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Energy Security and the Energy Transition: A Classic Framework for a New Challenge

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SUMMARY

Policymakers in the US and around the world are grappling with how to understand the security implications of an energy system in transition—and if they aren't, they should be. Recent attacks on Saudi facilities show that oil supply remains vulnerable to disruption. New energy forms can help reduce vulnerability to oil supply outages, but they also have the potential to introduce new vulnerabilities and risks. The US and its allies have spent the past 50 years building a robust domestic and international response system to mitigate risks to oil supplies, but similar arrangements for other energy forms remain limited. This paper offers a framework for assessing energy security based on an evaluation of vulnerability, risk, and offsets; this approach has been a useful tool for assessing oil security for the past 50 years, and it can be relevant for assessing energy security in an energy system in transition.

INTRODUCTION

Energy security considerations are not new phenomena. More than a century ago, addressing the risks in switching the Royal Navy's main source of fuel from coal to oil, Winston Churchill famously argued that "safety and certainty in oil lie in variety and variety alone." Access to oil supplies was a major strategic consideration for all the major actors during World War II, and it became a focus of individual citizens and their political leaders during the oil shocks of the 1970s. While these considerations have historically been motivated by consumers worried about access to uninterrupted supplies of oil, producing countries can equally raise concerns about shocks to—and the security of—demand.

In addition to geopolitical risk, the reliability of energy supplies has recently been threatened by factors ranging from weather events (the frequency and intensity of which are exacerbated by climate change) to terrorist activities, industrial accidents, and cyberattacks. The recent attack on Saudi oil facilities and resulting disruption of oil supplies,[1] hurricanes on the Gulf Coast (which disrupted oil and gas production and distribution, as well as the electrical grid), and high winds in California that caused widespread power outages have brought energy security once again into the global headlines.

Even with the US now on a trajectory to achieve the long-sought goal of energy self-sufficiency, global energy security remains a strategic and economic challenge. While self-sufficiency would alleviate some of the traditional concerns about global supply disruptions, the fact that many energy forms remain traded commodities means that foreign disturbances will continue to impact domestic markets. Rapid growth in the use of renewable energy (and use of batteries for electric vehicles and power grid management) may help mitigate conventional security concerns with regard

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to fossil fuels, although these changes may also reveal new risks. Moreover, the US and its allies have a cooperative system for dealing with oil supply disruptions—including both commercial and strategic oil stockpiles—but the framework for dealing with risks arising from the growing use of other fuels is very limited.

There are many approaches to appraising energy security. As a young energy security specialist in the US government in the 1980s, I learned an approach based on assessing vulnerability, risk, and offsets that I've found useful in evaluating oil security. In this paper, I argue that this framework can be useful for assessing the security of an energy system in transition—in particular, a transition away from coal and oil toward natural gas and renewables in part due to climate change. I will apply this framework of vulnerability, risk, and offsets to the current oil market and a potential future energy system in transition to renewable energy and natural gas. This discussion is not intended to be an exhaustive review of all potential facets of the issue, but as an illustration of the framework's application. I primarily focus on the US, but with some consideration of other key energy players and the world as a whole.

THE FRAMEWORK

The first element of the framework is **vulnerability**, which is how exposed the US and global energy systems are to a shock. This could include the size of the energy input to the economy (in absolute terms and especially in financial value), the degree of substitutability, and the concentration in key sectors, such as the importance of oil in transport. Vulnerability has loomed in public perceptions as an economic consideration, experienced as either price spikes and/or physical shortages. Other vectors of vulnerability can include potential adverse effects from a disruption for diplomatic, strategic, or military objectives. In recent years, environmental objectives—especially climate change—have emerged as increasingly important to assessing vulnerability.

In addition, **risk** assesses the chances of a shock. Considerations must include not only the probability of a disruption but also an assessment of the potential magnitude and duration. A large but brief shock (such as the one seen recently in Saudi Arabia) may be less disruptive than a small but long-lasting one.

