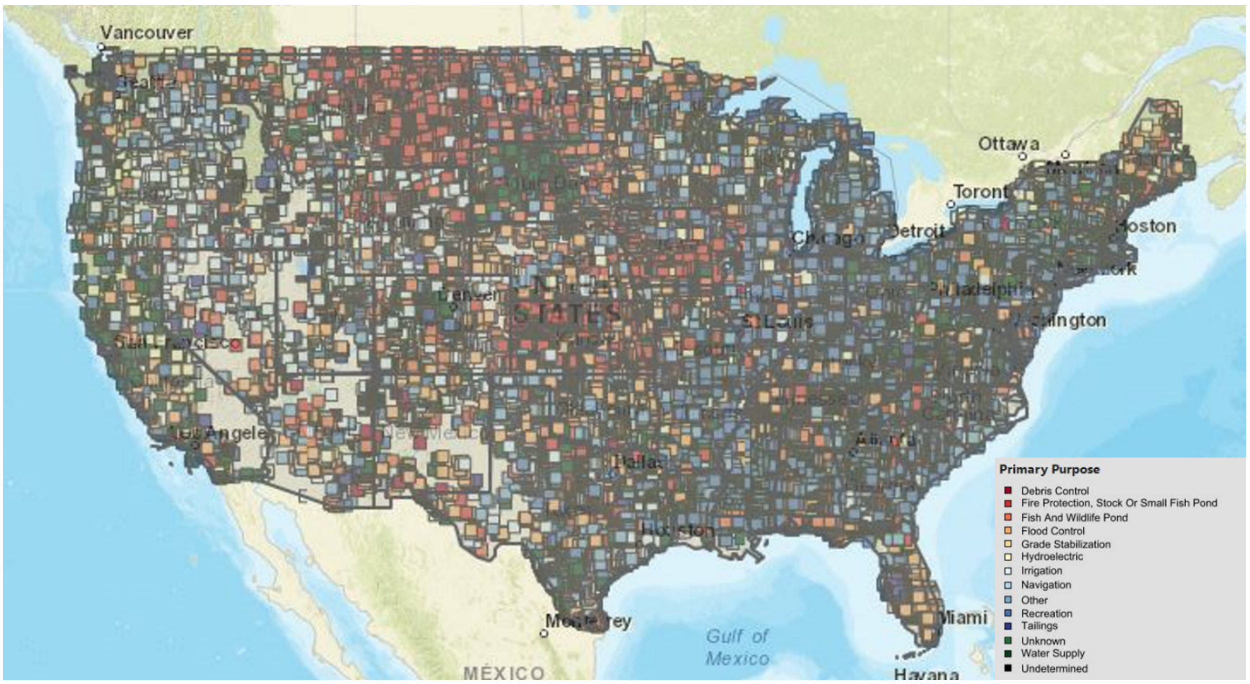

Figure 6-1. Dams in the United States [40]

6.2. Dependencies on the Electric Power Subsector

Hydroelectric dams are part of the Electric Power sector. They are a key to providing black start capability but are otherwise not impacted by power grid outages. There are no other significant direct impacts to dams due to power outages. Some of the functions of a dam, which rely on electric power, could likely be met by diesel generation on-site, which is designed for bringing the dam (and if needed the grid) back into operation via black start. These functions would include opening and closing of valves allowing for the movement of water (or limitation of movement of water) from the dam's pool to irrigation fed from the pool, or to points downstream.

6.3. Mitigations and "Tipping Points"

Depending on the elements of the primary electric grid impacted in the event, hydroelectric dams could provide a mitigative effect for unaffected substations and their service areas in the vicinity of a hydroelectric dam. The use of a hydroelectric dam as a primary local power source, creating an area with reliable power and other infrastructure service, would have to be examined based on the conditions of the electric grid following the causative event.

7. DEFENSE INDUSTRIAL BASE

7.1. Description of the Sector

The Defense Industrial Base (DIB) Sector is comprised of government (e.g., certain laboratories, special-purpose manufacturing facilities, capabilities for production of military materiel such as ammunition plants and arsenals) and private sector (e.g., independent and competing domestic and foreign companies and supply chains) that can support missions directly; perform research and development; design, manufacture, and integrate systems; and provide maintenance. [42] All of these are intended to support national defense requirements. The sector, and therefore, the businesses in critical manufacturing and other sectors on which it depends, is diverse in nature. Thus, consequences to the sector of a disruption of electric power will be unique to the geography of a disruptive event, to the ability to reassign contracted work to other facilities, if possible, and to the effects on supporting infrastructure.

7.2. Dependencies on the Electric Power Subsector

Impacts of the loss of primary electric power are likely to be immediate in most circumstances for facilities in the area affected by primary electric power outage. In some cases, likely for those operations deemed of critical importance within the Department of Defense, backup generation is likely to be present to mitigate any disruptive effects of a sudden power outage. As with other backup generation discussed in this document, limitations on operation then transfer over to fuel and maintenance limitations on the backup generators, and to competition for resources. Even for those elements without critical demand for power in a production process, the loss of electric power will impact the ability for basic facility operations – lighting, heating, ventilation, and air conditioning – to work in any effective manner, limiting what can be done productively by the sector in affected areas. Military facilities with integrative roles within the DIB Sector are likely to experience similar difficulties. Again, backup generation supply will be a long-term issue, though one from which a military installation can draw from an existing, on-site reserve.

7.3. Mitigations and "Tipping Points"

In the event of a long-term power outage over a large region, there could be labor shortage for private sector contractors due to uninhabitable conditions, which could shut down their operations. This could create supply chain issues for the DIB Sector, both within the directly affected area and beyond the directly affected area. Military bases can be isolated from the effects of grid outages where they manage their own microgrids. These, however, are typically designed only to satisfy the power demands of certain missions, and cannot in their current form be used to provide added capacity enabling support for base personnel and civilian contractors' individual demands.

8. ENERGY – NATURAL GAS

8.1. Description of the Sector

Natural gas is used by residential and commercial customers for heating, by industrial customers as fuel and raw material, and by gas-fired power plants for electricity production. Figure 3 shows a simplified representation of natural gas production and delivery infrastructure from wellhead to final consumers. Figure 4 shows the location of natural gas processing plants and intra- and interstate transmission pipelines in the continental United States. Regions with significant natural gas production coincide with the greatest density of processing plants.

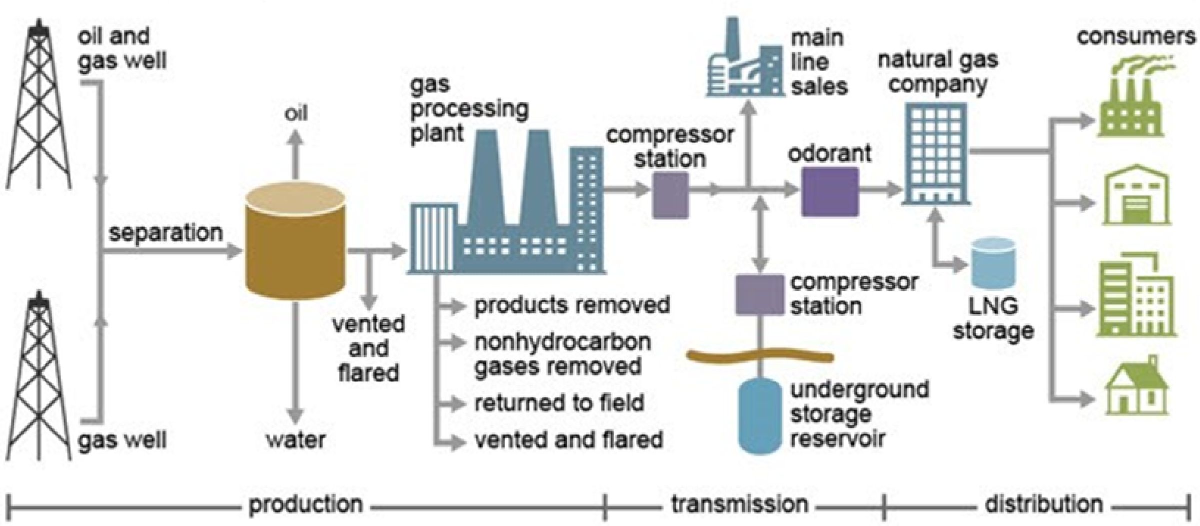

Figure 8-1. Elements of the natural gas production and delivery system [55]

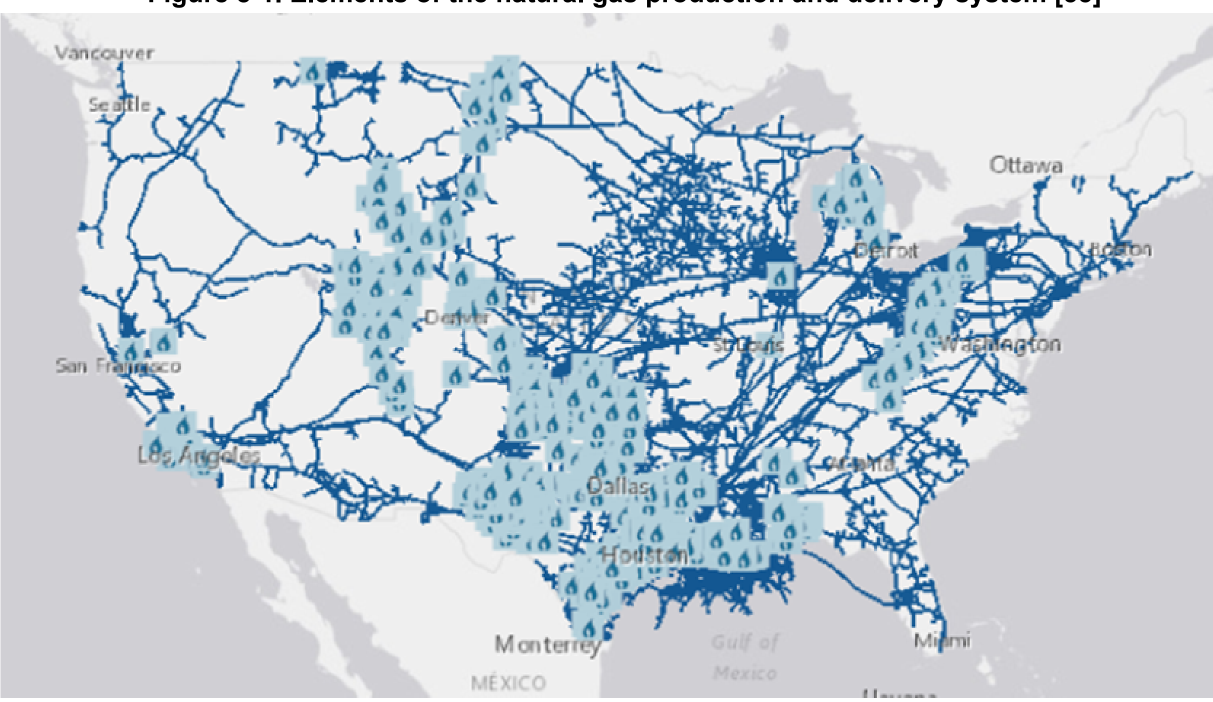

Figure 8-2. Map of U.S. natural gas processing plants and intra- and interstate pipelines [56]

8.1.1. Production

In the production segment raw natural gas is extracted from wells, gathered and compressed in a network of increasingly larger pipes, and fed to local processing facilities, which remove oil, water, natural gas liquids, and other impurities such as hydrogen sulfide and carbon dioxide.

