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Unveiling sectoral coupling for resilient electrification of the transportation sector

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Electrifying the transportation sector is crucial for reducing greenhouse gas emissions and offers numerous benefits including increased energy efficiency, lower total ownership costs, enhanced national energy security, and improved air quality. Despite the availability of necessary technologies, fully integrating the transportation and electricity sectors presents challenges in understanding all benefits and risks. Previous studies have not highlighted the role of coupling between these sectors. To better understand this coupling, this work reviews the structure of the current fossil-fuel-based transportation sector (including its dependence on the electricity sector) and case studies of its vulnerabilities to key risks. By adopting a systemic perspective, we uncover the indispensable interplay between the transportation and electricity sectors, shedding light on previously neglected dynamics. Leveraging the principles of grid architecture (GA), we introduce a hierarchical approach to assess vulnerabilities within the prevailing fuel-based transportation system and elucidate pathways for enhancement through electrification.

With increasing commitment by global communities to decarbonize investments, national electric grids are undergoing significant transitions from fossil-fuel-based thermal power generation to wind, solar, geothermal, hydro, and storage technologies. The transportation sector is reported to be the largest source of direct greenhouse gas (GHG) emissions and the second largest when indirect emissions from electricity use are allocated across sectors according to data provided by the Environmental Protection Agency (EPA)¹. The transportation sector is an end-use sector for electricity but currently accounts for a relatively low percentage of total electricity use. The US government has an ambitious federal goal of reducing GHG emissions by 50–52% by 2030 and reaching net-zero emissions no later than 2050². It aims to have zero-emission vehicles make up half of all passenger vehicles sold in the USA by 2030 and transition to a net-zero-emissions economy by 2050³. In June 2020, an announcement by the California Air Resources Board's Advanced Clean Truck Regulation to require 100% zero-emission truck sales by 2045 further pushed momentum toward electric vehicle (EV) adoption⁴. Soon, this mandate was adopted by 15 other states in the USA. A report highlighted the importance of regulating the emissions and fuel consumption of medium- and heavy-duty vehicles—a subset that contributes 22% of transportation energy use in the USA⁵. This emphasizes the importance of transitioning these sectors to electric power to reduce carbon emissions effectively.

In 2022, the electricity sector was the second-largest source of US GHG emissions, contributing 25% of the national total. However, since 1990, GHG emissions from electric power production have decreased by approximately 15% because of a shift towards lower- and non-emitting

sources of electricity generation and improvements in end-use energy efficiency. The transportation sector currently has a relatively low percentage of electricity use and thus indirect emissions, but it is growing because of the use of electric and plug-in vehicles⁶. In 2023, there was 3% reductions in CO₂ emissions primarily resulting from replacing coal-fired generations and replacing them with natural gas and solar and other renewable energy sources. However, the emissions from the transportation sector remained unchanged from 2022⁷.

“Sector coupling” is a concept that addresses a potential design for the power industry of the future. It requires the coupling of at least two sectors, like power-to-gas⁸. Traditionally, the energy sectors, i.e., electricity and heat supply, transport, and industry, have functioned largely independently from one another. Thus, the concept of sector coupling means that the electricity sector would become the central pillar of the energy system, supplying the other sectors—heat, transportation, and industry—with energy in various ways, a scheme described by the term “Power-to-X.” There are opportunities for efficient and flexible energy solutions realized by integrating independent sectors that otherwise would have little exchange of energy or mass flows among each other^{9,10}. The large-scale and rapid electrification of the transportation sector will introduce it to different kinds of dependencies on the electricity sector that we have not experienced before.

The current and future connections between the fossil fuel, electricity, and transportation sectors are not well understood or documented. Examining the dependencies within the fossil-fuel model offers critical insights for an electrified transportation future. By viewing both sectors together, we can see how the fossil fuel supply chain relies on electricity and

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how this interdependence will evolve as transportation shifts toward electrification. In this article, we map the sectoral coupling between the electric and transportation sectors for the current landscape dominated by internal combustion engine (ICE)-based transportation and future scenarios with increased penetration of EVs. This helps to systematically compare the performance of ICE- and EV-dominant transportation systems during different scenarios by developing a semi-quantitative methodology for evaluating and comparing the risks for both types of systems. Additionally, we provide insights regarding the benefits and risks associated with electrification.

In ref. 11, the authors investigate sector coupling in all energy sectors to understand its role in a decarbonized power grid through variability in energy production. The need for renewables to support the growth and expansion of electrified transportation has been studied in refs. 12,13. The authors of ref. 14 emphasize the impact of transportation electrification on the energy system and highlight a study examining a system with 100% electrified transportation. This will only be feasible where the additional load created due to transportation electrification is balanced by a significant rise in renewable energy generation. Similar studies have focused on understanding the role of sector coupling^{15–20}. Learning from these lessons empowers us to design a future transportation system that is both environmentally sustainable and resilient to the complex interplay between energy sectors. Embracing this proactive perspective allows us to provide a basis for a seamless transition to electrified transportation. Previously published articles reflect the fusion of upcoming energy systems and the escalating significance of electricity across all energy domains pertaining to a 100% renewable-energy-driven system but do not provide deep insight into the challenges faced by the legacy fossil-fuel-driven transportation system and the strong interties that it presently holds with the electricity sector. In this work, we utilize data to highlight the tight coupling between the fossil-fuel and electricity sectors that enable the transportation sector, along with the different vulnerabilities that have resulted in the unavailability of finished gasoline at the pumps. Although the shift toward renewable energy and electrified transportation is well studied, the complex dependencies between the fossil-fuel and electricity sectors remain insufficiently studied. This oversight poses challenges, as fossil fuels still play a vital role in electricity generation, grid stability, and peak demand management. Thus, a deeper understanding of these interconnections and vulnerabilities, particularly in relation to fuel supply disruptions, is essential in ensuring a smoother transition toward a resilient, fully decarbonized energy system.

An exploration of the intricate relationship between petroleum production and electricity usage unveils the multifaceted interplay between the energy sectors. Data from the Energy Information Administration (EIA) indicate that the total petroleum production of the USA averaged about 20.079 million barrels per day (b/d) in 2022²¹. Oil extraction wells located at remote sites may use diesel generators, but a fair number of oil wells depend on electricity. Based on Greenhouse Gases, Regulated Emissions and Energy Use (GREET) model-based data, which were available from EIA's annual survey in 2006, refineries in the USA purchased a total of 39,353 million kilowatt-hours of electricity for their operations²². Additionally, pumping crude or refined oil through pipelines and to or from tankers, barges, and storage requires electricity. This aspect of sectoral coupling is often missed and ignored; therefore, discussions about the impact on electricity demand tend to focus only on the potential increase in EV loads.

The maturity of technologies for fossil-fuel-dependent systems and the fuel supply chain has significantly improved over the past century. There have been various points in the past and present when the fuel supply chain has presented different challenges^{23–25}. This has resulted in problems for ICE vehicle users with regards to fuel availability and price volatility. Some of the major causes that have impacted the fossil-fuel supply chain include localized events like hurricanes, flooding, and wildfires and other global events like geopolitical disturbances, regional conflicts, and the pandemic. Various mitigation measures have been determined and executed that have further strengthened these systems' reliability and security. For example, after Hurricane Sandy, gas stations were required to equip themselves with

backup generators to help provide gas during outages²⁶; similarly, the Washington state legislature mandates facilities to have backup generators on site²⁷. In comparison, the technologies used in EVs are significantly newer and still evolving, and the EV charging infrastructure is in its infancy. The operation of legacy fossil-fuel-dependent transportation systems provides us with knowledge of and insights into what has and has not worked well for these systems. Comprehending their functioning will lead to a deeper grasp of the future needs of an electrified transportation system and pinpoint opportunities for enhanced system performance. Mapping and understanding the future coupling of the electricity and transportation sectors will improve the overall resiliency of the transportation sector and the economic efficiency of public and private investments by driving up the utilization of infrastructure investments and bringing down the dependence on fuel imports and the intermodal transportation of finished motor gasoline.

The expanding market for EVs in the coming years underscores the need for meticulous monitoring and strategic planning of the electric delivery system. The EV market in the USA has seen tremendous growth and potential in the last 5 years. Based on the current trend for EV sales, it is set to replace 5 million barrels of oil per day by 2030³. Identifying opportunities to address concerns that directly or indirectly impact access to charging will help to rapidly increase the rate of adoption. The demands on the charging infrastructure necessitate thorough evaluation. While infrastructure upgrades within the low-voltage grid are essential, the cumulative impact of EVs on the bulk power level must not be overlooked²⁸. The escalating presence of EVs may result in congestion at the bulk-grid level, introducing operational challenges and signaling the potential need for additional infrastructure upgrades and expanded capacity. Proactive planning and monitoring are imperative to ensure the seamless integration of EVs into the power grid²⁹.

In this work, we focus on the sectoral coupling between the electricity and transportation sectors based on the current landscape dominated by ICE-based transportation, and a future scenario with increased penetration of EVs is analyzed. Grid architecture (GA) methodologies have been utilized to study the overall shape of the converged system and the entity classes involved—an understanding of which enables the modeling of complex interactions³⁰. A converged system is the transformation of multiple systems that share resources and interact via an underlying cross-cutting architecture. In this paper, the electricity and transportation sectors are treated as a converged heterogeneous system that provides opportunities for new value stream innovation. This study first investigates the existing coupling between the electricity and fossil-fuel sectors that has heretofore been unexplored. The impact of a major event on the fossil-fuel supply chain has been quantified and evaluated, and qualitative sector-attributed data have been utilized to compare the current ICE-dominant and future EV-dominant scenarios to pinpoint the relative strengths and weaknesses of each. We highlight certain local events from the past and analyze the challenges faced by the present system and the response of a future system on qualitative terms. This provides a starting assessment of the potential superiority and weaknesses (real or perceived) for electrified transportation that need more research and development (R&D). This work looks into the finished gasoline supply chain to determine both the systemic strengths and weaknesses posed by this system.