Finally, **offsets** include the capacity and timeline to counter a shock. This could include the ability to increase production elsewhere, draw supply from inventories, switch to other energy sources, and/or reduce demand by conserving energy. The purpose of these interventions is to cushion the impact of the shock while giving markets—both producers and consumers—a chance to respond in a more orderly fashion.

Energy security policy can aim to address any of these dimensions. For example, vulnerability can be reduced by diversifying the fuel mix, risk can be managed via diplomacy or military power, and a strategic stockpile can be used to offset lost supply.

APPLYING THE FRAMEWORK TO OIL

Vulnerability

Global—and US—vulnerability to oil shocks has improved significantly in recent years, but it still remains a significant concern. The shale revolution has put the longstanding US goal of energy self-sufficiency within reach. The US recorded the world's largest ever increases in production of both oil and natural gas in 2018, and it is the world's largest producer of both fuels. In addition, the country is now a net exporter of natural gas and has seen net oil imports as a share of domestic consumption fall from a high of 60% in 2005 to just 11% last year.[2] The US Department of Energy's Energy Information Administration (EIA) projects that the US could become a net oil exporter as soon as 2020.[3] Rising oil and gas production have boosted the US economy via higher levels of investment, employment, and corporate/individual taxes, as well as the resulting decline in energy prices for consumers and businesses.[4]

Broader changes in the US energy system have also impacted US vulnerability. On the demand side, growing energy diversity and significant improvements in the efficiency of energy use have reduced America's vulnerability to supply disruptions. Oil's share of the US energy mix has declined from a peak of 48% in 1977 to just 36% last year; the share of oil in the global oil mix has also declined.[5] In addition, the amount of energy needed to produce a (real) dollar of GDP has fallen by more than 50% since 1980. As a result of greater efficiency and lower prices, spending on energy as a share of GDP has fallen from 13% in 1980 to roughly 5%.[6] The shale revolution and growing use of renewables have also contributed to reduced US CO_2 emissions from energy use by allowing natural gas to displace coal in power generation; emissions have fallen by 12% since 2007 (although they increased in 2018).[7]

The US shale revolution has also impacted global energy markets and energy security beyond the nation's borders.[8] Rising US oil production (and OPEC's desire to maintain market share) led to a sharp decline in oil prices in recent years: crude prices averaged above $100 per barrel during 2011–14 but now stand near $60.[9] While benefiting consumers, lower prices have created large budget deficits in oil-exporting countries and have prompted efforts in countries like Saudi Arabia to adopt economic reforms aimed at reducing dependence on oil revenues. The lower prices have also adversely affected energy producers in the US. The rapid growth of US natural gas exports is also impacting global markets. For example, Russia has been forced to price its natural gas exports to Europe more competitively due to growing competition from liquefied natural gas (LNG) from the US.[10]

Recent US energy trends stand in sharp contrast to other leading economic centers, which remain more vulnerable to global disruptions—at least when considering the degree of import-dependence. China, which was self-sufficient in oil in 1992, is now the world's largest oil importer, with net imports of nearly 10 million barrels per day (Mb/d) in 2018 (meeting over 70% of domestic energy consumption). China is also an increasingly large importer of natural gas (over 40% of its 2018 energy consumption), and the country even imports coal. Furthermore, Europe depended on imports of oil and natural gas in 2018 to meet roughly three-quarters and 55% of its consumption, respectively. Japan is almost entirely reliant on imported oil and natural gas, while India imports about 80% of the oil consumed and half of the natural gas used.[11]

While the impact of higher oil prices on the US economy is now more balanced, with producing regions benefiting even as consumers are adversely impacted, potential price spikes—and increased price volatility—stemming from global oil outages still pose risks to both households and industry. Oil remains the dominant energy source for the global economy, accounting for 36% and 34% of US and global energy consumption, respectively. Moreover, oil (and increasingly other energy forms) are global commodities, meaning that US markets remain vulnerable to the price effects of supply disruptions abroad, even as domestic production increases.

