SANDIA REPORT

SAND2019-3598
Unclassified Unlimited Release
Printed August 2017

Global Futures: The Future of Nonrenewable Resource Security

Drake Warren, George Backus, Wendell Jones, Thomas Nelson, and Howard Passell

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy?s National Nuclear Security Administration under contract DE-NA0003525.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology and Engineering Solutions of Sandia, LLC.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2019-3598
Unclassified Unlimited Release
Printed March 2019

Global Futures: The Future of Nonrenewable Resource Security

Drake Warren, George Backus, Wendell Jones, Thomas Nelson, and Howard Passell
Systems Analysis and Decision Support

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-0159

Abstract

Nonrenewable resources are distributed unevenly throughout the world. Throughout history, the ability to access nonrenewable resources has been a source of geopolitical tension. Modern civilization is increasingly dependent on unevenly distributed resources that are traded globally. This cooperation has helped to increase resource security by increasing affordable access to resources around the world.

The continued accessibility of nonrenewable resources is the key uncertainty to security over the next 15 to 25 years. Increased global demands for nonrenewable resources, fragility to resource shocks, and geopolitical upheavals may threaten nonrenewable resource security. A reduction in resource security could exacerbate defense and economic vulnerabilities to resource shocks, and increased fears of resource insecurity could drive conflict over resources leading to geopolitical upheavals.

National security organizations can help build resource security by making investments that create resilience to resource shocks. They can also promote international cooperation that builds trust. Together, increased resilience to shocks and increased global trust should help reduce fears of resource insecurity and expand global cooperation on resource issues, thereby bolstering resource security.

ACKNOWLEDGMENTS

We would like to thank the many people in Systems Analysis and Decision Support (150) and Systems Analysis and Engineering (8110) who helped provide feedback on our presentations and our research. We would like to thank especially Mark Ackermann, Cathy Ann Connelly, William Curtis, Celeste Drewien, Chad Haddal, Nancy Hayden, Brandon Heimer, Elizabeth Kistin Keller, Len Malczynski, Thor Osborn, Patricia Pacheco, Subha Shettigar, Russ Skocypec, Brad Smith, and Matthew Sumner. Additionally, we would like to thank the subject matter experts from across Sandia that we consulted in the course of this research: Kent Meeks (100), John Foley (111), Pat Sullivan (163), Marcus Woodson (163), Benn Tannenbaum (164), Tedd Rohwer (250), Scott Slezak (400), Ed Cole (1000), Tina Nenoff (1100), Cindy Phillips (1400), Ben Cook (1910), Karla Weaver (1911), Hy Tran (2500), John Rowe (5000), Dahlon Chu (5020), Ethan Blansett (5352), Gary Polansky (5400), Tan Thai (5600), Phil Dreike (5700), Rod Nagel (5786), Bill Miller (5900), Bill Tedeschi (5900), Declan Rieb (5957), Gary Laughlin (6020), Braeton Smith (6921), Vanessa Vargas (6921), Tom Corbet (6924), Ron Pate (6926), and Juan Torres (8040).

Contents

Figures

Tables

NOMENCLATURE

DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
GDP	gross domestic product
GF	Global Futures
LLT	Lab Leadership Team
NDS	National Defense Stockpile
NIC	National Intelligence Council
OPEC	Organization of the Petroleum Exporting Countries
REE	rare earth elements
U.S.	United States
USGS	U.S. Geological Survey
WWII	World War II

GLOSSARY

Nonrenewable resources	Resources that are extracted from the earth and are either not replenished or are replenished very slowly[1]
Scarcity	The state of demand for a resource exceeding its supply so that resource consumers are willing to pay for the resource or expend other resources to produce that resource[2]
Resource security	Reliable and affordable access to the utility of resources[3]
Resource insecurity	Uncertainty or doubt about the reliable and affordable access to the utility of resources
Resilience	The ability of society and its institutions to efficiently reduce the magnitude and duration of impacts to resource services from disruptions, price changes, and the increasing scarcity of resources[4]

[1] These resources are primarily included in US. Government statistics in North American Industry Classification System industry 21: Mining, Quarrying, and Oil and Gas Extraction.

[2] Scarcity means that a resource has a price above zero. Relative scarcity for a particular resource can change as demand and supply for the resource change. Relatively scarcity is usually reflected in the price of a resource when a market exists for the resource.

[3] For example, the "utility" of oil, natural gas, coal, and uranium is often energy. If any of those resources were inaccessible, some amount of energy could be obtained from a substitute.

[4] This definition is based on the definition from Biringer, et al, (2013, p. 107): "Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is that system's ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels."