8.1.2. Transmission

After processing, pipeline-quality natural gas is injected into large, high-pressure pipelines that form the intra- and interstate natural gas transmission network. Interconnections between these pipelines allow flexibility in the movement of gas between and within regions. To move natural gas from production areas to consumers that may be hundreds or thousands of miles away, compressor stations are located every 50 to 100 miles along transmission pipelines.

Connected to the transmission pipeline network, hundreds of large underground natural gas storage facilities provide a tool to balance gas receipts and deliveries on daily to seasonal time scales. For example, because natural gas consumption is highly seasonal, but production rates are generally constant, natural gas is withdrawn from storage during the high-demand winter period and injected during the lower demand summer period.

8.1.3. Distribution

Large gas-fired electric power plants and large industrial customers may draw their gas directly from the transmission network. Other electric and industrial customers and all residential and commercial customers draw their gas from a network of smaller, lower pressure distribution pipelines operated by their local natural gas distribution company, which connects to the transmission network via one or more "city gates."

8.2. Dependencies on the Electric Power Subsector

8.2.1. Gas Production

Equipment associated with natural gas production, gathering, and processing increasingly rely on the electric grid for power. [16] Loss of power to a natural gas production area is expected to significantly curtail production in that area for the duration of the outage.

8.2.2. Gas Transmission

Most large compressor stations are powered by natural gas drawn from the pipeline. To meet pollution regulations and/or lower costs, the electric grid increasingly powers compressor facilities near developed and populated areas. If a compressor station is forced offline due to lack of electric power, gas can still flow along the pipeline at a reduced rate. The overall reduction in pipeline flow capacity depends upon the spacing and compression power available at stations elsewhere along the pipeline. [16]

8.2.3. SCADA Communications

The flow of natural gas is controlled and measured from production to consumption at valve, meter, and compressor stations located throughout the natural gas system. Many of these stations are remotely monitored and controlled using SCADA systems. If SCADA communication to remote, unmanned facilities is lost due to electric power outage, personnel can generally be sent to allow local operation and monitoring. [16]

8.2.4. Gas Demand

During a widespread power outage, demand for natural gas for electricity generation and industrial use in the affected region will be significantly reduced. In the U.S. from 2010 to 2015, monthly electricity sector gas demand as a fraction of total demand varied from 25% in winter to 55% in summer. Industrial demand varied from 25% to 35% of the total. [51] Gas demand from residential and commercial customers may also be reduced, due to the requirement of electricity for operation of some gas-fired appliances and equipment.

While gas demand will be reduced during a major power outage, natural gas availability for use in gas-fired power plants used to restart the electric grid will be critical to recovery from the outage. In contrast to recovering from an electric power outage, recovering from a natural gas outage is always very slow, because personnel must visit every customer at least twice – once to turn off gas supply valves and once to turn on supply and relight pilot lights. In areas where gas-fired electric power plants are served by a local distribution company, rather than direct connection to the transmission pipeline network, recovery of the electric grid could be significantly further delayed if there has been a natural gas outage.

8.2.5. Market Operations

In the deregulated natural gas market, pipeline operators provide a transportation service; they do not buy and sell gas. Natural gas sales and purchasing and subsequent scheduling of transportation of that gas potentially across multiple pipelines is coordinated using modern business communication and information technology. While natural gas transmission and distribution networks can fall back on local control to ensure gas delivery, it is not known how natural gas market operations would adjust during a widespread electric power outage.

8.3. Mitigations and "Tipping Points"

A range of disruptive effects are seen in the natural gas subsector from the disruption of primary electric power:

Immediate

- Natural gas production decreases significantly in affected area.
- Natural gas demand decreases significantly in affected area.
- If the affected area is large, the capacity of pipelines in the area may be reduced due to loss of electric-powered compressor stations.

Hours to Days

- Continued pipeline operation requires deployment of personnel to remote stations.
- Pipeline operators withdraw gas from storage to compensate for lost production, if necessary.
- Market participants in affected area must implement contingency plans to facilitate gas purchasing and scheduling.

Weeks to Months

- If power outage has led to significant loss of U.S. gas production, the effects may spread out of the immediate outage area. Gas from storage should be sufficient to meet demand for as

> short as a few weeks to as long as several months. The ability of storage to meet demand would depend upon the extent of production loss, the amount of demand reduction, the amount of gas in storage at the start of the outage (lowest in spring, highest in fall), and geographic region (underground storage facilities are not evenly distributed). [16]

Unlike the electric power grid, which requires constant adjustment to balance supply and demand, dynamics in the natural gas system are much slower and require balancing on hour- to day-long time scales. These slow dynamics allow pipeline operators time to respond to system upsets through relatively manual control. Additionally, because most transmission pipeline compressor stations are powered by gas drawn from the pipeline, and because gas distribution to residential and commercial customers via local distribution networks is largely passive, the natural gas delivery system is relatively robust against electric power outage.

9. ENERGY – PETROLEUM FUELS

9.1. Description of the Sector

The transportation fuels supply network consists of many connected components, including oil fields, transmission pipelines, refineries, tank farms, which are highly dependent on electric power. The problem is to estimate how the functioning of this network depends on the availability of electric power.

This problem can be broken into two parts.

9.1.1. Component Capacity

How much and for how long is the capacity of each component decreased in the absence of electric power? This dependence can be represented as a graph of component capacity, relative to normal capacity, as a function of time, over a period including the outage time and the component recovery period. Each component has a characteristic capacity curve (shown in Figure 9-1).

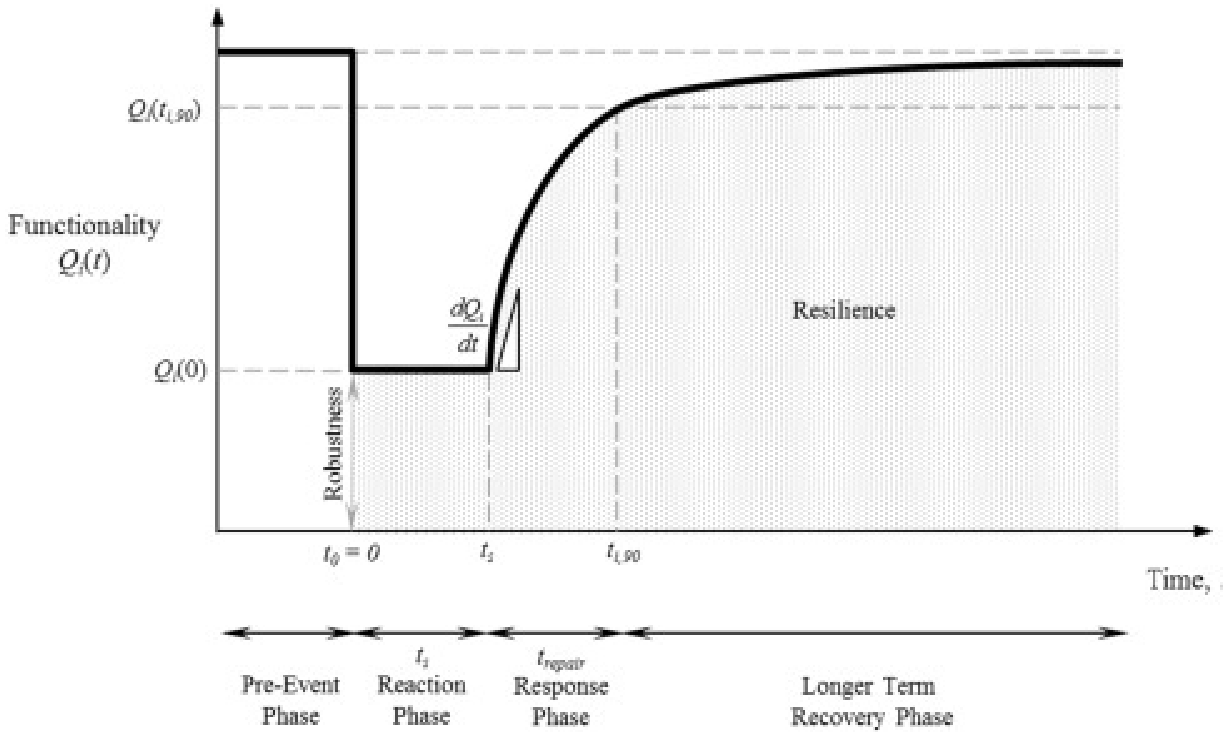

Figure 9-1. Capacity reduction and recovery of an infrastructure facility due to a power outage [62]

9.1.2. Supply Network Performance

If one or more components have reduced capacity, how much does the supply network's performance decrease? This performance can be displayed as maps of magnitude and location of fuel shortages at various times after the start of a power outage (as shown in Figure 9-2).