By conducting a system-level analysis, we have identified and discussed the factors impacting the reliability and security of the existing fossil-fuel-based transportation system. These insights offer valuable opportunities for learning and guide the development of a more robust and dependable electrified transportation system in the near future. We engaged with stakeholders and domain experts in carefully curating different scenarios that highlight the specific risks associated with the ongoing reliance on finished motor gasoline as transportation fuel (currently) and electricity (in the future). This has helped us to understand the present standings for both systems and the opportunities that would help to make the transportation system more resilient. Our study systematically assesses and compares risks by

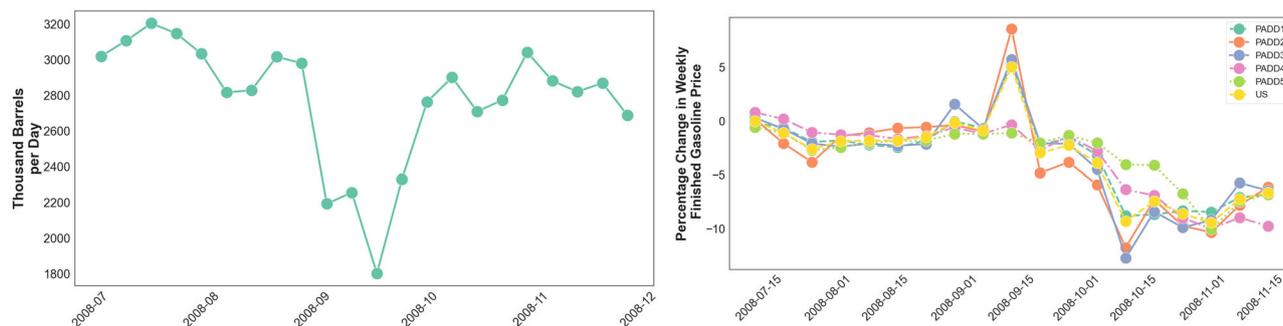


Fig. 1 | (left) PADD 3 finished gasoline production showing a significant shortfall during Hurricane Ike and (right) the percent change in the weekly price of finished gasoline over roughly the same time period. The production of fossil fuels was impacted when the surrounding region was hit by a hurricane, making the

refineries nonoperational because of the loss of electricity, flooding, and other challenges. Significant price fluctuations at the pumps were observed. Given the interdependent nature of the finished gasoline supply chain, the price increased in regions not directly impacted by the hurricane.

introducing a semiquantitative methodology for evaluating emergency scenarios in both ICE- and EV-dominant transportation systems.

The rest of the paper is structured as follows. Results section presents the findings from the study by assessing the different vulnerabilities that were seen during events like hurricanes and cybersecurity attacks. The collected data were used to analyze the associated risks. This framework was then compared with a future electrified transportation sector. Discussion section provides an in-depth understanding of the qualitative measures taken for the study that was used to formulate the risk matrix and thereby identify possible future opportunities. Methods section discusses in detail the topology used for quantifying the framework of risk assessment by identifying the threats and vulnerabilities of the existing fossil-fuel system and its associated impacts.

Results

It is important to recognize that assessing the performance of the fossil-fuel and electricity sectors on transportation 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, no methodology currently exists for systematically comparing the performance of ICE- and EV-dominant transportation systems. Therefore, in this section, we explore different approaches that provide a semiquantitative 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 electricity sectors have been summarized, and a data-based analysis has been performed to demonstrate the levels of risks with either system.

Vulnerabilities

The common expectation at a gas station is met with a sense of assurance of the ability to refuel. However, in areas susceptible to various extreme events like hurricanes, power outages, floods, geopolitical unrest, and compliance with Organization of the Petroleum Exporting Countries (OPEC) regulations, a range of challenges has been documented. These challenges, spanning from natural disasters to geopolitical factors, have disrupted the usual reliability and widespread affordability of the fossil-fuel supply. Consequently, the availability of finished gasoline becomes uncertain in the face of such events, creating a complex landscape where external factors can significantly impact the expected convenience of refueling.

Hurricane Ike. Hurricane Ike was a powerful Category 2 (according to the Saffir–Simpson hurricane wind scale³¹) 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 or Petroleum Administration for Defense District (PADD) 3 is an area of significant oil and gas production. The hurricane impacted offshore drilling and refining processes that affected production and supply. The

gasoline production of PADD 3 was significantly impacted, and production capacity fell by 26% compared to the previous week, as shown in Fig. 1.

Gasoline prices serve as a valuable marker to show the availability and accessibility of this essential resource. They are influenced by economic factors, supply and demand dynamics, geographical variations, environmental considerations, market competition, transportation infrastructure, government policies, and OPEC. Monitoring gasoline prices helps to understand the state of the gasoline market and its availability in a given region.

Because the aftermath of the hurricane caused several production facilities to shut down, the prices of finished gasoline increased by almost 5% for PADD 3. Interestingly, most of the impact of the hurricane was localized to the Gulf Coast region; the prices of finished gasoline increased by 8% in PADD 2 (Midwest), followed by PADD 1 (East Coast), where no significant impacts or damage caused by the hurricane was noted. The variations in prices during the hurricane are shown in Fig. 1.

Hurricanes Katrina and Rita. Hurricane Katrina was a Category 3 hurricane that made landfall near New Orleans, Louisiana (PADD 3) 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 disruption in the production of oil and gas in the Gulf of Mexico region, as shown in Fig. 2. 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 Hurricane Katrina, and Hurricane Rita further disrupted the recovery efforts that dented oil and gas production in the region. PADD 3 is the largest producer of finished gasoline, and the impacts of a hurricane or any major event that results in the shutdown of the refineries create national supply–demand challenges across the nation. The centralized nature of fuel production deeply aggravates this effect that leads to availability challenges coupled with a price increase at the pump.

Similar to the previous weather events discussed for Hurricane Ike, a substantial increase in the finished gasoline prices in PADD 3 was seen. The prices of finished gasoline rose close to 15% from the prehurricane week for the region, although a similar variation in prices was felt across the nation. Interestingly, although the effect of these hurricanes was localized to PADD 3, the price changes were felt more severely in PADD 1 and PADD 2, as shown in Fig. 2. The US Strategic Petroleum Reserve (SPR) (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; it played a crucial role in mitigating a significant long-term shortage of gasoline during emergency conditions by releasing several million barrels of crude oil) was

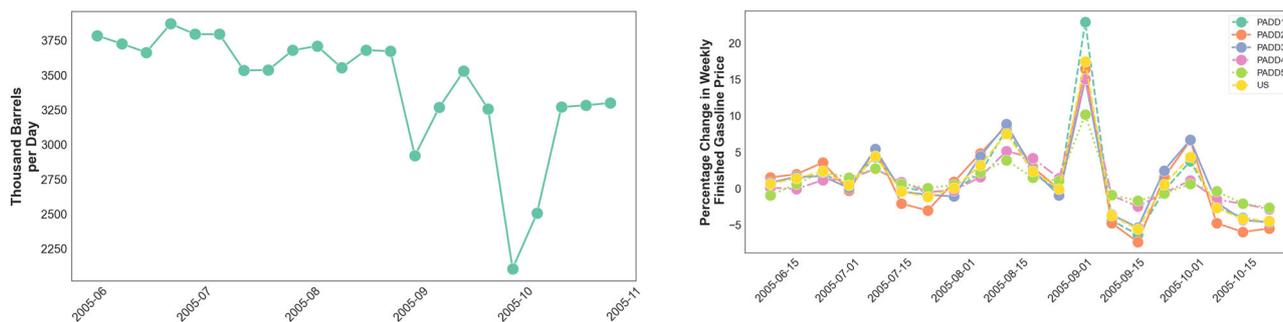


Fig. 2 | (left) PADD 3 finished gasoline production showing a significant shortfall during Hurricanes Katrina and Rita; (right) percent change in the price of finished gasoline over roughly the same time period. The production of fossil fuels was impacted when the surrounding region was hit by the hurricanes, making the

refineries nonoperational because of the loss of electricity, flooding, and other challenges. Significant price fluctuations at the pumps were observed. Given the interdependent nature of the finished gasoline supply chain, the price increased in regions not directly impacted by these hurricanes.

