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Coupling of the Electricity and Transportation Sectors – Part II

Risk Assessment

February 2024

Bhaskar Mitra
Seemita Pal
Hayden Reeve
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Richland, Washington 99354

Executive Summary

This comprehensive report explores the intricate interplay through “sector coupling” between the transportation and energy sectors and the critical infrastructure challenges faced by the United States. Aligned with the ambitious federal goal of reducing greenhouse gas emissions, the report analyzes the present vulnerabilities in the fossil-fuel supply chain, highlighting instances where the dependence on this industry has been susceptible to local and global disruptions. With a focus on risk assessment, this report establishes a framework to compare the fossil-fuel-based transportation sector with the burgeoning energy sector, considering the evolving technologies in electric vehicles (EVs) and the nascent charging infrastructure.

This study delves into the historical reliability of fossil-fuel-based transportation and identifies opportunities for strengthening sector coupling between the transportation and electric sectors. Assessments of the gasoline-diesel supply chain provide insights into both opportunities and threats, offering a roadmap for creating a more reliable and resilient electrified transportation system. We modeled sectoral coupling scenarios for the current internal combustion engine-based and future EV-dominant landscapes, leveraging qualitative sector attributes to identify relative strengths and weaknesses in Part 1 of the report.

In this report (Part 2), we continue to understand the role of the electric sector on transportation and develop a semi-quantitative methodology to evaluate and compare the risks associated with the fossil-fueled and electric transportation sector during emergency scenarios, drawing from real-world events like hurricanes and geopolitical disruptions. Different operational scenarios for the fossil-fuel and electrified sectors have been developed to understand the risks associated with them. This report concludes with recommendations for the architectural designs of electric charging infrastructure, underlining the need for informed decisions in the transition towards a sustainable and resilient transportation future.

Acknowledgments

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Acronyms and Abbreviations

DOT	Department of Transportation
EIA	Energy Information Administration
EV	Electric Vehicle
FHWA	Federal Highway Administration
ICE	Internal Combustion Engine
NACS	North American Charging Standard (also known as SAE J3400)
NESCOR	National Electric Sector Cybersecurity Organization Resource
NEVI	National Electric Vehicle Infrastructure
NIST	National Institute of Standards and Technology
O&M	operations and maintenance
PADD	Petroleum Administration for Defense Districts
SPR	Strategic Petroleum Reserve

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1.0 Introduction

The transportation and energy sectors are two of the 16 critical infrastructure sectors in the nation, as discussed in the previous part of the report. With the U.S. government having an ambitious federal goal of reducing greenhouse gas emissions by 50-52% by 2030 and reaching net-zero emissions no later than 2050,[1] it is essential to understand the key aspects that lead to the harmonizing effect of the different sectors. In Part 1 of this report series, we dive deep into the architectural aspects of the fossil-fuel supply chain. That report also reviewed present-day vulnerabilities associated with the supply chain and provided several case examples where the dependence on the fossil-fuel industry for transportation have been impacted due to several local and global events.

In this second part of the report, we establish a framework for risk assessment for comparing the present-day fossil-fuel sector and the futuristic electrified sector. We map the performance of both these entities and help to establish a risk assessment framework that would provide the opportunity for better understanding of the electrified transportation sector. Although technology maturity of these fossil-fuel-dependent vehicles and the supply chain has improved significantly over the past century, there have been various incidents (natural disasters, manmade events, geopolitical scenarios, etc.) when the supply chain was strained and created problems for internal combustion engine (ICE) vehicle users. However, typically mitigations have been determined and executed that have further strengthened the system reliability and security. In comparison, the technologies used in electric vehicles (EVs) are significantly newer and still evolving, and the EV charging infrastructure is in its infancy with significant portions of the infrastructure being planned and built as we develop this report.

The combination of the facts that the fossil-fuel-based transportation sector has operated reliably, and there are certain concerns about potential risks of electrified transportation, have led to ICE vehicles still being the technology of choice for a majority of users, although it is abundantly clear that decarbonization is an urgent need. The presence of the fossil-fuel-dependent transportation system creates a potential deterrence for end users to shift to EVs; on the other hand, it provides us with knowledge and insights on what has worked well and what has not for the transportation energy system. There are various opportunities and learnings that we can leverage with the strengthening of the 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 the utilization of infrastructure investments and bringing down the dependence on fuel imports and intermodal transportation of gasoline and diesel.

In Part 1 of this report[2], we provided a concise review of the gasoline-diesel supply chain in order to determine both the opportunities and threats posed by this system. Based on system-level analysis, the factors that have contributed to increasing the current fossil-fuel-based transportation system's reliability and security are identified and discussed. These provide us opportunities to learn from the current system to create a more reliable and resilient electrified transportation system in the near future. This report also pinpointed certain risks related to continuing using gasoline or diesel as the fuel for transportation.

In this report, the sectoral coupling between the electric and transportation sectors for current landscape with dominance of ICE-based transportation and future scenarios with increased penetration of EV are modeled. Qualitative sector attribute data are used to compare the current ICE-dominant and future EV-dominant scenarios of the converged sectors to pinpoint relative strengths and weaknesses of each. This provides a starting assessment of the weaknesses (real or perceived) for electrified transportation that need more research and development.

To systematically compare the performance of ICE- and EV-dominant transportation systems during emergency scenarios, a semi-quantitative methodology for evaluating and comparing risks for both types of systems has been developed and provided. Various types of events like hurricanes, geopolitical events, etc. that have impacted the fossil-fuel supply chain have been summarized and data-based analysis has been performed to demonstrate the type of vulnerabilities and the extent of impacts. Insights regarding benefits and risks associated with electrification have been provided based on stakeholder engagement conducted with selected representatives from national fleet managers as discussed in Part 1. Finally, recommendations on architectural designs of electric charging infrastructure based on understanding of the sectoral coupling between the electric and transportation sectors have been provided. The rest of the report is outlined as follows: Section 2.0 provides the motivation for using sector coupling; Section 3.0 provides an overview of the systemic risk assessment for the fossil-fueled and electrified transportation sectors; Section 4.0 provides recommendations for strengthening grid sector coupling discipline for electrified transportation; and Section 5.0 summaries the findings and next steps required.