Vulnerability, risk, and offsets can be a useful framework for assessing the security of an energy system in transition.

While net oil imports have fallen sharply, the US remains a significant importer due to a mismatch between the configuration of US refineries favoring heavy imported crudes and the light quality of domestic crude oil production. Gross oil imports in 2018 were still nearly 10 Mb/d of largely medium and heavy blends of crude oil.[12] Moreover, the adverse economic impact of an oil price spike would be front-loaded, whereas the benefits would take time to manifest. If world oil prices spiked, consumers would see higher fuel costs quickly. The benefits of higher prices on domestic producers would take time to materialize through business decisions including higher capital spending and job creation, as well as dividends and distributions to shareholders.

In addition to pure economic considerations, others have examined how the shale revolution and growing energy self-sufficiency has impacted the broader strategic calculus for the US and other key countries.[13] The strategic and economic vulnerabilities of the current US and global energy system stemming from rising

CO_2 emissions (as well as local impacts including land and water use) have been considered by many.

Finally, oil remains the dominant fuel for transport, including for military equipment; access to fuel therefore remains a key vulnerability from a military perspective. Indeed, a key dimension of vulnerability for oil is its concentration in transport and petrochemicals and a lack of large-scale, affordable substitutes.

Risk

Global oil supply disruptions are significant and have helped to support oil prices in recent years, even with rapid growth of US production. The recent attacks on Saudi oil facilities briefly resulted in the loss of 5.7 Mb/d of crude oil production, 0.7 Mb/d of natural gas liquids, and 2 billion cubic feet per day (Bcf/d) of natural gas production, according to official Saudi statements, making it the largest supply disruption ever. Even before those attacks, the EIA reported that nearly 3 Mb/d of world oil supply was disrupted as of August 2019—about 3% of global supply.[14] In particular, US sanctions have significantly reduced Iranian production. Venezuelan output has also fallen sharply in recent years, even before the recent imposition of US sanctions, which have further reduced production and exports. In addition, significant outages continue in Libya, Syria, and Yemen due to civil unrest.

The US and other countries have built a significant capacity for addressing oil supply disruptions.

Rising Middle East tensions also pose the risk of more significant disruptions. The recent attacks on Saudi infrastructure (including oil fields, processing facilities, pipelines, and tankers) highlight the risk to not only Saudi supplies but broader regional production and exports, with nearly 21 Mb/d of oil (according to EIA) transiting the Strait of Hormuz last year.[15] Iranian officials continue to threaten regional oil flows in the face of tighter US sanctions. Other key energy trade chokepoints include the Suez canal/Suez-Mediterranean pipeline and Bab el Mandeb (at opposite ends of the Red Sea), the Turkish Straits, and the Strait of Malacca in Asia.

US oil and natural gas production is commonly viewed as less risky than importing supplies from other regions such as the Middle East. However, the US supply has experienced both large increases and declines over the past decade due to investment decisions by domestic operators in response to volatile oil prices, as well as the impact of hurricanes. Moreover, policy changes at both the federal and state levels can significantly impact both investment and production, as seen in the calls for a domestic ban on hydraulic fracturing.[16]

Many other factors have also impacted oil supplies in recent years, including industrial accidents and storms. In particular, hurricanes have impacted US refinery and pipeline operations, the natural gas system, and the domestic electricity grid. Energy systems in many Caribbean nations have also been impacted by hurricanes. Cyber and terrorist threats also pose risks to critical domestic (and global) energy infrastructure, as seen in the attack that disabled over 30,000 computers at Saudi Aramco in 2012.[17]

On a positive note, US oil and gas security is bolstered by strong relations with the country's primary trading partners, especially its neighbors in the well-integrated North American energy market. In particular, Canada and Mexico are the leading destinations for US exports of crude oil and refined products, and they are also the leading suppliers to the US, along with Saudi Arabia. Canada and Mexico are also the largest destinations for US natural gas exports, and Canada is the largest source of US natural gas imports.