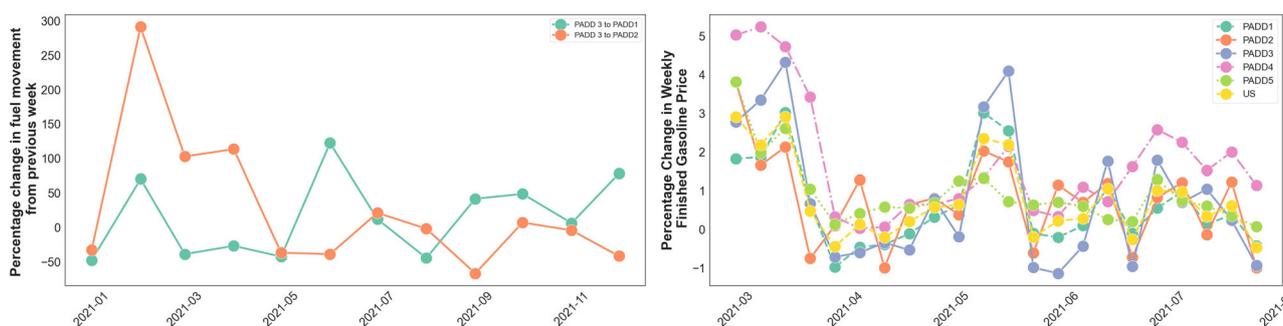


Fig. 3 | Colonial pipeline shutdown: percent changes in (left) movement of finished gasoline between PADD 3 and other regions and (right) in finished gasoline prices. Because of the shutdown of a major fuel transport artery, the delivery of

finished gasoline was severely impacted. Significant price fluctuations at the pumps were observed because of panic buying and because pumps eventually dried out.

strained and had to release several thousand barrels of crude oil to mitigate a long-term price increase and inconvenience.

Colonial pipeline shutdown. The Colonial Pipeline plays a crucial role in the US 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 5500 miles long and has the capacity to transport 2.5 million barrels of oil each day³². In May 2021, the cybersecurity infrastructure of the pipeline was breached, leading to a shutdown of its operations³³. Several reports of gas station outages were reported across the states of North Carolina and Virginia. The price of gasoline rose steadily because of increased demand from panic buying.

Since the Gulf Coast region is the largest producer of oil, supply cuts from the region were difficult to mitigate once the movement of oil was affected because the pipeline shut down. Figure 3 shows a decline in gasoline movement between PADD 3 to PADD 2 and PADD 1.

A substantial rise in gasoline prices occurred in PADD 3 and PADD 1; however, the rest of the country felt its impact as well, and the average gas prices in the USA rose close to 3%, as shown in Fig. 3. The resilience of the finished gasoline infrastructure supply chain is underscored by its robustness; nevertheless, the susceptibility arising from a dependence on localized production introduces a noteworthy vulnerability.

Other accident-related events

In previous sections, we discussed how major events have created disruption in the finished gasoline supply chain, leading to shortages and increased prices at the pump. There are also concerns related to safety and environmental risks that arise from the operation of the finished gasoline supply chain. Beyond the challenges of burning fossil fuels, which emit substantial amounts of CO₂, CO, and other compounds, it is

essential to recognize their significant impact on climate. Another downside is spills, which can lead to ecological and economic damage. These can happen because of pipeline leaks, train derailments, or other industrial disasters. Pipelines and railways are the predominant drivers that keep crude oil supplied to different sections of the country where it is not available in abundance. The intricate movement of crude oil and its products will be discussed in Results section.

Assimilating data from the United States Coast Guard National Response Center (USCGNRC), which serves as an emergency response center that reports pollution and railroad incidents, we found a significant number of incidents registered with oil spills at different stages of oil delivery, including pipelines, storage tanks, etc., as shown in Fig. 4³⁴.

Figure 5 shows the number of spills of predominantly crude oil occurring in every state that was recorded by the Pipeline and Hazardous Materials Safety Administration (PHMSA) since 2010³⁵. These events have approximately costed \$5 billion dollars.

Information and data

Considering some recent hurricane events—namely, Irma, Florence, and Michael—that happened in PADD 2, we analyzed information that helps us to explore the distinctions between conventional transportation systems reliant on fossil fuels and the innovative electrified transportation systems of tomorrow. Taking a similar approach to assess the change in finished gasoline price, we can see that during the three hurricanes shown in Figs. 6 and 7, there was a significant change in the price of finished gasoline at the pump. Moreover, some of the price changes notably occurred even before the storms’ landfall, suggesting a trend where people started stocking up on finished gasoline for emergencies and initiated evacuation procedures. The price change during Hurricane Irma was the largest since Hurricane Katrina in 2005³⁶.

Fig. 4 | Incidents occurring for different modes of crude oil transportation. This figure shows a detailed distribution of incidents associated with various modes of crude oil transportation, including pipelines, railways, trucks, and maritime shipping, over the past decade. Each mode of transport is examined for its frequency of incidents, the severity of spills, and the environmental impact. The data underscore the relative risks and benefits of each transportation method, highlighting the higher frequency of large-scale spills associated with pipeline failures and the increased risk of accidents in rail and truck transport.

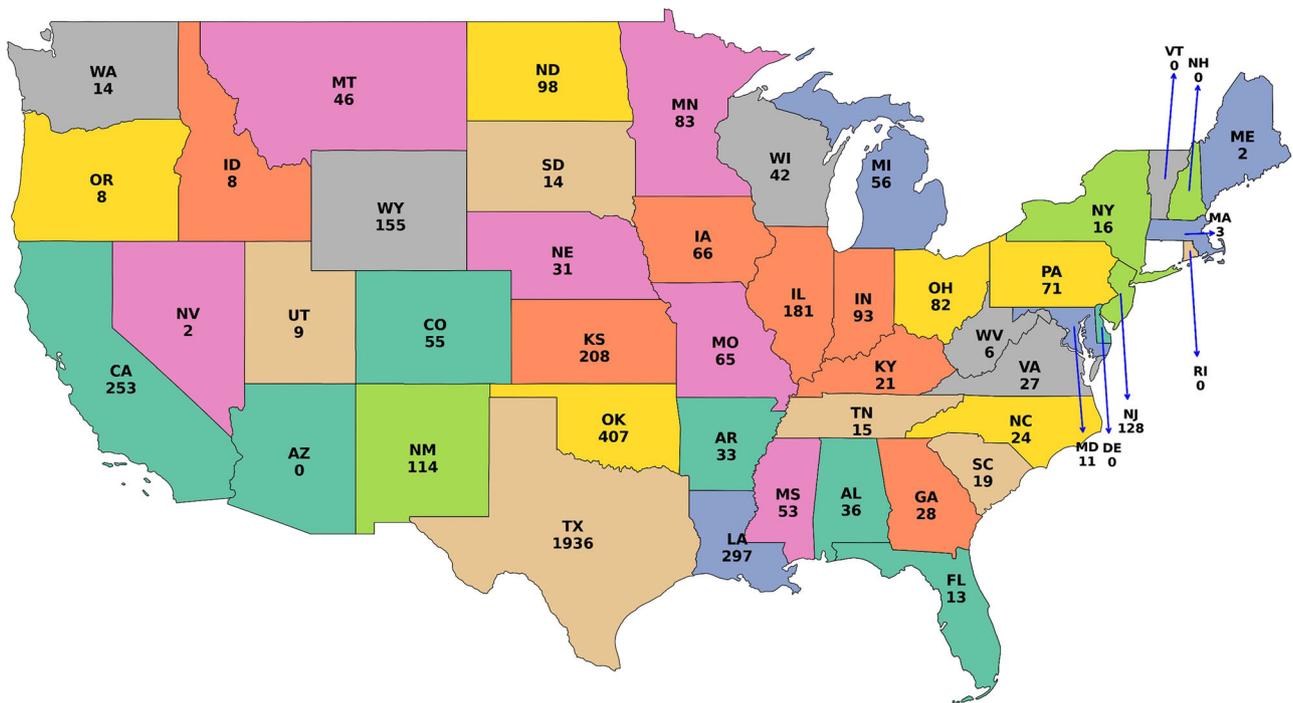
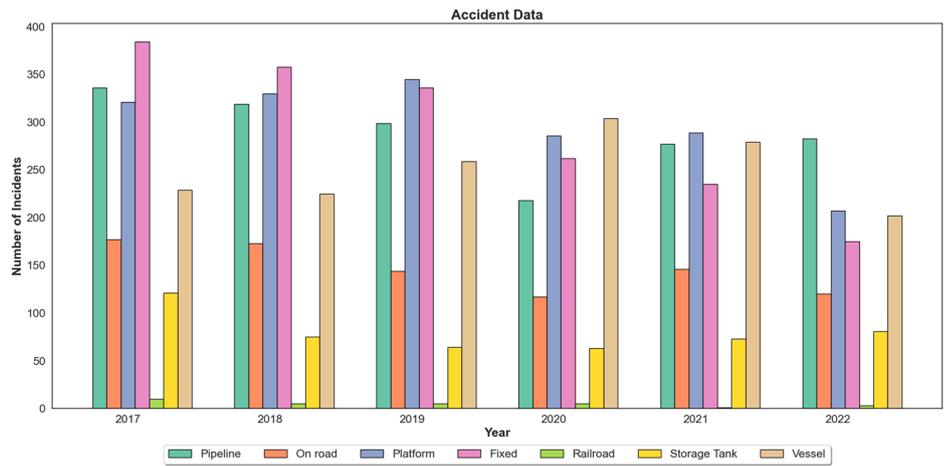


Fig. 5 | Oil and gas spill incidents across states since 2010. This map highlights the geographic distribution and frequency of these incidents, showcasing which states have experienced the highest number of spills in the contiguous USA.

Fig. 6 | Percent change in the price of finished gasoline during Hurricane Irma. This illustrates the fluctuations in finished gasoline prices across different regions during Hurricane Irma as it disrupted supply chains, caused widespread power outages, and led to panic buying and fuel shortages during September 2017. The data highlight the percent change in prices before, during, and after the hurricane made landfall.

