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Coupling of the Electricity and Transportation Sectors – Part I

Sector Overviews

April 2024

Bhaskar Mitra
Seemita Pal
Hayden Reeve
Michael Kintner-Meyer

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Abstract

"Sector coupling" is a concept that addresses potential designs for the future power industry. Traditionally, the energy sectors (i.e., electricity supply, transport, and industry) have functioned largely independently from one another. Sector coupling aims to create a more integrated and sustainable energy ecosystem where various sectors work together to meet energy demand, manage resources effectively. Thus, the concept of sector coupling means the electricity sector would become the central pillar of the energy system, supplying the other sectors (transportation and industry) with energy in various ways, a scheme described by the term **Power-to-X**. This report delves into the ambitious goal set by the United States to achieve net-zero emissions by 2050, with a pivotal milestone of making half of all passenger vehicles sold in America zero emission by 2030. Central to achieving this objective is the electrification of the transportation sector, resulting in complex interactions between this sector and the electric industry. As electric vehicles become more prevalent, a shift in the dependency on electricity for vehicle charging emerges, alongside a reduction in the electricity demand associated with maintaining the fossil fuel supply chain.

Both electricity and fossil fuel have been identified as critical infrastructure sectors, the transportation sector's historical reliance on fossil fuels, and the mature supply chain supporting them are explored. This study emphasizes the existing sectoral coupling between the electric energy and transportation sectors, extending beyond vehicle charging to essential operations at refineries, pipeline facilities, storage, and fuel extraction. Recognizing the critical dependency of fossil fuel supply chain operations on the electric sector, this research underscores the need for a comprehensive view of the evolving dynamics between the transportation and electric sectors.

This study has been split into two segments, Part I provide an overview of the existing fossil fuel supply chain architecture and the electrical sector. We provide an in-depth analysis of the grid-transportation sectoral coupling, its interactions, the vulnerabilities, and the essential takeaways that would help us to address them and apply toward an electrified transportation sector in the future. We engaged with stakeholders to understand their expectations in enabling an electrified transportation. We accumulate the understandings from the current fossil-fuel-based system in developing a risk matrix*,* by identifying all the threats and vulnerabilities and how would they apply to both the current and future transportation systems in Part II of this report.

Executive Summary

The U.S. Government has ambitious federal goals of reducing in greenhouse gas emissions 50–52% by 2030 and reaching net-zero emissions no later than 2050. It aims to have zero-emission vehicles make up half of all passenger vehicles sold in America by 2030 and to build a net-zero-emissions economy by 2050. To achieve these goals one of the critical steps includes electrification of the transportation sector, which will introduce different kinds of interactions between the transportation sector and the electric sector. On one hand the dependency on electricity for charging electric vehicles will increase, but on the other hand the need for electricity for maintaining the fossil fuel supply chain will decrease.

The transportation and electricity sectors are two of the 16 critical infrastructure sectors in the nation. The transportation sector's heavy reliance on gasoline and diesel for fuel has led to the development and maintenance of a mature supply chain system for the sourcing, transportation, and storage of these essential fossil fuel products. Historically, the transportation sector has also been dependent on the electric sector, not for direct vehicle charging, but for enabling the operations at refineries, pipeline facilities, storage facilities, and fuel extraction sites. **In defining the past and present-day transportation sector, the sectoral coupling that already exists between the electric energy sector and the transportation sector is often ignored. It is important to take a convergent view of the transportation and electric sectors to recognize the critical dependency of fossil fuel supply chain operations on the electric sector and understand the transition of the coupling between the two sectors as more of the transportation sector is electrified.**

Grid Architecture is a type of system architecture. It is a top-level view of the whole electric power grid that enables reasoning about the grid's properties, behavior, and performance. To understand the coupling between the current fossil fuel sector that powers transportation with the electricity infrastructure, we utilize the concepts developed from Grid Architecture. This approach of studying the coupled system as a starting step helps in identifying the current and future points of coupling between the sectors, understanding the coordination between the diverse set of entities for enabling functioning of both the sectors, and communicating a common future vision of the coupled system to different types of stakeholders. It also enables us to determine the structural changes necessary for ensuring equal or better performance of the transportation sector as the coupling evolves. Understanding the necessary interactions and the key role played by the different components helps us have a holistic understanding of the current fossil fuel infrastructure.

Acknowledgments

This project was supported by the Department of Energy, Office of Electricity, Grid Controls and Communications Program. The authors would like to thank Christopher Irwin of the Department of Energy, Office of Electricity for the opportunity to explore the sectoral coupling of the electric grid with the transportation sector. We appreciate his guidance on addressing the newly emerging and forming interdependencies of the sectors through the lens of opportunities and threats.

Acronyms and Abbreviations

CCS	Combined Charging System
DOT	Department of Transportation
EIA	Energy Information Administration
EPCA	Energy Policy and Conservation Act
EV	Electric Vehicle
FHWA	Federal Highway Administration
FMCA	Federal Motor Carrier Safety Administration
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use
HOS	Hours of Service
ICE	Internal Combustion Engine
LACT	Lease Automatic Custody Transfer
LMP	Locational Marginal Price
OPEC	Organization of the Petroleum Exporting Countries
PADD	Petroleum Administration for Defense Districts
PHMSA	Pipeline and Hazardous Material Safety Administration
SPR	Strategic Petroleum Reserve

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1.0 Introduction

The U.S. Government has ambitious federal goals of reducing greenhouse gas emissions by 50-52% by 2030 and reaching net-zero emissions no later than 2050 [1]. It It aims to have zero-emission vehicles make up half of all passenger vehicles sold in America by 2030 and to build a net-zero-emissions economy by 2050. For achieving these goals one of the critical steps includes electrification of the transportation sector. While the technologies necessary to electrify our transportation sector are becoming available, there are challenges related to public perception of the performance and availability of charging infrastructure that can potentially slow down the adoption of electric vehicles (EVs). One of the critical steps towards addressing this challenge is ensuring that the performance of the electrified transportation system matches or exceeds the performance of the existing fossil-fuel-based transportation system that has developed and matured over almost a century and is regarded to be a reliable system. In comparison, the electrified transportation system is in its initial stages of deployment. Ensuring the successful electrification of the transportation sector necessitates the detailed understanding and systematic mapping of historical and future couplings between these sectors.

The U.S. Energy Information Administration (EIA) estimates that petroleum is currently the largest source of energy consumed in the United States, contributing 35.8 quadrillion Btu of energy (i.e., 36% of total energy) in 2022. Among the end-use sectors, transportation is the highest consumer of energy with 90% of that energy being sourced from petroleum as shown in Figure 1. Due to this high level of motor gasoline and diesel (distillate) fuel consumption for the transportation sector, it has been a major emitter with total emissions equal to about 30% of total U.S. energy-related CO_2 emissions in 2022.[2] Apart from greenhouse gases, fossil-fuel-based transportation equipment emits over 20% of the world's black carbon, which can cause serious health problems, especially for communities near heavy industry and ports.[3] Failure to curtail the emissions will exacerbate the climate crisis and harm our communities, particularly vulnerable populations.[4] Therefore, it is critical to strategize and implement necessary steps in order to minimize the use of fossil fuel in the transportation sector, and this can be enabled by encouraging the accelerated adoption of EVs.

Large-scale and rapid electrification of transportation will introduce different kinds of dependencies between the transportation sector and the electric energy sector that we have not experienced before. In the case of fossil-fueled internal combustion engine (ICE) vehicles, the fuel supply chain involves different energy-intensive processes like extraction of crude oil, refining, pumping, and fuel dispensing. These processes and many others are directly dependent on the electricity sector for their operation; however, when understanding the operation paradigm for fossil fuel-based transportation sector, we often do not recognize the various dependency it has on the electric energy sector. We only start to recognize the present sectoral coupling between the electric energy sector and the transportation sector when we take a system's view of the convergent system.

Electricity plays a crucial role in refining crude oil and transporting crude and refined oil through pipelines using pumps. The symbiotic relationship is multifaceted, with electrical power playing a pivotal role in powering crucial operations that span the entire petroleum supply chain. This interplay highlights the significance of a reliable and robust electrical infrastructure in supporting the oil industry's intricate operations, ensuring seamless production and distribution of refined petroleum products to meet global energy demands. We highlight some data obtained from publicly available sources on the usage of electricity from fuel extraction to final delivery.

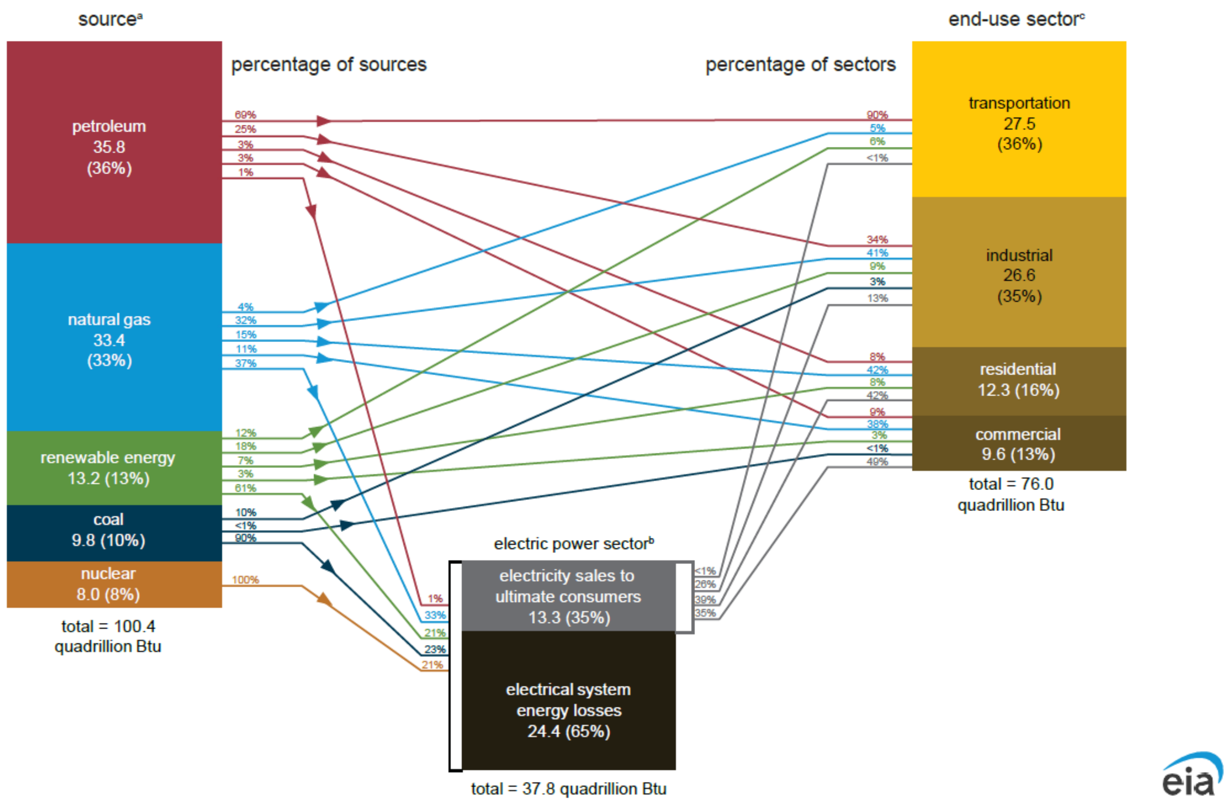


Figure 1. 2022 U.S. energy consumption in quadrillion Btu and percentages by source and sector. (Source: EIA)[5]

As an example, a production weighted average oil well in Wyoming was producing 114 barrels per day (bpd) of 35º API oil and 604 bpd of water at a depth of 7,966 feet and for that process it was estimated to be using 468,000–648,000 kWh of electricity per year.[6] In comparison, EIA's data for 2022 indicate that U.S. total petroleum production averaged about 20.079 million bpd. Based on GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies) model-based data, which was available from EIA's annual survey in 2006, refineries in the United States purchased total 39,353 million kWh of electricity for its operations.[7] This number may be reduced now due to the decrease in the number of refineries and the increase in efficiency of the processes. Additionally, pumping crude or refined oil through pipelines, to or from tankers, barges, and storage, requires electricity. This aspect of the sectoral coupling is often missed and ignored, and therefore discussions about the impacts on electric demand tend to focus only on the potential increase of EV loads.

In this report, an architectural approach is taken to understand the energy sector couplings of the current transportation sector that is dominant with ICE vehicles. Although technology maturity of these fossil-fuel-dependent vehicles and the fuel supply chain has improved significantly over the past century, there have been various points in the past and present when the fuel supply chain has presented different challenges and created problems for ICE vehicle users, events like hurricanes, cyberattacks, pandemics, and flooding have hampered the availability of fuel. In this report the currently weakly coupled electric–transportation sectors will be compared to the strongly coupled system of the future. This will include assessment of impact on the transportation system and the overall region, not only during normal times but also during and after emergency events. Such an assessment is incomplete if financial impacts are not included.

For traditional infrastructures mitigations have been determined and executed that have further strengthened the system reliability and security. In In comparison the widespread use of EVs is a recent trend that is still evolving, and the EV charging infrastructure is in its early stage of widespread deployment. There are also public concerns regarding whether a transportation sector that depends on electricity will be reliable enough, especially during times of adverse events.

The reliability demonstrated by traditional transportation systems offers a positive opportunity for understanding both successful and unsuccessful aspects of the existing infrastructure. By recognizing the strengths of fossil-fuel-dependent transportation, we can leverage this wealth of knowledge to construct a more resilient and efficient foundation for the ongoing shift toward decarbonization.

In essence, the challenges posed by the legacy fossil-fuel-based transportation landscape can be viewed as stepping stones toward a greener and more sustainable future. There are various opportunities we will gain by strengthening sector coupling between the transportation and electric sectors. The transition from ICE vehicles to EVs is likely to create opportunities where more integrated systems may improve the overall economic efficiency of public and private investments by driving up utilization of infrastructure investments and bringing down the dependence on fuel imports and intermodal transportation of gasoline and diesel.

The rest of the report is outlined as follows: Section 2.0 provides an overview of the fossil-based transportation infrastructure and supply chain; Section 3.0 provides an overview of the electricity infrastructure; Section 4.0 outlines the sectoral coupling between the grid and transportation sectors, and discusses the different vulnerabilities in the fossil-fueled system and events that resulted in significant challenges to the end user; Section 5.0 highlights and captures a synopsis of stakeholder engagements as we move toward electrified transportation, the anticipated challenges, the risks, and understanding different opportunities to make a faster adaptation; and Section 6.0 concludes the first half of the report with important lessons learned and a prelude to the expectations in Part II.

2.0 Overview of Fossil-based Transportation Fuel Infrastructure and Supply Chain

The U.S. transportation sector heavily relies on fossil-based fuels, primarily gasoline and diesel. This dependence has given rise to an intricate infrastructure and supply chain that spans the globe, ensuring the uninterrupted flow of these critical energy resources. This supply chain has been mapped to characterize the performance and vulnerabilities of the current fossil-fueled transportation system. Such an analysis is required, in part, because the current production and delivery system is less regulated than the electricity production and delivery system, resulting in less documentation of system requirements and performance levels. This mapping will also be utilized in later sections to compare to future electrically powered transportation sectors. It will enable us to determine how the electricity delivery system may need to be enhanced to ensure equal or greater reliability of the currently weakly coupled electric–transportation sectors where the transportation sector is heavily reliant on global fossil fuel supply chain operations. Thus, it is essential to understand the process of how crude oil gets transformed into usable gasoline, diesel, and other products, and then gets transported and delivered for usage. This section summarizes the background information regarding the supply chain of the petroleum-based transportation fuels and provides an understanding of economic conditions on fuel prices and vice versa. A holistic and sufficiently detailed architecture of the fossil fuel supply chain infrastructure from extraction wells to fuel stations has been mapped.

Before going into a more detailed description of the various stages of the gasoline and diesel supply chain, it is important to learn about the Petroleum Administration for Defense Districts (PADDs) that form the basis for segmenting the national fuel markets, and assessing the regional fuel storage, transportation, and overall operations.