2.0 Motivation for Sectoral Coupling Assessment

Sectoral coupling, a dynamic and transformative approach in the realm of energy systems, emerges from the recognition that the synergistic integration of various sectors holds the key to achieving unprecedented levels of efficiency, sustainability, and resilience. Sectoral coupling, as the term suggests, focuses on integration of different sectors like electricity and transportation to achieve greater efficiency, sustainability, and synergy. This approach is motivated by the pressing need to address global challenges, including climate change and resource depletion, while simultaneously unlocking new opportunities for innovation and economic growth. By strategically linking sectors and optimizing their interactions, sectoral coupling aims to create a harmonized energy landscape that not only meets the diverse needs of modern society but also paves the way for a more sustainable and interconnected future. Some of the key motivations for sectoral coupling are as follows:

1. Reducing greenhouse gas emissions – By electrifying transportation, especially using EVs, the overall carbon footprint of the transportation sector can be significantly reduced. This contributes to efforts to mitigate climate change and decrease dependence on traditional ICE vehicles.
2. Energy efficiency – EVs are more energy efficient than traditional ICE vehicles. Sectoral coupling aims to leverage this efficiency to optimize the use of electricity in transportation, reducing overall energy consumption.
3. Energy storage – EVs and their batteries can serve as distributed energy storage systems. When connected to the grid, these batteries can store excess electricity during times of high generation and release it back to the grid during periods of high demand, contributing to grid stability.
4. Technological advancements – Advances in technology, such as smart grids, vehicle-to-grid communication, and energy management systems, facilitate seamless integration between the electrical and transportation sectors. This allows for more intelligent and efficient-energy use.
5. Diversification of energy sources – By coupling the electrical and transportation sectors, there is an opportunity to diversify energy sources. This can include not only electricity from conventional power plants but also from various renewable sources, contributing to energy resilience and security.
6. Economic benefits – The transition to electrified transportation and sectoral coupling can stimulate economic growth by creating new industries, jobs, and opportunities related to renewable energy, EV manufacturing, and associated technologies.

The coupling of the electric and transportation sectors holds immense promise for addressing critical challenges in our energy landscape. Through initiatives like electrification of transportation and advancements in sectoral coupling, we stand to achieve significant reductions in greenhouse gas emissions, enhance energy efficiency, and bolster energy storage capabilities. Moreover, technological innovations pave the way for smarter energy management and integration, while diversification of energy sources strengthens resilience and security.

3.0 Framework for Systematic Risk Assessment

In Part 1 of this report series, we highlight the convergence of the fossil-fuel and transportation sectors, their vulnerabilities, and interfaces on a high level. The fossil-fuel system has co-evolved over a hundred years, along with changes to the needs of the transportation sector. Although development and adoption of EVs as an alternate mode of transportation is in its early stage, the existence of the current fossil-fuel supply infrastructure provides us with knowledge and insights on what has worked well and what has not. When transitioning into a new system, we derive lessons learned from the current fossil-fuel based infrastructure; however, to-date metrics that would help to determine performance levels are not well identified.

It is important to recognize that assessing performance of the two types of systems in an ad hoc manner would not be sufficient to determine the next steps necessary for enabling the transition from the present fossil-fuel-dependent system to the electrified system of the future. However, currently no methodology exists for systematically comparing the performance of ICE- and EV-dominant transportation systems. Therefore, this section provides a semi-quantitative methodology for evaluating and comparing risks between the two types of systems. Various types of events like hurricanes, geopolitical events, etc. that have impacted the transportation and electric sectors have been summarized and data-based analysis has been performed to demonstrate the level of risks with either of the two systems.[3-4]

3.1 Framework for Risk Assessment

It is known that *risk* is a measure of the extent to which an entity is threatened by a potential circumstance or event and is typically a function of the adverse impacts that would arise if the circumstance or event occurs, and the likelihood of occurrence.[5] Risk assessment involves identifying threats and vulnerabilities, and then estimating the impacts due to the potential exploitation of those vulnerabilities by the possible threat actors.[6] *Threat* is defined as any circumstance or event with the potential to adversely impact organizational operations (including mission, functions, image, or reputation), organizational assets, or individuals.[7] The National Institute of Standards and Technology (NIST) defines *vulnerability* as “weakness in an information system, system security procedures, internal controls, or implementation that could be exploited or triggered by a threat source.”[7]

There are different methodologies for risk assessment; however, one common approach is to identify the relevant threats and vulnerabilities and determine the likelihood of their occurrence. This likelihood of occurrence combined with level of adverse impacts provides the estimation of risk. Appropriate mitigations are then identified to lower risk where deemed necessary.

The National Electric Sector Cybersecurity Organization Resource (NESCOR) Technical Working Group 1 has developed multiple documents on the topic of potential cybersecurity failure scenarios and impact analyses for the electric sector. They serve as resources for utilities to gain an understanding of cybersecurity risks and are intended to be useful for risk assessment among several other benefits.[8] Although the NESCOR work products specifically focus on cybersecurity risks, the overall approach for assessing the risks is relevant for broader risk assessment and is fit to be adapted for the purposes of assessing risks in electric and transportation sector converged systems. Therefore, using a similar approach, we developed a risk assessment framework to identify and score the risks due to a range of different threats that can impact the fossil-fuel-dependent or electrified transportation systems. This framework helps in comparing the performance of the two systems in a more objective manner.

3.1.1 Threats and Vulnerabilities

A risk assessment starts with the essential first step of identifying the potential threat factors. A threat model lists all the threat agents that could create a failure scenario or can contribute to creating one. The threat model includes adversaries who may be driven by different objectives to exploit certain vulnerabilities in the system, failures (in people, processes, and technology, including human error), loss of resources, accidents, and natural hazards. Starting with the threat model enables identification of all the relevant failure scenarios that could otherwise be missed if there is a lack of understanding of the comprehensive set of threat agents. Taking into consideration the types of threat agents and vulnerabilities they exploit is also critical for determining mitigation strategies after the risk assessment is complete. Table 1 provides the threat model that has been developed and lists the identified threats and vulnerabilities along with specific examples for the reader.

Table 1. Transportation sector threat model.