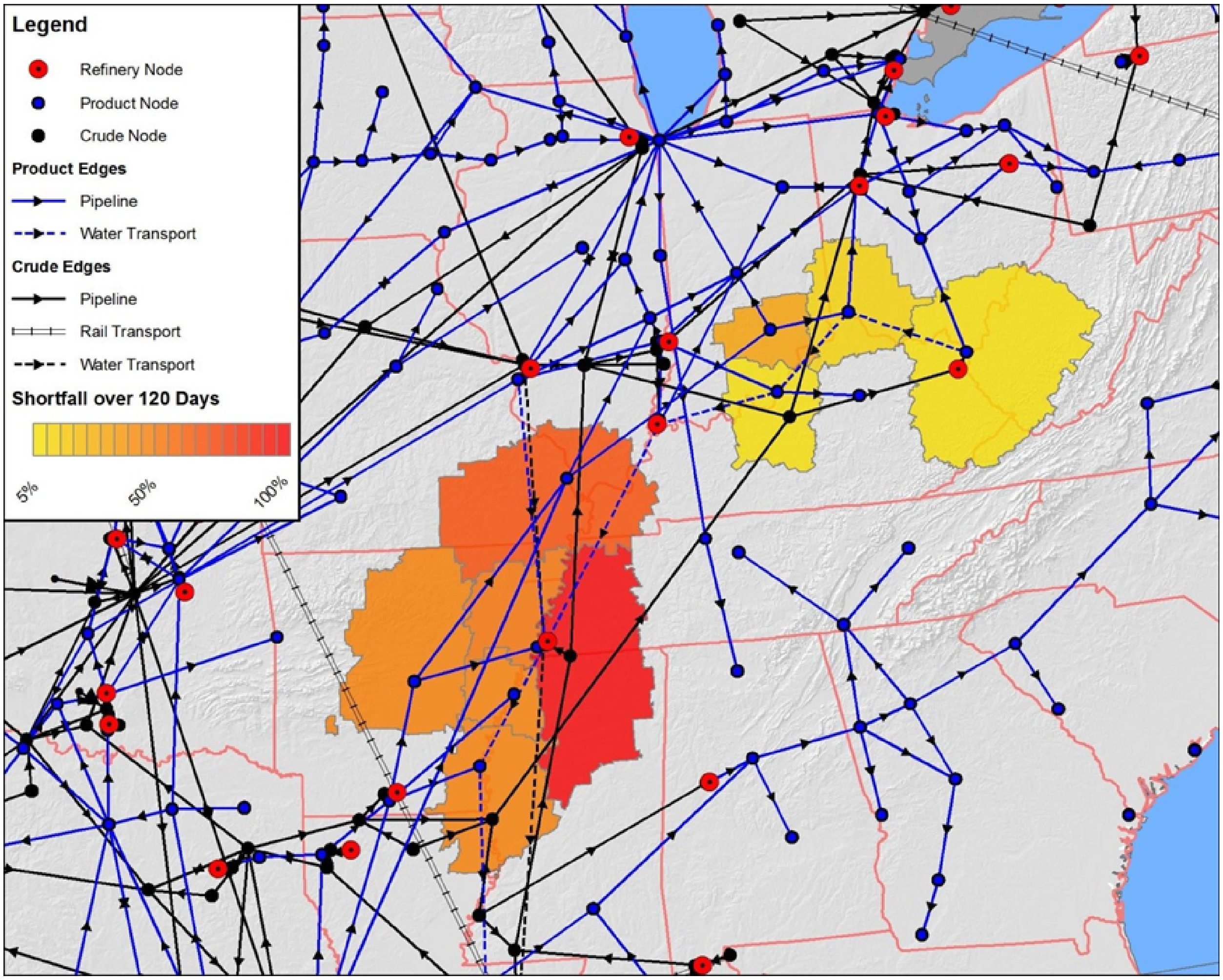

Figure 9-2. Simulated fuel shortage in the central United States after several major pipelines in the Mississippi River valley are disrupted, using the NISAC National Transportation Fuels Model [61]

9.2. Dependencies on the Electric Power Subsector

The definitions of "component" and "supply network" in this discussion depend on the level of aggregation that is used. An individual refinery, for example, could be considered as a component of a national-scale transportation fuels supply network, or as the network itself. In the latter case, the components might be individual process units or other parts of the refining operation. For this discussion, we will consider facilities to be components. Although each individual facility has a unique capacity timeline when experiencing an electric power outage, this discussion will consider effects on infrastructure in the following classes of components:

- Oil field production
- Ports and other transportation Facilities
- Refineries
- Distribution

Each of these component classes (shown among the elements of the petroleum supply chain in Figure 9-3) are dependent on electrical power for such things as powering processes, lighting and safety equipment, office operations, communications, and control systems, and each could have mitigation options such as back-up power generation or moving control and business functions to alternate facilities that could reduce the impacts of a power outage.

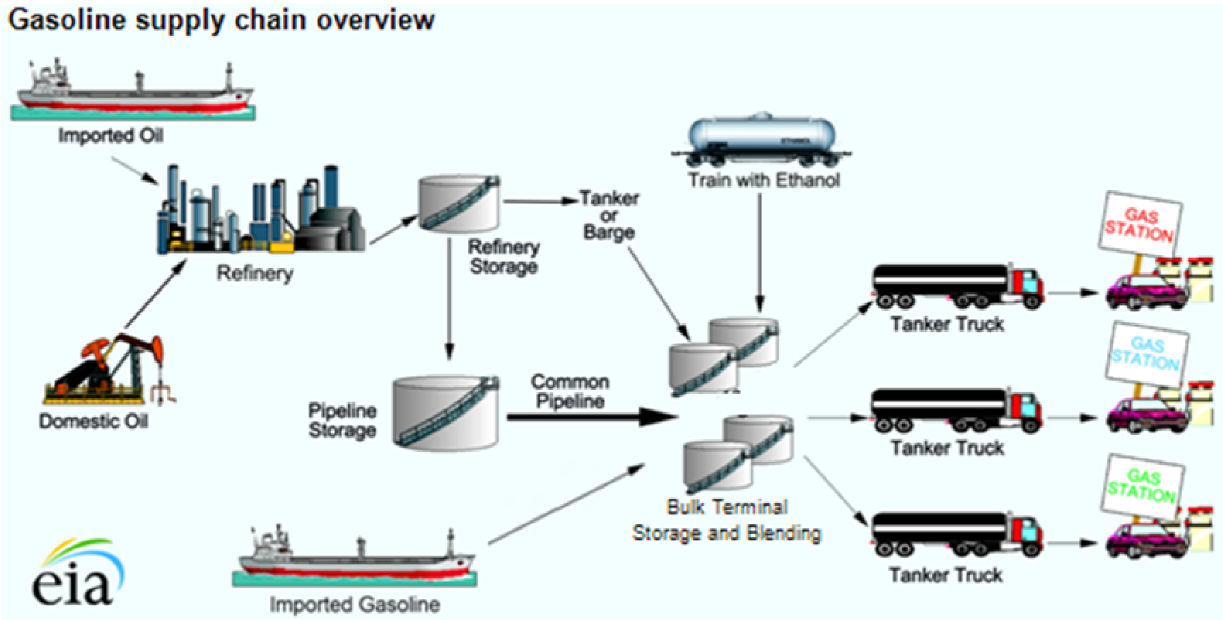

Figure 9-3. Petroleum supply chain [53]

Providing good estimates of the degree to which a particular component could operate during a power outage is probably best done by analysis by subject matter experts that have detailed knowledge of the operations and available options of each facility. The estimate will also depend on the extent and expected duration of the power outage. Each situation is unique and generalizing (accurately) is difficult. Following is a summary of selected information that provides some insight into the range of responses to power outages.

9.2.1. Oil Field Production

There are several methods used in lifting oil from reservoirs and moving it through gathering lines to transmission system loading points. There is some dependence on electric power, and a regional power outage would decrease production by some amount. However, crude oil from other producing areas or from imports can substitute for lost production in a single production area. We think that reduced crude oil production is not a serious concern with respect to impacts of power outages.

9.2.2. Crude Oil and Refined Product Transportation

Transmission pipelines that transport crude oil and refined products have a strong dependence on electric power. The power is used to run pumps on the main pipelines and at tank storage along the pipelines, for control systems, and communication networks. Typically, loss of power for control and communication functions is not expected to result in disruptions to pipeline operations because these functions can continue by using on-site back-up generators or by shifting the functions to an alternate site. Pump stations require more power and can only function during power outages if very large portable generators are available and electrical systems have been modified to allow their use.

Kilgore and Neubauer [18] provide a detailed description of the efforts to use multiple 2000-kilowatt portable generators to power pump stations on the Colonial Pipeline System during power outages caused by hurricane Katrina. This was a major, expensive effort that provides insight into the feasibility of operating a large pipeline system during a power outage and this experience will help with planning for future events. The main options that are available during power outages include using the portable generators, running the pipelines at lower flow rates with several pump stations not operating, and adding drag reducing agents to the pipeline liquids.

This case indicates that although logistically complex and expensive, it is possible to operate large transmission pipelines at reduced rates during extended power outages if preparations have been completed. Although some time would be required to receive, install and test the portable generators, it seems reasonable to assume that large transmission pipelines would not be a primary bottleneck during a prolonged power outage.

The functioning of transmission pipelines depends on having tankage for storage at pipeline junction points and at loading transfer points for water and rail shipments. The pumping, blending, and metering systems of these storage terminals have a dependence on electric power that is similar to that of the distribution terminals discussed below.

Transportation by petroleum tankers or barges would not be affected by a power outage. Both are self-powered and can generally load or unload under ship power. Onshore loading and unloading facilities are susceptible to reduced efficiency or totally disrupted, depending on their reliance on electric power supplied from onshore or inland sources. Power to marine installations could be temporarily supplied by berthed vessels or barges. [28]

9.2.3. Refineries

Many refineries have on-site power generation and some of them could continue operations during power outages. However, some of these refineries with on-site generation generate much more power than they consume, and therefore depend on an operating power grid to shed excess power. These refineries would not likely be able to function during power outages.