Offsets

The US and other countries have built a significant capacity for addressing oil supply disruptions over the past 50 years, often in a cooperative fashion. The first and most important line of defense is an integrated global market, which quickly and efficiently reallocates supply in response to unexpected changes in global supply and demand patterns. Deep financial markets also allow market participants to manage their risks through hedging. Price volatility is a feature of this system, however, which can have adverse impacts on consumer and investor confidence and planning, as well as lead to politically unpopular price movements.

This highlights an important (and unavoidable) tension for policymakers in terms of when to rely on market forces and when to intervene. Policy intervention—or the expectation thereof—can impede the normal functioning of the marketplace, so when is it appropriate? For example, some have argued that the creation of a strategic stockpile adversely impacted energy security by reducing incentives for industry to hold commercial stockpiles. In practice, US and International Energy Agency (IEA) policy has developed a view that strategic stocks should be used to manage physical shortages rather than price volatility, though this has always been a judgment call.

Both commercial and government inventories are another key offset. Members of the IEA—including the US—are obliged to hold oil inventories sufficient to cover 90 days of imports.[18] The IEA reports that member states hold roughly 1.5 billion barrels of "public" strategic stocks, in addition to nearly 3 billion barrels of commercial stockpiles (held by companies in the normal course of their operations). China and India are not IEA members, but as significant oil importers, they have also begun to build both commercial and strategic oil stockpiles.

It is important to note, however, that strategic stocks are largely held as crude oil. Disruptions to US refining and pipeline operations (for example, from Superstorm Sandy in 2012 and Hurricane Harvey in 2017) have begun to broaden the focus to include other dimensions of the oil value-chain even though the Strategic Petroleum Reserve (SPR) continues to be exclusively held as crude oil.

In addition, IEA member countries have developed emergency response protocols for sharing oil supplies in the event of a disruption, as well as restraining demand and encouraging fuel switching. The member countries have also begun to engage in coordinated discussions to improve the resilience of the energy system more broadly in the face of threats ranging from climate change to cyberattacks.

On the supply side, Saudi Arabia and other OPEC members have played an important role in offsetting supply disruptions by utilizing their spare production capacity. Saudi Arabia is unique in having invested to maintain a significant buffer of spare production capacity as its contribution to improving global oil security. Before the recent attacks, Saudi Aramco said that its maximum sustainable production capacity was 12 Mb/d, with production near 10 Mb/d. The EIA estimated that the total OPEC spare production capacity stood at about 2 Mb/d—largely in Saudi Arabia—slightly below the historical average.[19] It remains unclear how the recent attacks have impacted Saudi production and capacity; Saudi officials say that production has been restored to pre-attack levels and that they expect capacity to be fully restored by the end of November 2019.

Many observers have noted that the nature of US shale development—with far less capital cost per well and much faster drilling and completion than offshore platforms—allows production to respond more quickly to changing market conditions. This increased price response therefore improves US and global energy security while also improving the country's foreign policy leverage.[20] However, this price response still takes months to have a significant impact on US production, meaning it can not be a first response to future supply disruptions.[21]

Saudi Arabia is unique in having invested to maintain spare production capacity.

APPLYING THIS FRAMEWORK TO A FUTURE ENERGY SYSTEM

While the energy future is highly uncertain, almost all forecasters expect oil to decline in importance as a share of total energy consumption and relative to economic activity. Meanwhile, most forecasters expect natural gas and renewable energy to grow in importance (both as a share of total energy consumption and in absolute terms), with wind and solar energy expected to grow rapidly. More concerted action to address climate change would accelerate this transition.

The displacement of oil by other energy sources would reduce vulnerability to oil shocks, but it could introduce new vulnerability and risks.