Threats	Vulnerabilities	Examples
Natural disasters	Lack of climate hardening	Tornados, hurricanes, flood, earthquake, cyclone
Geopolitical instability	Dependence of economy on imports or exports of energy	Oil embargo, terrorism events like 9/11 attack, OPEC regulations, Ukraine war
Cybersecurity threats	Cybersecurity vulnerability	Cybersecurity attack such as the Colonial Pipeline
Threats to transportation and storage of fuel	Physical vulnerability of transportation and storage infrastructure	Failures or other incidents leading to leaks, spills, or fire
Pandemic or other global events	Change in electricity or transportation needs	COVID-19 pandemic
Extreme weather	Extremes of temperature because of changing weather patterns, thereby resulting in increased demand for electricity. Depending on the available capacity, this can cause independent system operators to operate below reserve margins. Increased risks of wildfires from power lines. Reduced efficiency or shutdowns of the cooling systems at power plants.	Can reduce efficiency at refineries
Workforce	Workforce vulnerability	Lack of training programs, shortage experienced personnel
Panic buying/ consumption	Demand surge or capacity limitation	Shortage of supply or limiting capacity of transmission/distribution
Accidents/faults caused due to negligence	Errors, poor design, noncompliance, inadequate policies or processes, inadequate testing, or maintenance that leads to degradation of systems	Faults caused by vegetation outgrowth or animal burrowing, etc.
Physical attacks	Physical security vulnerability	Attack on infrastructure

Table 1 outlines the potential threats to the transportation system from natural disaster to human-made threats and highlights several additional threats that could disrupt the transportation sector by disrupting the fossil-fuel or energy supply. It is interesting to note that hazards, pandemic, workforce issues, panic buying/consumption, and physical faults are applicable for both types of systems (ICE and EV dominated). Global geopolitical instability and threats to transportation and storage of fuel has the potential to impact the fossil-fuel-dependent transportation sector more than electrified transportation. Such threats tend to sustain for a while after they emerge and can lead to impacts for a few weeks or even months. Cybersecurity threats are typically a greater concern for electrified transportation due to increased network connectivity of both the supply chain equipment and the end-use EVs. However, given the dependency of the fossil-fuel sector on electricity, communications, and control networks, it is highly likely that the fossil-fuel supply chain will feel impacts from cybersecurity events as well. Accidents from downed transmission lines, faulty conductors, and other sources are a cause of concern in the electric sector. Disruption of utilities can potentially impact electrified transportation.

The associated likelihood of the threats can be identified as high, medium, or low (H, M or L). The defined likelihood for each of the threats is not a probabilistic model but an understanding based on a set of factors that may contribute to its increased occurrence. Stakeholders within the electric and transportation sectors will have more granular information for the territory and system under consideration that would help to narrow each threat more specifically. Different parts of the country have varied likelihood of being affected by natural disasters like wildfire, hurricanes, or tornados, and thus their likelihood varies between L, M, and H. Similarly geopolitical instability might not affect the nation's electricity infrastructure directly; however, different components that enable a stable electricity infrastructure are dependent on other countries to maintain a stable supply chain, thus their likelihood varies between L and M depending on present-day relationships. Similarly, other threats and their likelihood to affect the transition to an electrified transportations sector have been provided in Table 2. These metrics can help to have a better understanding of the varied threats in the electrified transportation sector and can be later modified depending on the region and system specifics.

Table 2. Likelihood of occurrence for different threats in the electrified transportation sector.

Threats	Likelihood
Natural disasters	L/M/H (depends on region and time of year)
Geopolitical instability	L/M (depends on geopolitical conditions of the period under consideration)
Cybersecurity threats	M
Threats to transportation and storage of fuel	M/H
Pandemic or other global events	L
Workforce	M
Extreme temperature	H
Panic buying/consumption	L
Accidents/faults	L
Physical attack	L (but increasing)

3.1.2 Impacts

It is essential to establish the possible impacts for each of the above-mentioned threats and their consequences. For example, unavailability of finished gasoline or lack of charging capabilities due to a hypothetical cybersecurity event could impact not just the transportation operations but also lead to impacts on the economy for the period of disruption.

There are 12 categories of potential impacts, and their brief descriptions are provided below.

1. System scale of delivery issues – The impact from this failure could be either geographically localized or might affect regionally or even nationally.

2. Safety concern – Safety criteria that consider whether there is a potential for injuries or loss of life.
3. Ecological concern – Failure scenario that could cause damage to the environment locally or more widespread. The type of damage could also be reversible or permanent.
4. Price impact – Failure scenario that creates a change in the price of either finished gasoline or electricity.
5. Response and restoration costs – Expected costs to respond to the threat and reinstate the system to full operational capacity, resembling its state prior to the occurrence of the failure event. The costs can be determined relative to the operations and maintenance (O&M) budget.
6. System downtime – Failures or inadequacies of the infrastructure that could impact sales.
7. Data compromise – This category considers different types of data breaches that can lead to loss of availability, integrity, or confidentiality of information.
8. Negative impact on production – This category considers the loss of production capacity of finished gasoline for ICE and electricity generation needed for EV charging.
9. Negative impact on transmission/storage – This category takes into consideration the impacts on transmission and storage of energy, which are critical in maintaining reliability and resiliency of the system. In the electric system, negative impacts could mean an event requiring action(s) to relieve voltage or loading conditions, or transmission separation or islanding, up to collapse of the interconnected electrical system. In the fossil-fuel system, it could mean disruption in the movement of fuel through one or more modes due to underlying reasons. This category also considers the reduction in stored energy from baseline value in order to mitigate the threat and restore the system to its state prior to the occurrence of the failure event.
10. Negative impact on customer service – This category assesses the delay or inability of end users to utilize the facility.
11. Immediate economic damage – This category assesses the extent of damage and its lasting impact on the economy.
12. Supplier revenue loss – This category evaluates the impact on both customers and the community. The absence of energy to power vehicles can have far-reaching consequences across the broader economy, resulting in stranded deliveries and individuals unable to commute to work.

The impact categories and associated rubric for scoring are provided in Table 3. For each impact category, there are four possible scores. If no impact of that category is observed or estimated then the score is 0. The score increases to a maximum of 3 if the highest level of impact is observed or estimated. The total impact score is the cumulative of the scores for all categories for a specific threat/scenario.

Table 3. Evaluation of different impact criterion for a particular event.