9.2.4. Distribution

The distribution segment in the oil supply network includes storage of product in distribution terminals, truck loading and transportation of refined products to retail stations, and operation of retail stations, all dependent on the power grid. [36]

9.2.4.1. Distribution Terminals

Refined products move by rail and pipelines from refineries to terminals, which are used primarily for storage, blending, and marketing of these products. Finished products are moved mainly by pipelines and barges to bulk storage and blending terminals. These terminals consist of tankage, piping, pumps, and electrical systems. Additives, like ethanol, are blended with finished petroleum products at the terminal before the final product is shipped to customers. Electronic meters control the blending ratios and calculate the quantity of ethanol to be loaded. Loading ratios are programed to suit all blends by making software changes and adding new product codes. Loading rack plumbing and metering is designed for current volume and ratios. The terminal operators are responsible for the accuracy and calibration of all systems. Due to dependence on electronic components, distribution terminals are likely to be disrupted during a power outage.

The truck loading system consists of piping, pumps, injection systems, and electronic metering. The electronic meter serves as the brain of the rack and functions through the use of electro-magnetic identification cards. These cards are issued to customers and contain data that allows terminal entry, volume allocation, and pricing, as well as truck safety inspections and driver qualifications. It is at the rack, where the final product is made using required additives. The additives are most commonly injected at the truck loading rack either sequentially, as the product enters the tank truck, or in one dose at the beginning of the loading process. During a power outage, modern industry loading racks cannot control the blend, and loading, so tanker truck loading may be completely disrupted.

9.2.4.2. Transportation to Retail Stations

Trucks deliver refined products to the end user at retail, commercial, or government sites. Once the product is loaded on the truck, the truck operator assumes responsibility for custody, quality, and safety of the product. It is the duty of the truck operator to ensure that a tank truck is properly loaded with correct ratios of ethanol and detergent additives. Product custody is transferred to the retail or commercial site once the delivery to the designated storage tank is completed. The U.S. Department of Transportation and the Environmental Protection Agency (EPA) require bills of lading to follow product to the final destination. Although a power outage may not directly affect movement of trucks, since the upstream truck loading at the terminal storage cannot control the blend, there may be legal liabilities preventing the truck operators from loading and transporting fuel.

9.2.4.3. Retail Stations

The retail station is the final step in the gasoline supply. Fuel distribution functions are dependent on electrical power, so a disruption would severely affect their functioning.

Retail stations vary in size, but most will have at least four dispensers per island, specifically two cabinets with fueling nozzles on each side. Retail gasoline inventories are managed by various means. Individual single site owners may order their supply directly. Larger retail organizations will use modern satellite technology to feed a central inventory management system that will monitor site inventories and dispatch resupply based on run-out projections. Other options include outsourcing inventory management to the common carriers (truck companies) to manage inventories.

Upstream disruptions in the transport of product to retail stations will affect outlets by limiting supply. As with other parts of the gasoline supply process, retail outlets are also affected by power outages, which prevent inventory management, regular retail operations, and pumping. Alternative power generation in retail stations widely depends on discretion of the owners or managers. Some states have enacted laws requiring backup generators at certain retail stations. [24]

Mandating transfer switches or generators does not address issues not related to electricity at a retail station. Additionally, given all power-related challenges upstream, the cost of generators, and physical storage space limitations at retail stations, the role of stocking generators as mitigation for the effects of widespread long-term power disruptions is not clear [25] and cannot be described without accounting for these upstream disruptions.

9.3. Mitigations and “Tipping Points”

During disruptions to the transportation fuels supply network, market transactions, business decisions, and (sometimes) regulatory actions work together to mitigate shortages of supplies. Mitigating behaviors include re-routing shipments, drawing down inventories, and using surge capacities of undisturbed components. The ability of these behaviors to reduce impacts on fuel supplies depends on the capacity of system components to transport, process and store crude oil and refined products, the connectivity of the components, and inventory levels at the time of the disruption. The impacts of a power outage will depend on the position of disrupted components within the supply network. Closure of a particular refinery, for example, could have a larger or smaller impact on fuel availability than another refinery of the same size but located in a different part of the network.

Forecasting how the fuels supply network would respond to a specific power outage is difficult without the help of computer models. There are a number of types of models that have been applied to simulate the performance of infrastructure systems during disruptions. [30] The modeling approaches that are best suited for simulating the impacts of power outages on fuel supplies are those that employ a network representation, rather than an aggregated representation, of the fuels supply network. This is because it is important to include the constraints imposed by the actual connectivity of the network components. Different infrastructure network models differ mainly in how they compute flows on the network components. Examples of methods include market-based models, optimization models, System Dynamics models, physics-based models, and hybrid approaches.

10. EMERGENCY SERVICES

10.1. Description of the Sector

The Emergency Services Sector is comprised of five distinct disciplines:

- Law Enforcement
- Fire and Emergency Services
- Emergency Management
- Emergency Medical Services
- Public Works

These disciplines are conducted through the use of manpower and equipment, often using elements of the Transportation Sector, to meet the general set of emergency response missions – saving lives, protecting property, assisting the community, and aiding in recovery from emergencies. [46]

10.2. Dependencies on the Electric Power Subsector

Numerous dependencies on the electric power sector exist for elements of the Emergency Services Sector:

10.2.1. Emergency Services Facilities

Facilities that house the disciplines of the Sector, described above, rely on electric power for functions as simple as facility entrance and egress. Where these facilities have badged, automated entry and exit, loss of primary electric power is likely to lead to operation of local backup generation. For some facilities (such as fire stations), protocol of the facility will require either inbound or outbound doors to be open for bays at all times.

Communications system impacts, especially in the cellular network, may limit the ability of individuals in distress to communicate that need to emergency services personnel, as battery backup-supported cell towers fail and if generator-supported towers are unable to be refueled to maintain service.

10.2.2. Emergency Services Vehicles

Emergency Services vehicles face the same limitations that other vehicles face: The constraints of an outage on the transportation network. This will, in turn, impact response time and service effectiveness. Fuel limitations will be somewhat different for Emergency Services vehicles, as they can utilize dedicated fueling resources (provided backup generation and continued supply of fuel is present).

Communications limitations will extend to these vehicles as well, as degradations in the cellular network will limit the ability for emergency services sector automated dispatch systems to work.

10.2.3. Emergency Services Personnel

Emergency Services Personnel in some cases can use their vehicle to support their ability to commute to and from work, providing local service in their neighborhood in addition to supporting a larger area. This can help to provide a minor mitigation to the communications limitations identified above.

10.3. Mitigations and "Tipping Points"

While less reliant on electric power than other sectors, the Emergency Services Sector's dependencies as a whole – on power, petroleum fuels, communications, transportation, and others – suggests degraded performance.

11. FINANCIAL SERVICES

11.1. Description of the Sector

The banking and finance sector has a fundamental instrumental role in all economic activity by facilitating payments. This requires maintaining a stable currency, providing ready access to currency for cash transactions, and check processing. These payment modes are rapidly being superseded by electronic payment systems which function by adjusting account balances through data networks. Besides the instrumental role of enabling payments, the fundamental economic functions of the financial system are: to create and allocate money through credit; to allow individuals and organizations to manage financial uncertainty and risk; and to rapidly and efficiently disseminate information about the state of the system through price discovery.

11.2. Dependencies on the Electric Power Subsector

Virtually all banking and finance functions require maintaining and transmitting information. They therefore depend on operation of data centers and the data networks that connect them. This dependency is well understood within the industry, and "emergency preparedness is an important component of … bank examination procedures." [38] Financial institutions and data centers have backup generation, and the core functions that support markets, commercial, and government operations of should continue to function provided fuel is available.

Retail bank outlets' and Automated Teller Machine (ATM) access to backup power has considerable regional variability. Some may have no backup power, or only battery backup allowing hours of service. Local currency shortages and limited account access may be expected.

11.3. Mitigations and "Tipping Points"

Given availability of communications, some consumers can execute payments and conduct other basic financial transactions using phones or other internet access devices. Portable ATMs with generators can be deployed for currency distribution, however the number available, deployment logistics, and security may limit the speed and scope of this mitigation. Banking services in support of markets and commercial firms can be expected to continue as long as communications systems and fuel are available. Core financial institutions employ geographically dispersed backup data centers, suggesting persistence through fuel or communications outages confined to individual states.

12. FOOD AND AGRICULTURE

12.1. Description of the Sector

The Food and Agriculture Sector broadly consists of upstream crop and animal operations (farms, orchards, vineyards, dairies, cattle production, hog production, poultry and egg production, etc.) that produce, harvest, and pre-process the commodity grains and oil seeds, vegetables, fruits, nuts, meat, poultry, and dairy feedstocks that go into the making of food products. It also consists of mid-stream processing, packaging, transport, storage, and wholesale distribution, followed by downstream retail delivery, sales, preparation, and service of food and beverage products to end-use consumers. End-use food and beverage products span the range of fresh, frozen, dried, condensed, canned, bottled, packaged, prepared, and served. Both the upstream production and the mid- and down-stream processing, delivery, storage, and preparation elements of the overall Food & Ag Sector are generally widely distributed, with some regional concentration associated with the production, processing, packaging, and distribution of certain food products.

The regional concentration and flows of food products from specific upstream and midstream production, processing, storage, and distribution operations will depend on what the specific products are, where the agricultural source operations for those products are located, the seasonality associated with the growth and harvesting of the plant or animal products, and where the dominant processing and packaging centers for those specific products are located. Also, a factor in the spatial and temporal distribution and flows of food products will be whether the products are sourced domestically, or whether they are imported from foreign sources. This overall value chain and the associated spatial and temporal flow of products is complex and dynamic, especially in the sense that it also intersects with other industrial, commercial, institutional, and residential sectors of society and the economy, spanning both rural and urban areas of the country. Throughout this value chain, the entities and operations involved in the day-to-day flow of agricultural feedstocks and food goods and services are reliant on the availability of electric power. Food supply related impacts from prolonged electric power loss in any given region will depend on where the region is located, what time of year the outage occurs (which relates to climate conditions and may also relate to the seasonal timing of certain fresh food products), what portion of the supply chain for specific food products falls within the impacted region, and what specific part of the food supply chain and end-use sector is being considered. Examples of food-related electric power dependencies and interdependencies are given below.

12.2. Dependencies on the Electric Power Subsector

12.2.1. Upstream Agricultural Crop, Orchard, or Animal Production, Harvesting, and Pre-Processing

In the upstream portion of the Food and Agriculture Sector, power could be required for water pumping for irrigation. The loss of such power, depending on the time of the year and the growth stage of the crop, could cause crop damage or loss.