2.1 Petroleum Administration for Defense Districts

PADDs are geographic aggregations of the 50 states and the District of Columbia into five districts (as shown in Figure 2):

- PADD 1 is the East Coast
- PADD 2 the Midwest
- PADD 3 the Gulf Coast
- PADD 4 the Rocky Mountain Region
- PADD 5 the West Coast

During World War II, the Petroleum Administration for War, established by an Executive Order in 1942, used these five districts to ration gasoline. Although the Administration was abolished after the war in 1946, Congress passed the Defense Production Act of 1950, only now called the Petroleum Administration for Defense Districts. , the PADDs. The PADD regions enable regional analysis of petroleum product supply and movements

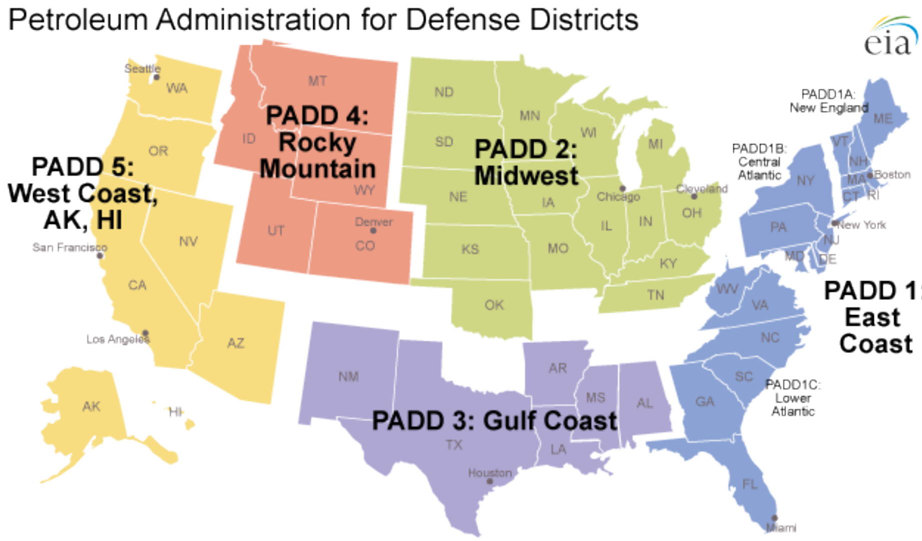


Figure 2. Division of PADD.[8]

2.2 How Does the Gasoline-Diesel Infrastructure and Supply Chain Work?

This subsection provides an overview of the fuel supply chain for ICE vehicles, imports and exports, and strategic reserves. The gasoline and diesel supply chain is divided into five high-level stages as indicated at the bottom of Figure 3:

- Stage 1: Extraction and storage, transfer to refineries, and refining
- Stage 2: Transmission to terminals
- Stage 3: Aggregation, storage, and distribution
- Stage 4: Retail
- Stage 5: Delivery to vehicles

Stage 1 comprises all the processes before crude oil is separated into different user products. This mainly involves extraction and storage, movement to a refinery, and refining. Stage 2 involves distribution of the products from refineries into different locations through different modes of transport. Stage 3 is when finished gasoline is made available to local regions for further distributed. Stage 4 ensures delivery of the fuel to local gas stations. Finally, Stage 5 is the final delivery point on the architecture when fuel is pumped into vehicles.

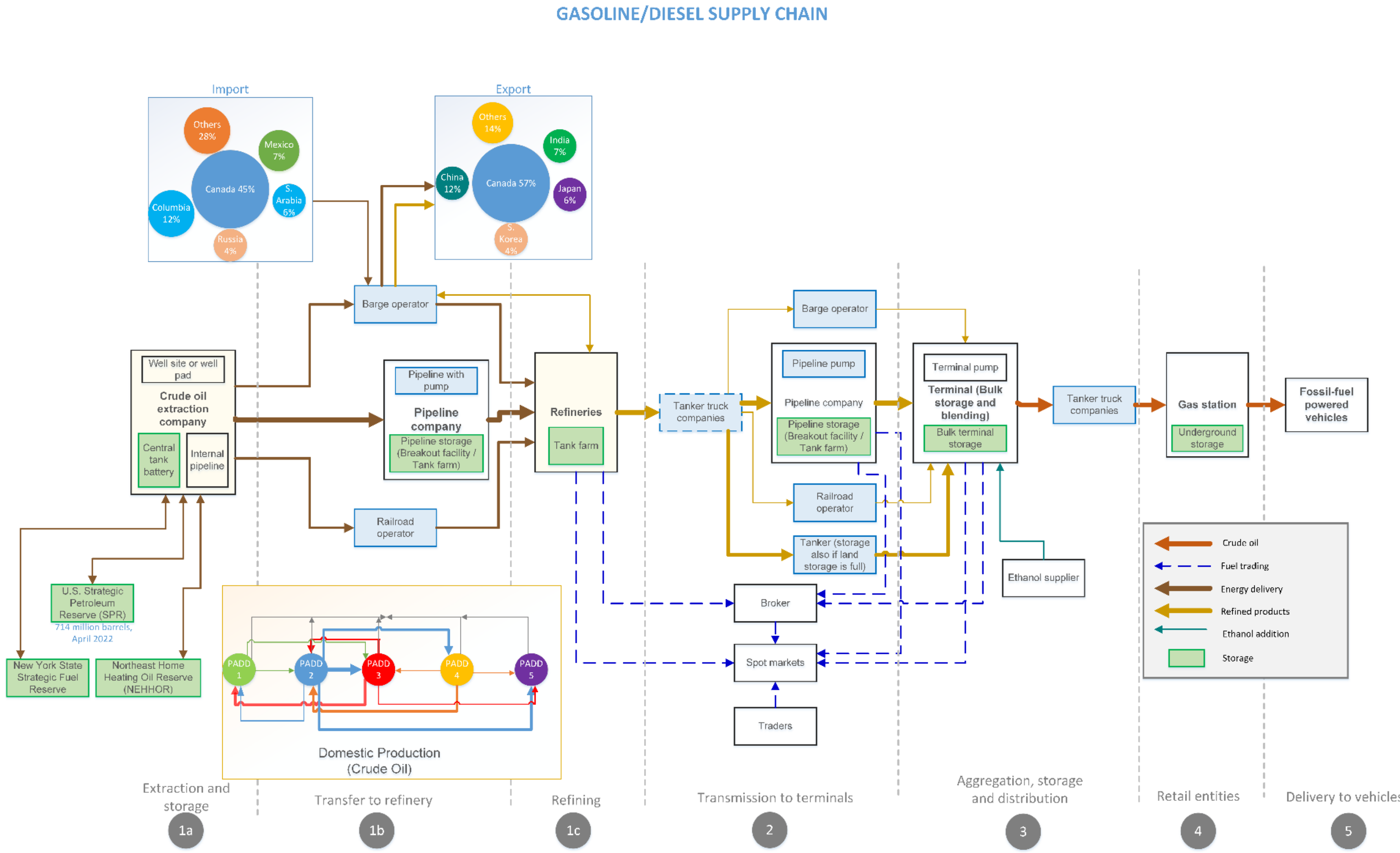


Figure 3. Fuel delivery architecture.

2.2.1 Extraction and Storage

Petroleum, also called crude oil, is a fossil fuel found in vast underground reservoirs beneath land or the ocean floor. Once crude oil is extracted from wells by a drilling process, it is stored in large tanks (to help smooth out supply and demand discrepancies) before being transported to refineries. Producers also use storage inventory to respond to commodity prices: storing more when the prices are lower and withdrawing when prices are high.

2.2.2 Transfer to Refinery

Crude oil is typically moved by railways, pipelines, and barges from production areas to crude storage terminals where it is held until it can be refined. Figure 4 shows the network of pipelines in USA that helps to transport fuel across different regions. Above ground tanks are used for storage. In recent years, increased production in areas that lack pipeline or waterway access has resulted in more oil being transported by train in tank cars.

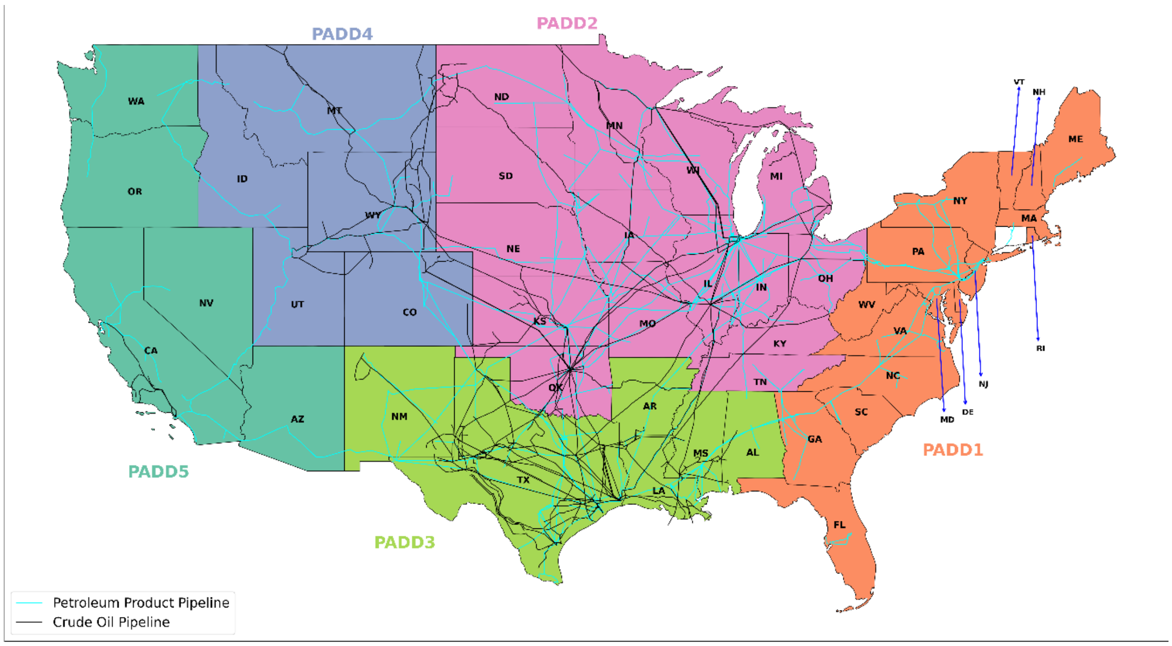
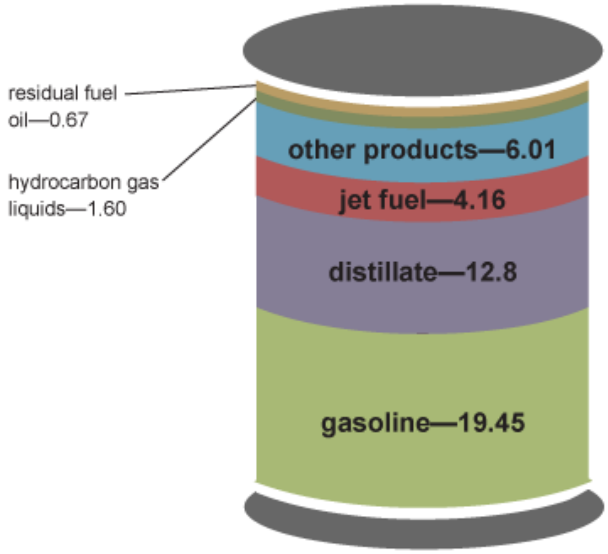


Figure 4. Network of pipelines in USA that helps to transport fuel across different regions.[9]

2.2.3 Refining

Refineries are large-scale industrial facilities where different parts of the crude oil are separated to produce various commercial products.[10] Figure 5 shows the breakdown of the different petroleum products that may be produced from a 42-gallon barrel of light crude oil, with major products being 19 to 20 gallons of motor gasoline and 12 to 13 gallons of ultralow sulfur distillate fuel oil (most of which is sold as diesel fuel and in several states as heating oil).[11]



Data source: U.S. Energy Information Administration, *Petroleum Supply Monthly*, March 2023, preliminary data
Note: A 42-gallon (U.S.) barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain. The sum of the product amounts in the image may not equal 45 because of independent rounding.

Figure 5. Petroleum products made from a barrel of crude oil. (Source: EIA)

More than half of the oil refining capacity in the United States is located on the Gulf Coast, with the rest dispersed across the country. Refineries are typically located close to extraction sites or transportation pipelines and waterways. Oil refineries operate 24 hours a day, seven days a week, but must be shutdown periodically for maintenance and repair. Generally, this type of maintenance is scheduled in the spring and fall when changes must be made at the refineries to switch production from summer to winter gasoline, and vice versa.

Since refinery shutdowns can impact regional gasoline supplies, scheduled shutdowns for maintenance are usually planned well in advance and carefully monitored. Transportation and distribution plans may need adjustments to ensure uninterrupted fuel supplies. Unscheduled refinery outages, however, can occur due to technical problems or extreme weather, and they can result in various impacts, including fuel shortages and higher prices.

2.2.4 Transfer to Bulk Storage Locations

Most diesel and gasoline fuel is moved by pipeline from refineries and ports to terminals near major consuming areas[12]. Pipelines, barges, and tankers move gasoline to product terminals where it is stored before being blended with ethanol for end-use.

There is a vast network of pipelines that connect certain parts of the PADDs, shown in Figure 4, which are utilized as the major mode of fuel transportation. Pipelines are cost effective, have high efficiency with a continuous 24/7 operation under normal conditions, and do not add to direct emissions during transportation. However, building new pipelines is expensive, regulatory aspects challenge development, they are time consuming to build, and geographical barriers prevent development of new pipelines in certain parts of the country, for example, connecting the central parts of United States to the West Coast. Most pipeline infrastructure is not interconnected, unlike electric transmission networks, and thus when under maintenance or out of service for other reasons reliability is affected.

Pipelines over the years have not only been used as a major transportation method but have found prominence as a form of storage. Although they are not usually used as long-term storage facilities, they play a vital role in maintaining an efficient supply chain. Storage vessels may be used at pipeline facilities to relieve surges or receive and store crude oil for later re-injection and continued transportation along the pipeline. Often the pipeline breakout facility will include a Lease Automatic Custody Transfer unit to allow crude oil or condensate to be transferred from tanker trucks into storage vessels at the facility. Below are the types of facilities based on storage capacity.

- If the storage capacity is less than or equal to 300,000 barrels of crude oil or condensate, the facility is classified as a Pipeline Breakout Facility. Pipeline pumps may be located at these facilities.
- If the facility has pipeline pumps and storage vessels with less than or equal to 10,000 barrels of total storage capacity, the facility is classified as a Pipeline Pump Station.
- If the facility has a storage capacity greater than 300,000 barrels, it is considered a tank farm. Typically, a tank farm is a collection of large storage tanks of crude oil and/or condensate.

Gasoline and other refined petroleum products, such as kerosene, diesel, and jet fuel, are sent through the pipelines in batches with no physical separation between one product and the next. Some mixing or commingling of products may occur because of which systems are in place to isolate these mixtures from the pure products on either side of the interface. Since mixing is possible, the quality of the products must be tested to make sure they meet required specifications as they enter and leave pipelines. When product fails to meet local, state, or federal specifications, the co-mingled liquid, which is also known as "*transmix,*" is either removed and transported back to a refinery for further processing or may be sent to special processing plants that re-refine it into saleable products.[10] Ethanol for blending into gasoline is typically transported by rail.

2.2.5 Bulk Storage and Blending

Gasoline is sent to terminals for storage until it is needed at retail outlets. Distribution terminals have huge storage tanks that hold regular and premium grade gasoline, diesel fuel, and ethanol. The gasoline storage tanks typically contain base fuels from many different refineries and oil companies, which means all gasoline is the same at this point. The distribution terminal also has numerous smaller storage tanks that contain fuel additive packages that vary from standardized supplier formulations to brand-specific mixtures developed by individual oil companies. These fuels must meet requirements that change with both the season and the location where the fuel will be sold. For example, summer gasoline is blended to vaporize less easily, which helps reduce evaporative emissions, while winter gasoline is blended to vaporize more easily, which helps with cold engine starting and drivability.

Between the PADD regions, the United States maintains an average stock of several thousand barrels of gasoline that are essential for the transportation sector. Stocks maintained across the different PADD regions in pipelines are shown in Figure 6. Bulk terminals and refineries double up as storage facilities and play a vital role of processing and storing both crude oil and finished products. The Gulf Coast (PADD3) maintains the highest quantity of refinery storage among all the other regions as shown in Figure 7.

Tanker ships are used for temporary storage when land storage is at capacity, making it the most expensive option.