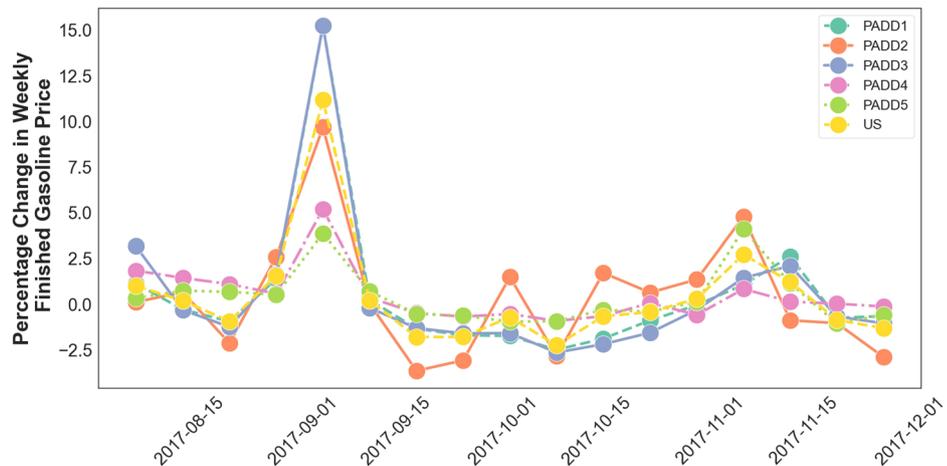


Fig. 7 | Percent change in the price of finished gasoline during Hurricanes Florence and Michael. This illustrates the fluctuations in finished gasoline prices across different regions during Hurricanes Florence and Michael as they disrupted supply chains, caused widespread power outages, and led to panic buying and fuel shortages. The data highlight the percent change in prices before, during, and after the hurricanes made landfall.

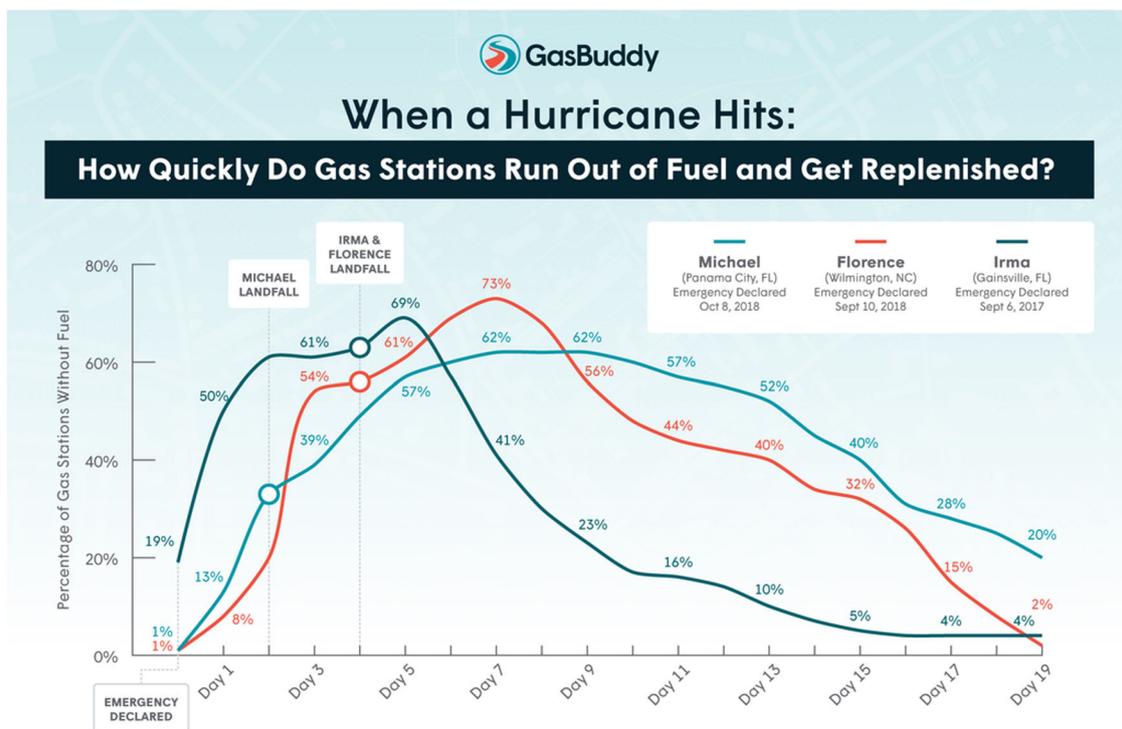
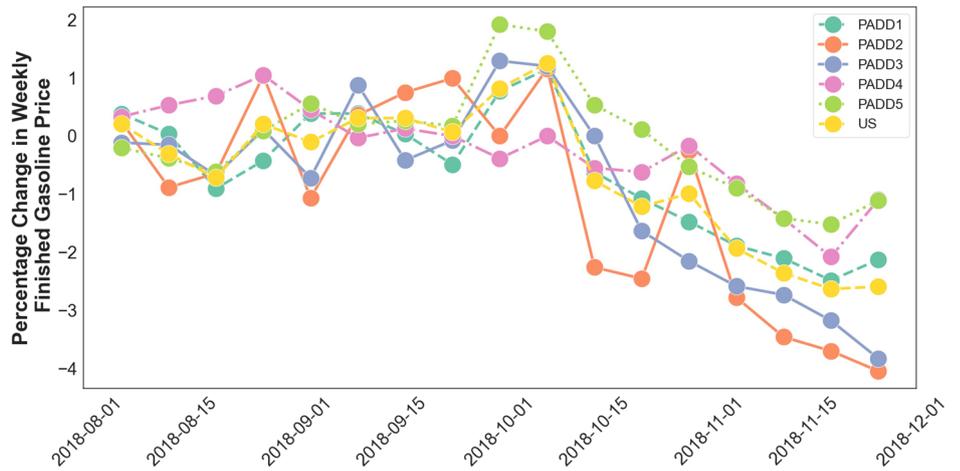


Fig. 8 | Restoration time at gas stations following Hurricanes Irma, Florence, and Michael³⁹. This highlights the percentages of gas stations that reported outages during these hurricanes. Given the complexity of the fossil fuel supply chain, several

factors influence the availability of finished gasoline at the pumps, leading to a long time to return to normal conditions.

This deepens our understanding of the extent to which the fossil-fuel architecture is interlinked and its intricate complexity, where significant impacts are felt. Hurricanes like Katrina and Rita that made landfall in PADD 3 (a major oil-producing region) created large shortages in fuel production across the region, and price increases were seen across the nation. On the other hand, during Hurricane Irma that made landfall in PADD 1, which is the highest finished-gasoline-consuming region, notable price changes were seen in areas not affected by the hurricane’s landfall. Price changes were driven by increased supply challenges, and meeting demands resulted in panic buying before the landfall of the hurricane. Considering the price of finished gasoline as a marker, we see spikes during an event. The price fluctuations are quickly stabilized. This is possible because of the availability of storage facilities for fossil fuels at different local and regional areas in the form of tankers, barges, and storage terminals³⁷,

and the federal government has supported the market by releasing crude oil from the SPR in some scenarios³⁸.

GasBuddy is a service that provides near real-time information on fuel prices across various locations³⁹. An analysis indicated that a considerable proportion of fuel pumps in the regions affected by the hurricanes’ landfall experienced a notable shortage of finished gasoline at numerous service stations. This number substantially rose during the landfall of the hurricanes, and it took almost three weeks to return to normalcy, as shown in Fig. 8. The surge in demand before and during the hurricane in non-oil-producing regions created a shortage in the other regions as well, where some gas stations in states like Texas reported outages even when there were no effects from the hurricane.

For a comparative study to understand how electricity end users were affected, we used information from Environment for Analysis of

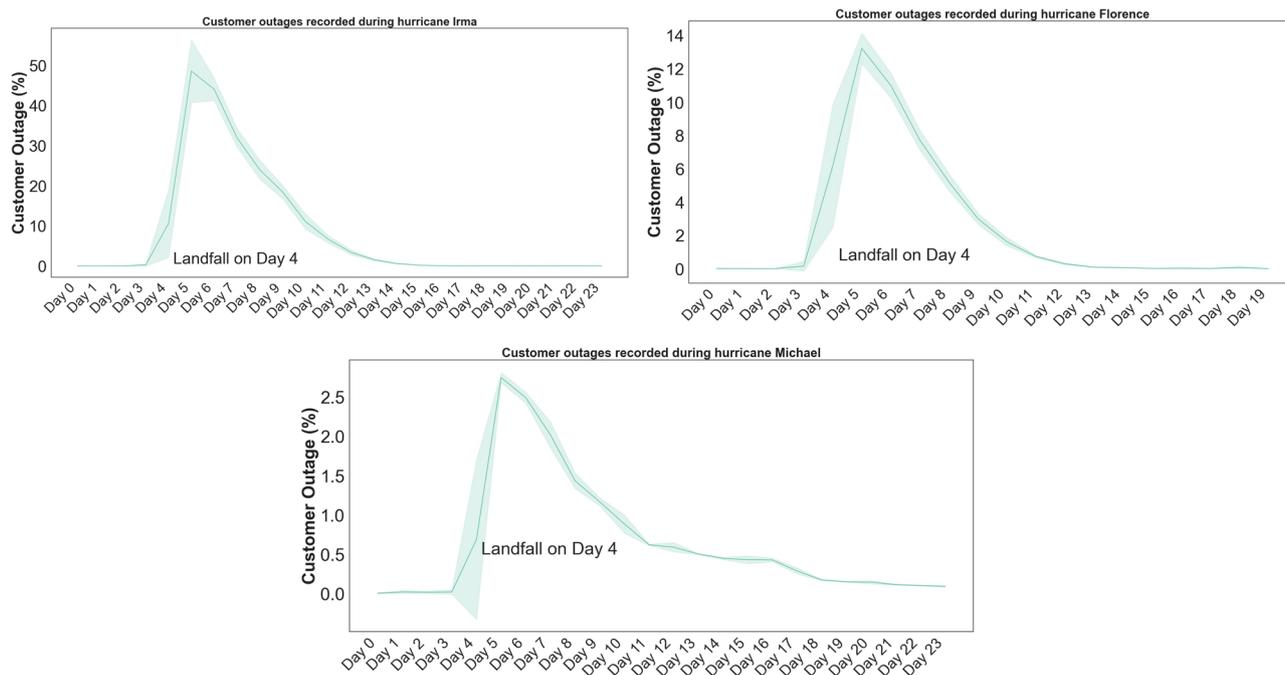


Fig. 9 | Percentages of customers that reported outages during Hurricanes (top left) Irma, (top right) Florence, and (bottom) Michael. Utilities reported outages peaking on the day of landfall, and a peak in outages was seen the next day. With restoration efforts going into action immediately after the hurricanes, we seen a drop in the percentage of customers that reported outages.