Categories	Criteria and Scoring Rubric
System scale of delivery issues	0: None; 1: local gas/charging station affected; 2: gas/charging stations in a region affected; 3: gas/charging stations affected across the nation.
Safety concern	0: None; 1: <20 injuries related to ICE vehicles or EV or infrastructure; 2: >20 injuries related to ICE vehicles or EV or infrastructure; 3: > 100 injuries and/or death related to ICE vehicles or EV or infrastructure.

Categories	Criteria and Scoring Rubric
Ecological concern	0: None; 1: local ecological damage such as fire or spill, repairable; 2: permanent local ecological damage; 3: widespread temporary or permanent damage to one or more ecosystems.
Price impact	0: None; 1: <10% change in average daily/weekly price; 2: >10% change in average daily/weekly price in affected region; 3: >10% change in average daily/weekly price across the nation.
Response and restoration cost	0: None; 1: marginal (within maintenance budget); 2: up to 2% of O&M budget; 3: >10% of O&M budget.
System downtime	0: None; 1: isolated recoverable challenges or errors for a nozzle/port; 2: unplanned unavailability of multiple nozzles/ports or stations for less than 8 hours; 3: unplanned unavailability of multiple nozzles/ports or stations for more than 8 hours.
Data compromise	0: None; 1: loss of essential information (reversible); 2: loss of essential information (reversible with consequences); 3: shutdown of operation leading to outages.
Negative impact on production	0: None; 1: small extraction, refinery, generation facility offline or degraded operation of large facility; 2: more than 10% loss of extraction, refinery, generation capacity for 8 hours or less; 3: more than 10% loss of extraction, refinery, generation capacity for more than 8 hours.
Negative impact on transmission/storage	0: None; 1: transportation, transmission, storage level down by <10%; 2: transportation, transmission, storage level down by >10% but Strategic Petroleum Reserve (SPR)[*] release not needed; 3: transportation, transmission, storage level down by >10% and SPR release needed.
Negative impact on customer service	0: None; 1: up to 4-hour delay in customer ability to contact provider and gain resolution, lasting one day; 2: up to 4-hour delay in customer ability to contact provider and gain resolution, lasting a week; 3: more than 4-hour delay in customer ability to contact provider and gain resolution, lasting more than a week.
Immediate economic damage	0: None; 1: local businesses down for a week; 2: regional infrastructure damage; 3: widespread runs on banks.
Supplier revenue loss	0: No effect; 1: negative publicity but does not cause financial loss; 2: negative publicity causing up to 10% reduction in revenue; 3: negative publicity causing more than 10% reduction in revenue.

3.1.3 Risk

Finally, an assessment of relative risk is developed based on the threat and likelihood categories and levels introduced above. (A worked example of the scoring system, applied to hurricanes Ike and Irma and their aftermaths is presented in the next section.) The overall risk assessment is conducted in accordance with the threat categories outlined in Table 1. The risk assessment utilizes the threat likelihoods (from Table 2 or an adapted version) and the total impact scores (from Table 3). We then amalgamate these factors (i.e., sum the impact scores) to ascertain the level of risk, as shown in Table 4. For instance, if the likelihood of a threat is deemed low and the cumulative estimated impact of the threat falls below a score of 6, then the risk level is categorized as low. Conversely, if the likelihood of the threat likelihood is high and the total estimated impact score surpasses 12, the risk is deemed high—an assessment that aligns with common intuition. To establish impact thresholds, the team performed assessments

[*] The SPR refers to a government-controlled emergency stockpile of crude oil and petroleum products, primarily maintained to provide a quick and reliable source of energy during times of energy crises, natural disasters, or other emergencies. The U.S. SPR played a crucial role in mitigating a significant long-term shortage of gasoline during emergency conditions by releasing several million barrels of crude oil.

on various events (an example for hurricanes is presented in the next section), ensuring a comprehensive understanding of the risk landscape. This approach aims to provide a robust framework for assessing and mitigating risks posed by potential hazards.

By integrating threat likelihood and impact assessments, we enable informed decision making and proactive risk management strategies to enhance resilience and minimize the adverse impacts of future events.

Table 4. Risk matrix assessment example.

		Threat Likelihood		
		Low	Medium	High
Impact	High (>12)	M	H	H
	Medium (7-12)	M	M	H
	Low (0-6)	L	M	M

3.2 Use Cases for Comparison of Risk

To understand the scoring system, we provided one example: Hurricane Ike. We analyze the devastation caused by the hurricane according to the impacts introduced in Section 3.1.2. An example impact analysis and likelihood of occurrence on today's transportation infrastructure dominated by ICE and a futuristic transportation sector involving predominantly EVs for Hurricane Ike is shown in Table 5.

Table 5. Impact analysis for Hurricane Ike example.

Criterion	ICE	EV
System scale of delivery issues	3	2
Safety concern	0	0
Ecological concern	3	1
Price impact	3	2
Response and restoration cost	3	3
System downtime	3	3
Data compromise	0	0
Negative impact on production	3	1
Negative impact on transmission/storage	3	3
Negative impact on customer service	0	0
Immediate economic damage	1	2
Supplier revenue loss	0	0
TOTAL	**22**	**17**

Hurricane Ike hit the U.S. mainland in September 2008. It was a powerful storm with damaging winds; a category 2 hurricane during landfall. From the limited data available, the impact categories were scored for the system that existed during that time, which is dominated by fossil-fuel-dependent ICE. Based on the characteristics of the hurricane and observed impacts on the electric sector, scores were also estimated for the different categories assuming a scenario with electrified transportation. It is observed that the ICE-dominated, weakly coupled, grid-transportation sector has a higher level of impact primarily due to the change in oil prices and the ecological impacts caused by oil spills.

As noted in Part 1 of this report, Petroleum Administration for Defense District (PADD) 3 is the largest producer of oil in the United States. Hurricane Ike resulted in shutdown of 14 refineries that accounted for almost 3.8 million barrels of production per day.[9] This led to substantial shortage in fuel across the nation. The highest score of 3 was allotted to it under system scale and delivery issues. The hurricane impacted the power grid and resulted in widescale outages across the region; however, the lingering effects of the outage was only local and did not spread across the nation, thus getting a score of 2 that reflects more regional and local impacts. Similarly, approximately 500,000 gallons of oil were spilled from 1,500 sites into different regions resulting in large scale ecological concerns;[10] however, trees knocked out several lines leading to power outages but no ecological damages were reported. With a transportation sector dominated by EVs, it is assumed there will be damage caused to vehicle batteries that could lead to leaks and local concerns.