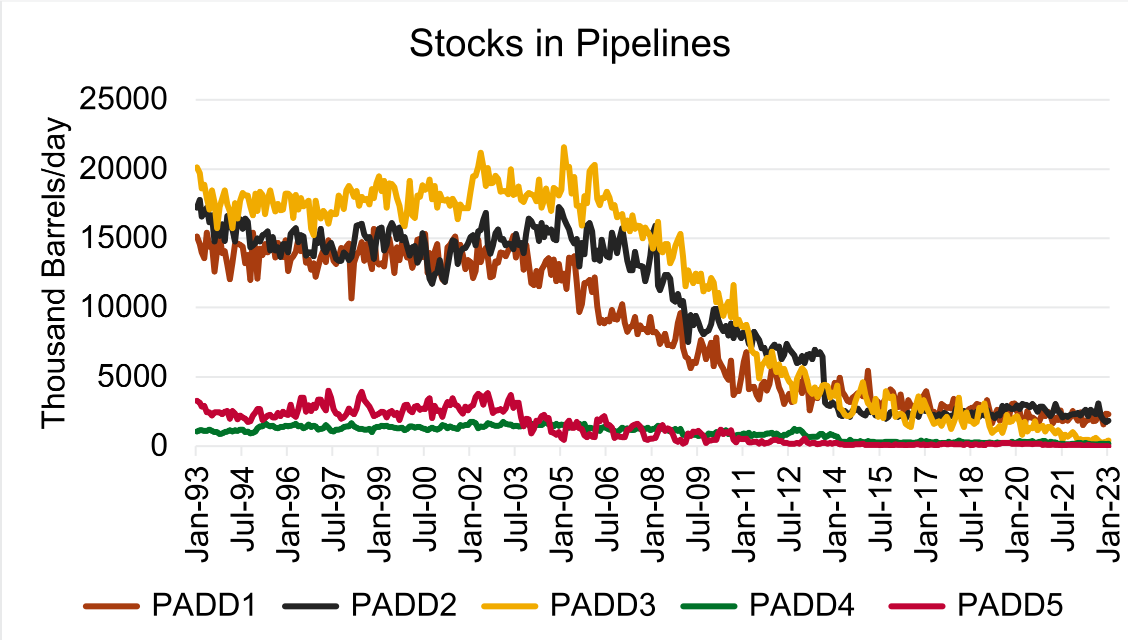


Figure 6. Stocks of finished gasoline in pipelines across different PADDs.[13]

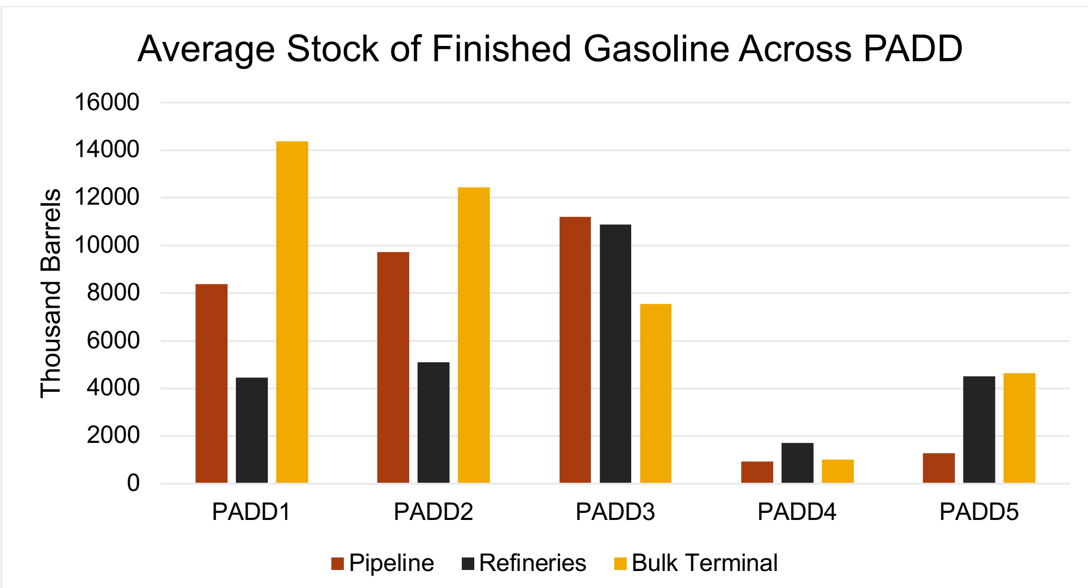


Figure 7. Average stock of finished gasoline across PADDs.

2.2.6 Retail Distribution

Gasoline and even diesel fuel are delivered from terminals to service stations by tanker trucks that can hold up to 10,000 gallons of fuel. Most tanks on these trucks have multiple compartments so they can carry several different types and grades of fuel. When the tanker truck is filled at the distribution terminal, ethanol (where appropriate) and a specific fuel additive package are blended with the base gasoline as it is pumped into the tank. This is the point where generic base gasoline becomes a branded product with unique characteristics. Tanker trucks deliver gasoline and diesel fuel from the distribution terminal to service stations where it is stored in underground tanks. Most stations have tanks for regular and premium gasoline, a tank for diesel if they sell it, and possibly a tank for pure ethanol as discussed later.

2.2.7 Delivery to ICE Vehicles

The retail station is the final step in the gasoline supply chain. Some retail outlets are owned and operated by refiners, while others are independent businesses that purchase gasoline from refiners and marketers for resale to the public. The price at the pump also reflects local market conditions and factors, such as the fueling location and the marketing strategy of the owner.

2.2.8 Exports and Imports

Apart from domestic production and consumption of petroleum products, it is important to note that there are imports and exports. In 2022, total petroleum exports (predominantly crude oil) were about 9.58 million barrels per day and total petroleum imports were about 8.32 million barrels per day, making the United States an annual net total petroleum exporter for the third year in a row.[14] Because of various logistical, regulatory, and quality considerations, which are outside the scope of this report, exporting and importing some petroleum is the most economical way to meet the market's needs.

2.2.9 U.S. Strategic Petroleum Reserve

In some countries, like the United States, the government stores crude oil reserves instead of a commercial company. Emergency crude oil is stored in the U.S. Strategic Petroleum Reserve (SPR), the world's largest supply of emergency crude oil. These stocks are stored in huge underground salt caverns along the coastline of the Gulf of Mexico. The President, under the authority of the Energy Policy and Conservation Act, can make decide to withdraw crude oil.

2.3 Factors Affecting Fuel Prices

Crude and refined oil are global commodities, and therefore prices are primarily determined globally based on various supply and demand related factors. Geopolitics, natural events, and organizational influences can impact production, supply, and demand of crude oil, and thus influence prices. It should be noted that the Organization of the Petroleum Exporting Countries (OPEC), which consists of 13 country members with some of the world's largest oil reserves, regularly meets to set oil production targets and coordinate output to help manage global oil prices for the entire group. This organization can significantly influence oil prices by setting production targets for its members. There are other factors that impact the price of crude oil.[15]

The cost of gasoline or diesel primarily depends on the cost of crude oil, refining costs, distribution and marketing costs, and taxes as shown in Figure 8. The cost of crude oil as a share of the retail gasoline or diesel price varies over time and across regions of the country, and is a significant portion of the final product price. There are 46 key oil exporting countries, but crude oil prices are generally quoted based on one of three main products: West Texas Intermediate Crude, North Sea Brent Crude, and United Arab Emirates Dubai Crude. The pricing of these products serves as a barometer for the entire petroleum industry. Oil prices are based on the cost for a 42-gallon “barrel” of crude, a unit of measure that dates to the dawn of petroleum drilling.

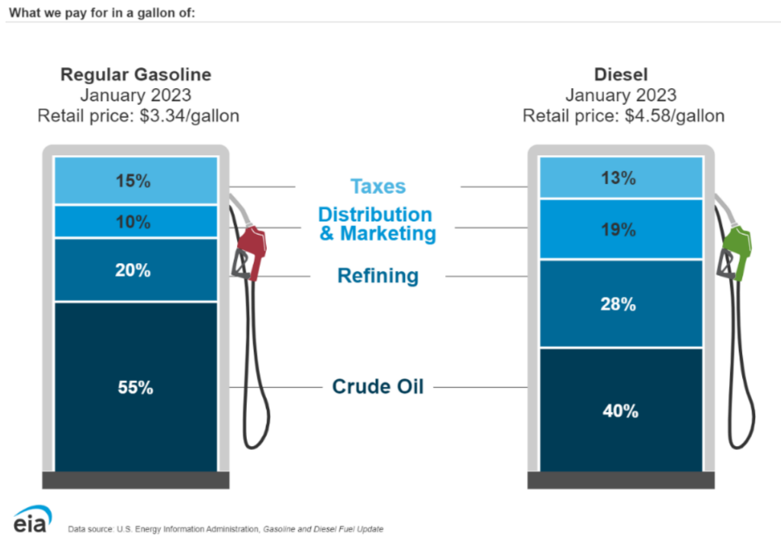


Figure 8. Breakdown of price of a gallon of gasoline and diesel.[16]

Costs related to refining and associated profits vary seasonally and by region in the United States. Gasoline prices are also affected by the cost of other ingredients that may be blended into the gasoline, including fuel ethanol, and the type of processing technology being used for production.

Federal tax on motor gasoline of 18.40 cents per gallon include excise tax of 18.30 cents per gallon and the federal Leaking Underground Storage Tank fee of 0.1 cents per gallon. As of January 1, 2022, total state taxes and fees on gasoline averaged 31.02 cents per gallon. Sales taxes, along with taxes applied by local and municipal governments, can have a significant impact on the price of gasoline in some locations.

The cost of doing business by individual gasoline retailers can vary greatly depending on where a gasoline fueling station is located. These costs include wages and salaries, benefits, equipment, lease or rent payments, insurance, overhead, and state and local fees. Even retail stations close to each other can have different traffic patterns, rent, and sources of supply that affect their prices. The number and location of local competitors can also affect prices.

Crude and refined oil pricing is an important point to keep in mind when comparing a fossil-fuel-dependent transportation system and an electrified transportation system. Electricity, unlike fossil fuel, is only generated and transmitted locally or regionally, and its price is not influenced by global supply and demand. In addition, electricity prices at the wholesale and retail levels are determined by regulated markets and rate-making processes.

3.0 Overview of the Electric Sector

The electricity transmission and distribution system are crucial components of the overall electric power infrastructure. It involves the efficient and reliable transportation of electricity from power generation sources to end users, ensuring that electricity reaches homes, businesses, and industries. Figure 9 shows a depiction of the electricity transmission and distribution system up to the end user.

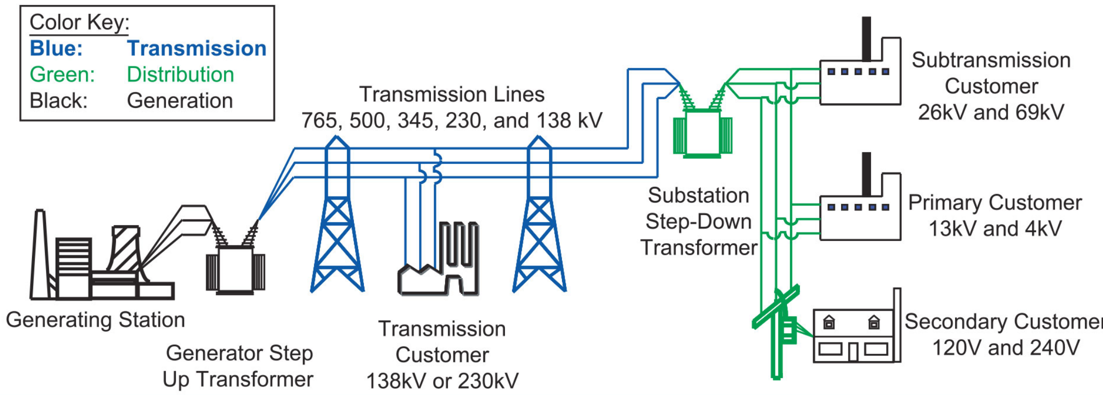


Figure 9. High-voltage electricity transmission corridor that feeds into distribution feeders for delivery to customers.[17]

3.1 Generation

The process of producing electrical power begins at power plants, which can use various energy sources such as coal, natural gas, nuclear, hydroelectric, wind, solar, and others.

3.1.1 Transmission

The generated power is transmitted over long distances from power plants to load centers using high-voltage transmission lines. Transmission system voltages tend to vary above 138kV and above, which helps to minimize the losses during transmission. Transformers are used to step up the voltage for efficient transmission and step it down for distribution.

3.1.2 Transformers

Transformers are key components in the transmission and distribution system. They step up voltage for efficient transmission and step it down for safe distribution to consumers.

3.1.3 Distribution

Electricity is further transformed and distributed to local communities, neighborhoods, and individual consumers at the distribution level.

3.1.4 Storage

Storage technologies in the electric sector play a crucial role in balancing supply and demand, managing intermittent renewable energy sources, and enhancing grid reliability. Some of the available storage options include battery energy storage, pumped storage hydropower, and super-capacitors .

3.2 Challenges in Sector Coupling with EV Integration

With electrified transportation, the coupling between the electric sector and the transportation sector is becoming increasingly stronger; however, there is a lack of established channels for exchange of communication and coordination between these two sectors. One of the biggest challenges to the buildout of a complete EV charging infrastructure continues to be existence of overly complicated interactions and lack of formalization of the necessary coordination between stakeholders. Identification of the entity classes that are directly or indirectly involved throughout the lifecycle of EV projects; determination of the necessary interactions between pairs of entity classes; and development of a coordination framework will be crucial in eliminating delays in the interconnection process and have the foundation for having managed charging in the future.

The electrification of the transportation sector necessitates an increased electricity generation capacity. To meet the excess demand from the transportation sector, developers nationwide are investing in renewable energy projects.; however, these projects typically take around four years from entering the interconnection queue to becoming operational. In response, the Department of Energy (DOE) has launched a new initiative to streamline the permitting and interconnection process. A critical aspect of this effort involves utilities clearly outlining the necessary information for site preparation and indicating readiness for charging infrastructure installation. Likewise, charger builders must provide detailed specifications including location, load, site plans, and existing easements. Establishing a transparent coordination framework between utilities and builders can significantly accelerate the approval process.

During the operational phase too, the electric sector may need to know forecasts of demands by loads including EVs, and the transportation sector will benefit from information regarding potential/predetermined outages or peak charges anticipated by the responsible electric utility. Coordination is especially critical for setting up managed charging capabilities and to ensure EV charging infrastructure availability before, during, and after emergency scenarios to ensure public safety and security. It is necessary to develop a reference architecture for achieving simplification and common understanding of the complex industry structure of the converged grid-transportation system. Electrification will lead to stronger sector coupling between the electric and transportation sectors. A coupling diagram that discusses the interaction of the transportation sector with the electric grid is shown in Figure 10.

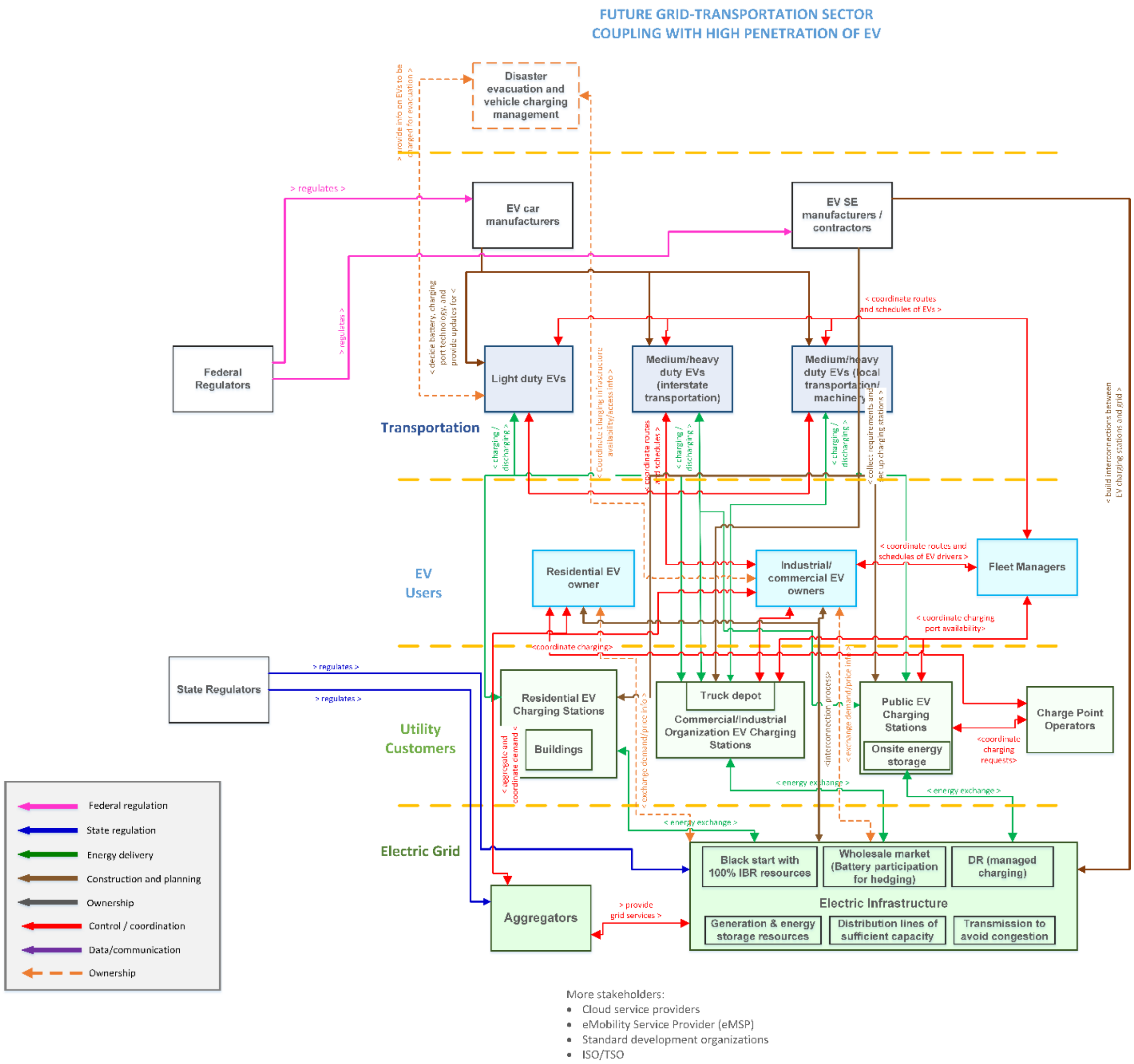


Figure 10. Future coupling of grid-transportation sector with higher dependency on electrified transportation.