Table 1 | Impact analysis for hurricanes

Criterion	Ike		Irma	
	ICE	EV	ICE	EV
System scale of delivery issues	3	2	2	2
Safety concern	0	0	0	0
Ecological concern	3	1	1	1
Price impact	3	2	3	2
Response and restoration cost	3	3	2	3
Negative impact on sales/billing	3	3	0	0
Data compromise	0	0	0	0
Negative impact on production	3	1	3	1
Negative impact on transportation/transmission level	3	3	0	0
Negative impact on customer service	0	0	0	0
Immediate economic damage (refers to the functioning of society as a whole)	1	2	1	1
Immediate economic damage	0	0	0	0
Supplier revenue loss	0	0	0	0
TOTAL	22	17	12	10

Geo-Located Energy Information (EAGLE-ITM)⁴⁰ that pulls from dynamic datasets to provide near real-time coverage of the entire electric grid. EAGLE-ITM reports electricity service outages at 15-minute intervals for 3044 out of 3226 US counties. We collected archived data during the periods of Hurricanes Michael, Irma, and Florence to create an understanding of the recovery of the electric grid⁴¹. Our analysis showed that there was a significant spike in the number of customers that reported outages on the day of landfall for each hurricane; however, the number started dropping significantly. Electrical outage recovery, aiming to restore service to prehurricane levels, demonstrated an average duration of 9 days. The recovery timeline serves as a critical benchmark, showcasing the resilience

and response efficiency of the electricity infrastructure. Referring to Fig. 9, the graphs vividly illustrate the percentages of customers reporting outages during Hurricanes Irma (in Florida), Florence (in North Carolina), and Michael (in Florida) and provide a visual insight into the impact and recovery patterns associated with these significant weather events. With an electrified transportation system, the availability of fuel (electricity in this regard) can be on site (e.g., rooftop solar, battery storage); this provides end users with the opportunity to charge their vehicle with the restoration of the power grid.

As seen in Fig. 9, customer outages as reported by the utilities immediately begin to show a downward trend following landfall and continues to decline as the hours progress. However, the fuel delivery architecture is dependent on several factors to ensure its availability. The sheer complexity requires a large amount of time to restore a gasoline station to its proper pre-event conditions.

Use cases for a comparison of risk

We identify 12 different categories of potential impacts on transportation system (both EV and ICE) discussed in Table 5. To understand the scoring system, we provide couple of examples from the vulnerabilities discussed in the Methods section for Hurricanes Ike and Irma. We analyze the devastation caused by these hurricanes according to the threats listed in Table 3.

Comparison of risk for Hurricanes Ike and Irma. Table 1 presents an impact analysis of today’s transportation infrastructure dominated by ICEs and a futuristic transportation sector that predominantly involves EVs for Hurricanes Ike and Irma.

As noted, earlier PADD 3 is the largest producer of oil in the USA. Hurricane Ike resulted in the shutdown of 14 refineries that account for almost 3.8 million barrels of production per day. This led to a substantial shortage in fuel across the nation. Thus, the highest score of 3 was allotted to it under system scale and delivery issues. The hurricane impacted the power grid and resulted in wide-scale outages across the region; however, the lingering effects of the outages due to the hurricane were only local and did not spread across the nation, thus a score of 2

Table 2 | Comparison of the characteristics of present (fossil fuel dependent) and future (electrified) grid-transportation systems

Category	Fossil-fuel supply chain	Electricity supply chain
Energy independence	Depends on global imports and exports of crude oil; shortage of supply impacts the entire economy.	With increased clean energy adoption, the nation will be relieved of its interdependence on the global crude oil market.
Coupling between sectors	Dependent on electricity for refining, pumping, dispensing, etc.	EVs are completely dependent on the electricity sector, and with clean energy adoption, fossil-fuel needs for power production will be reduced.
Production location	Only well sites and refineries; fossil fuels may be imported.	Spread throughout the nation, and distributed energy resources (DERs) can be local.
Dependence on transportation	Highly dependent on 190,000 miles of pipelines; 1000s of rail cars, vessels, barges, and 100,000 tanker trucks for fuel distribution; a massive amount of fossil fuel consumed for transporting finished motor gasoline.	Dependence on electricity infrastructure; with a reduction in fossil-fuel-based generation, dependence on pipelines and the transportation sector for the supply chain will be further reduced.
Transmission speed	Days to weeks.	Close to the speed of light.
Energy storage	Massive storage of crude and refined oil exists.	Energy storage is currently sparse and limited.
Strategic reserve	Helps relieve rare situations of acute shortage.	Distributed storage facilities are available; however, strategic storage similar to the SPR does not exist.
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 (continually increasing).
Market dynamics	Fossil fuel cost is market based and “controlled/set” by a multinational oil cartel.	Electricity price is mostly region/location based and often is 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.

was assigned to more regional and local impacts. Similarly, approximately 500,000 gallons of oil were spilled from 1500 sites into different regions, resulting in large-scale ecological concerns. Trees knocked out several lines leading to power outages, but no ecological damage was reported⁴². With a transportation sector dominated by EVs, it is assumed that there will be damage to vehicle batteries that could lead to leaks and local concerns. To justify our scoring for the price impact criterion, we looked at the changes in finished gasoline production and prices in PADD 3 and other regions during this period, as shown in Fig. 1. In a transportation sector dominated by EVs, scenarios may arise where there is a surge in demand for charging due to evacuation needs or the utilization of vehicles as mobile batteries. The increased demand for electricity, particularly in regions transitioning to electrified transportation systems, may result in a temporary spike in the locational marginal pricing (LMP). This surge in the LMP reflects the dynamic balance between supply and demand in the electricity market, where increased demand can drive up prices at specific locations. However, it is essential to note that the impact of this price escalation is typically confined to regions experiencing heightened demand. Other areas of the country may not feel the same level of price increase because of differences in demand patterns, generation capacity, and transmission constraints. Therefore, while localized regions may experience significant price fluctuations, the broader nationwide impact is often limited. The localized nature of the impact implies that while there might be a temporary increase in electricity prices in certain areas, the broader national electricity market may remain largely unaffected. This distinction highlights the importance of considering the geographical context when analyzing the potential impacts of EV charging dynamics on the electricity market.

Hurricane Ike hit mainland USA in September 2008; it was a powerful storm with damaging winds—a Category 2 hurricane during landfall. Based on limited available data, the impact categories were scored for the system that existed during that time, which is dominated by fossil-fuel-dependent ICEs. Given the characteristics of the hurricane and the observed impacts on the electricity sector, scores were estimated for the different categories assuming a hypothetical scenario with completely electrified transportation. In scenarios where EVs dominate, the transportation sector would experience a lower level of impact.

Hurricane Irma hit mainland USA in September 2016 and was also categorized as a powerful storm: Category 4 during landfall. However, from

an impact perspective for both ICE- and EV-dominated systems, the total score for Irma was 10, which is less than that of Hurricane Ike.

Discussion

The fossil-fuel market operates within a framework centered on tangible resources, relying heavily on extensive infrastructure for both extraction and transportation processes. In stark contrast, the electricity market functions on the flow of electrons through a sophisticated grid system, which dynamically responds to factors such as generation costs and the integration of renewable energy sources. Fossil-fuel prices are subject to fluctuations in global demand and geopolitical events, while the electricity market is shaped by constantly shifting demand patterns and regulatory frameworks that ensure reliability and foster fair competition. As the energy landscape continues to evolve, understanding these fundamental distinctions becomes increasingly vital for effectively navigating the diverse challenges and opportunities inherent in each market. Several key categories were used to compare the characteristics of both current and future grid-transportation coupled systems. From the categories presently identified, the fossil-fuel supply chain has an advantage over the electricity supply chain, but the electricity supply chain has advantages in certain categories. In the following paragraphs, we discuss the identified categories in detail and a summary is presented in Table 2.

The placement of energy storage throughout the delivery chain and the point-of-sale experience are categories where the fossil-fuel supply chain currently has an advantage over the electricity supply chain, with several storage locations available. Since EVs are completely dependent on the electricity infrastructure for operation, this necessitates prioritizing infrastructure upgrades and maximizing investment utilization to ensure robustness and scalability. Having distributed storage options increases grid redundancy and provides opportunities to increase grid strength. Presently, the electricity infrastructure struggles to provide options for storage over a long duration. The strategic placement of energy storage resources needs to be prioritized, as this can help mitigate disaster scenarios and provide charging in times of need. Similarly, hydrogen can be seen as an alternative to batteries that can provide storage over a long duration⁴³. When we discuss market operations, fossil-fuel markets are often influenced by global commodity prices, long-term contracts, and spot markets, whereas electricity markets operate through various regional market structures, including wholesale markets, power exchanges, and bilateral contracts⁴⁴. The electricity

market in the USA is less subject to challenges posed by geopolitical scenarios that can influence its operations.