Vulnerability

The displacement of oil by other energy sources would clearly reduce US and global vulnerability to oil shocks, but it could also introduce new vulnerabilities and risks to the energy system. For example, the IEA's New Policies Scenario sees oil's share of global energy use falling from 32% to 28% by 2040 (with oil remaining the largest single fuel source), while gas and renewables gain market shares (to 25% and 20% respectively by 2040).[22] Moreover, in the IEA's Sustainable Development Scenario (consistent with meeting the UN's sustainable development objectives, including limiting the impact of climate change to 1.5˚C or less), renewables play a much greater role, accounting for 31% of the global energy mix by 2040.[23] A similar range of scenarios can be developed for potential pathways for the US energy system.

Greater emphasis on energy efficiency is another key feature common to many forecasts. Since policies such as improved vehicle efficiency standards help to reduce the amount of energy needed to produce a dollar of economic output, improved energy efficiency would also reduce the economy's vulnerability to energy shocks.

The rapid growth of new energy sources can also introduce new vulnerabilities into the US and global energy systems. For example, global markets are much less developed for natural gas than for oil—today, about one-third of global gas consumption is traded internationally, compared to about two-thirds of oil. While trade creates exposure to international risks, it also provides greater flexibility. For example, Japan was able to increase imports of fossil fuels to maintain power availability after the Fukushima nuclear disaster caused a sharp reduction in nuclear power. Gas trade is growing, with rapid growth of liquefied natural gas in particular helping create a more global natural gas market.

Meanwhile, renewable energy is almost exclusively domestically produced, which is a significant security benefit. But production of inputs to these energy sources are frequently produced abroad, and—at least for now—are highly concentrated in a few countries. For example, while power from renewable energy is domestically produced, China dominates the global production of rare earth metals (an important component for batteries), solar power panels, and batteries for electric vehicles. Additionally, two-thirds of the world's cobalt production (another battery, solar panel, and wind turbine component) is concentrated in the Democratic Republic of Congo, a country with a history of human rights abuses and corruption. In contrast, the US, as the world's largest oil and natural gas supplier, accounts for just 13% and 20% of global oil and natural gas production, respectively.

The expected growth in renewable energy and batteries will also require an unprecedented increase in the mining and refining of ores. Given the long lead times for developing new mines and the environmental and social issues related to mining and refining (both heavily fossil-fuel dependent), such growth poses a risk of future supply shocks. Moreover, both the US and Europe are highly dependent on ores that are mined and refined outside of their borders.[24]

A key factor of many energy forecasts is an expectation that the role of electricity will continue to grow as a share of total energy use in the US and globally. Growing dependence on power and the ubiquity of electrical equipment in the modern economy mean that vulnerability to electrical supply outages will likely grow. The unique properties of power markets (with largely domestically produced electricity and substantial reserve margins to maintain supply availability, but with virtually no effective storage capability) stretch the application of our framework, but we still can find useful insights. For example, improved data gathering can lend insight into the frequency, duration, and impact of power outages, and the economy's vulnerability to such outages.

Finally, in assessing vulnerability, there is an important distinction between fuel that is consumed (such as oil, natural gas, or electricity) and equipment that produces (such as wind turbines and solar panels) or stores (such as batteries and pumped hydro) energy. A disruption in the trade of the equipment that stores energy would not immediately disrupt energy availability, but it would have delayed impacts on investment and therefore future energy availability.[25] In this sense, the potential disruption of fuels poses a much more substantial short-term vulnerability to the US and global energy systems.

Risk

The assessment of supply risks for non-oil energy sources is still in its infancy. While oil supply disruptions have historically been the focus of energy security discussions, other energy forms are not without risks.

For natural gas, we have seen large-scale supply disruptions. As with oil, hurricanes have caused significant disruptions of US natural gas production, processing, and pipeline flows. Hurricanes and storms also pose significant and potentially widespread risks to the power system. In addition, geopolitical disputes also have the potential to disrupt natural gas supplies. Russian gas exports to Europe, which account for one-third of the continent's gas consumption, have been disrupted several times over the past decade—for example, as a result of disputes with Ukraine over pipeline transit. Flows of LNG through the Strait of Hormuz or other chokepoints also face the risks to oil discussed above.