4.0 Grid-Transportation Sector Coupling

This section maps and analyzes the coupling between the transportation and electric sectors. The electric grid helps to power the fossil fuel infrastructure that in turn supports the transportation sector. Section 4.1 focuses on the current coupling between the grid and fossil fuel supply chain. Sections 4.2 through 4.4 discuss vulnerabilities of the existing fossil fuel supply chain for the transportation sector. Understanding the grid-transportation sector coupling is critical for guiding convergence of the electric and transportation sectors in a manner that enhances the economic efficiencies and benefits to both these sectors. It encourages us to envision the development of smart infrastructure where collaborative efforts among public and private stakeholders have the potential to create a more resilient and economically integrated energy system capable of meeting the evolving demands of our interconnected world.

4.1 Interactions Between Electric and Fossil Fuel Sectors

This section details the coupling between the electric grid and the fossil fuel supply chain (Figure 11). The fuel supply chain infrastructure, which includes production, distribution, and retailing of gasoline (petrol), is dependent on the electricity infrastructure in several ways. While this coupling may be weak in some instances, there is existence of a coupling which is important to study.

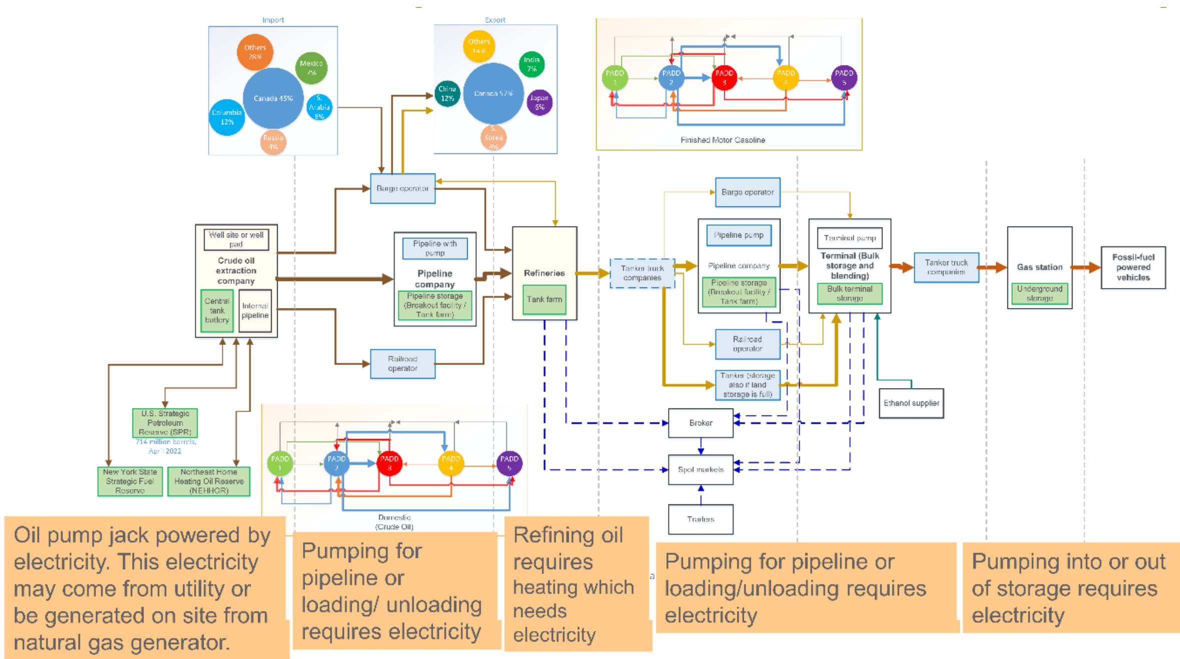


Figure 11. Current coupling between fuel and electrical sector from a sector coupling perspective.

All the stages and steps discussed in Figure 3 related to fuel delivery architecture are reiterated in Figure 11 with a fresh visualization on the coupling of the electric sector with the fuel delivery infrastructure. The fossil fuel supply chain is directly dependent on the electricity infrastructure in the following ways:

1. **Fuel extraction:** Electricity plays a crucial role in the extraction of crude oil. For example, a production weighted average oil well in Wyoming produces 114 barrels per day of 35º API

oil and 604 bpd of water at a depth of 7,966 feet, and for that process it is estimated to be using 468,000–648,000 kWh of electricity per year. In comparison, U.S. EIA's data for 2022 indicates that U.S. total petroleum production averaged about 20.079 million barrels per day.

2. **Refining:** The refining of crude oil into gasoline at petroleum refineries often requires significant amounts of electricity. Electricity is used to power various equipment, such as pumps, compressors, and distillation columns, which are essential for the refining process.

Based on the EIA Refinery Capacity Report of 2022,[18] refineries in the United States purchased 42,698 million kWh of electricity for its operations as shown in Table 1. This represents approximately 1% of the U.S. electrical consumption. Electricity purchased by the refineries over the last decade is shown in

Figure 12.

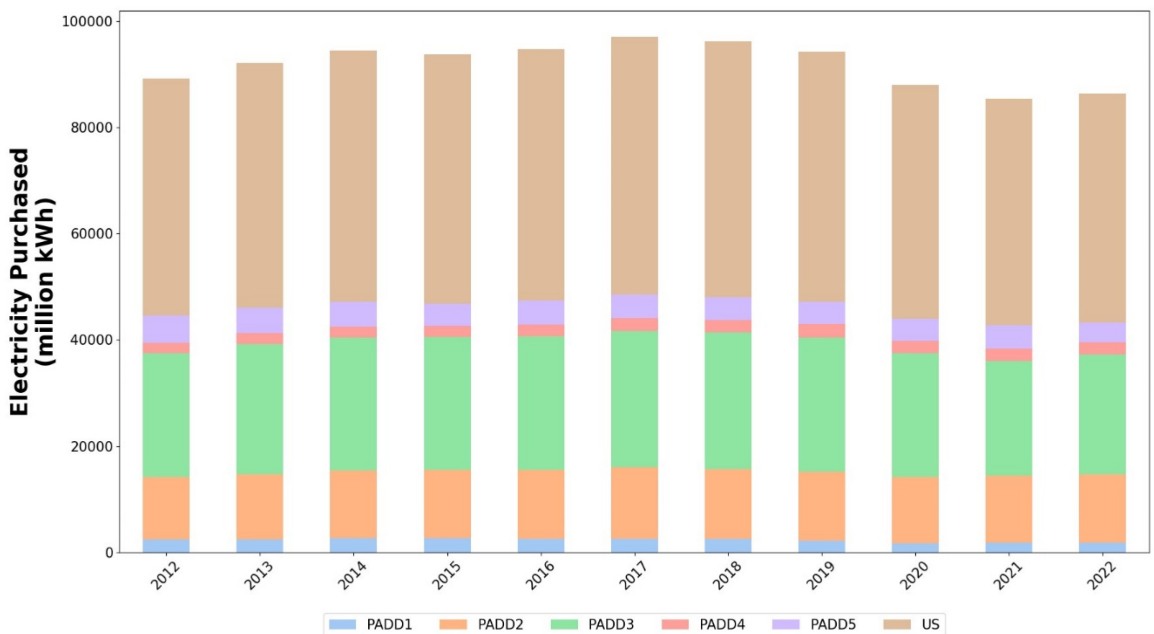


Figure 12. Electricity purchased by refineries at different PADDs.

Table 1. Purchased electricity at refineries by PADD in 2021.[18]

Commodity	PADDs					United States
	I	II	III	IV	V	
Purchased Electricity (million kWh)	1,804	12,673	21,560	2,305	4,356	42,698

3. **Fuel pumping and distribution**: Electrically powered pumps are used to move gasoline through pipelines and loading/unloading operations at distribution terminals. The operation of gasoline distribution networks, including pipelines, storage tanks, and loading facilities, relies on electricity.

4. **Gas stations**: Retail gas stations depend on electricity for various functions, including powering fuel dispensers, lighting, payment systems, and security systems.

5. **Emergency backup power**: Many gas stations are equipped with backup generators that are typically powered by diesel or natural gas to ensure fuel availability during power

outages. These backup generators are crucial for maintaining operations during emergencies.

As can be seen with the current structural setup of operation for fossil-fuel-powered vehicles to operate efficiently, the oil and gas industry is heavily reliant on the efficient and uninterrupted supply of power from the electricity infrastructure.

4.2 Vulnerabilities of Current Grid-Transportation Coupled System

The fossil fuel supply chain has matured over almost a century and is touted to have high levels of reliability and resiliency. However, this system has some unique vulnerabilities due to the heavy dependence on production, transit, and storage of hazardous fossil fuel. Disruptions can affect any part of the fossil fuel supply chain, which can lead to impacts that are not often publicized. During major disruptions, such as hurricanes or power outages, DOE issues situation reports to provide information about the effect on gasoline supply and other energy infrastructure and supply issues.

4.2.1 Extraction

With the different stages of processing crude oil into a finished usable product, process starts from extracting the fuel from different sites. Supplies of domestic crude oil are affected whenever offshore platforms stop producing crude oil because of unsafe operating conditions caused by weather. High winds and rough seas that come with hurricanes often cause offshore platforms to shut down production. A high-impact hurricane event can result in a temporary loss of significant amounts of monthly offshore crude oil production and a nearly equivalent temporary loss of refining capacity. Outages on the scale of 1.5 million barrels per day have been reported, as estimated due to hurricanes, and this can increase monthly average U.S. retail gasoline prices by 25–30 cents per gallon, with such pricing effects diminishing over time.[19] Examples of times when the domestic crude oil supply was affected include hurricanes Katrina and Rita in 2005, and hurricanes Ike and Gustav in 2008. These hurricanes led to a reduction in crude oil production in the Gulf of Mexico as shown in Figure 13.

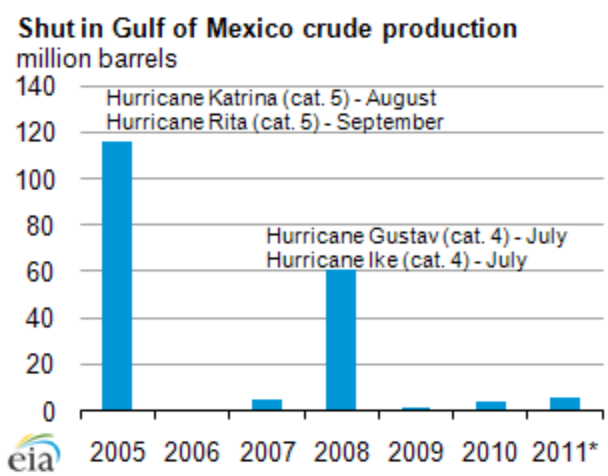


Figure 13. Example showing impact on crude oil production due to hurricanes[20]

4.2.2 Transfer to Refinery

Areas of the nation that receive crude oil via pipeline can become supply-constrained when pipelines cannot operate because of power outages or other disruptions. When gasoline or crude storage terminals lose power, supply can be limited because pipelines and barges have no way to load or discharge product.

All crude oil transport methods carry potential risks to the environment.; however, oil train derailments pose additional hazards because trains routinely travel through cities and towns where oil spills and potential fires could cause significant property damage and loss of life. To address these concerns, the U.S. Department of Transportation released a comprehensive final rule in May 2015 that contained upgraded tank car standards, new operational guidelines for moving large volumes of flammable liquids by rail, and enhanced emergency response planning and training. However, such spills have still not been eliminated. As recently as March 16, 2023, a freight train derailed on the Swinomish Reservation near Anacortes, Washington, and led to the spill of an estimated 5,000 gallons of diesel. While the environmental impact is still being assessed by the Washington State Department of Ecology, there are mounting concerns regarding impacts to humans and wildlife in the area. According to the Pipeline and Hazardous Materials Safety Administration, spills predominantly of crude oil since 2003 to 2022 have cost approximately $5 billion. Figure 14 shows the annual number of events that results in spillage of crude oil.

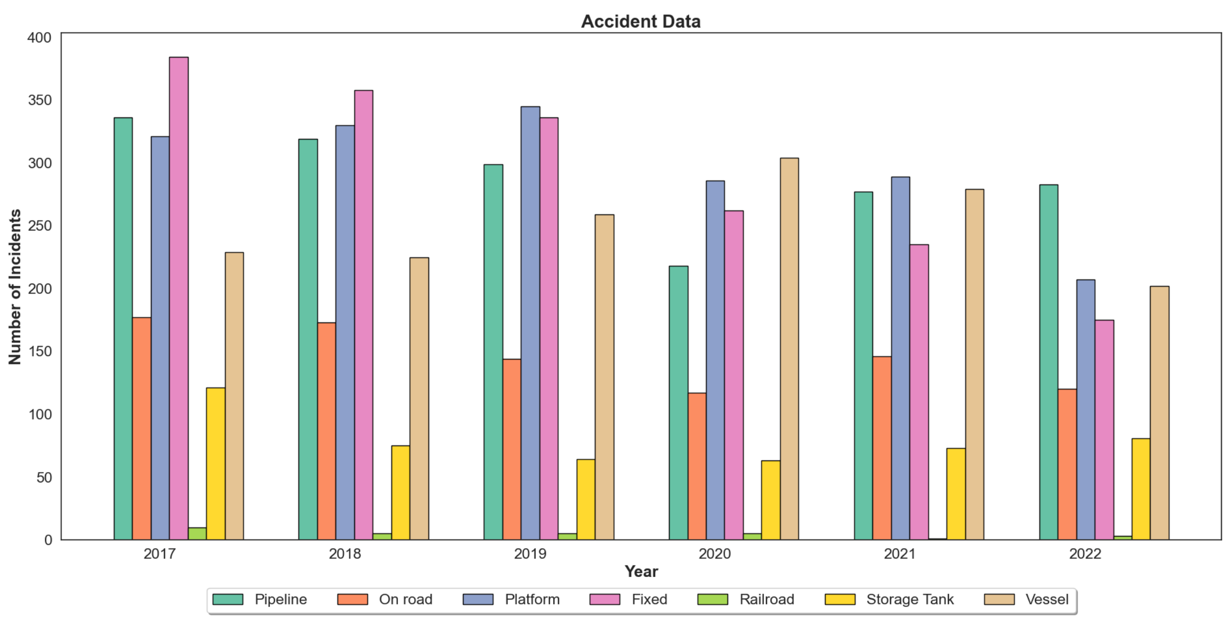


Figure 14. Annual data of accidents that lead to spillage of crude oil.

4.2.3 Refining

Refineries manufacture crude oil into gasoline and other petroleum products. Hurricanes can result in flooding that damages refining equipment or causes power outages, preventing refineries from operating. When refineries do not operate, total U.S. gasoline production can decline and affect supplies of gasoline.

4.2.4 Transfer to Bulk Storage Locations

Areas of the nation that receive gasoline or diesel via pipeline can become supply-constrained when pipelines cannot operate because of power outages or other disruptions. When gasoline or crude storage terminals lose power, supply can become constrained because pipelines and barges have no way to load or discharge product. Barge traffic may also be disrupted when the water levels of rivers are low, when harbor waters freeze, or when ports are closed. Rail shipments of ethanol might be affected by disruptions at terminal rail loading facilities. Supply of ethanol can be affected by droughts as was seen in the summer of 2012 due to low production of corn. Oil train derailments pose additional hazards because trains routinely travel through cities and towns where oil spills and potential fires could cause significant property damage and loss of life.

4.2.5 Bulk Storage and Blending

If terminals do not have power, tanker truck loading is disrupted.

4.2.6 Retail Distribution

Severe weather conditions (e.g., blizzards) can cause disruptions if trucks are not able to transport gasoline from terminals to gas stations because of poor road conditions. Distribution from terminals was a problem after Hurricane Sandy in 2012. Imbalances in supply and demand may also occur when a region changes from one gasoline formulation to another and refiners, distributors, and marketers adjust supply for the new product.