Power may also be required for the supply of water and environmental conditioning of facilities (heating or cooling, depending on the season and types of animals) for agricultural animal operations, without which the animals will not thrive and may be damaged or die.

Power will be required for pre-processing facilities operations and environmental control (e.g., cooling, drying, refrigerated storage, milking machines and milk processing for dairies, etc.), the loss of which could shut down operations or cause product damage or loss without control of the environment (e.g. drying and/or keeping products cool to prevent spoilage, cows that cannot be properly milked in a timely way will be damaged).

Most importantly, power will be required for the health and well-being of workers and their families. The loss of power for employees and their families impacts living conditions in homes and apartments and the availability of necessary functions (lights, electric appliances, water, gas for heating and cooking, cold storage for perishable food, home heating or cooling, etc.), without which workers could not function well as employees and would eventually need to leave to find better living conditions for themselves and their families.

12.2.2. Midstream Agricultural and Food Product Processing, Packaging, Transport, and Storage in Distribution Centers

At midstream, power will be required for facilities operations – lights, electrical equipment for processing, packaging, and internal movement of materials (e.g., conveyor belts, motor/pumps, electric forklifts, etc.) and environmental control for product storage, without which facility operations would stop and perishable food products would rapidly degrade or spoil.

Vehicles needed for food product transport from upstream agricultural sources to midstream processing and distribution storage, and then on to downstream retail distribution, will be reliant on the availability of fuel, the supplies of which will be impeded by the loss of power to the regional fuel supply infrastructure (pipelines, storage depots, service stations), all of which require power for operation.

As with the upstream portion of the Sector, power will be required for the health and well-being of workers and their families. The loss of power for employees and their families impacts living conditions in homes and apartments and the availability of necessary functions (lights, electric appliances, water, gas for heating and cooking, cold storage for perishable food, home heating or cooling, etc.), without which workers could not function well as employees and would eventually need to leave to find better living conditions for themselves and their families.

12.2.3. Downstream Commercial Distribution, Re-Packaging and or Preparation, and Sales of Food Products

Power will be required for the operation of retail convenience stores, grocery stores, restaurants, diners, cafes, hotels, caterers, convention centers, tourist venues, and other suppliers of food products in the impacted region. Loss of power will not only prevent normal facility functions such as lighting, water supply, natural gas supply, and appliances for on-site food product preparation and clean-up, but it will also prevent the function of cold storage capability (refrigerator and freezer systems) that is critical to maintaining the viability of fresh or frozen food products that will quickly perish otherwise.

Again, power will be required for the health and well-being of workers and their families, loss of which impacts living conditions in homes and apartments and the availability of necessary functions (lights, electric appliances, water, gas for heating and cooking, cold storage for perishable food, home heating or cooling, etc.), without which workers could not function well as employees and would eventually need to leave to find better living conditions for themselves and their families.

12.2.4. Institutional Organizations that Purchase, Store, Prepare, and Serve Food Products

Institutional organizations such as schools and universities, hospitals, prisons, airports, nursing homes, food banks, churches, and other groups who store, prepare, and provide food products to end-use consumers as part of their organizational function or mission, all rely on electrical power for their operation. Without power the normal operations of these institutional facilities would not be possible, including the preparation of meals and the storage of perishable fresh and frozen food products. Bringing in prepared meals or otherwise ready-to-consume food products from elsewhere could replace on-site storage and preparation, but loss of other facility functions without power would still be a problem for continued operations.

12.2.5. Private Individuals and Families that Purchase, Store, Prepare, and Serve Food Products

Power will be required for the health, well-being, and productive functioning of the general public and society at large. Loss of power will impact the ability of individuals and families to maintain suitable living conditions, including food storage and preparation, in homes, apartments, or other housing arrangements. This includes the availability of necessary functions (lights, electric appliances, water, gas for heating and cooking, communications and entertainment, cold storage for perishable food, home heating or cooling, etc.). Without electric power and the function it enables in modern society, residents in the impacted region could not function well for long as individuals, families, employers, employees, public or private sector leaders, service providers, or any other role. Society at large would be subject to increasing stress and the risk of severe breakdown. Many people in the region who are under duress but able to leave would eventually do so to find better living conditions for themselves and their families. People who are not able to leave would need help.

12.3. Mitigations and "Tipping Points"

Mitigation of all phases of the Food and Agriculture Sector would include the availability of local backup power from backup generators or renewable energy power generation, if local resources permit. The duration and cost of maintaining backup generation requiring liquid or gas fuel supplies will then depend on the availability and cost of replacement fuel supplies. Power generation from intermittent renewable energy sources (e.g., solar PV or wind) without energy storage capability will also be subject to periods without power during periods of insufficient solar and wind resource. Backup generators and/or renewable energy power systems with energy storage may also be generally beyond the capability or site suitability for supporting the homes, apartments, or other housing for employees, and may be infeasible in urban environments in the downstream portion of the chain, and at commercial food preparation facilities.

Mitigation for fuel supplies include having local reserves of stored fuel as part of food transport company operations, with back-up power available to operate the local fuel storage pumps. The success of this mitigation alone will be limited by the time required to exhaust the local fuel supplies. Longer-term operation under prolonged regional power loss would require bringing in fuel supplies from outside the impacted region.

13. GOVERNMENT FACILITIES

13.1. Description of the Sector

The Government Facilities Sector includes office buildings, installations, embassies, courthouses, and other government-owned or leased facilities in or on which activities of local, county, state, tribal, and Federal government are performed. This includes everything from schools and other educational facilities; military installations; national laboratories; monuments and icons; and general government buildings not otherwise included in other sectors (such as fire and police stations included in the Emergency Services Sector). The sector also includes cyber systems that provide support to the function of the sector (including the security of said facilities and electronic assets used to support the election process), as well as the personnel that perform essential functions that enable the sector to function. [51]

13.2. Dependencies on the Electric Power Subsector

13.2.1. Facilities

Similar to the Commercial Facilities Sector, the facilities in the Government Facilities Sector are dependent upon electrical power to provide operations of typical government functions.

This sector, as described above, includes office buildings that provide space for government and other infrastructure sectors to operate. Often these are co-located within the same facility. Facilities in this sector providing critical functions may be better prepared to weather long term power outages (through the presence of backup generation capacity) but are still dependent upon individuals to keep the buildings operational and to fulfill the necessary functions.

13.2.2. Cyber Systems

Cyber systems – whether those providing data and mission function for government offices, security for buildings, or support for other functions – are heavily reliant on electric power for function, and the lack of commercial electric power is therefore an immediate limitation to the ability of government facilities to perform their missions.

13.2.3. Essential Personnel

Additionally, this sector provides employment for an extensive percentage of the U.S. population, including personnel essential to government function. If this sector is without power for a significant period, it will remove a substantial part of the U.S. economy and may produce financial hardships for many. This will impact other sectors as individuals are forced to consume social services (if available) for basic needs.

13.3. Mitigations and "Tipping Points"

Many government facilities are unlikely to have backup generation. These facilities, and their functions, will be impeded immediately by an extended electric power disruption. Facilities providing time- and mission-sensitive government function are likely to have backup generation on site, requiring regular refueling in the event of an extended disruption of commercial electric power, though even these facilities will face constraints from functionality dependent on cyber systems and on personnel who are also challenged by an extended outage.

14. HEALTHCARE AND PUBLIC HEALTH

14.1. Description of the Sector

Healthcare is a combination of the personnel and facilities that support the physical and mental well-being of a community. [52] This is generally considered to include the hospitals and doctors that work there, but also includes mental health facilities, pharmacies, dialysis centers, and a host of other specialized facilities and personnel. The majority of the healthcare provided in the United States is privately owned and operated.

Public health encompasses a diverse set of industries including healthcare, disease surveillance, and food quality assurance. Additionally, public health is closely tied to issues of water quality, sanitation, and environmental quality.

14.2. Dependencies on the Electric Power Subsector

14.2.1. Public Health

Public health involves a range of organizations private and public and is heavily dependent upon electricity. Disease surveillance requires communications, information technology, and frequently transportation to meet with individuals or doctors. Some disease surveillance has been completed following disasters to determine causes of increased disease observation. In New York City during the 2003 power outage, increases in gastrointestinal illnesses were linked to increased meat or seafood ingestion during the power outage. The conclusion was the increase in illness might be related to ingesting spoiled or improperly prepared foods. [22] During the 2003 blackout, additional restaurant inspectors were brought in to assist in inspecting restaurants to ensure proper disposal of spoiled food. Furthermore, emergency orders were issued that allowed spoiled food to be removed by the Department of Sanitation as private contractors were overwhelmed by the amount of goods to be removed. [6]

Public health is an overarching sector that requires many other sectors and groups to function. As our ability to maintain health through a population diminishes, the population is unable to function. All sectors depend upon individuals being healthy and able to work. Maintaining a functional public health system is critical to allowing other sectors to continue to operate.

14.2.2. Hospitals

Hospitals are dependent upon electricity. Patients can be dependent upon electrically powered equipment, health records are stored digitally, and hospital infrastructure is required to operate. Many states and the National Fire Protection Association have regulations and standards relating to emergency and standby power systems for healthcare facilities. These regulations are designed to allow a hospital to continue to function in the case of power loss. However, they are not fool-proof and are intended to support the hospital for a short period only. While generators are required to be in place, they do not always work properly. During the 2003 blackout, four of the 75 hospitals (5%) in New York City were without power at some point during the blackout. [19]

In the absence of electrical power, small and individual practices (personal care physicians) will not be able to operate. This will lead people to seek medical care at emergency departments even for medical issues that would not normally send an individual to the hospital. In addition to the role that hospitals play for existing patients, power outages increase the number of hospital admittances. In New York City, during the August 14-15, 2003 blackout there was a 122% increase in accidental deaths and a 25% increase in non-accidental (disease related) deaths. This caused 90 additional deaths during the blackout and mortality risk remained slightly elevated through the rest of the month. [3]

Additionally, the health care sector is strongly dependent upon the transportation, communications, water, and chemical industry sectors. Increasingly, hospitals are using electric health records that require computers and an operating network to function. Hospitals work to control costs by minimizing inventory and relying on just-in-time supply chain approaches where goods (medication and healthcare supplies for example) arrive as current inventory is exhausted. Any disruption of the supply chain can quickly shut down a health care facility even if the facility has electricity.