Other energy forms have also experienced supply outages or threats of disruption. Coal shipments from Australia (one of the world's largest exporters) were disrupted by bad weather in 2017. Furthermore, the Chinese government has used its dominance of rare earth supplies as leverage in the past, and it has threatened to disrupt supplies in the face of growing trade tensions with the US and other partners. China's dominance in the global export of wind turbines, solar panels, and electric vehicle batteries could also be put at risk under future conflict scenarios. Finally, Indonesia has proposed to ban nickel ore exports from January 1, 2020, to stimulate domestic processing of the metal.[26]

The digital revolution as applied to the energy system can also mitigate risk, as well as introduce new risks. For example, the software of a "smarter," more connected energy system could be significantly more robust, reducing risks of disruptions, but it could also be more vulnerable to cyberattack. Power grids have come under cyberattack in Ukraine and elsewhere, and US utilities have been subject to penetration attempts.[27]

More broadly, assessing the risks of disruption for non-oil energy sources is hindered by a lack of historical data. For example, while the EIA tracks global oil supply disruptions monthly, they do not have a corresponding effort for other energy forms.[28] While domestically produced renewable energy may not be subject to geopolitically driven disruptions, all domestic energy supplies remain at risk to disruptions due to factors including weather and industrial accidents. Greater reliance on distributed energy forms can reduce the risk of large-scale systemic outages, but may lead to more frequent—albeit smaller and more localized—disruptions. Moreover, the control systems for energy infrastructure produced abroad may also be at greater risk to hostile cyberattack.

Accordingly, a data-gathering exercise to understand the true risks to energy sources other than oil—both domestic and global—would be an appropriate first step to understanding potential risks of an energy transition. In addition to gathering historical data, another approach to assessing the potential frequency, magnitude, and duration of disruptions in these new energy forms could be a survey of expert opinions. The US Department of Energy has in the past conducted expert workshops to gauge the risks of oil supply disruptions (including frequency, magnitude, and duration) as part of its work to determine the proper size of the SPR.

Offsets

Historically, energy security assessments have been directed at oil supplies, and the resulting domestic and multinational framework is therefore heavily oriented toward managing oil supply risks. What can we say about the various offset mechanisms discussed above when applied to a transitioning global energy system?

The assessment of energy security must evolve along with the energy system.

In terms of the markets, international trade of natural gas and critical metals needed for renewables and batteries is growing, but global markets are much less deep and liquid compared to oil. Furthermore, there are no viable futures markets for some metals, making it difficult for market participants to assess their vulnerabilities and impossible to manage them by hedging. Natural gas markets are also becoming more globally integrated via rising LNG trade. Within the US, the gas and power markets are large and efficient, though the power grid and marketplace are regional rather than national. Large, efficient markets greatly assist in managing vulnerabilities and risks, but the lack of a truly national grid—and of a coordinated national response capability—is a potential limitation on the robustness of the US power system.

With regard to inventories, US commercial inventories of natural gas are large, helping to manage what has traditionally been large seasonal variation in domestic demand. There is no government stockpile, and gas storage is much smaller relative to consumption in many other regional markets around the world. In terms of the metals needed for renewables, solar panels, wind turbines, and batteries, there is no reliable global data for commercial inventories, nor are there strategic government stockpiles. Note that electricity—unlike oil or gas—cannot currently be stored economically at scale; the future will depend on the economic and technical development of large-scale, grid-connected batteries.

In the power system (unlike oil and natural gas production operations), the concept of reserve margins to manage unexpected swings in demand and variability of supply is well-established. The importance of these reserves will grow as intermittent renewables become more important. But for the broader energy system, such practices are not institutionalized. Moreover, there is no global or domestic supplier that invests in maintaining a buffer of spare production capacity for new energy sources to help manage disruptions, as Saudi Arabia does for oil. As with oil, US shale gas production can respond more quickly to price signals than other gas resources, but not quickly enough to be a first responder in a shock.