4.2.7 Delivery to ICE Vehicles

As with other parts of the gasoline supply chain, retail outlets are affected by power outages. Some states have enacted laws requiring backup generators at certain retail stations. In addition, disruptions in earlier steps in the supply chain affect retail outlets by limiting the availability of gasoline supply.

4.2.8 Imports and Exports

Supplies of seaborne imported gasoline, which are mostly gasoline blending components, and imported crude oil are affected whenever U.S. ports are closed. Hurricanes in the Gulf of Mexico and along the East Coast often cause ports to close because of unsafe shipping conditions, loss of power, or both. Examples include Hurricane Katrina, which damaged and closed the Port of New Orleans in 2005, and Hurricane Sandy which closed the Port of New York in 2012. Both ports are major entry points for crude oil and gasoline imports.

4.3 Common Impacts of Shocks to the Fuel Supply Chain

There can be impacts on price and availability of gasoline fuel due to adversarial events. The supply of gasoline is largely driven by crude oil supply and refining, imports of gasoline, and gasoline inventories (stocks). The global interconnectedness of the fossil fuel system helps to maintain a resilient supply chain; however, a political conflict in an oil-producing country or a disaster hampering the shipping route can have a ripple effect on the price and availability worldwide. Such consequences have negatively hampered availability and prices in United States, although some of the events were not local to the mainland. Some of the major events shown in Figure 15, namely (1) the 9/11 terrorist attack, (2) low spare capacity, (3) global financial crisis, (4) cuts in OPEC production, and (5) the COVID-19 pandemic, created shocks across the globe affecting crude oil prices in USA.

Several local events like hurricanes, cyberattacks, and flooding have challenged the production and availability of fuel to the end user. Some of these events impacted the electric grid resulting in disruption of fuel production. We later draw a parallel analysis where the restoration of the grid happens at a faster pace, but several complex interactions can slow the anticipated time to return to normalcy.

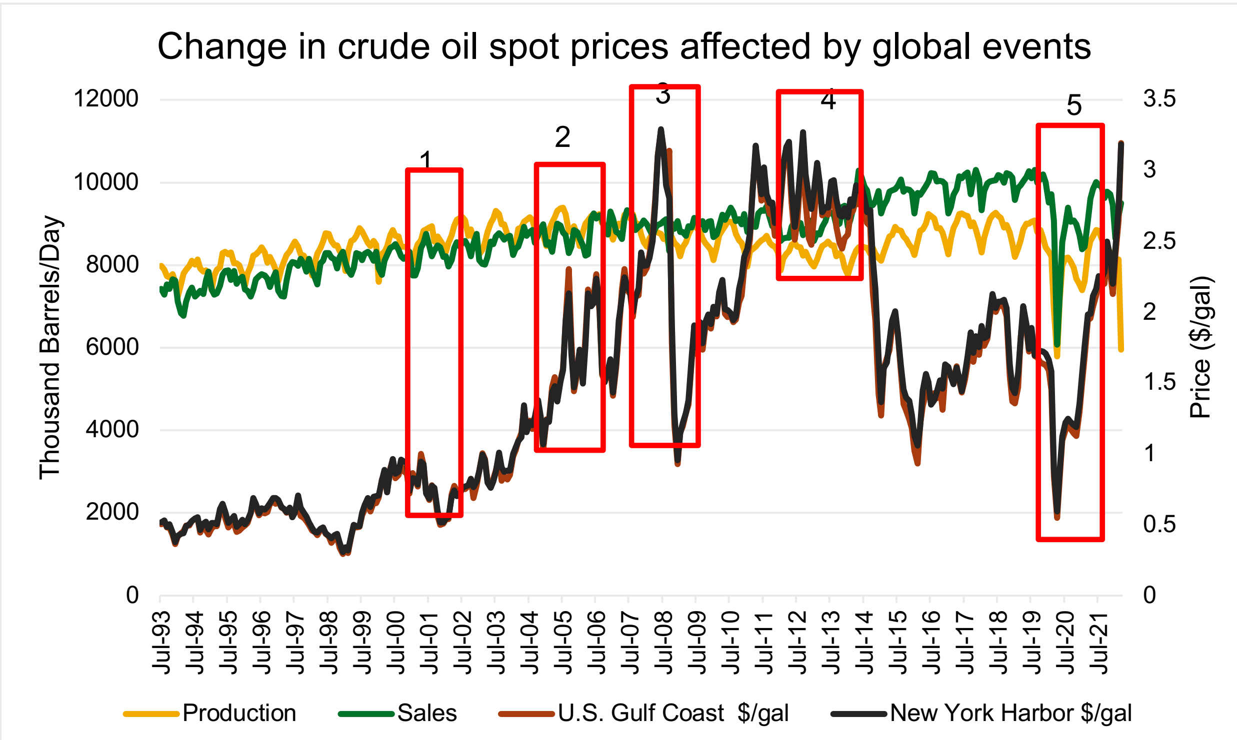


Figure 15. Change in price due to global events.[21-23]

Crude oil and finished gasoline stocks are essential to maintain a country's (i) energy security, (ii) economic stability, (iii) emergency response, (iv) national security, and (v) geopolitical stability. Under stress scenarios, crude oil stocks are the cushion between major short-term supply and demand imbalances, and stock levels can have a significant impact on gasoline prices.

In 1970, there was a severe energy crisis in the United States due to the oil embargo imposed by OPEC. Gasoline supply and demand were heavily impacted as a result and led to the sharp increase of gasoline prices and shortages in supply. In response, the Energy Policy and Conservation Act of 1975 was passed to establish the SPR, with the goal to provide a strategic cushion under different scenarios.[24] Years of expansion have seen the Energy Policy Act authorize the SPR to hold 713.5 million barrels. There have been several occasions when reserves from the SPR were utilized to stabilize the energy market and ensure adequate supply of fuel. The United States has several other forms of storage in pipelines, refineries, and terminals that help to maintain energy security. Below are examples of different types of shocks to the fuel supply chain and impacts described on a high level.

4.3.1 Hurricane Ike

Hurricane Ike was a powerful Category 2 hurricane that made landfall on September 13, 2008, near Galveston Texas. The size and intensity of the storm resulted in severe economic damage. The Gulf Coast (PADD3) is an area of significant oil and gas production. The hurricane impacted offshore drilling and refining processes that resulted in affecting production and supply. The gasoline production of PADD3 was significantly impacted and fell to 26% lower production capacity than the previous week as shown in Figure 16.

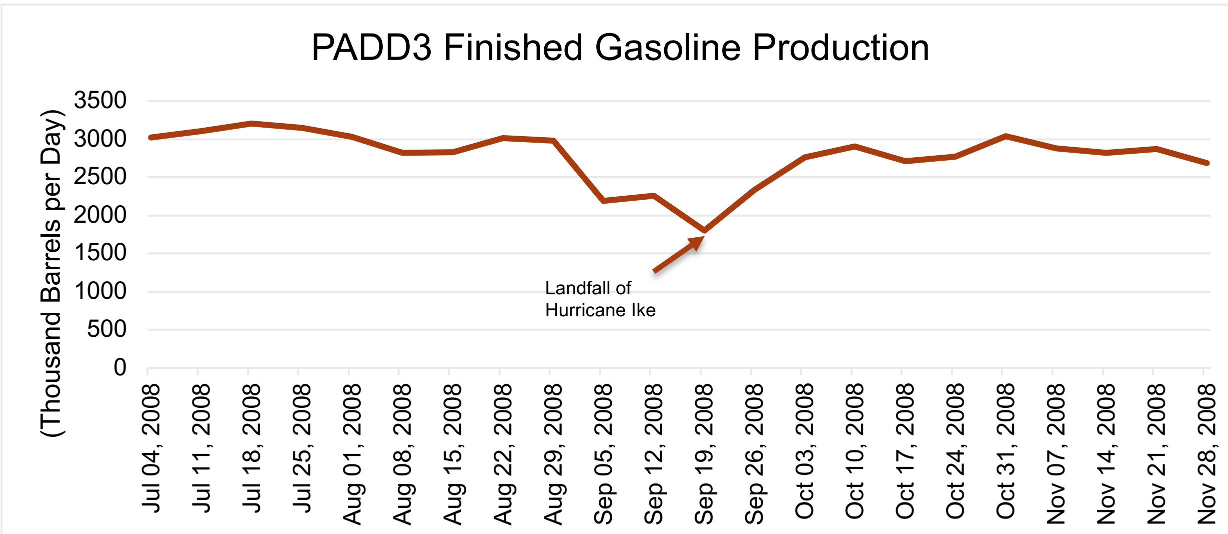


Figure 16. PADD3 finished gasoline production during hurricane Ike.[25]

In the storm aftermath, oil and gas prices experienced fluctuations, with PADD3 gasoline prices rising over 5% compared to the previous week. Interestingly, although the event was localized to the Gulf Coast, the highest change in the price of gasoline was 8% in PADD2 (Midwest) followed by PADD1 (East Coast) where no effects were felt as shown in Figure 17.

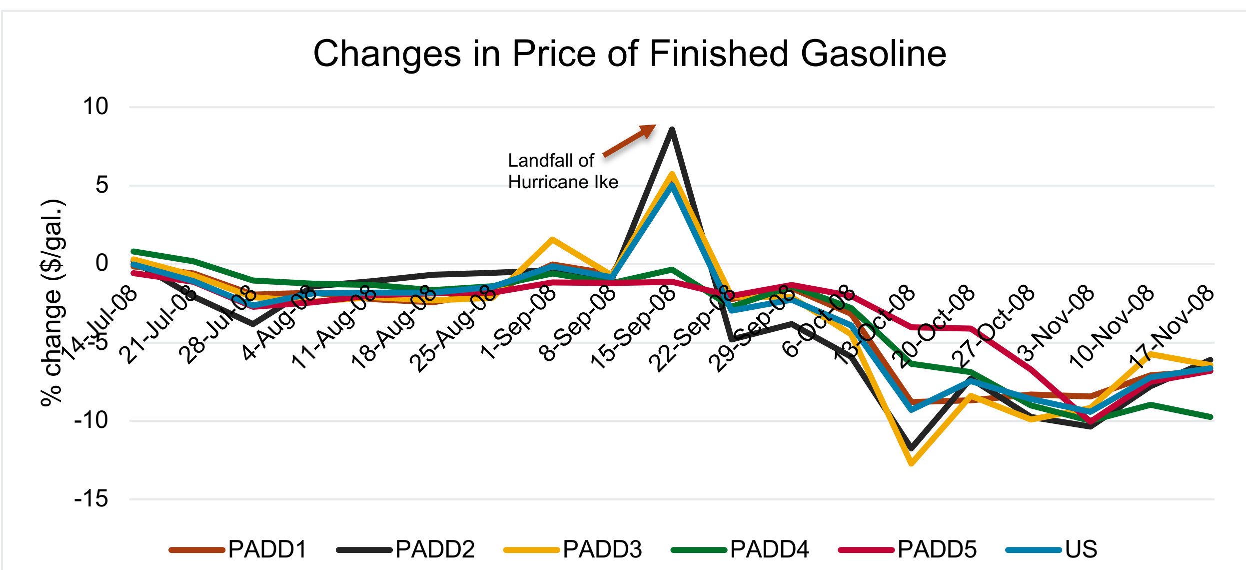


Figure 17. Change in finished gasoline prices during Hurricane Ike.

Due to reports of the storm's path and state emergency declaration, nearly 75 gas stations in Houston area ran out of gasoline[26] before landfall of the hurricane. Usually gas stations have adequate storage of gasoline available on site, however increased buying triggered a shortage of fuel availability (Figure 18). Such unprecedented conditions of fuel availability do challenge evacuation, daily operations, and emergency response activities.

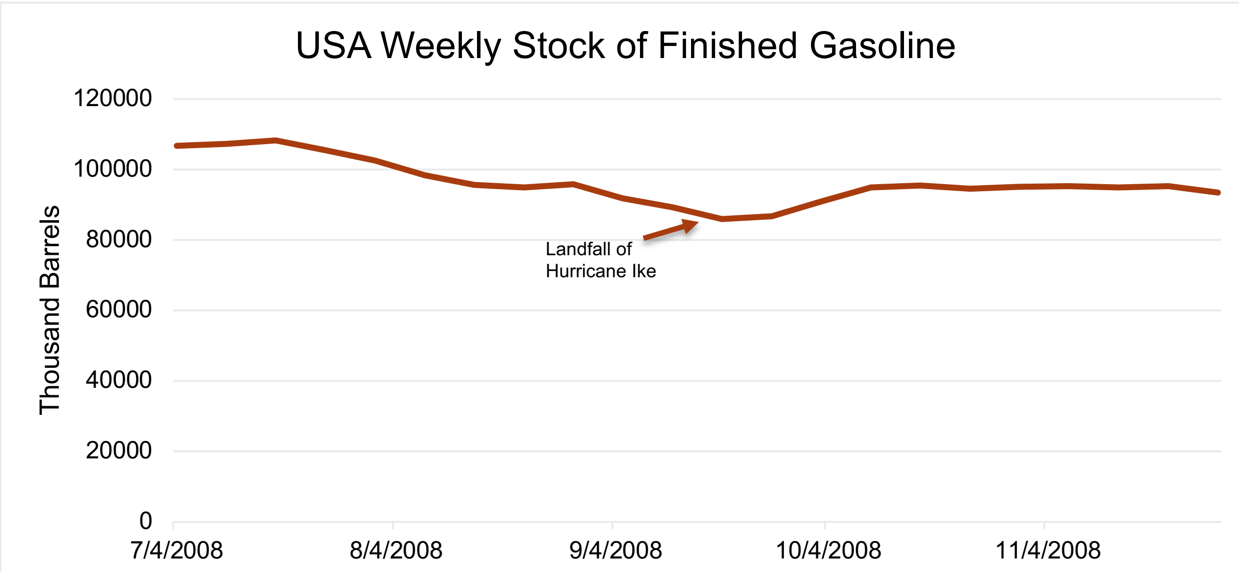


Figure 18. Weekly stock of finished gasoline in during Hurricane Ike.[27]

4.3.2 Hurricane Katrina

Hurricane Katrina was a Category 3 hurricane that made landfall near New Orleans, Louisiana, on August 29, 2005. The powerful winds from the hurricane, storm surge, and flooding created extensive damage to property including the oil and gas pipelines, refineries, and other crucial infrastructure. This led to the disruption in the production of oil and gas in the Gulf of Mexico region as shown in Figure 19. In the coming months, the region was hit with another devastating Category 3 hurricane, Rita, on September 24, 2005. The production of the region was already stressed from the aftermath of Katrina, and Hurricane Rita further disrupted the recovery effects that dented the oil and gas production in the region. PADD3 is the largest producer of gasoline and impacts of hurricanes or any major events that result in the shutdown of the refineries and create national demand-supply challenges across the nation. The centralized nature of fuel production deeply aggravates this effect, which leads to some level of depletion of oil from the stocks.

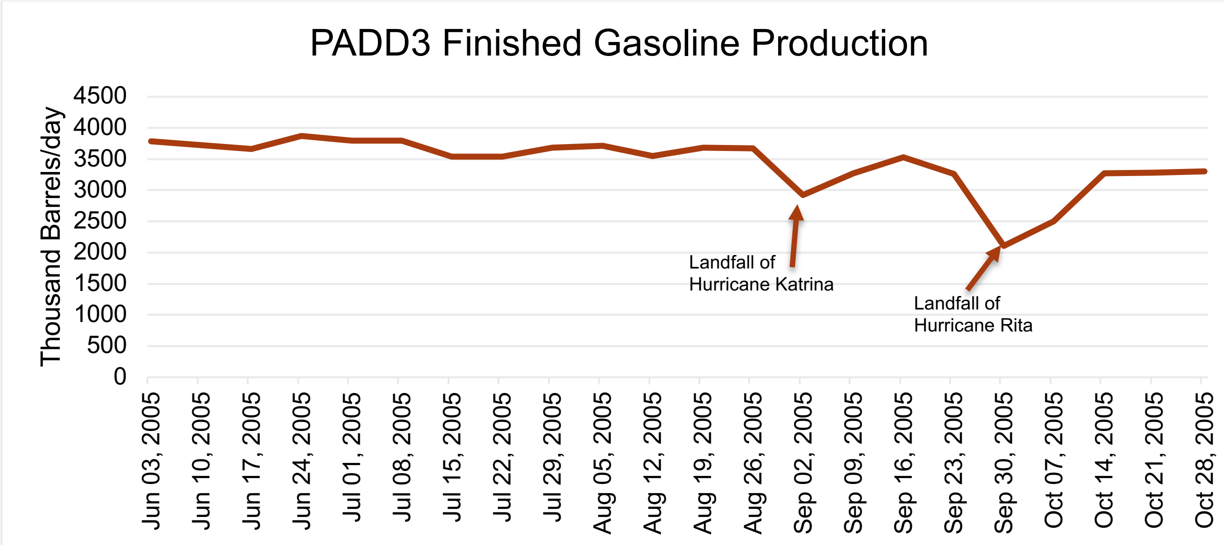


Figure 19. Finished gasoline production in PADD3 during Hurricanes Katrina and Rita.[25]

As an aftermath of the hurricane, there were substantial increases in the finished gasoline prices in PADD3. Prices rose close to 15% from the pre-hurricane week for the region, although similar variations of prices were felt across the nation. Interestingly, although the effect of the hurricane was localized to the PADD3 region, the price changes were felt more severely in PADD1 and PADD2 compared to PADD3 as shown in Figure 20. Figure 21 shows reduction in the stock of finished gasoline in the United States.