Other sectors are dependent upon the healthcare system operating correctly and efficiently to keep staff working and to prevent disease from moving through a population. In the absence of functional healthcare, individuals may not be able to go to work due to being ill, injured or needing to take care of an ill family member. Keeping the healthcare system operational will keep the workforce able to function. This has both an immediate and long-term impact upon other sectors and systems – individuals may be out for short-term illness or longer term depending upon the specifics.

14.2.3. Ambulatory Care

Ambulatory or outpatient care covers a wide range of medical procedures and treatments that do not require overnight or long periods in a hospital. This includes normal visitations to personal care physicians, office-based surgery, and long-term treatments like dialysis. Individuals with kidney problems can receive treatment in the form of dialysis. Dialysis is a process where blood is filtered by a machine that will duplicate the function of a person's kidneys. A single treatment lasts about four hours and is done roughly three times a week. These machines are dependent upon electrical power and treatments frequently are done at medical facilities outside a hospital dedicated to providing dialysis treatment. At the end of 2009, there were 398,861 dialysis patients with end-stage renal (kidney) disease. Of these, the majority (365,566) were treated in an in-center dialysis center. [26]

In a study done following Hurricane Sandy, only 28% of the facilities questioned said they had a backup generator on site. While the majority had short term (under 24 hour) power outages it was estimated that 44% of the patients missed one or more sessions. This compares to a normal rate of 5 – 9%. This can be due to difficulty in traveling, no power at the facility, or difficulty in reaching patients or the facility due to telecommunications failures. Eleven percent of the facilities had a generator delivered by their parent company. On average it took 24 hours for the generator to be delivered and installed. [1] Some states do require dialysis treatment facilities to be equipped with backup power, but not all states have the requirement. Patients that require treatment will be forced to go to hospitals where they can receive dialysis. This is a time-consuming treatment that is a large power and manpower draw on hospitals if external facilities cannot provide treatment. During Hurricane Sandy, Beth Israel Hospital in New York City went from no patients presenting with a need for dialysis to approximately 45 within 48 hours. [15]

Additionally, individuals on chronic medications may be unable to receive their medications from pharmacies and may choose to go to hospitals to look for care. This has both a short term and a long-term impact as there will be a delay depending on how much medication is available at an individual's home and their ability or willingness to go without.

14.2.4. Home Medical Equipment

Individuals can use several different types of home assisted breathing apparatuses (for example, ventilators, oxygen concentrators, or nebulizers) that require electricity. These assist with breathing by providing increased percentages of oxygen or keeping airways clear. Additionally, individuals may depend upon motorized wheelchairs for mobility. Many of these machines have battery backups or options for short-term manual bypass. In the 2003 blackout, a study conducted of the impact of the blackout on emergency medical systems revealed that failure of home respiratory equipment had a substantial impact on the number of patients presenting with respiratory complaints. During the 18-hour impact period, 52% of the respiratory complaints were related or precipitated by the failure of respiratory equipment. In another study during the same power outage, 9% of the triaged patients were identified as having a medical device that failed. 56% presented in the first four hours of the blackout. 57% of the patients that came to the emergency room were admitted into the hospital. These hospitals accounted for 14.2% of the patient hours in the emergency room. This accounted for 22% of the total hospital admissions from the emergency room during the 24-hour study period. [13]

14.2.5. Mental Health and Drug Treatment

In 2008, 13.4% of adults received mental health treatment including prescription, outpatient and inpatient treatment. [27] Often for these individuals, continuity of care is critical to recovery. Several studies mentioned concerns for elderly individuals who may have dementia or Alzheimer's, but no specific numbers were provided as to the impact on healthcare facilities during an emergency setting. There were specific mentions of individuals who were unable to leave their buildings due to power outages shutting down hall and stairway lights. Individuals can also be unable to reach mental health hotlines due to communication problems.

Several studies mentioned the impact of individuals who would normally receive treatment for opioid addiction at methadone clinics or other treatment facilities. In the wake of Hurricane Sandy, many patients found their clinics closed and went to hospitals to receive treatment. [2] This increases the number of non-critical patients at hospitals and absorbs resources that may be needed elsewhere.

In both cases, the dependencies are similar: power to operate the offices and clinics that are used, transportation (public or private), and pharmacies (chemical sector). Offices are often located in commercial facilities instead of hospitals and are unlikely to be equipped beyond short-term power backups for emergency lighting.

14.3. Mitigations and "Tipping Points"

Healthcare systems are set up on the assumption that if the power fails, hospitals will remain with power and operational through backup generators. While generators will not power everything in the hospital to the same level they were on main power, they do provide enough power for the hospital to function. Demand for power from hospital generators will be very high. In addition to the everyday demands on hospitals, there will be increased demand from a variety of different needs. This suggests that setting up additional charging facilities will be critical to preventing overwhelmed critical facilities. Similar to the way cooling stations are employed during heat waves, charging stations can provide an opportunity for critical equipment to be charged without creating the additional demands on valuable healthcare workers. This will also lower the tipping point where that facility can no longer function due to overloaded demand on personnel or supplies.

The development of microgrids, small areas that can produce and distribute power independently or in conjunction with a larger power grid, are a strong option to mitigate the impact from large scale power outages. Microgrids can allow the powering of critical infrastructure facilities for longer periods and can be expanded beyond the capacity of a single or small cluster of buildings. [20, 34] These will not replace power grids, but serve to provide critical backup power to critical infrastructure. In regard to healthcare, using a microgrid to power both a hospital and a facility for providing needs like dialysis and power charging for home medical devices can prevent a hospital from being overwhelmed by non-critical cases. This would allow the hospital to more efficiently serve the population and enable less community disruption.

15. NUCLEAR REACTORS, MATERIALS, AND WASTE

15.1. Description of the Sector

The Nuclear Reactors, Materials, and Waste Sector is comprised of the nation's nuclear power plants (both active and decommissioned); non-power reactors used for research, testing, and training; manufacturing facilities that produce reactors or reactor components; facilities that manufacture or use radioactive materials used in medicine, industry, and education; nuclear fuel cycle facilities; and facilities involved in the transportation, storage, and disposal of nuclear materials.[47]

15.2. Dependencies on the Electric Power Subsector

Commercial nuclear reactors produce power for the electric grid. They are typically co-sited with generators designed to provide, at a minimum, sufficient power to allow for a safe shutdown of the reactor from a major disruption to the grid, in accordance with standards set by the Nuclear Regulatory Commission (NRC). Thus, the impact of a disruption of electric power would be minimal on the safety of a commercial nuclear reactor, but it would likely lead to that reactor shutting down until such time as reliable commercial electric power were available in the affected area around the reactor. Non-power reactors, such as those used by universities for education, fall under the same NRC guidelines.

Manufacturing facilities, whether those that manufacture reactors and reactor components or those that manufacture radioactive materials, are likely to face some of the same issues seen elsewhere: immediate shutdown of nonessential operations, and generator-supported safe shutdown of essential functions, if not designed for continuous operation disconnected from commercial electric power. Fuel cycle and storage and disposal facilities are likely to be subject to the same constraints, with backup power required for maintaining adequate ventilation.

15.3. Mitigations and "Tipping Points"

Performance of the elements of the Nuclear Reactors, Materials, and Waste Sector are limited in the event of a large-scale disruption but are often important in the restoration process. Safe shutdown of processes and continued safeguarding of elements of the nuclear life cycle through disposal, particularly maintaining an adequate supply of fuel for backup generators supporting storage facility ventilation, is essential.

16. TRANSPORTATION SYSTEMS – AIR TRANSPORTATION

16.1. Description of the Sector

The key aspects of Airports and the Air Transportation subsector of the Transportation sector as it relates to servicing the economic needs during nominal and emergency operations can be broken down into the following areas:

- Nominal Business Demands
- Emergency Service Demands
- Nominal Operational Requirements
- Emergency Operational Requirements

16.1.1. Nominal Operations

During nominal operations airports and air transportation make important contributions to a well-functioning economy; delivering people and cargo, especially time-critical cargo, into a region to support all areas of demand; from business, or personal travel, to essential supplies, documents, or products for industry, tourism, finance, health care, and beyond.

As with other sectors, air transportation operates and coordinates with other supply and demand networks, often with just-in-time scheduling and reserves to meet normal fluctuations and unknowns. Failover systems, particularly emergency power from battery supply and engine-driven power generators, are deployed at higher volume airports to reinforce safety-critical functions, such as air traffic control, navigation, and runway lighting.

16.1.2. Airport Operation Essentials

There are remarkably minimal essentials needed for an airport to support basic operations. The major requirement is already permanently in-place – a long stretch of intact runway pavement for landing aircraft. Runway lighting and a very modest amount of power would be needed to support night operations. Surprisingly enough, there are many regional airports serviced by major air carriers that do not have control towers today. Local air traffic control is not essential for airport operations unless there is a very high number of flights that need to be coordinated. Basic local air traffic control can be managed with a controller, hand-held radios, and a pair of binoculars. Local navigation systems are not required except during times of very low ceilings and visibility while space borne global positioning system (GPS) navigation and approach functions will often prove adequate. For limited traffic situations, radar services are not essential, and where needed, regional air-traffic control can often be supported by radar sites tens of miles away and air route traffic control center (ARTCC) facilities that are hundreds of miles away.

16.1.3. Emergency Scenarios

During times of major weather events or national emergencies such as ice storms, hurricanes, severe floods, earthquakes, etc. including those causing long-term power outages, the demands and utility on the air transportation sector changes significantly. When major disruptions impact a region, the impacts affect all sectors resulting in a near immediate drop in the nominal air transportation demands supporting industry and tourism. This is accompanied by a sharp increase in demands on emergency service support, such as population evacuation, medical transportation, critical food, water and emergency supplies, as well as the influx of medical, search and rescue, emergency, law enforcement or National Guard personnel.

16.1.4. Reduced Demand

This change in the function and utility of air transportation reduces many of the nominal demands and requirements listed above. Normal business, tourism, and materials demands will essentially come to a stop in an area stricken by long-term power outages. In fact, the basic operational requirements to meet needs placed on an airport during a major emergency falls dramatically. Without nominal passenger and cargo utilization, security, passenger services, water, electric power, road and light rail transportation demands all fall off dramatically.