Furthermore, the IEA has begun to expand discussions of emergency preparedness to include other forms of energy. Some European countries, such as Spain,[29] have begun to impose natural gas storage obligations on companies. Unlike oil, however, there are no formal, binding multinational agreements laying out obligations for holding and releasing inventories, sharing supplies, fuel switching, or demand restraint. Furthermore, there is no organized system in the US, nor a cooperative multinational effort, to hold strategic stockpiles for non-oil energy forms.

CONCLUSION

The domestic and international assessment of—and policies aimed at improving—energy security must evolve along with the energy system. Growing reliance on natural gas and renewable energy help mitigate vulnerability to future oil supply disruptions. But with these alternatives playing a much larger role in the global energy economy, and with mining of base metals and manufacturing of new energy components concentrated abroad, these same dynamics also raise the prospect of new vulnerabilities and risks that must be understood and managed. Data collection is always a good place to start; cooperative efforts to systematically gather information on the relevant indicators for new energy forms is in its infancy. Moreover, a robust set of capabilities and institutions has been built up over the past 50 years for managing oil supply risks, but such capabilities are limited for other energy forms. The framework of assessing energy security by analyzing vulnerability, risk, and offsets—and building domestic and international policies to address these three factors—can be a useful approach in tackling this emerging challenge. While the application of this framework to the new energy system discussed here is by no means definitive, it may serve as a useful starter to the conversation, here in the US and abroad.

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ENDNOTES

1. See for example: Mark Finley and Kenneth B Medlock III, "Attacks on Saudi Oil Facilities Cast a Huge Shadow of Uncertainty on the Oil Market," Forbes Blog, September 17, 2019, http://bit.ly/2CASl56.

2. "Petroleum Overview," Monthly Energy Review, US Energy Information Administration, accessed October 31, 2019, http://bit.ly/2CB16fr.

3. "U.S. Petroleum and Other Liquids Supply, Consumption, and Inventories," Short-Term Energy Outlook, US Energy Information Administration, accessed October 31, 2019, http://bit.ly/2Q7KzYn.

4. See for example Nida Çakir Melek, Michael Plante, and Mine K. Yücel, "Resource Booms and the Macroeconomy: The Case of U.S. Shale Oil," Federal Reserve Bank of Kansas City working paper, December 2018, http://bit.ly/2qDyTBT; "Dallas Fed: US Shale Boom Accounted for 10% of US GDP Growth," *Journal of Petroleum Technology*, August 22, 2019, http://bit.ly/36WF2cS.

5. Oil consumption has increased over this period, but less rapidly than overall energy consumption. "Primary Energy Consumption by Source," Monthly Energy Review, US Energy Information Administration, accessed October 31, 2019, http://bit.ly/2O4KHF8.

6. "Primary Energy Consumption, Energy Expenditures, and Carbon Dioxide Emissions Indicators," Monthly Energy Review, US Energy Information Administration, accessed October 31, 2019, http://bit.ly/2qNyZH1.

7. Ibid.

8. See for example Jim Krane and Kenneth B. Medlock III, "Geopolitical dimensions of US oil security," *Energy Policy* 114 (March 2018): 558-565, https://doi.org/10.1016/j.enpol.2017.12.050.

9. US crude oil prices have traded at a substantial discount to international prices in recent years due to domestic infrastructure bottlenecks and shifting trade flows.

10. See for example Nathalie Hinchey and Anna Mikulska, "LNG Versus Russian Gas In Central And Eastern Europe: Playing Poker On A Continental Scale," Forbes Blog, August 24, 2017, http://bit.ly/34VsS2p; Nathalie Hinchey, "The Impact of Securing Alternative Energy Sources on Russian-European Natural Gas Pricing," *The Energy Journal* 39, no. 2 (2018), http://bit.ly/33zj4uy.

11. "Statistical Review of World Energy," BP, 2019, https://on.bp.com/2Q9vs0C.