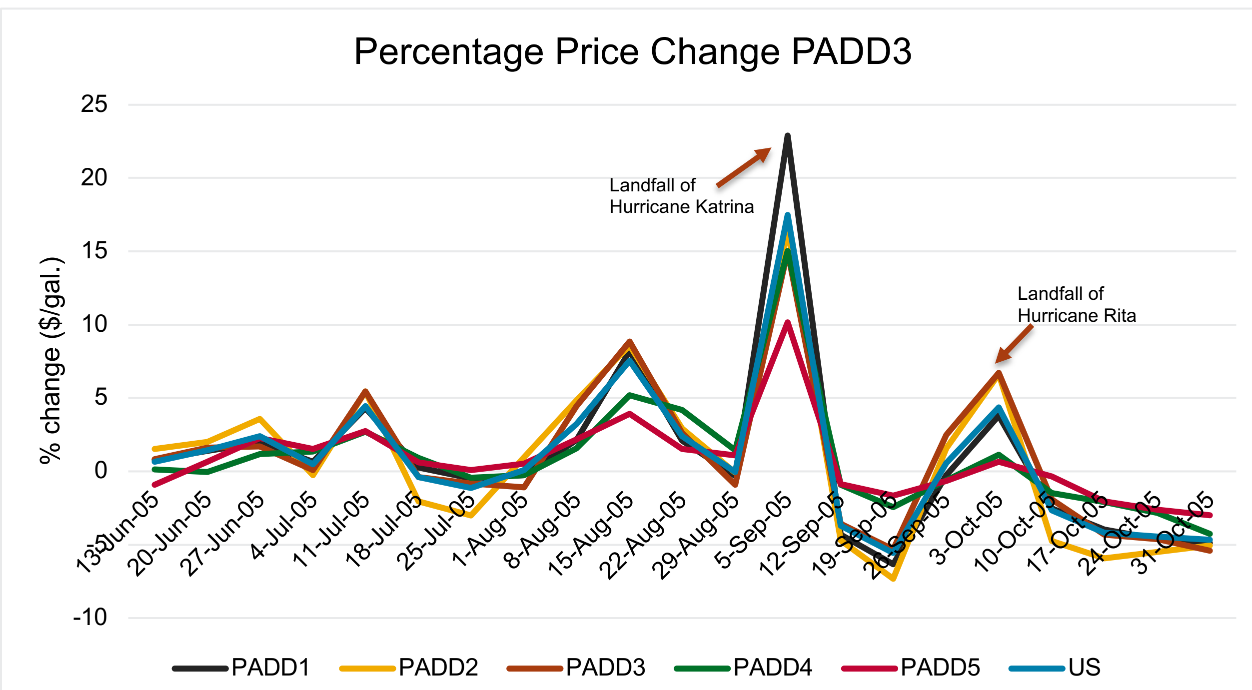


Figure 20. Change in finished gasoline prices after Hurricanes Katrina and Rita.

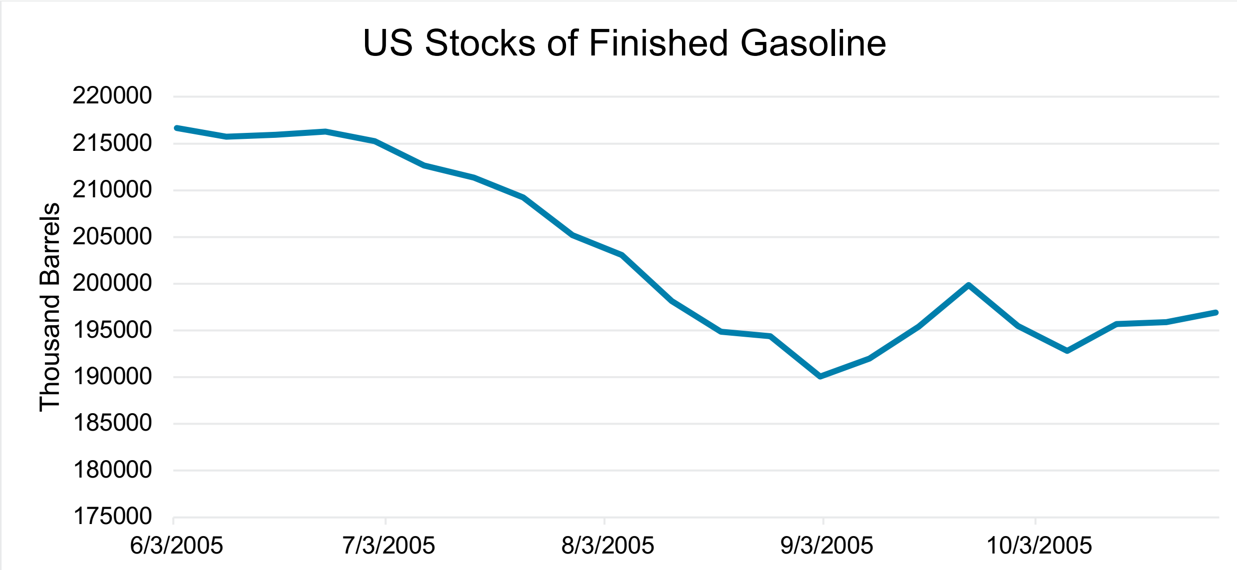


Figure 21. Weekly stock of finished gasoline in USA.[27]

4.3.3 Global Financial Crisis

The world faced a severe economic crisis between 2007 and 2009. It originated in the United States, but the impacts were felt worldwide.[28] The oil and gas industry were plagued with several challenges during this period that affected its operation and stability: (1) reduced demands; (2) supply chain disruptions; and (3) volatility in product prices.

Lack of demand, with industries scaling back production due to lack of market sales, resulted in oil companies cutting their production. Movement of freight, shipping, and travel saw a significant drop in the demand for finished gasoline. Leading up to the financial crisis there was a surge in production from oil-rich countries. This resulted in oversupply, thus putting a downward trend to oil prices that fell almost by 30% across the different regions of the nation as shown in Figure 22.

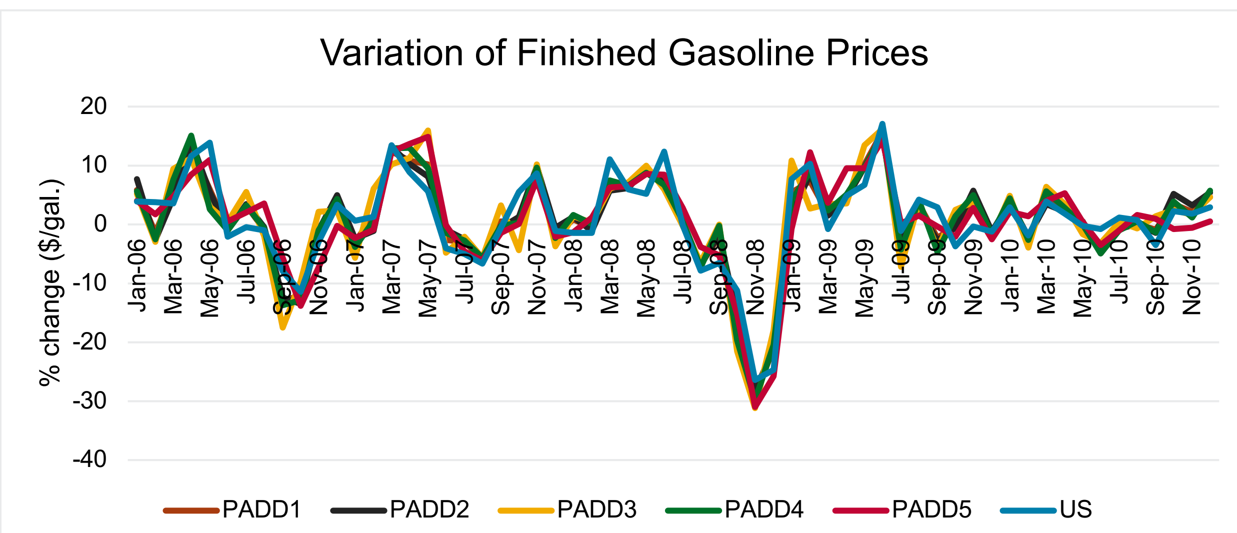


Figure 22. Change in finished gasoline prices during the global financial crisis.

4.3.4 COVID-19 Pandemic

The COVID-19 pandemic had a profound impact on the oil and gas industry, causing unprecedented disruptions and challenges. The pandemic, which began in late 2019, led to a global health crisis and triggered an economic downturn. The oil and gas industry, being closely tied to economic activity and energy demand, faced several significant consequences during this period. With travel restrictions on inter- and intra-country travel, demand for finished gasoline saw a sharp decline. Due to the demand shock the storage facilities were overwhelmed and it resulted in a significant drop of prices during April 2020 as shown in Figure 23. The production had to be scaled back gradually until need for pre-pandemic levels of productions were seen around late 2021 as shown in Figure 24.

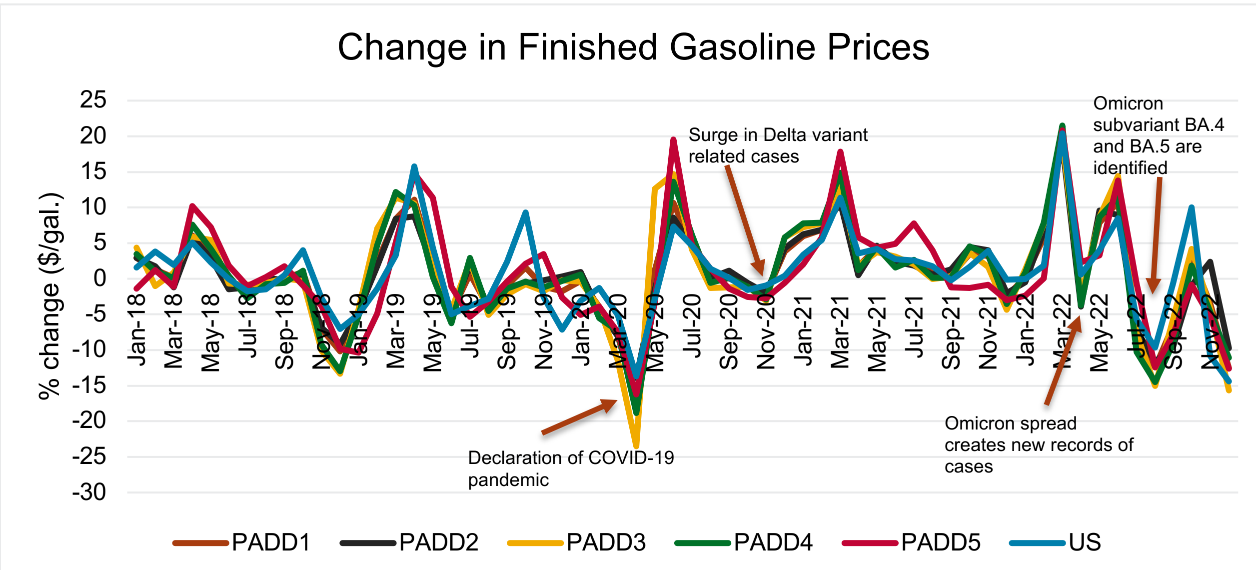


Figure 23. Change in finished gasoline prices during COVID-19 pandemic.

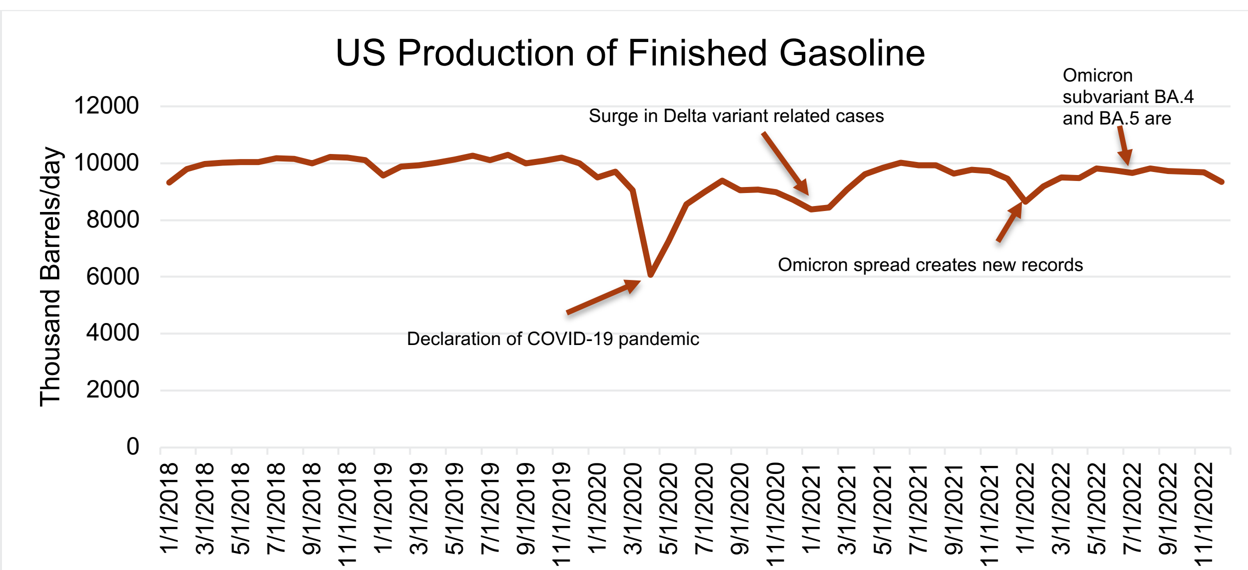


Figure 24. Finished gasoline production in US during COVID-19 pandemic.[25]

4.3.5 Colonial Pipeline Attack

The Colonial Pipeline plays a crucial role in the U.S. energy supply chain. It connects the Gulf Coast to the East Coast and provides essential delivery of crude oil to the northeast sections of the country. The pipeline is 5,500 miles long and has the capacity to transport 2.5 million barrels of oil each day. In May 2021, the cybersecurity infrastructure of the pipeline was breached, which led to the shutdown of its operations. Several reports of gas station outages were reported across the states of North Carolina and Virginia. The price of gasoline rose steadily due to increased demand from panic buying. Figure 25 shows a decline of gasoline movement from PADD3 to PADD2.

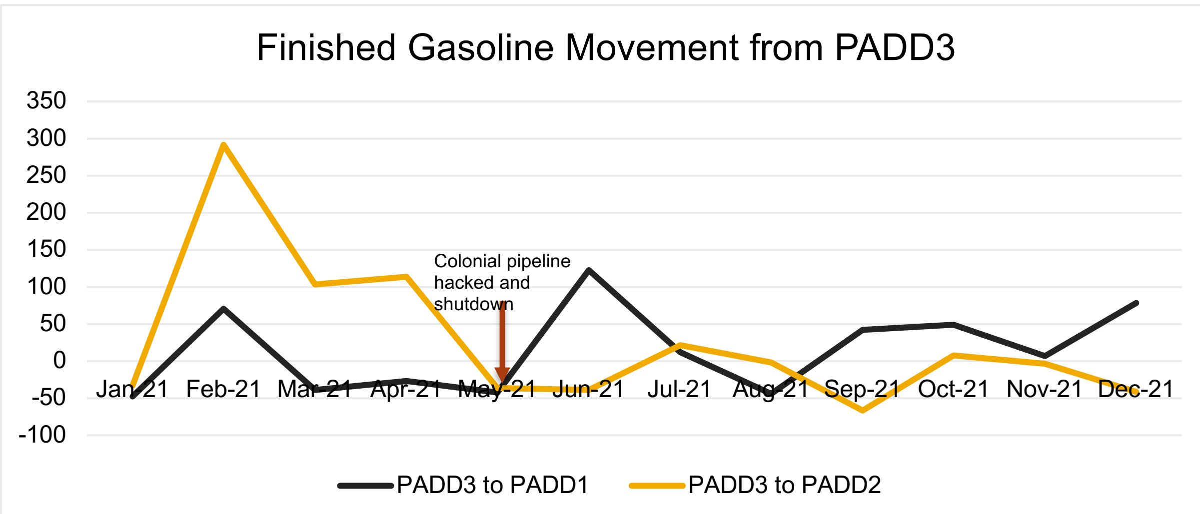


Figure 25. Movement of finished gasoline between PADDs.[29]

Figure 26 shows the rise in gasoline prices as in PADD3 (Gulf Region) and PADD1 (East Coast), however the rest of the country felt its impact as well and the average gas prices in the United States rose close to 3%. The supply chain structure of the gasoline infrastructure provides overall robustness, however the dependency on it due to localized production can create regional vulnerabilities.