To justify our scoring for the price impact criterion, we looked at the change of finished gasoline in PADD3 and other regions during this period. In an EV-dominated transportation sector there could be excess demand to charge vehicles to either evacuate or use the vehicle as a mobile battery, this could lead to temporary increase of the locational marginal price of electricity, but this effect will again be regional to wholesale prices (not to retail prices), and its impact not felt throughout the nation.

Hurricane Irma hit the U.S. mainland in September 2016, and was also categorized as a powerful storm that was category 4 during landfall. However, from the impact perspective for both ICE- and EV-dominated systems, the total score for Irma came to 10, which is less than that of Hurricane Ike.

4.0 Recommendations for Strengthening Grid-Transportation Sector Coupling and Its Application

This section summarizes the strengths of the present grid-transportation system, which is highly fossil-fuel dependent versus the strengths of the grid-transportation system of the future, which is expected to be highly electrified. Based on the high-level comparison of these two systems, as well as a systematic approach of their performance under adverse conditions, recommendations are provided for enhancing the grid-transportation converged systems in an accelerated manner to perform at par or better than the current fossil-fuel-dependent transportation system.

4.1 Strengths of the Fossil-Fuel-Dependent Grid-Transportation Converged System

The fuel-delivery network refers to a network of facilities, systems, and processes to enable the production, transportation, distribution, storage, and delivery of fuel. Networks of pipelines, refineries, storage facilities, and distribution centers are complimented by the transportation sector (including water, rail, and road) to deliver fuel to gasoline stations as described in the previous sections. The fuel supply chain is highly reliable. Based on the assessment of the architecture of the system that has been performed as part of this effort, the following factors are attributed to its reliability:

1. Storage – The fossil-fuel supply chain is flexible to changing demands by location and time which may happen due to several different factors. This flexibility is imparted by the presence of vast amounts of stored crude and refined oil throughout the system. The ability to adapt to changes enhances the robustness of the fuel-delivery architecture.

   Local events that create temporary production and supply disruptions can still create shortages in gasoline stations affecting evacuation, freight, supply chain movements, etc. Data collected from the Energy Information Administration (EIA) show an annual inventory to consumption in different PADDs (Figure 1). An average of 234 million barrels (excluding SPR, New York state reserves, and storage of gas stations) is maintained. This capacity is estimated to last for 27 days. The inventory of finished gasoline does not include the additional stock of crude oil maintained at SPRs.

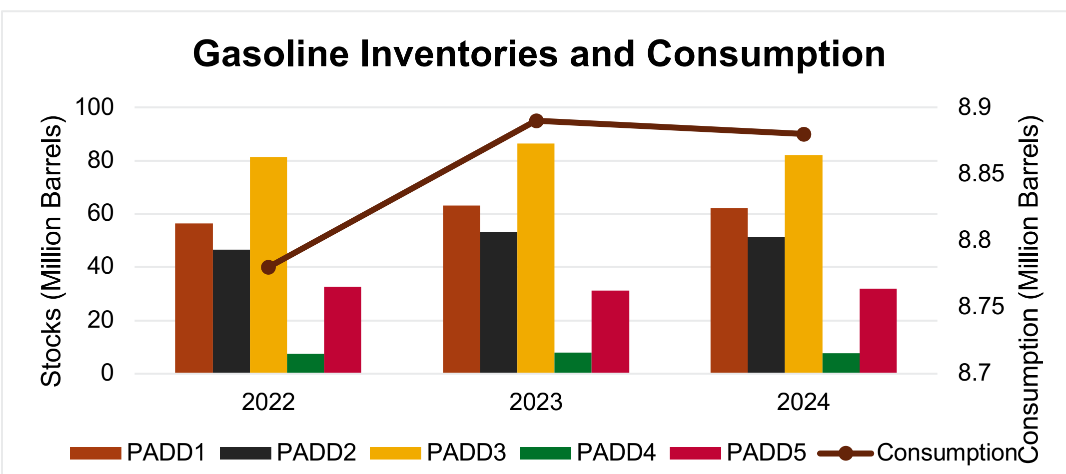

Figure 1. Annual finished gasoline inventory and consumption at different PADDs.

Our analysis using data and information collected from EIA and other agencies[11,12] show an interesting analysis of stocks at local gas stations. Daily gasoline sales averages around 7,000 barrels as shown in Table 6.

Table 6. Gasoline sales chart.

Daily Gasoline Sales				From EIA		
# Sales per dispenser/hour		Total Sales	Total Gasoline Sold	Total Gasoline Sold/Day	Estimated Gasoline Pumps	Total Sales/ Pump
8am to 9pm	Otherwise	[9 dispensers/ station]	[Avg 9.5 gal/sale]	8.79 million barrels	147,000	7,175 Gallons
6	3	837	7,951 Gallons			

With an estimated storage of 30,000 to 40,000 gallons available and the consumption pattern shown in Figure 1, it is estimated that gas stations have 3 to 5 days of supply. Therefore, there exists a huge cushion of fuel stock that is a critical factor behind the current level of reliability and resiliency of the fossil-fuel-dependent transportation system. However, still under scenarios of acute disruption in the supply chain due to natural disaster, cyberattack, or emergency declaration, panic buying may lead to untimely shortages of gasoline that can add to the frustration and challenges of people trying to evacuate from different regions.

2. SPR – Over the years and through multiple events, the fuel-delivery system has learned to harden the system further to be more resilient to adverse events. After the oil embargo, the SPR was set up as the world's largest supply of emergency crude oil. It was established primarily to reduce the impact of disruptions in oil supplies. The sheer size of the SPR (authorized storage capacity of 714 million barrels) makes it a significant deterrent to oil import cutoffs and a key tool in foreign policy. Emergency drawdowns and exchange agreements from the SPR have occurred multiple times since 1991. Emergency drawdowns typically occur when the United States is confronted by economically threatening disruptions in oil supplies.[13] Currently, present-day storage for electric grids do not reach a similar scale; however, strategic locations are identified where alternative fuel storage units will be set up to increase adaptation of alternative fueled mode of transportation.