Options for refueling a vehicle on site at a customer residence are currently absent in the current fossil-fuel-dependent infrastructure (other than some biofuel refueling options), whereas with an electrified system, users can rely on their already available charging infrastructure to meet some basic needs. These will necessarily help during extreme weather events, where reports have previously shown gas stations running out even before a hurricane landfall or during a cybersecurity event^{45,46}. By possessing on-site charging capabilities, identified evacuation zones can strategically prepare for safe and hassle-free evacuation by ensuring that vehicles are fully charged. Similarly, critical equipment and infrastructure need to be strategically placed. Finally, the harmonization of standards, charging ports, and data availability needs to be standardized. This would help to improve the point-of-sale experience for end users. EVs would play a role in enhancing demand flexibility by helping to shift charging to off-peak hours by participation in demand response programs. They can also absorb excess renewable energy, maximizing its use and supporting grid stability.

The identification of suitable opportunities to address concerns related to EV charging is a critical task in the ongoing transition towards sustainable transportation. Recognizing the specific needs and challenges associated with EV charging infrastructure allows for targeted and effective solutions. Utilities are actively exploring strategic opportunities for planned charging in evacuation zones as needed, mirroring the alert systems employed during peak load periods^{47,48}. This proactive approach aims to alleviate stress on the grid and enhance preparedness, ensuring efficient and reliable EV charging services in critical scenarios. These processes involve thorough assessments of urban planning, transportation patterns, and energy infrastructure to pinpoint areas where EV charging stations can be strategically deployed. Additionally, understanding the concerns of potential users, such as range anxiety and charging accessibility, plays a crucial role in tailoring opportunities to meet these challenges head-on.

For this study, we have taken a qualitative measure in designing and formulating the *risk matrix* from publicly available information. Collaborative efforts between governments, private enterprises, and communities are essential for fostering a comprehensive approach to identify and capitalize on opportunities that will facilitate the widespread adoption of EVs, contributing to a cleaner and more sustainable future. Currently, work with specific states has been carried out to help them understand and establish a *risk matrix* with a future-facing outcome focusing on the role that transportation electrification would play in the present fossil-fuel supply chain.

Recognizing the opportunities that may arise from these mutual influences will enable us to identify synergies and tipping points where positive feedback can accelerate the adoption of EVs and smart charge management strategies. Collaborative efforts among governments, industries, and communities will be crucial in overcoming the challenges of electrifying transportation and accelerating the shift toward a cleaner, more resilient future. Developing metrics that provide a comprehensive set of measures for comparing the state of EV technology and transportation services with traditional fossil-fuel-based transportation technology is essential. These metrics can guide future R&D activities and inform regulatory actions. For instance, setting minimum requirements for the electricity infrastructure to ensure service assurance and access comparable to those of fossil-fuel-based transportation systems would be one such metric.

Methods

In this section, the coupling between the transportation and electricity sectors is mapped and analyzed to understand how the electric grid helps to power the fossil-fuel infrastructure that in turn supports the transportation sector. In addition, this section presents the approaches taken to develop the risk assessment framework by identifying the potential threat factors that could create a failure scenario or can contribute to creating one. Finally, the possible impacts for each of the threats and their consequences are discussed.

Finished motor gasoline infrastructure and supply chain

A holistic view of the fossil-fuel supply chain has been created by developing industry structure diagrams, as described within the GA discipline. To understand the finished gasoline supply chain in depth, we have divided it into five high-level stages, as shown in Fig. 10:

- 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. They mainly involve extraction and storage, transportation to the refinery, and refining. Stage 2 involves the distribution of the products from refineries to different locations through different modes of transport. Stage 3 makes finished gasoline available to local regions for further distribution. Stage 4 ensures delivery of the fuel to local gas stations, and Stage 5 is the final delivery point along the chain when it is pumped into vehicles.

The PADDs are geographic aggregations of the 50 states and the District of Columbia into five districts⁴⁹. Currently, the USA is able to meet its demands for gasoline through its own production, with PADD 3 being its predominant producer of crude oil. Pipelines, barges, and tankers move gasoline to product terminals, where it is stored before being blended with ethanol for end use. Most finished motor gasoline is moved by pipeline from refineries and ports to terminals near major consuming areas. There is a vast network of pipelines that connect different parts of the PADDs, as shown in Fig. 11. This figure shows the pipelines carrying finished petroleum products and crude oil in the contiguous USA; pipelines that travel across borders have been omitted. Pipelines are utilized as the major mode of fuel transportation since they are cost effective and highly efficient during continuous 24/7 operation under normal conditions.

The current transportation-sector fuel supply chain infrastructure, which includes the production, distribution, and retailing of gasoline, is, to a large extent, dependent on the electricity infrastructure in several ways.

1. Fuel Extraction: Electricity plays a crucial role in the extraction of crude oil. A production weighted average oil well producing 114 barrels per day is estimated to be using 468,000–648,000 kWh of electricity per year.
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 Refinery Capacity Report of 2022, refineries in the USA purchased 42,698 million kilowatt-hours of electricity for their operations. The electricity purchased by refineries over the last decade is shown in Fig. 12.
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: They depend on electricity for various functions, including powering fuel dispensers, lighting, cash registers, and security systems. Most gas stations have electrical connections to ensure the continuous operation of these essential systems.
5. Emergency Backup Power: Many gas stations are equipped with backup power generators that run on electricity, typically powered by diesel or natural gas, to ensure fuel availability during power outages⁵⁰. These backup generators are crucial for maintaining operations during emergencies.

In ref. 51, the authors discuss the interdependence between the electricity and natural gas sectors, but currently, there is no established framework that discusses the dependency of the current fuel delivery

GASOLINE/DIESEL SUPPLY CHAIN

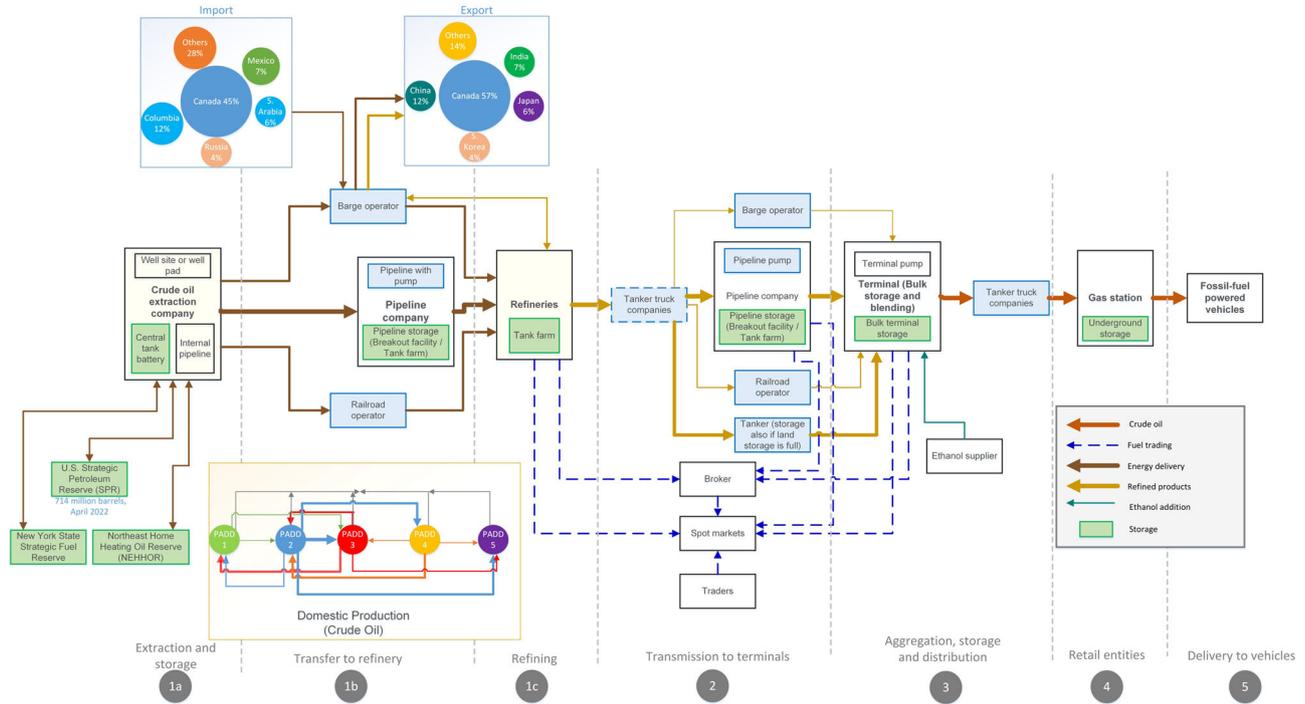


Fig. 10 | Fossil-fuel delivery architecture. This figure shows a comprehensive overview of the fossil-fuel delivery architecture, detailing the complex supply chain from extraction to end-use.