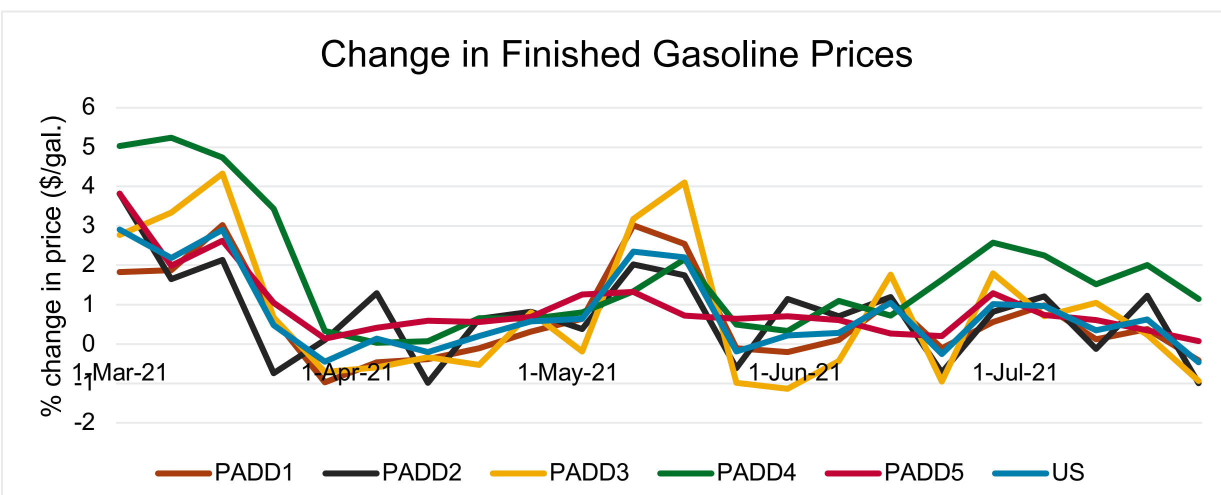


Figure 26. Changes in finished gasoline prices during Colonial Pipeline shutdown.

4.3.6 Flooding in Florida

On April 12, 2023, regions of Florida received an unprecedented amount of rainfall, close to 650 mm in 24 hours, as shown in Figure 27. A flood emergency was declared in the state, which led to the shutdown of many roadways and airports. The increasing demand and fuel shortages resulted in slowing down fuel distributions in different regions and the State Emergency Response Team was deployed with 500,000 gallons of fuel to the southeast part of the state.[30] Although trucks carrying fuel were reported to arrive by April 18, significant fuel shortages were still recorded.[31] The three-day fuel outage percentage for key locations (as marked in Figure 27) is shown in Figure 28.

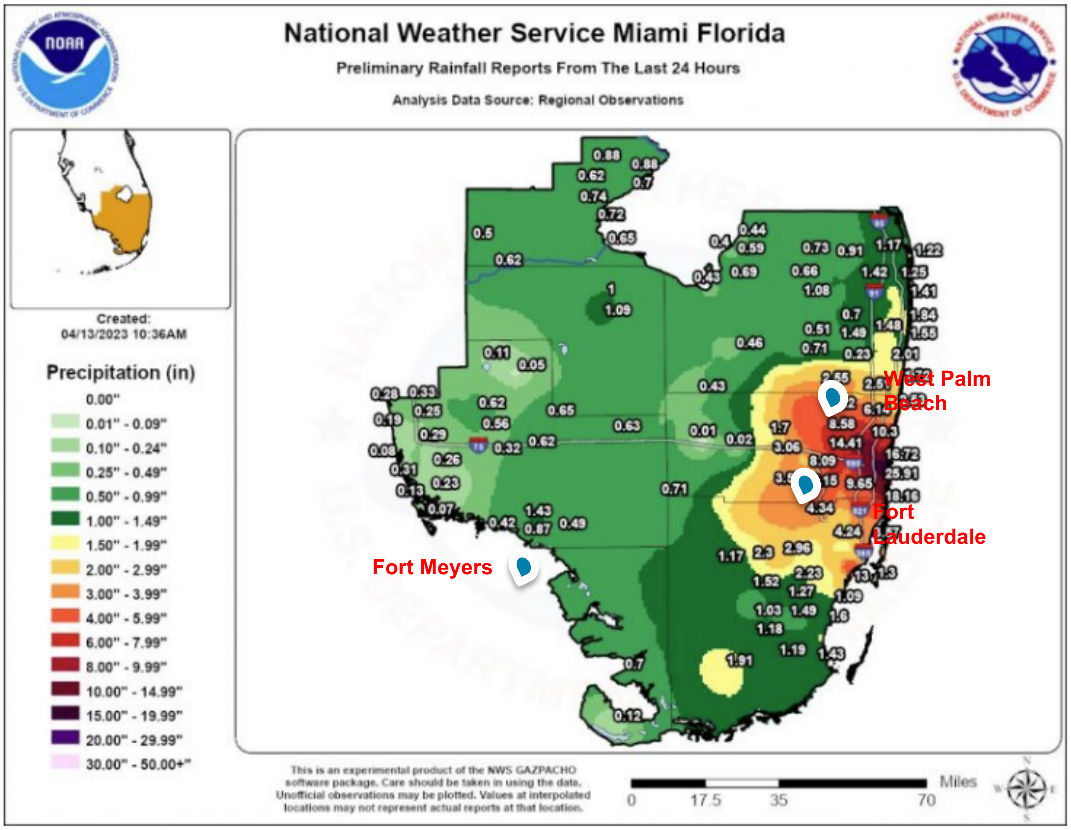


Figure 27. Rainfall recorded in Florida in April 2023.

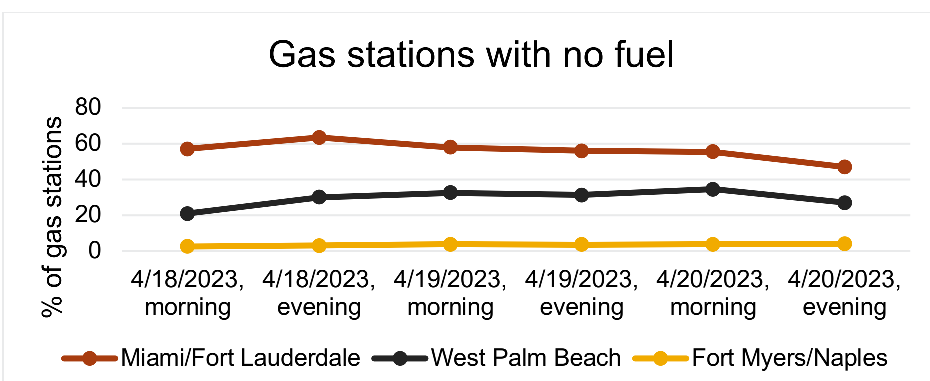


Figure 28. Fuel stations with no gas in Florida.[32]

4.4 Takeaways on Discussed Vulnerabilities

From the discussion and understanding, the interconnected fuel network provides robustness to the model; however, an increased dependency on intraregional fuel movements also adds certain challenges to the supply chain. Figure 29 shows the average movement of finished gasoline across PADD regions from January 2000 to June 2023 (monthly-thousand barrels). It can be seen that most regions have a high degree of dependency on PADD3 for finished gasoline to meet their demands. Events that disrupt the production of finished gasoline in PADD3 affect most of the other PADD regions. The reflection of such scenarios can be seen in the vulnerabilities discussed where outages due to hurricanes have impacted price changes throughout the nation.

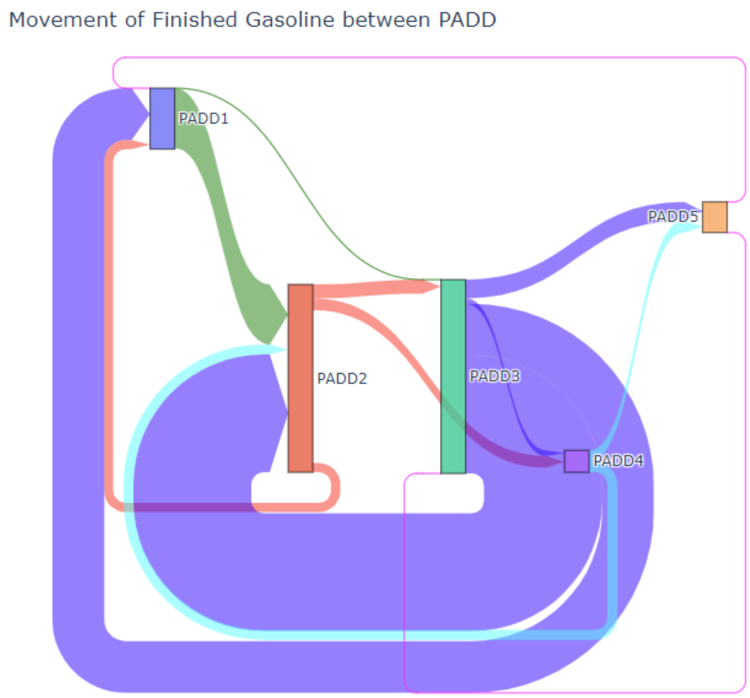


Figure 29. Movement of finished gasoline between PADDs.[29]

It is also noted that local and global events have the potential to impact fuel supply and prices. Local events not only impact prices of fuel locally, but also impact fuel prices of dependent PADD regions. Global events cause national and global price impacts and typically the percentage of change in price may be higher.

When we arrive at a gas station, there is an expectation that we will be able to fill up the tank. However, areas where extreme scenarios like hurricanes, outages, floods, and other natural disasters have been reported, outages in gas stations have been recorded. Figure 30 shows a study performed by GasBuddy to assist Federal Emergency Management Agency and refueling efforts. As seen during Hurricane Michael, almost 30% of the gas stations ran dry before the hurricane made landfall in Florida. The numbers kept growing steadily to almost 60% five days after landfall. The devastation and outages caused by the hurricane dictates how long it takes to return to pre-hurricane conditions, the average has been close to 3 weeks.

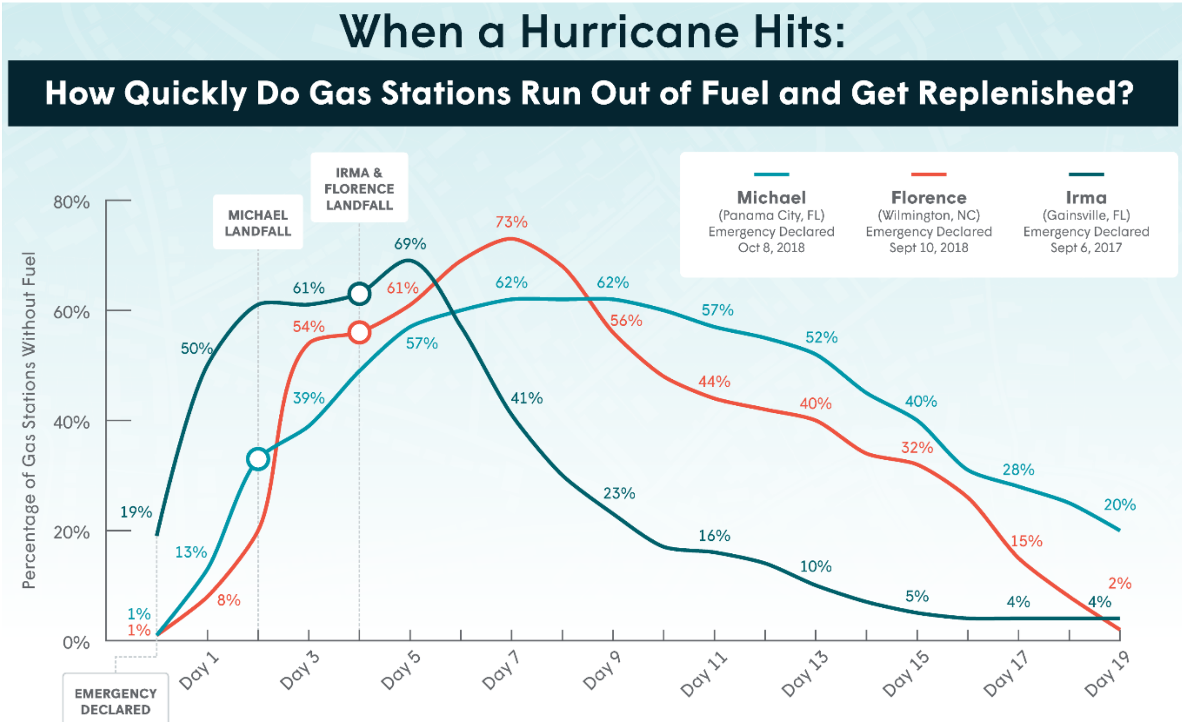


Figure 30. Time to return to normalcy for gasoline stations after a hurricane.[33]

EAGLE-I[34] is an interactive geographic information system enabling users to visualize and map the nation's energy infrastructure, providing near-real-time updates on the electric, petroleum, and natural gas sectors. During Hurricanes Irma and Michael in Florida, and Florence in North Carolina, it was instrumental in capturing electrical system outage data. Analysis of the data reveals that on September 10, 2017, the day of hurricane landfall, most customers began reporting outages, peaking the following day. Figure 31 shows the day of the recorded hurricane landfall, most customers started reporting outages that peaked the next day; however, there is a downward trend in the customers having an outage after the following day. It takes almost three weeks for fuel stations to recover after the declaration of an emergency (Figure 30), due to complexities involving fuel delivery and other infrastructure functioning properly. Electric outages take fewer days in comparison, especially since most of the electricity is generated within the state boundaries. With the infrastructure being repaired, customers are expected to receive power immediately, as shown for all the three hurricanes Irma (Figure 31), Michael (Figure 32), and Florence (Figure 33). For each of the scenarios shown, Day 4 is the day of landfall for the hurricane.

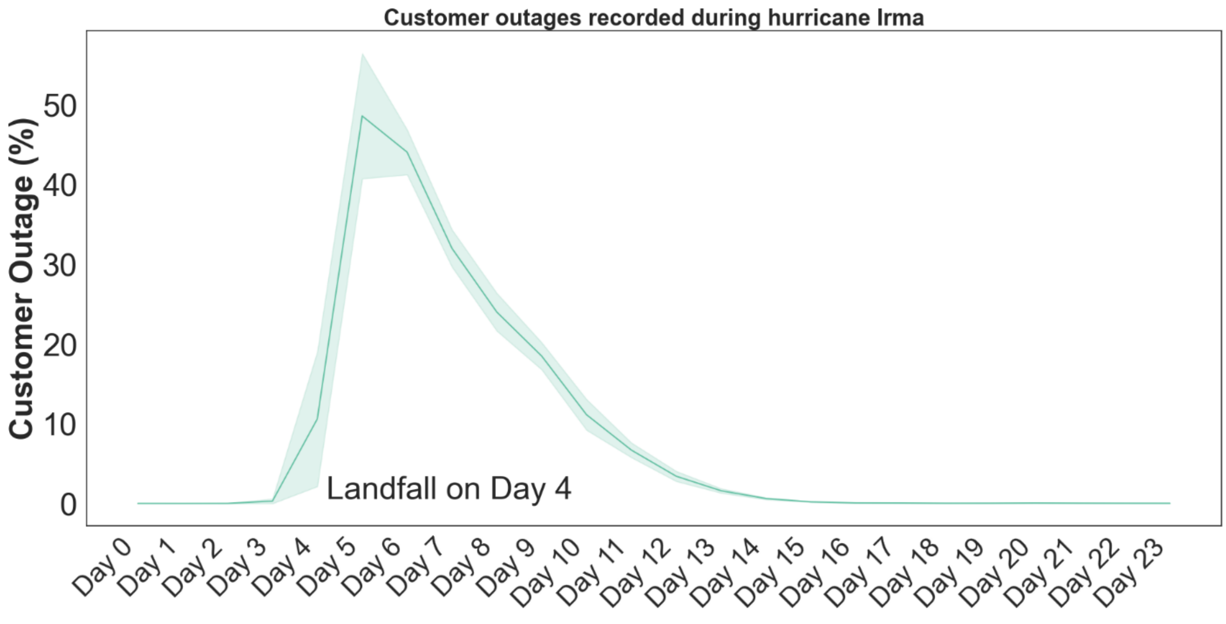


Figure 31. Outages recorded in 2017 during Hurricane Irma.