3. Global auction influencing prices – Oil prices are the result of thousands of transactions taking place globally at all points in the supply chain. Essentially oil markets are a global auction; therefore, when markets are tight (when demand is high or available supply is low), the bidder must be willing to pay a higher price, while during times when demand is low or available supply is high, a bidder may choose not to outbid competitors and instead wait for lower priced supplies.[14] The established market for electrical systems are regional. Market participants understand the day-ahead prices and expected variations, and these prices are not influenced by geopolitical challenges. The absence of direct price regulation in our system offers a crucial advantage by fostering greater market flexibility. Without rigid price controls, market forces can respond dynamically to changes in supply and demand, allowing prices to adjust more freely in response to underlying economic conditions.

4. Standardization – The end-use interfaces are standardized. For example, all gas stations need to comply with refueling hardware specifications for nozzles and typically sell three main grades of gasoline based on the octane level. The experiences at the final delivery points (e.g., gas stations) are uniform for end users. For the electric charging infrastructure, differences of charging standards, multiple stakeholder engagement, and different charging

levels makes the final end-user application more complex than the fuel-delivery architecture. Efforts are currently made for a unified infrastructure akin to the existing fuel network in the future.

5. Redundancy and diversity – A strong interconnected fuel-delivery architecture ensures the system is redundant. The dependence on multimodal transportation and diverse entities for movement and storage of oil introduces diversity in the system. Therefore, if one section of the system is degraded/disrupted then it relies on the remaining sections to ensure oil supply chain disruption is avoided.
6. Business architecture – The gasoline supply chain is decentralized in nature. Several operators are involved in transportation, distribution, storage, and other operations. Similarly for sales, retailers, distributors, and suppliers operate independently within specific regions or markets. There may be few entities that are large enough to have their presence in all segments of the system and therefore have a vertically integrated and centralized system, but such entities are not the most common.

4.2 Strengths of Grid-Transportation Converged System with Electrified Transportation

The electric power delivery system is an ultra-large-scale, complex system consisting of generation, transmission, and distribution sectors facilitating the production, transmission, and delivery of electricity from the various energy sources to the loads. With electrification of the transportation system, the reliance on gasoline and diesel supply chains for fuel decreases and the reliance on the grid for electric energy supply increases.

Reliance on fossil fuel for the transportation sector introduces national security concerns since there is interdependence on global imports and exports of oil. Also, since oil prices are largely determined by OPEC’s activities, these cannot be controlled by a single nation. Periods of low fuel supply globally have the potential to increase oil prices, which can negatively impact the economy. Electricity prices, on the other hand, are not directly dependent on any global market or global cartel. Electrified transportation provides greater independence from global energy markets and geopolitical concerns potentially increasing natural energy and economic security.

Crude oil is generated at well sites that are concentrated in specific areas. Crude oil refining happens at refineries that are typically located closer to the production or intake sites. This makes oil production and refining somewhat localized in nature. Electricity is generated regionally, and with the increased penetration of distributed energy resources (DER), it can also be generated locally if needed.

Unlike the fossil-fuel-dependent system that is critically dependent on the transportation sector for movement of fuel, the electric sector is only indirectly dependent on the transportation sector for movement of resources to generation plants (for example, rail transport of coal). The number of fossil-fuel-based generators has been reducing and renewable generation is expected to increase in order to meet the nation’s clean energy goals, and therefore the existing dependence will further reduce.

The transportation of fossil fuel is dependent on several other factors, and it takes days to weeks to deliver fuel; this speed limitation can exacerbate fuel availability challenges especially in times of crisis. However, electrical infrastructure can deliver to end users at the speed of light. Electrified transportation has another advantage of enabling on-premises vehicle charging, which is especially true in case of personal EVs. Personal ICE vehicles can only be refueled at gas stations.

4.3 Requirement of Information Exchange Between Involved Entities

With an evolving electrified transportation sector, there will be a pressing need to have access to different entities for an efficient operation of the charging network. Presently, end users of the fossil-fueled transportation sector operate independently from the operational patterns of utilities. However, any outages could disrupt the ability to pump gasoline. In an electrified transportation ecosystem, utilities would need to collaborate closely with local and federal departments of transportation to identify travel patterns especially for freight and invest in developing charging infrastructure. Currently, utilities manage demand peaks through efficient load estimation and economic dispatch models, responding to fluctuations over several hours. However, the installation of megawatt-level charging stations may introduce unexpected demand peaks. Failure to anticipate these charging requests could result in unforeseen outages. Similarly, freight and trucking operators expecting to charge onsite or at different locations along a route may need to coordinate such requests in advance to facilitate a smooth charging experience. Utilities on the other hand can post real-time outage information and help reroute vehicles expecting to charge from getting stranded at those locations.

4.4 Summarized Comparison

Table 7 provides a summarized comparison of the two systems and their characteristics. The cells with light green background indicate the advantages under the different categories that have been considered.[15]

Table 7. Comparison of characteristics between present (fossil-fuel dependent) and future (electrified) grid-transportation converged system.

	Fossil-Fuel Supply Chain	Electricity Supply Chain
Energy independence	Depends on global imports and exports of crude oil; shortage of supply impacts entire economy	With increased clean energy adoption, the nation will be relieved of interdependence on the global crude oil market
Coupling between sectors	Dependent on electricity for refining, pumping, dispensing, etc.	EVs are completely dependent on the electric sector, and with clean energy adoption, fossil-fuel needs for thermal generation will be reduced
Production location	Only well sites and refineries, and may be imported	Spread throughout the nation, DERs can be local
Dependence on pipelines and transportation	Highly dependent on 190,000 miles of pipelines; 1,000s of rail cars, vessels, barges, and 100,000 tanker trucks for fuel distribution; massive amount of fossil fuel consumed for transporting gasoline and diesel	Dependent on electric infrastructure; with reduction of fossil-fuel-based generation, dependence on pipelines and transportation sector for supply chain will further reduce
Transmission speed	Days to weeks	Approximately the speed of light
Energy storage	Massive storage of crude and refined oil exists	Energy storage is currently sparse and limited
SPR	Helps relieve rare situations of acute shortage	Distributed storage facilities are available; however, strategic storage similar to SPR do not exist