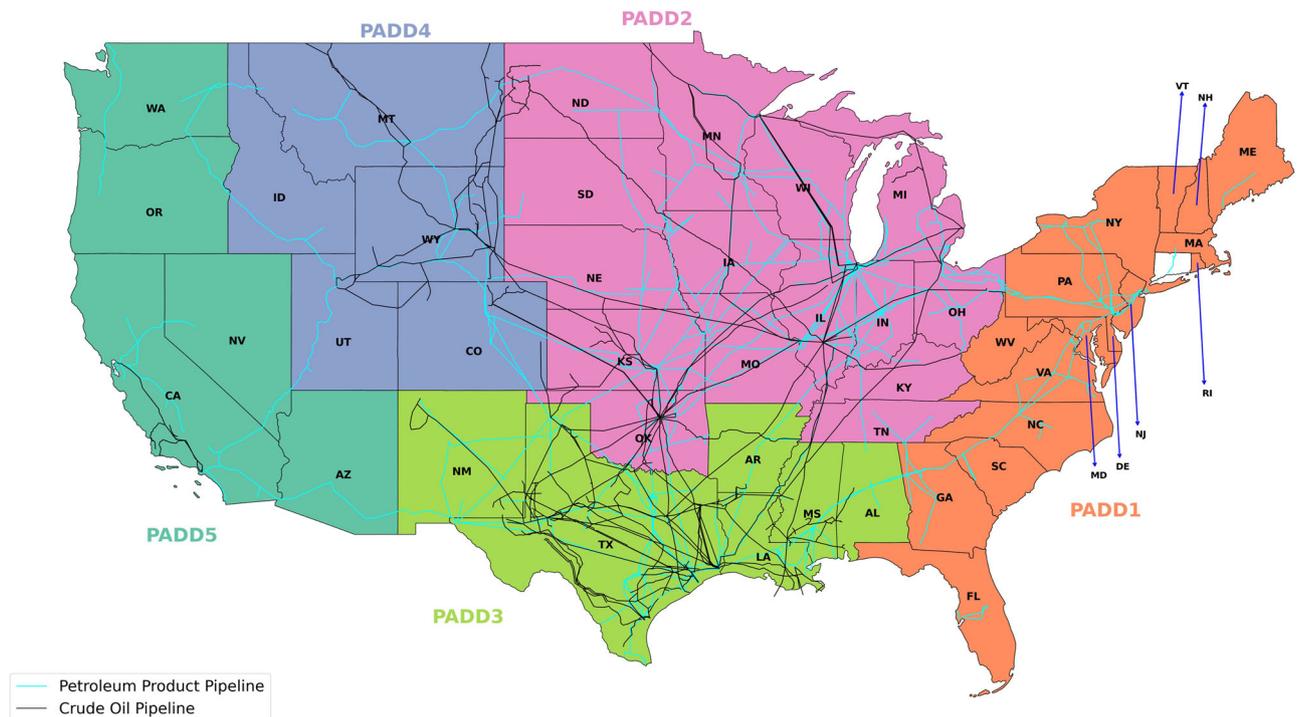


Fig. 11 | The intricate network of pipelines that connect different PADDs to maintain efficient flow of fuel. The interconnected nature of the pipeline network allows for flexibility and resilience in the fossil-fuel supply chain. In the case of disruptions in one area, alternative routes can be used to maintain supply continuity.

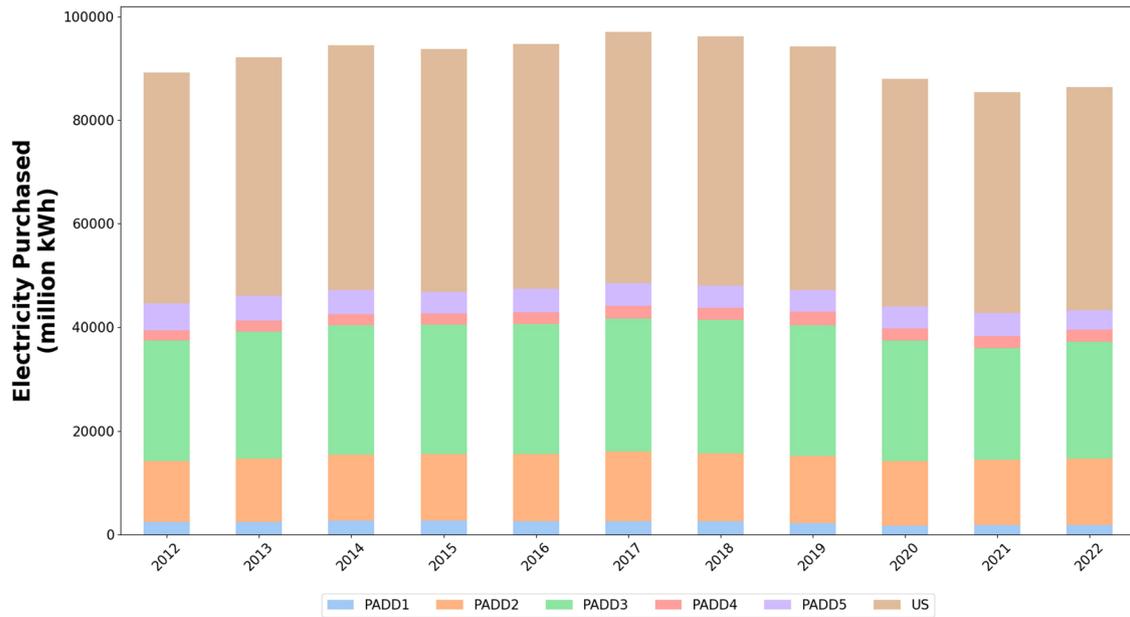


Fig. 12 | Electricity purchased by refineries at different PADDs⁶⁵. This figure highlights the regional variations and trends in energy consumption within the refining sector over the last decade.

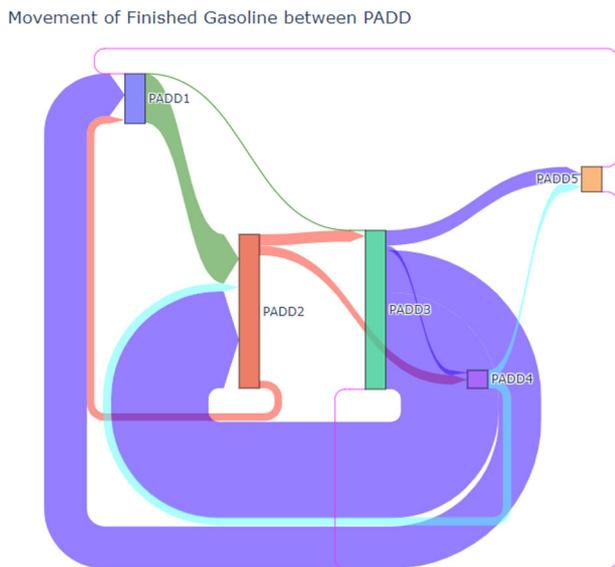


Fig. 13 | Movement of finished gasoline between PADDs highlighting the key interregional interdependencies. This relationship aids in strategic planning for emergency response, infrastructure investments, and regulatory measures to ensure a stable and resilient fuel supply across the USA.

architecture on the electricity sector. The interconnected fuel network provides robustness to the delivery chain; however, an increased dependency on intraregional fuel movements adds certain challenges to the supply chain. Figure 13 shows the average movement of finished gasoline across PADDs between January 2000 to June 2023 (monthly thousand barrels). It can be seen that most regions have a high degree of dependency on PADD 3 for finished gasoline to meet their demands. Events that damage the production of finished gasoline in PADD 3 affect most of the other PADDs. The reflection of such scenarios can be seen in several vulnerabilities that have impacted price changes throughout the nation.

Framework for systematic risk assessment

The previous section helps understand the convergence of the fossil-fuel and transportation sectors, their vulnerabilities, and the interfaces at a high level. It is clear that although technological maturity of ICE vehicles and the finished motor gasoline supply chain has been enhanced over the past century, there are still multiple vulnerabilities in the system due to the sheer dependence on multiple factors like production, geopolitics, weather events, and transportation to make it available to end users. We have highlighted the negative impacts experienced because of adverse events by analyzing the available data.

It is important to recognize that assessing the performance of the fossil-fuel and electrified transportation systems in an ad-hoc manner would not be sufficient to determine the next steps necessary for ensuring a robust transition to an electrified transportation system. There currently is no methodology that exists to systematically compare the performance of ICE- and EV-dominant transportation systems^{52–55}. Therefore, this section provides a semistructured methodology for evaluating and comparing the risks between the two types of systems. Various types of events like hurricanes, geopolitical events, etc. that have impacted the transportation and electricity sectors have been summarized, and a data-based analysis has been performed to demonstrate the level of risk with either of the two systems.

Framework for risk assessment

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. 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. 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*”⁵⁶.