16.2. Dependencies on the Electric Power Subsector

Significant direct dependencies exist on electric power to operate terminals, security, and passenger services, as well as runway lighting, radar, air traffic control computers, voice and radio navigation essentials. Indirect dependencies on electric power include the following:

- Telecommunications to facilitate coordination of all movements as well as essential air traffic control systems.
- Fuel has a dependency on electric power for pumps for pipeline delivery and dispensing to aircraft.
- Other fundamentals depending on electric power include water and wastewater, security/law-enforcement, and other basic services.

16.3. Mitigations and "Tipping Points"

There really are no delayed impacts or "tipping points" that would cause an airport to become completely non-operational. Most major airport air traffic control, runway lighting, navigation aids, as well as remote radar sites, and key navigation facilities are equipped with emergency power generation. For long-term power outages, these facilities would require regular fuel resupply, and for very long-term power outages, generator maintenance and constant running life may become a limiting factor; however, as outlined above, many of these facilities could be non-functioning and worked-around operationally.

In major regional emergencies, due to the very limited list of essentials for basic airport operations supporting emergency supplies, organized evacuations, and influx of key responders, most airports would be serviceable. Alternate methods of loading and unloading cargo or personnel can be arranged. Portable basic air traffic control could be supported with basic battery powered equipment, and reduced traffic flows could alleviate the need for radar traffic separation. Other navigation, lighting, fuel, or air traffic control needs can be operationally worked-around or done without. Basic requirements of air transportation to meet the emergency should be available. Fuel requirements could be serviced by trucking-in fuel or having aircraft land with enough reserves to depart for refueling elsewhere.

Fuel availability may become a problem when local supplies become exhausted or inaccessible due to power or pumping incapacity. Resupply of fuel via pipeline or road transportation would be useful, but again not essential as aircraft could land with enough fuel on board to depart to another airport that is not impacted.

17. TRANSPORTATION SYSTEMS – RAIL TRANSPORTATION

17.1. Description of the Sector

The Rail Transportation subsector of the Transportation Systems Sector is comprised of an array of elements supporting both passenger and freight traffic. Passenger rail includes light and heavy (subway) rail and trolley systems, which are frequently run on system-specific networks for urban and suburban environments in large cities, and Amtrak commuter rail, run primarily on the nation's Class I rail network. Freight rail includes more than 1.3 million freight cars [48] moving between 480,000 and 580,000 carloads per week [4] of bulk commodities (e.g., coal, chemicals, grain, petroleum) and intermodal containers from point to point via rail reclassification yards used to disassemble and reassemble trains to new destinations on a national system. Passenger and freight cars on the national rail network are supplemented by roughly 20,000 locomotives; these are primarily run with diesel fuel.

In addition to the rail vehicles described above, remote switching systems with are essential to the function of the network, allowing for shunting of trains onto sidings or alliterate tracks, enabling increased capacity on single-track elements of the rail network.

17.2. Dependencies on the Electric Power Subsector

Metropolitan light and heavy rail and trolley systems are heavily dependent on commercial electric power. These systems rely on electric power for their motive power, so a lack of electric power would stop this rail traffic outright. Additionally, switching and control of these systems relies on electric power, so the ability to switch cars from one track to another would be disabled. For most of the metropolitan areas in which these systems are established, they provide a critical and irreplaceable volume of movement, the lack of which would prevent people from commuting to and from work, school, and commercial shopping areas.

Freight rail is likewise reliant on electronic switching. It is reliant on power at classification yards for the proper assembly of freight trains headed to a particular destination and at points between classification yards for switching and siding of rail cars. Freight rail locomotives are diesel powered, so any disruption to electric power that leads to cascade effects in terms of the availability of diesel fuel at freight rail yards could further hinder freight rail traffic, though this disruptive effect is buffered by fuel in locomotives and fuel that might be able to be pumped (with backup generators) out of storage in classification yards. These same impacts experienced by freight rail would also be experienced by commercial passenger rail systems, such as Amtrak.

17.3. Mitigations and "Tipping Points"

The energy demand for a metropolitan rail system is significant enough that backup generation is not a reasonable alternative. Thus, mitigations for large-scale metropolitan systems appear to be limited at best. Freight rail traffic may have additional time before disruptive effects are seen, as diesel fuel is likely to be available for some time (though demanded by an increasing number of entities for backup purposes). The crucial role that freight rail plays in moving commodities around the country needs to be understood, as some outage cases could lead to disruptions of critical commodities moved by rail (refined products, food) while other commodities usually reliant on the rail network (coal, primary metals) may, depending on the disruption, be reduced in quantity due to the direct effects of the power outage. A close examination of individual scenarios for the needs for additional rail traffic and those commodities for which rail traffic will decline will depend on the geography of the outage itself.

18. TRANSPORTATION SYSTEMS – ROAD TRANSPORTATION

18.1. Description of the Sector

The Road Transportation subsector of the Transportation Systems Sector is comprised of over 6 million miles [29] of roadways and supporting infrastructure, designed for the movement of vehicles of all types: automobiles, buses, motorcycles, and all types of trucks. Truck traffic is a frequent long-distance and short-haul means of transportation if goods of all types, used in many of the other sectors described in this document.

18.2. Dependencies on the Electric Power Subsector

Disruption of traffic lights is the first, and obvious sign of a power outage. Such a disruption leads to an increase in the number of accidents at intersections, and a general slowdown in traffic, as roadways with traffic lights are fed by traffic from limited-access highways without lights, leading the system as a whole to operate with great inefficiency.

The second, but more significant, disruption to road transportation from a power outage, is from the cascading impacts of disruption to fuel service stations. Powered fuel pumps, without backup generation, are unable to distribute fuel to cars. These same stations, without communications, cannot process debit and credit transactions. This will limit transportation substantially in areas where backup generators are not required by law or available in sufficient quantities to operate the whole of a fuel service station.

18.3. Mitigations and "Tipping Points"

Several states have taken action in recent years, as described elsewhere in this document, to increase requirements for backup generator capability at fuel service stations. In some cases, however, this is an ex post requirement: Generators must be brought in within 24 hours after an outage event begins. These rules are designed for notice events, such as hurricanes. Many of the possible events associated with this work are no-notice events and these rules will not allow for timely assistance.

In some locations, local power production could be used for operating traffic lights without commercial power. Solar panels could enable basic functionality of individual lights. Systemic control within an urban environment, so as to minimize traffic time, is a different issue, but one which can be dealt with using backup generation as needed to enable integrated system operation.

19. TRANSPORTATION SYSTEMS – WATER TRANSPORTATION

19.1. Description of the Sector

The water transportation subsector of the Transportation Sector is a geographically complex and diverse system made up of waterways, ports, and intermodal landside connections. It includes nearly 95,000 miles of coastline, 361 ports, more than 25,000 miles of navigable waterways, and more than 29,000 miles of Marine highway. [48] This combination of inland (primarily barge-based) commodity transportation and international (primarily ship-based) commodity transportation has unique dependencies on electric power.

19.2. Dependencies on the Electric Power Subsector

19.2.1. Inland Commodity Transportation

Inland, principally barge-based commodity transportation is limited primarily to low-value, high volume commodities such as grain, coal, petroleum products, chemicals, and other raw materials. Most US inland commodity transportation flows along the Mississippi river system. The Mississippi River system transports 60% of US grain shipments, 22% of oil and gas shipments, and 20% of coal shipments. [12]

Other major waterways include the Intracoastal Waterway (Gulf, Atlantic, and Florida Gulf sections), Alabama River, Savannah River, Chesapeake Bay system, Delaware River, Hudson River, and Connecticut River, the Great Lakes system, the Columbia River, and the Sacramento/San Joaquin River systems.

Barging of commodities on inland waterways includes several dependencies on electric power.

19.2.1.1. Loading onto dry cargo barge

Often a grain elevator, gravity-fed loader, or conveyor is used to deposit material onto a barge, and a large crane may then be deployed to even out loads on barges. There are various power options, whether all-electric, diesel-hydraulic, or diesel-electric. [5]

19.2.1.2. Transportation of barge

Upriver or downriver, barges are either self-propelled or accompanied by a tugboat or towboat. Nearly all river going tugboats are powered by a diesel engine, which drives a propeller. An electric utility outage would not impact this propulsion directly but may eventually impact the communications systems that tugs use for navigation and safety. Tugs rely on two-way marine radios, capable of communicating on both land and marine channels. The tug will be able to communicate with other tugs during a power outage but may not be able to communicate with land-based entities, such as lock-and-dam operators, that themselves have lost power.

The lock-and-dam system enables transportation along rivers that would nominally be too steep for commodity transportation. These lock-and-dam systems are present on the upper Mississippi River, the Tennessee-Tombigbee waterway, and the Columbia River among others. While the filling of a lock with water is gravity-fed, the opening of lock gates often relies on electric power. [39] Some lock-and-dam systems themselves generate hydroelectric power, which may have local black start capability and therefore may be able to remain online as an electrical island during an outage.

19.2.1.3. Unloading of dry cargo barge

Unloading of a dry cargo barge is done by either a grab bucket or continuous barge unloader, sometimes referred to as a digging ladder. The grab bucket is attached to a crane, whereas a continuous barge unloader is a collection of buckets attached to a continuously-moving roller chain. Grab bucket unloading is more likely to depend on diesel propulsion, while continuous barge unloaders are often electrically powered.

19.2.2. International Commodity Transportation

International Commodity Transportation includes container ships, bulk and break-bulk ships, liquid tankers, refrigerated, and roll-on, roll-off (RORO) transportation. This element of the sector includes many higher-value commodities (automobiles, consumer electronics) than are found in inland waterway transportation. Many of the same issues seen in inland commodity transportation are seen at coastal ports on the Atlantic, Pacific, and Gulf coasts.

19.2.2.1. Loading and Unloading of Container Ships

Container ships are unloaded using cranes. Much as with the bulk cargo cranes used in inland water transport, cranes will vary in fueling, though many have been electric power-exclusive historically at northeast ports.