	Fossil-Fuel Supply Chain	Electricity Supply Chain
On-premises energy replenishment	Some industrial and commercial entities may have on-premises refueling	Most residential, commercial, and industrial entities may primarily depend on on-premises recharging
Energy cost	Fossil-fuel cost is market based and influenced by multinational oil cartel	Retail and wholesale electricity prices are region/location based and often highly regulated or monitored
Point-of-sale experience	Fossil refueling experience is standardized, fast, and accessible	EV charging has a competing set of charger and platform formats

Based on Table 7, energy storage, strategic reserve, and point-of-sale experience are the categories where fossil fuel has a current edge over the electricity supply chain. Since EVs are completely dependent on the electricity infrastructure for operation, it is essential to enhance the electric sector architecture to make it more robust by prioritizing infrastructure upgrades and use of investment for creating jobs. Strategic reserves for energy storage needs to be planned to help mitigate disaster scenarios and provide charging in times of need. Steps are being taken to identify essential corridors[16] where some of the reserves can be built and can help to charge vehicles in times of need. Similarly, critical equipment and infrastructure needs to be strategically placed. And finally, harmonization of standards, charging ports, and data availability need to be standardized. This would help improve the point-of-sale experience for end users.

4.5 Setting Minimum Requirements for Access to Charging

One of the major concerns related to EV charging happens at the end-user interface. While the EV market has seen tremendous growth and potential in the last 5 years, addressing the concerns related to charging infrastructure availability, charging speed, and charger compatibility and standards, the public charging experience and several other challenges have not been clearly articulated. Identifying opportunities to address these concerns that directly or indirectly impact access to charging will help rapidly increase the rate of adaptation. In Table 8, we list the concerns and steps that are needed to address these challenges.

Table 8. Identification of appropriate opportunities to address concerns related to EV charging.

Concerns	Opportunities
Extent of availability of charging infrastructure	Guidance necessary on how submission and approval of interconnection requests may be made streamline and consistent across states to reduce process delay
Charger out of service	Amendment of exclusion criteria related to availability requirement mentioned in the National Electric Vehicle Infrastructure (NEVI) requirements (discussed in Section 5.5)
Data sharing and cybersecurity	Minimize data sharing between exchanging entities to those essential for enabling charging and secure the communication
Inconsistencies in connector	The final rule of NEVI had backed combined charging systems to include J3400 but as long as it has CCS connectors first, gradually automakers like Ford, General Motors, Fisker, Hyundai, and Kia have decided to join the agreement to adopt Tesla’s North American Charging Standard (NACS) charging port, the most common charging standard in North America
Inconsistencies in payment method adoption	NEVI has attempted to initiate this effort, but it needs to be harmonized through stakeholder engagement and then standardized
Inferior public charging experience (software/app issues, payment processing error, screen issues)	Apps should be optional (almost like brand loyalty cards/accounts) and payment interfaces should be similar to gas stations

Continuation of service during major events	Needs dedicated research based on analysis of electric grid, transportation, and gas station/charging station data for events (pre-, during, and post-event)
Lack of operational models to compare use cases	Needs to be developed, benchmarked, and made widely available

4.6 Setting Minimum Requirements for Enhanced Reliability of Charging Infrastructure

The Department of Transportation (DOT) along with the Federal Highway Administration (FHWA) released a final action rule for NEVI. This final rule establishes regulations that define the minimum standards and requirements for projects funded under the NEVI Formula Program and projects for the construction of publicly accessible EV chargers under certain statutory authorities, including any EV charging infrastructure project funded with federal funds that is treated as a project on a federal-aid highway.[17] The guidelines and prerequisites encompass the different aspects of EV charging infrastructure. Interoperability that has been a major concern for enabling wider acceptance of EV charging has been investigated under this guideline. Processes to handle data, their format, submission procedures, etc. are the other list of items that have been covered. Furthermore, these regulations address the network connectivity of EV charging infrastructure and ensure that information regarding publicly accessible EV charging infrastructure, including locations, pricing, real-time availability, and accessibility through mapping applications, is made readily available.

The guidelines that EV charging infrastructures established through this funding have an average annual uptime greater than 97% per charging port, which roughly translates to less than 11 days of outages. However, the 97% is stated while allowing a number of exclusions. The exclusions include hours of operation beyond the specified hours of operation of the charging station, electric utility service interruptions, and failure to charge or meet the EV charging customer's expectation for power delivery due to the fault of the vehicle, scheduled maintenance, vandalism, or natural disasters. The uptime minutes are calculated as:

$$Uptime = \frac{T_{total} - (T_{outage} - T_{excluded})}{T_{total}} x100$$

where,

T_{total} total minutes in a calendar year,

T_{outage} total minutes of outage in the previous year,

$T_{excluded}$ minutes of outage due to other challenges as mentioned in the guidelines.

This is a starting point for ensuring greater accessibility and reliability of the charging stations; however, two issues are observed that need to be addressed:

- Data for verifying uptime – This final rule establishes quarterly, annual, and one-time data submittal for all projects funded under the NEVI Formula Program and any EV charging infrastructure project funded with federal funds that is treated as a project on a federal-aid highway. However, the data submittal request does not include data required to verify uptime of charging points or improve uptime definition and exclusion criteria. The data submittal request also does not include the forecasted maintenance schedule. Without these data it is difficult to determine duration of discontinuity in operation of individual charging ports due to maintenance activities. These maintenance activities are expected to reduce uptime from the stated 97%, and a baseline setting on the average cumulative maintenance period would be beneficial. Submittal of a forecasted schedule of maintenance would help distinguish between unplanned and planned maintenance periods.

- Exclusion criteria – The exclusion criteria include electric utility service interruptions, which means the reliability of the charging station will be 97% or less (since there are more exclusion criteria) after the outage hours due to utility service disruptions that have been already subtracted. Further, during utility outages residential/commercial/industrial charging may be impacted. So, it would be critical for the public charging stations to be operational for EV loads in critical need of charging so that transportation-dependent operations are not impacted. Therefore, including this exclusion criteria would add a significant level of inconvenience for EV owners.