12. With exports of crude oil and refined products of about 7.5 Mb/d, US net oil imports were just over 2 Mb/d in 2018.

13. See for example Meghan O'Sullivan, *Windfall: How the New Energy Abundance Upends Global Politics and Strengthens America's Power* (New York: Simon & Schuster, 2017); *Hearing on Geopolitics of US Oil and Gas Competitiveness, before the House Committee on Foreign Affairs Subcommittee on Terrorism, Nonproliferation, and Trade*, 115th Cong. (2018) (statement of Kenneth B. Medlock III, Senior Director of the Center for Energy Studies), http://bit.ly/2q4gFtd; and Krane and Medlock III, "Geopolitical dimensions."

14. "Estimated unplanned liquid fuels production outages," Short-Term Energy Outlook, US Energy Information Administration, accessed November 1, 2019, http://bit.ly/2qHJEmH.

15. Justine Barden, "The Strait of Hormuz is the world's most important oil transit chokepoint," US Energy Information Administration, June 20, 2019, http://bit.ly/2q1b0nK.

16. See for example Natasha Turak, "Elizabeth Warren's fracking ban would be bad news for the US, IEA chief says," *CNBC*, September 9, 2019, https://cnb.cx/33DNsEa.

17. See for example Nicole Perlroth, "In Cyberattack on Saudi Firm, U.S. Sees Iran Firing Back," *New York Times*, October 23, 2012, https://nyti.ms/34Lm6Mq.

18. With US imports declining, the required inventory coverage (measured in days of imports) has also declined, which has been a contributing factor to the recent decision to sell off a portion of the US SPR.

19. "OPEC Crude oil (excluding condensates) Supply," Short-Term Energy Outlook, US Energy Information Administration, accessed November 1, 2019, http://bit.ly/32xrukQ. In addition, some producers may be able to "surge" production, temporarily increasing supply beyond normally accepted operating standards, for example by relaxing reservoir management guidelines.

20. See for example *Hearing on Geopolitics of US Oil and Gas*.

21. See for example Richard G. Newell and Brian C. Prest, "Is the U.S. the New Swing Producer? The Price Responsiveness of Tight Oil," Resources For the Future working paper, June 2017, http://bit.ly/2O0CToa.

22. Today, natural gas and renewables are a smaller share of the US and global system compared to oil. Natural gas and renewables account for about 22% and 15%, respectively, of global energy consumption. Renewables here include hydro, bioenergy, wind, and solar. Source: International Energy Agency, *World Energy Outlook 2019* (France: IEA, 2019), http://bit.ly/36W2EyD.

23. In the Sustainable Development Scenario, the IEA assumes that as world oil demand falls sharply (by 36 Mb/d in 2040 relative to their New Policies Scenario), both OPEC and non-OPEC producers reduce output to maintain relatively constant market shares. The geopolitical and economic implications of such sharp reductions, and the potential risks to supply that might result, are not explored in the IEA *World Energy Outlook*.

24. See for example *Hearing on Sources and Uses of Minerals for a Clean Energy Economy, before the US Senate Committee on Energy and Natural Resources*, 116th Cong. (2019) (statement of Mark P. Mills, senior fellow at the Manhattan Institute), http://bit.ly/36W1V0c.

25. There are of course many other sources of risk for future investments in energy infrastructure, most notably in future prices, government policy, and technological innovation.

26. See "Indonesia releases nickel ore export ban decree," *Reuters*, September 4, 2019, https://reut.rs/36YScq0.

27. See for example: Robert M. Lee, Michael J. Assante, and Tim Conway, *Analysis of the Cyber Attack on the Ukrainian Power Grid* (Washington, D.C.: Electricity Information Sharing and Analysis Center, 2016), http://bit.ly/2qJfhMK; and Blake Sobczak, "First-of-a-kind U.S. grid cyberattack hit wind, solar," *E&E News*, October 31, 2019, http://bit.ly/2KeSmjg.

28. In the US and many developed economies, there is data on power supply disruptions held by grid operators, although such data is rarely aggregated to a national level for use in the type of studies envisioned here.

29. See "Natural Gas," Cores, accessed November 1, 2019, http://bit.ly/2CAf6px.

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