19.2.2.2. Port of Entry Activities

Unloading of container ships and movement of containers from the container yard to trucks or trains for delivery nationwide is unique to the international side of water commerce. It also requires a substantial information trail (bill of lading) as most of the commodity movements are imports from foreign ports. This "paper trail" has increasingly become electronic in nature, meaning that a disruption to electric power impacting the ability to access records could lead to ships being unable to unload, or cargo piling up in ports, until sufficient recordkeeping can be done to allow for entry, grinding commercial commerce to a halt. Based on experiences seen from "work to rule" port labor issues in the past, capacity for storage at ports is limited at best, and could handle but a fraction of an extended disruption, if cranes could function.

These issues also impact port facilities that handle other commodities. RORO facilities, which handle the import and export of automobiles, would face significant impact, with substantial financial impact to vehicle dealers.

19.3. Mitigations and "Tipping Points"

Mitigation options for port operations are limited at best. The information requirements allowing for smooth function of container ports, and the ability to make lock and am systems function properly, are the most limiting to commerce, impacting what goods may be available throughout the nation.

20. WATER AND WASTEWATER SYSTEMS

20.1. Description of the Sector

Public water systems are regulated by statutes of the Safe Drinking Water Act. Over 286 million Americans get their drinking water from public water systems, while 44.5 million are served by individual domestic systems. [23] There are over 150,000 public water systems in the United States; however, eight percent of these systems provide water to 82 percent of the U.S. population. [41] Sixty-eight percent of public supplies comes from surface water; the remaining is largely from groundwater. In contrast there are only 16,000 publicly owned wastewater treatment systems in the U.S. with about 75% of the U.S. population served by sanitary sewage systems, the remaining operate on individual septic systems.

20.2. Dependencies on the Electric Power Subsector

Drinking and wastewater systems are highly dependent on electrical services. In fact, the Electric Power Research Institute has recently found that U.S. public drinking water systems use roughly 39.2 billion kilowatt hours (kWh) per year, which corresponds to about 1% of total electricity use in the U.S., while municipal wastewater treatment systems use approximately 30.2 billion kWh per year, or about 0.8% of total electricity use. [31] Electricity is used all major functions including pumping, treatment, conveyance and disposal. Analysis of the sector indicates that direct water services (e.g., water heating, pumping and treatment) accounted for 8.4% of the 2010 annual primary energy consumption in the U.S. [33]

Planning by drinking and wastewater utilities is increasingly considering issues of energy use. There is a significant financial incentive as energy costs account for 25–40 percent of the operating budgets for wastewater utilities and approximately 80 percent of drinking water processing and distribution costs. [21] Utilities also realize that energy use is likely to increase due to such factors as growing reliance on desalination, [8] increasing utilization of recycled wastewater, new regulations requiring advanced treatment of drinking water, [60] and declining groundwater levels. [59] Among the ways utilities are responding is by promoting water savings to save energy (and vice-versa) [57] and viewing domestic wastewater not as a waste stream which needs to be disposed but as a resource from which to generate energy. [14]

20.3. Mitigations and "Tipping Points"

Without electricity, water and wastewater services are largely crippled. However, drinking water systems tend to have 12 hours or more of potable water storage in their systems so service can continue for outages of relatively short duration. Domestic water services are lost almost immediately as individual homes have little storage of treated water. Wastewater plants are at particular danger as sewage will continue to gravity feed to the plant but without means of treating the water releases of raw sewage to the environment can happen. [7] Best management practices from the EPA [58] and a number of states stipulate backup power services [11, 35, 37]; however, no statutory requirements have been identified. It is uncertain to what extent drinking water and wastewater plants have invested in backup energy services. It is assumed that backup power capacity is very limited and would only allow limited operations at any given water/wastewater plant.

A key interdependency is with water for firefighting. Loss of electrical services could compromise water deliveries, which means a lack of water to fight fires.

21. SENSITIVITY OF INFRASTRUCTURE SECTORS TO DISRUPTION OF ELECTRIC POWER

The electric power subsector is crucial to the continued operation of many other infrastructures, as has been noted throughout this document. This section summarizes the sensitivity of these sectors, and catalogues their respective "tipping points" for disruption leading to impact in the ability of each sector to provide service absent an adequate supply of commercial electric power, into three groups:

- Group 1, those sectors whose operation is necessary for the physical operation of the electric grid;
- Group 2, those sectors whose operation provides necessary support for the regular operation of the electric grid; and
- Group 3, all other sectors.

The descriptions of tipping points are categorized in two ways:

- Those tipping points seen in days to weeks following the commencement of an electric power disruption; and
- Those tipping points seen weeks to months following the commencement of an electric power disruption.

Table 20-1 shows the tipping points for Group 1 sectors. Table 20-2 shows the tipping points for Group 2 sectors. Table 20-3 shows the tipping points for Group 3 sectors.

Loss of commercial electric power will impact all sectors, with cascading impacts from the disruption of all aspects of the petroleum fuels supply chain creating the opportunity for severe transportation restrictions and impacts on the Water and Wastewater Sector impacting limited supplies of potable water in urbanized areas.

These indirect impacts to the transportation infrastructure will limit the ability of needed goods (especially food and fuel) to reach the affected area, limit the ability of merchants to sell said goods, and reduce the habitability of affected areas (warmer climates in the Summer, colder climates in the Winter).

This set of constraints on transportation and habitability will likely lead many to leave the affected area, if they can, at minimum until the outage is restored. In some cases, as was seen after Hurricane Katrina, if the disruption is long enough lived, departures will turn into migrations, with long-term net economic effects.

Backup generation, where available, will keep some services active in many infrastructures. These services, however, will be competing for the same scarce pool of fuel for their backup generators, placing increased value on the ability to move fuel for said generators – and for other transportation – from unaffected areas into the affected area. Prioritization at a local, State, and Regional level will be of value to the extent that it preserves vital services, serving as a bulwark against leaving the affected area, particularly among those necessary for restoration of disrupted critical infrastructure.

Table 21-1. Summary of impacts of extended grid outages to sectors necessary for the physical operation of the electric grid

Sector	Tipping points – days to weeks	Tipping points – weeks to months
Communications	Loss of backup generators as on-site fuel supply is exhausted, unless replenished.	Loss of redundancy in backup generators as required maintenance and repairs are performed.
Dams	Loss of local generation; loss of black start capability.	None.
Energy – Natural Gas	Loss of electrical power to gas pipeline compression stations reduces throughput of pipeline, impacting gas-fired power production.	As more natural gas customers lose service, restoration time lengthens once service is restored. Reduced pressure in lines can lead to freeze-off.
Nuclear Reactors, Materials, and Waste	Loss of nuclear generating capacity due to lack of a suitable offsite power source, depending on fuel availability of offsite sources.	Loss of significant amount of generating capacity.
Transportation Systems – Rail Transportation	Loss of traffic signals at railroad crossings; loss of power for coal loading and unloading equipment and conveyor belts in plants. Loss of electrically-powered metropolitan rail systems.	Reduction in rail transport throughput capacity nationally, as affected network elements operate below design capacity, potentially impacting other sectors (e.g., water transportation).
Transportation Systems – Water Transportation	Loss of power for coal loading and unloading equipment. Loss of power for fuel terminal barge loading equipment.	Reduction in water transport throughput capacity nationally, potentially impacting other sectors.

Table 21-2. Summary of impacts of extended grid outages to sectors providing necessary support for the operation of the electric grid

Sector	Tipping points – days to weeks	Tipping points – weeks to months
Energy – Petroleum Fuels	Immediate—loss of ability to pump fuel at the retail station.	Loss of distribution facilities as they run out of fuel for backup generators; loss of refinery capacity.
Financial Services	None—all significant financial institutions have geographically dispersed backup data centers.	Loss of ability to operate power markets; loss of ability to purchase goods and services.
Transportation Systems – Road Transportation	Loss of ability to deploy staff where needed.	Migration of employees out of affected area; loss of ability to deploy staff where needed.

Table 21-3. Summary of impacts of extended grid outages to other sectors

Sector	Tipping points – days to weeks	Tipping points – weeks to months
Chemicals and Hazardous Materials	Loss of backup generators as on-site fuel supply is exhausted.	Loss of backup generators as required maintenance and repairs are deferred; supply chain problems when existing stock of product is exhausted.
Commercial Facilities	Loss of refrigerated stock absent backup generation. Loss of the ability to make transactions dependent on electric power (credit/debit card transactions).	Economic hardship for employees; migration out of affected area.
Critical Manufacturing	Loss of backup generators as on-site fuel supply is exhausted.	Loss of backup generators as required maintenance and repairs are deferred; supply chain problems when existing stock of product is exhausted.
Defense Industrial Base	Loss of backup generators as on-site fuel supply is exhausted.	Loss of backup generators as required maintenance and repairs are deferred; supply chain problems when existing stock of product is exhausted.
Emergency Services	Loss of backup generators as on-site fuel supply is exhausted. Loss of immediate ability to respond to emergencies.	Loss of backup generators as required maintenance and repairs are deferred. Long-term loss of capabilities to respond to emergencies as responders migrate out of affected area.
Food and Agriculture	Loss of environmental conditioning for animals; loss of food processing capabilities, loss of functionality at distribution centers, food spoilage.	Loss of ability to feed population (creating need to bring food in from unaffected regions).
Government Facilities	Loss of backup generators as on-site fuel supply is exhausted. Loss of ability to operate schools, public access parks, and government buildings.	Loss of backup generators as required maintenance and repairs are deferred. Loss of civil order.
Healthcare and Public Health	Loss of backup generators as on-site fuel supply is exhausted. Loss of ability to operate hospitals, clinics, laboratories, dialysis centers, and other healthcare facilities. Loss of human life from acute and chronic conditions.	Loss of backup generators as required maintenance and repairs are deferred. Long-term loss of human life.
Transportation Systems – Air Transportation	Impacts to normal business demand-level operations at airports whose fuel supply is impacted by disruption.	Impacts to airline and air cargo firm business practices.
Water and Wastewater Systems	Use of backup generators for water treatment and pumping is erratic. Loss of potable water is not tenable as local homes and businesses have very little water storage. Loss of water also reduces firefighting capabilities, potentially leading to loss of life.	Migration of citizens out of affected area with economic hardship.

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