If we look at the fossil-fuel-dependent transportation system, we will find that a number of gas stations have backup power during an emergency. Some of the states require backup power or provide support for gas stations to install backup generation. For example, the New Jersey Economic Development Authority had announced revised guidelines for the Retail Fuel Station Program, which was a $7 million grant program allowing retail gas stations faster and more reliable access to backup power during an energy emergency, addressing emergency fuel supply challenges highlighted during Superstorm Sandy.[18] Florida and Louisiana require motor fuel facilities, including service stations, to be able to switch to an alternative energy source during a power outage.[19,20] AB 1339, was proposed in the California legislature in 2011 to allow service station owners a tax credit for up to half the cost of buying and installing an emergency standby generator, up to $2,500 per generator.[2]

It is important to look at the SAIDI (System Average Interruption Duration Index, which is the minutes of electric interruptions per year, the average customer experienced) and CAIDI (Customer Average Interruption Duration Index, which is the average number of minutes it takes to restore electric interruptions) for different utilities.[21] We need to systematically study the estimated average duration of outages at charging stations within any utility's territory, and the percentage of EVs that may need to be served to not impact transportation-dependent activities during that time, to determine if all charging stations need to have some energy storage or strategically selected public stations should have energy backup.

4.7 Requirements for Investigating Disaster Mitigation

Using the electrified transportation system as a model for disaster mitigation would require comprehensive analysis of different factors:

1. Review existing disaster preparedness and response plans to understand the current strategies in place.
2. Identify gaps and areas where EVs could enhance disaster response capabilities.
3. Evaluate the existing EV charging infrastructure in the disaster-prone areas.
4. Assess the capacity of charging stations to support emergency response activities.
5. Estimate vehicle availability to perform essential evacuation tasks.
6. Investigate the resilience of the EV charging infrastructure to power outages and disruptions that may occur during disasters.
7. Identify and install strategically alternative power supply sources that would serve in emergency situations under different disruptions.

8. Conduct public awareness campaigns to educate the community about the role of EVs in disaster mitigation and response.
9. Implement data management systems to track and analyze the movement of EV fleets during disaster response.

4.8 Other Structural Changes

Following are some structural changes that are needed to improve the performance of the charging infrastructure.

- The electricity delivery chain for EV charging would benefit from greater decentralization instead of depending on utilities and their centralized operations. This can be achieved by integrating DERs, including energy storage strategically, and enabling bidirectional power flow between the grid and the vehicles.
- New business models need to be explored. It is known that gas stations make most of their profits in their stores on sales of food and drinks, and over time that business model has become prevalent. In case of charging stations, given the expected charging time, the business model needs to be modified to fit the needs of EV owners. For example, dining or parking conveniences need to be considered for inclusion into the business models of the charging stations.

5.0 Summary and Next Steps

The key outcome of this sector coupling report addresses in detail the overall existing architecture of the fossil-fuel industry from extraction to final delivery to the consumers as discussed in Part 1 of the report. The fossil-fuel industry has evolved over more than a century and at present is reliant on a robust network of delivery systems using pipelines, railways, barges, and on-road transportation to deliver fuel. The expanse of the fuel architecture extends beyond the nation, and the complexity of this system using multimodal transportation for fuel delivery is high; therefore, shocks to the oil supply chain (irrespective of whether they are local or global) are difficult to navigate. Since some of the PADD regions have greater concentration of facilities for crude oil production or refining, local events can have far-reaching impacts in multiple PADD regions that may be dependent on the affected region for oil supply.

The robustness in the supply chain is further achieved through abundance of storage at different points in the supply chain. We estimate there would be approximately 27 days of uninterrupted supply of finished gasoline to meet the continuous demand under severe challenges that can halt extraction. Even with such a robust supply chain management, there have been scenarios when the vulnerabilities were exposed under conditions of natural disaster, cyberattack, geopolitical tensions, and even the recent global pandemic. When severe shortages of fuel were recorded that led to spikes in prices, the shortages were met through release of crude oil from the SPR. Even with a highly redundant and robust fuel-delivery architecture supplemented by storage at all stages, studies have shown it takes almost three weeks after an event to return to normal conditions. Currently the fossil-fueled transportation sector is heavily reliant on the electricity infrastructure to extract, refine, transport, and make fuel available for use.

The transition to a fully electrified transportation sector provides an abundance of opportunities for innovation, growth, and sustainability. Transportation is one of the primary producers of greenhouse gas emissions, and as we seek to reduce the dependance on fossil fuels, electrification of the transportation sector seeks to play a major role in achieving these goals. To assess the impacts to threats and vulnerabilities, we took inspiration from NESCOR and developed a risk assessment matrix that identifies the threats and vulnerabilities for both ICE and EVs and how different failure modes would impact their operation. Information was available to assess and score the ICE vehicles; however, the authors used their judgement and understanding to provide similar evaluation metrics for an EV-dominated society. Our assessment and evaluation show that EV domination would be at a lower risk of failure than ICE with the current available infrastructure. By comparing the current infrastructure for both ICE and EV we highlight their individual advantages in certain sections and areas of improvement for an EV-dominated transportation sector.

FHWA, along with DOT, released the NEVI Formula Program that establishes regulations that defines the minimum standards and requirements for projects that would help to establish and develop the EV infrastructure. We spoke with several stakeholders to identify pain points and understand what would make it easier to transition their fleets to EVs. There was consensus on several challenges that were raised and some of those will be addressed in the NEVI guidelines. It was understood that the current lack of case studies and data prevents further assessment; however, there are opportunities for demonstration projects that would help to bolster the confidence of stakeholders.

As immediate next steps, there is a need to create case studies to understand the role of EVs in response to edge-cases (i.e., disaster scenarios). How can development and strategic placement of energy storage facilities help to relieve pressure from the charging stations by considering the average outage scenarios in different regions? Would better use of home charging in response to evacuation orders bolster local generation in certain areas or coordination between several entities? By analyzing historical outage data and disaster response scenarios, recommendations can be developed to boost the energy infrastructure to adequately manage additional demand from EV charging under stressed conditions. Most agencies transitioning to EVs expect to own their charging infrastructure to avoid complexities that currently exist with public charging facilities. The pattern of charging would vary between entities dependent on their usage, which would lead to several complexities especially when planning a trip. A centralized infrastructure that uses information from several entities to develop a fleet management tool will be essential. This will help consumers understand and plan under outage scenarios and efficiently map their route and charging.

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