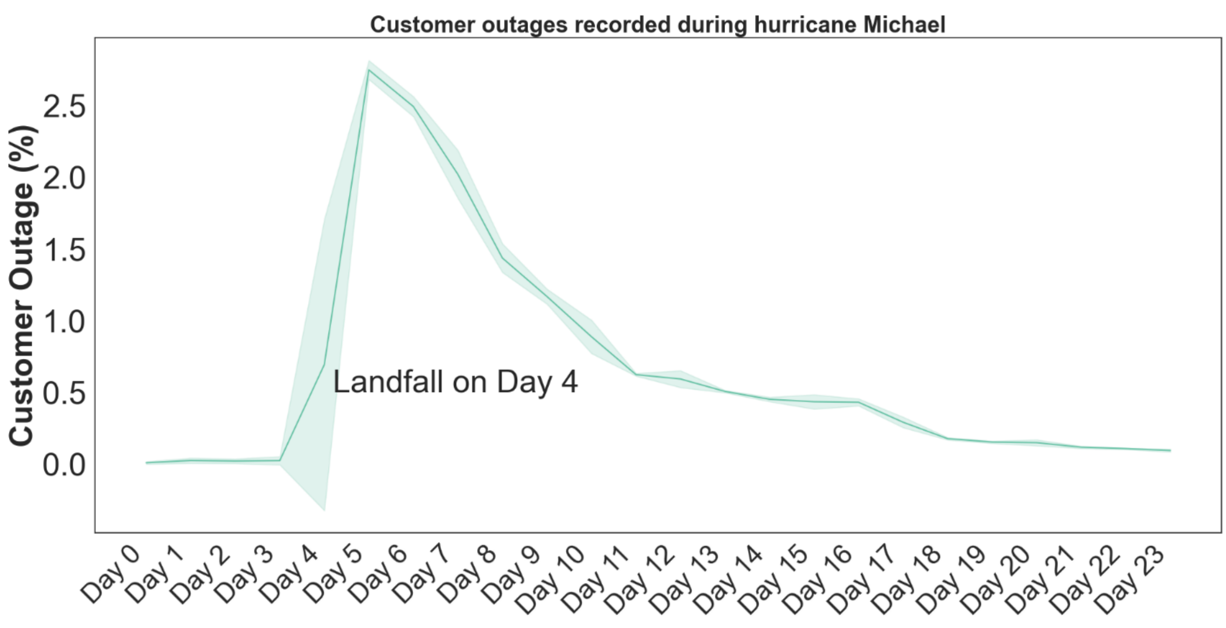


Figure 32. Outages recorded in 2018 during Hurricane Michael.

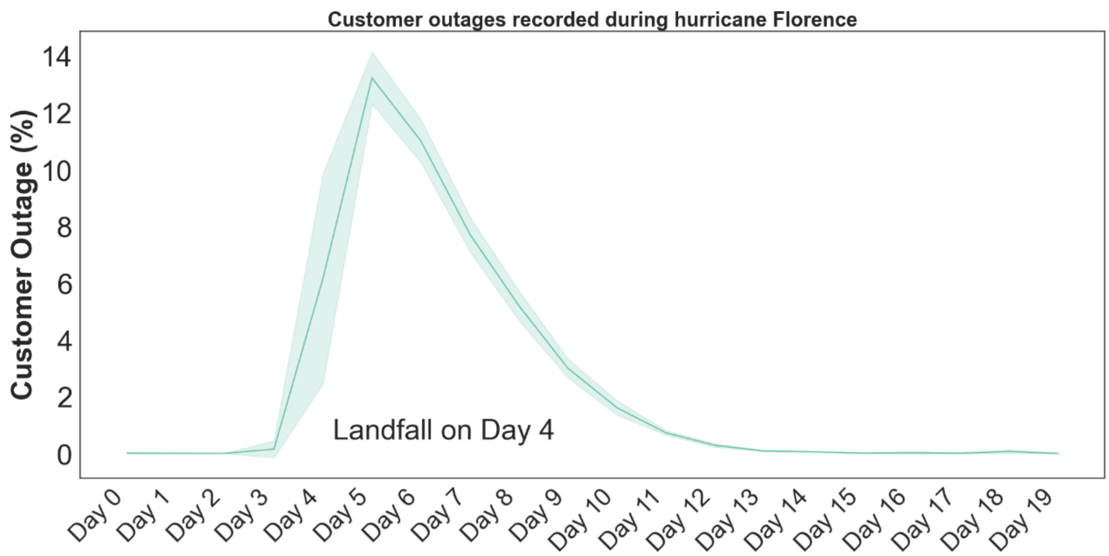


Figure 33. Outages recorded in 2018 during Hurricane Florence.

Similarly, fuel availability was impacted near Gainesville, Florida, as early as 20 hours before Idalia made landfall (Figure 34).

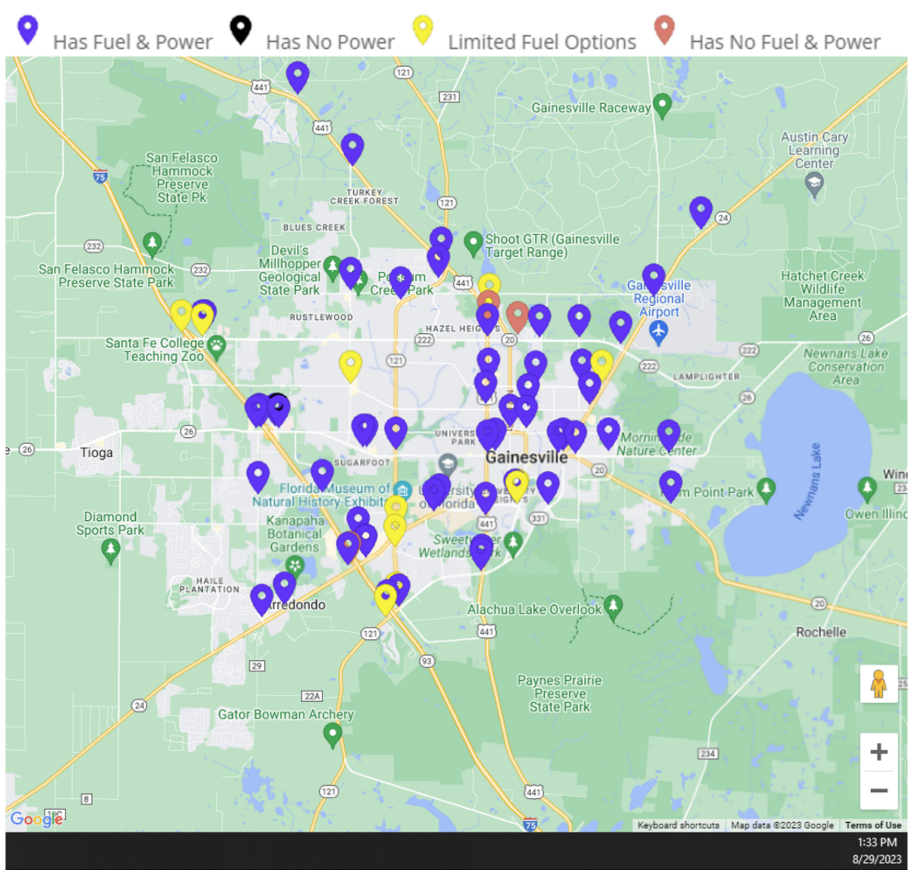


Figure 34. Impact on fuel availability at gas stations before landfall of Hurricane Idalia.[35]

As discussed, U.S. finished gasoline supply to the end users is largely relied upon by the intermodal transportation and high storage capacity available at strategically different locations. In spite of the existence of regional fuel stocks,[36] which is a critical factor behind the current level of reliability and resiliency of the fossil-fuel-dependent transportation system, still certain scenarios can lead to acute disruption in the supply chain.

During events, different types of impacts are experienced not only by the transportation sector but by the entire economy that is dependent on transportation. Despite the substantial reserve of fuel, a pivotal element contributing to the present reliability and resilience of the transportation system reliant on fossil fuels, specific situations can still result in severe disruptions to the supply chain. These events bring about various impacts not only on the transportation sector but also on the broader economy interconnected with transportation dependencies.

5.0 Stakeholder Conversation

As the automotive industry moves toward electrification, understanding the needs of the diverse stakeholder classes becomes paramount. Fostering effective engagement and gathering essential insights are crucial for determining the necessary actions for accelerating the transition to electrified transportation. Through our initial internal conversations, we were able to collect and recognize the opportunities by understanding the stakeholder pain points. We engaged in conversation with four different stakeholders who would form the consumer segment for EVs. The stakeholders are enlisted in Table 2.

Table 2. Stakeholder conversation.

Type	Title
HDV Fleet Operators	President / CEO
Department of Homeland Security	Fleet Manager
Last-Mile Delivery	Corporate Controller/Sustainability Team
Transportation Department	Deputy Director, Highways Division
Mid-Mile and Last-Mile Delivery	Fleet Management Director

Questions to the stakeholders were curated around:

1. Major barriers to EV adaptation
2. Highest uncertainties that quantify the risks for EV adaptation
3. Challenges experienced towards electrification of fleet
4. On-premises charging vs public charging
5. Biggest pain points related to current fuel/charging infrastructure
6. Conversations with utilities on setting up chargers on site
7. Cost of ownership of EV fleet
8. Research and development effort that would be beneficial to stakeholders involved in transportation electrification.

5.1.1 Summary of Conversation with Multiple Stakeholders

Stakeholder conversations form the bedrock of effective collaboration and decision making in any project context. The paradigm shift toward transportation electrification has emerged as a transformative force, promising to revolutionize the way we move people and goods. Building a robust charging infrastructure to overcoming technological limitations and addressing consumer concerns, the journey toward sustainable transportation electrification is not without its hurdles. In the following paragraph we summarize the responses to the questions that we asked stakeholders from different organizations that are taking a leadership role in defining transportation electrification.

The commercial trucking industry is not one size that fits all so the requirements for different vehicles vary. Currently commercial trucks operate in different terrains and delivery loads impact the mileage. Usually large, long-distance trailers that use diesel as fuel have a capacity to drive 1,600 to 1,800 miles before needing to refuel (approximately 200 to 300 gallons). One of the major concerns the current industry has with EV adaptation is range anxiety and time required to charge to full capacity.

It should be noted that, based on the strict Hours of Service regulations set by the Federal Motor Carrier Safety Administration, a truck driver can be behind the wheel for a maximum of 11 hours in a 24-hour period, which is followed by a mandatory break of about 10 hours. The 11-hour work window is further split into mandatory breaks of at least 30 minutes after 8 hours of continuous service. Distance traveled in 8 hours is not expected to exceed 500 miles. The current range of commercial trucks available from different manufacturers (like Tesla, Daimler, and Peterbilt) offer ranges of 350–500 miles (under ideal conditions) on a full charge and can charge to 80% in 30–90 minutes if fast charging is available. Provided drivers start their trips on full charge, daily driving hours or miles is not expected to be impacted substantially. However, the planning for charging would be different from how fueling is scheduled, and therefore business models need to be updated accordingly.

One of the major concerns that was highlighted by the commercial trucking fleet operator was a problem with overnight parking for large trailers, especially in big cities. Effective siting of projects allowing overnight charging of such trucks will help to alleviate overnight parking issues. The commercial trucking fleet organization raised questions regarding current grid capacity and how utilities plan to handle that when additional load from EVs is added on top of the current load. They have considered alternative fuel opportunities such as hydrogen as well; however, the high infrastructure and fueling prices are a huge deterrent for scaling up commercial trucks operating with hydrogen. It was pointed out that there is lack of real-world data on operation of long-haul electric trucks, and demonstration projects[37] could help to elevate confidence on EVs and therefore increase their adoption.

The authors of this report had a similar round of discussions with one federal organization and one mid- and last-mile company. The private fleet operator agreed that in the long run maintaining EV fleets may be cheaper, and charging is cheaper than refueling. However, with EVs being an emerging technology, there are potential challenges with adaptation, especially with vehicle production and delivery at scale. However, they currently do not have enough data to effectively quantify the challenges.

The private operator expects to have charging facilities located on site and not depend on public facilities unless otherwise necessary. However, they are concerned about the amount of upgrade each location would require and how the EVs would charge during outages. They are currently testing several routes with a smaller number of EVs, and determining what criteria would need to be added or modified to their route planning tool for efficient and effective delivery. Detailed statistics of the pilot programs were not available. With the fleet company expecting to do most of its charging on site, the companies are expected to perform major upgrades to their facilities and infrastructure; however, they are yet to evaluate several aspects such as interconnection requests, data to be shared with utilities, etc.

The federal entity responsible for last-mile delivery expressed concerns with vehicle mileage, downtime, and challenges that would come with new infrastructure. Similar to the private entity, they are expecting to perform most of their charging on site, but some locations are plagued by lack of parking space needed for vehicle charging. Following the Delivering for America Act, the organization must perform essential services and cannot let their services be impacted. The upfront cost to acquire EVs remains a barrier and there is no visible return of investment metrics that can be referred.

We had conversations with personnel from a state department of transportation who have utilized a completely different model while adapting EVs into their fleet. Rather than owning the vehicles, they went the route of acquiring services from contractors. This model has been highly successful since this relieves the agency from dealing with challenges of owning a vehicle, supply chain concerns, repairs, etc. Currently they have around 300 EVs, both light-duty and mid-duty vehicles, and plan to add another 100 into their fleet. As part of the contract, the service contractor has built fast charging points in combination with traditional charging at their specified facilities. To reduce the charging load on the grid, the contractor has installed several photovoltaic and battery packs on the charger sites that help to achieve the net-zero goals.

Federal agencies responsible for safeguarding the interests of the nation from internal and external threats are concerned with infrastructure availability, cybersecurity, and supply chain issues that have plagued widespread EV adoption. EV vehicles may be required to share information back and forth with the charging point provider or network, and the department is worried about cyber threats. Given the challenges associated with public charging (i.e., unavailability of spaces, wait time, vandalism) the agency expects the majority of charging to happen across stations owned and operated by them. This would provide more control and help reduce concerns. However different subagencies have different missions and would thus need different adoption models. The agency plans to introduce EVs for administrative purposes initially and then gradually increase adoption.

5.1.2 What are their concerns/requirements to electrify vehicles?

From our discussions, there was a consensus about the need for electrifying the transportation sector and the benefits it would provide. Some of the major challenges identified by the stakeholders are summarized below.

1. Range
2. Charging time
3. Extent of availability of charging infrastructure
4. Data sharing and cybersecurity
5. Charger connector inconsistencies and payment method adoption
6. Inferior public charging experience
    a. Charger out of service
    b. Software glitch
    c. Payment processing error
    d. Screen issues – unresponsive or glare
7. Continuation of service in times of outage, or before and after any weather event
8. Lack of operational models to compare use cases.

6.0 Conclusion

This study helps to holistically establish the architectural standing of the fuel delivery system and establishes coupling with the electric grid. In the stages of fuel delivery mentioned from extraction to pumping in gas stations there is a dependency on the electricity network for efficient operation. The fuel delivery architecture is strengthened by a robust network of delivery options including pipelines, railway networks, barges, and on-road transportation. The redundancy is further strengthened by availability of storage terminals at different locations in the form of refineries, storage terminals, and even pipelines. Data suggests that movement of fuel between the PADD regions ensures an adequate availability of finished gasoline for end users. However, certain events in the past and present have challenged the highly redundant and mature gasoline infrastructure that have led to shortage of gasoline at the pumps. Natural calamities, man-made events, and geopolitical events have created turmoil in the availability of finished gasoline that has led to significant demand and supply challenges thus affecting the final price at the pumps. Data from Gas Buddy reveals that after a natural disaster, it typically takes nearly three weeks for fuel stations to resume normal operations. In contrast, electric infrastructure outages are typically resolved more swiftly by utilities. This comparison highlights that while electric outages are efficiently managed, the availability of fuel at pumps is influenced by various other factors beyond restoration efforts alone. With a future electrified transportation sector with electricity available on site it will be easier for consumers to charge and be prepared in the case of an expected emergency. Despite the significant stockpile of fossil fuels, which plays a crucial role in maintaining the current reliability and resilience of the transportation system, certain circumstances can still lead to significant disruptions in the supply chain. These events bring about various impacts not only on the transportation sector but also on the broader economy interconnected with transportation dependencies. Finally, we engaged in conversation with stakeholders to understand their major hurdles and challenges that would slow the growth of EV adoption.

In the next part of the report, we evaluate the motivation for understanding the concepts of sector coupling and help develop a framework that would address the associated risks and vulnerabilities with different modes of transportation. These observations aid in comprehending the intersection of the two sectors and their interactions at a broad level. While the prevalence of mature ICE vehicles may dissuade end users from transitioning to EVs, which are still in a relatively early stage, the coexistence of ICE vehicles and the current fuel supply infrastructure offers valuable insights into the successes and failures of the existing system.

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