The National Electric Sector Cybersecurity Organization Resource (NESCOR) Technical Working Group 1 (TWG1) has over the years developed multiple documents on the topic of potential cybersecurity failure scenarios and impact analyses for the electricity sector⁵⁷. 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. Although the NESCOR work products specifically focus on cybersecurity

Table 3 | Potential threats and hazards to the transportation sector

Threats	Vulnerabilities	Examples	Sector impacted (fossil fuel or electricity)
Natural disasters	Physical damage to infrastructure	Tornadoes, hurricanes, floods, earthquakes, cyclones	Both
Geopolitical instability	Dependence of economy on imports or exports of energy	Oil embargo, terrorism events like the 9/11 attack, OPEC regulations, conflicts	Fossil fuel
Cybersecurity threats	Cybersecurity vulnerability	Cybersecurity attack	Both
Threats to transportation and storage of fuel	Physical vulnerability of transportation and storage infrastructure	Failures or other incidents leading to leaks, spills, or fire.	Fossil fuel
Pandemic or other global events	Change in electricity or transportation needs	COVID-19 pandemic	Both
Workforce training programs	Workforce vulnerability	Shortage of tanker truck drivers, experienced personnel for inspecting and repairing tanker trucks, electrical linemen	Both
Extreme weather	Extremes in temperature due to changing weather patterns, thereby resulting in increased demand for electricity. Depending on the available capacity, this can cause independent system operators (ISOs) to operate below reserve margins	Can disrupt refinery operations, leading to decreased efficiency, increased operational costs, safety hazards, and environmental concerns	Both
Panic buying/consumption	Demand surge or capacity limitation	Shortage of supply or limiting capacity of transmission/ distribution	Fossil fuel
Accidents/faults	Varies, e.g., errors, poor design, non-compliance, inadequate policies or processes, inadequate testing or maintenance, degradation of system	Faults caused by vegetation outgrowth, animal burrowing and other conditions	Both
Physical attacks	Physical security vulnerability	Attack on infrastructure	Electricity

risks, the overall approach for assessing risks is relevant for broader risk assessment and is fit to be adapted for the purposes of assessing risks in the electricity and transportation sectors. 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 potentially impact a fossil-fuel-dependent or electrified transportation system. This framework helps in comparing the performance of the two systems in a more objective manner.

Threat and vulnerabilities. Threats to the energy infrastructure encompass everything from natural disaster events to human-made threats such as physical or cyberattacks⁵⁸. Each threat corresponds to a wide range of potential cascading impacts. 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 the 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 the vulnerabilities that they exploit is also critical for determining mitigation strategies after the risk assessment is complete.

Table 3 highlights the potential threats to the transportation system from natural disasters 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, lack of training programs, panic buying/consumption, and physical faults are applicable to both types of systems (ICE and EV dominated). Global geopolitical instability and threats to the transportation and storage of fuel have the potential to impact the fossil-fuel-dependent transportation sector more than electrified transportation. Such threats tend to be sustained for a while after they emerge and therefore can lead to impacts for a few weeks or even months. Cybersecurity threats are typically a greater concern for electrified transportation due to the increased network connectivity of both the supply chain equipment and end-use EVs. Given the dependency of the fossil-fuel

sector on electricity, communication, and control networks, it is highly likely that the fossil-fuel supply chain will feel impacts. As shown in Fig. 4, several thousand barrels of oil are spilled each year as a result of accidents in transportation and storage facilities. They tend to pose ecological challenges. This has led to near term shortages in fuel availability. The loss of jobs during economic volatility can create a shortage of skilled labor in the energy industry. Energy producers face risks to business continuity and escalating costs due to their failure to address labor shortages⁵⁹. Extreme temperatures present vulnerabilities to the oil and gas industry due to their potential to stress equipment, disrupt operations, increase energy consumption, and compromise safety measures, ultimately leading to reduced efficiency and increased operational risks. The demand for electricity has been seen to surge with the rise in temperatures, where sometimes utilities had to opt for rolling outages or voluntary demand reduction from customers to prevent blackouts. Panic buying threatens both the fuel and electricity sectors by creating unexpected spikes in demand, straining supply chains, and potentially causing shortages. This can lead to increased operational challenges, market volatility, and potential disruptions in service delivery, impacting the stability and reliability of both industries. Accidents are a greater concern in both the fossil-fuel and electricity sectors; the disruption of the operation of utilities due to accidents can potentially impact the transportation sector in both the long and short term. Physical attacks pose a significant threat to both the fuel and electricity sectors, as they can result in damage to critical infrastructure, the disruption of operations, safety hazards, and the potential loss of life. Such attacks, whether through sabotage, vandalism, or terrorism, can lead to production shutdowns, supply chain interruptions, and increased security costs, ultimately impacting the stability and resilience of these essential sectors^{60,61}.

Taking inspiration from threat models developed for the electricity sector in the cybersecurity domain, we adopt the threats and their associated likelihoods for the transportation sector that can affect its operation. Some of the threats have been adopted from critical infrastructure in Minnesota (MN)⁶², the energy infrastructure in Europe⁶³, and safety in general, where the cause of failure is due to human error⁶⁴. The associated threats can be

identified as High, Medium, or Low (H, M, or L, respectively). The defined likelihood for each threat is not a probabilistic model but an understanding based on a set of factors that may contribute to its increased occurrence, as discussed in Table 4.

Impacts

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

We have identified 12 categories of potential impacts, as discussed in Table 5, and brief descriptions are provided below.

1. System scale of delivery issues: The impact from this failure could be geographically localized.
2. Safety concern: Safety criteria consider whether there is potential for injuries or loss of life.

Table 4 | Likelihood of occurrence for different threats

Threats	Likelihood
Hazards	L/M/H (dependent on the region and time of the year, can be abrupt)
Geopolitical instability	L/M(depends on the period under consideration)
Cybersecurity threats	M/H
Threats to transportation and storage of fuel	M/H
Pandemic or other global events	L
Lack of training programs	M
Extreme temperature	H
Panic buying/ consumption	L/M
Accidents/faults	M
Physical attacks	L (but increasing)

3. Ecological concern: A failure scenario could cause damage to the environment, and this damage could be local or more widespread. The type of damage could also be reversible or permanent.
4. Price impact: A failure scenario that creates a change in the cost (wholesale or retail) of either finished gasoline or electricity.
5. Response and restoration cost: Expected cost 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 the inadequateness of the infrastructure that could impact its operation is included through this criterion.
7. Data compromise: This category considers different types of data breaches that can lead to the 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 ICEs and the electricity generation needed for EV charging.
9. Negative impact on transmission/storage: This category considers the impacts on the transmission and storage of energy, which are critical in maintaining the reliability and resiliency of the system. In an electric system, the negative impacts on transmission could mean an event requiring action(s) to relieve voltage or loading conditions, or transmission separation or islanding, up to the collapse of the interconnected electrical system. In the fossil-fuel delivery 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 a 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.

Table 5 | Evaluation of different criteria 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 over the USA.
Safety concern	0: None; 1: <20 injuries related to ICE vehicles or EVs, or infrastructure; 2: >20 injuries related to ICE vehicles or EVs, or infrastructure; 3: >100 injuries and or death related to ICE vehicles or EVs, or infrastructure.
Ecological concern	0: None; 1: Local ecological damage such as a localized 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 USA.
Response and restoration cost	0: None; 1: Marginal (within maintenance budget); 2: Up to 2% of the O&M budget; 3: >10% of the O&M budget.
System downtime	0: None; 1: Isolated recoverable challenges or errors for a nozzle/port; 2: Unplanned unavailability of multiple nozzles/ports, leaving customers stranded for less than 8 h; 3: Unplanned unavailability of multiple nozzles/ports, leaving customers stranded for more than 8 h.
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: Less than 10% extraction/refinery/generation facility offline or degraded operation of a facility; 2: More than 10% loss of extraction/refinery/generation capacity for 8 h or less at a facility; 3: More than 10% loss of extraction/refinery/generation capacity for more than 8 h at a facility.
Negative impact on transmission/storage	0: None; 1: Transportation/transmission/storage level down by <10%; 2: Transportation/transmission/storage level down by >10%, but 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 a 4 h delay in a customer’s ability to contact provider and gain resolution, lasting one day; 2: Up to a 4 h delay in a customer’s ability to contact provider and gain resolution, lasting a week; 3: More than a 4 h delay in a customer’s 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: No financial loss; 2: Causing up to 10% reduction in revenue; 3: Causing more than 10% reduction in revenue.

Table 6 | Risk matrix assessment

		Threat likelihood		
		Low (L)	Medium (M)	High (H)
Impact	High (>12)	M	H	H
	Medium (7–12)	M	M	H
	Low (0–6)	L	M	M

Table 5 summarizes the impact categories and the associated rubric for scoring. For each impact category, there are four possible scores. If no impact of that category is observed/estimated, then the score is 0, and the score increases to a maximum of 3 if the highest level of impact is observed/estimated. The total impact score is the sum of the scores for all categories for a specific threat/scenario. We use the scoring rubric to perform an impact analysis during different events; an example is demonstrated in Table 1.

Risk

Risk can be defined as the potential for an unwanted impact from an event. An assessment of relative risk can be developed based on the threat and likelihood categories and levels discussed in the Impacts subsection. Risk assessment utilizes the threat likelihoods (from Table 4 or an adapted version) and the total impact scores (from Table 5). We evaluate risk levels by summing the impact scores of various factors, as outlined in Table 6. For example, when the likelihood of a threat is low and the total estimated impact score is less than 6, the risk is categorized as low. Conversely, if the threat likelihood is high and the cumulative impact score exceeds 12, the risk is classified as high, consistent with intuitive reasoning. To define impact thresholds, the team conducted assessments across diverse scenarios, including hurricanes, ensuring a thorough understanding of the risk landscape. This methodology provides a solid foundation for evaluating and mitigating risks associated with potential hazards. By integrating threat likelihood and impact analysis, this approach supports informed decision-making and proactive risk management, enhancing resilience and minimizing the negative consequences of future events.

Data availability

The data used to analyze the various events is available at <https://doi.org/10.6084/m9.figshare.25338247>.

Code availability

All necessary codes developed for this study can be made available by the authors upon request.

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Author contributions

B.M. and S.P. contributed to the study design and analysis along with data collection. B.M. wrote the manuscript. S.P., H.R. and M.K.M. provided

comments and guidance for the manuscript. All the reviewers have read and approved the manuscript.

Competing interests

The authors declare no competing interests.

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