1. BACKGROUND FOR GLOBAL FUTURES SERIES

As an outcome of the Sandia Lab Leadership Team's (LLT) strategic planning process, Center 0100 was asked to provide periodic one-hour information briefings on global futures (GF) relevant to Sandia. The intent was to create a discussion forum focused on GF, exploring possible implications for national security and Sandia's mission.

The briefings topics include:

- Arctic Security
- Urbanization and Megacities
- Technology Empowerment
- Demographic and Economic Divergence
- Nonrenewable Resource Security (this report)

The method used to develop the series briefings was to survey diverse perspectives of realizable GF centered around a given topic area and identify the spectrum of resulting global implications.

The rationale for the GF series of briefings research are presented in Figures 1 through 3.

Figure 1. National Security Is Inherent in Sandia's Mission

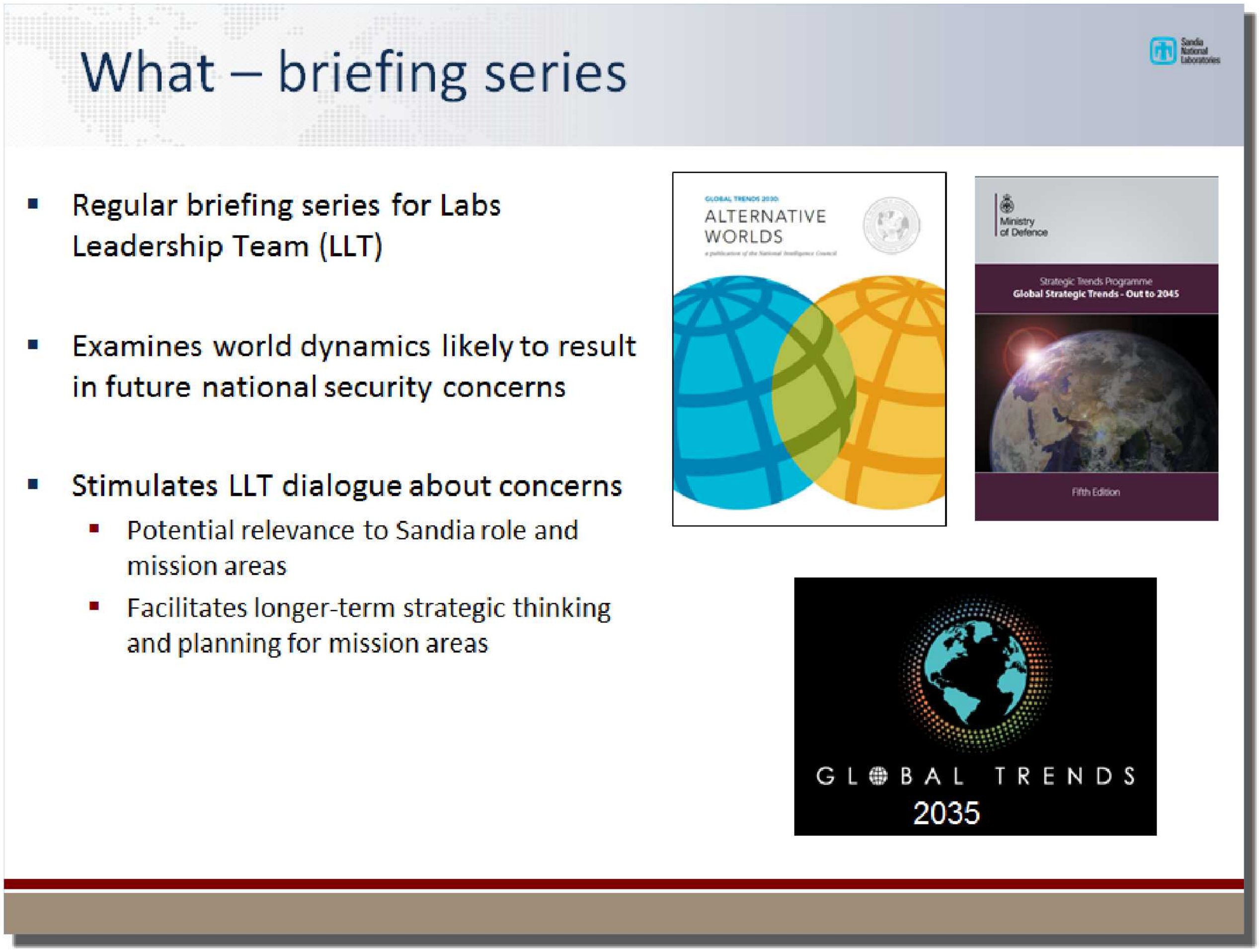


Figure 2. Purpose of the Series Briefing to Sandia Labs Leadership Team

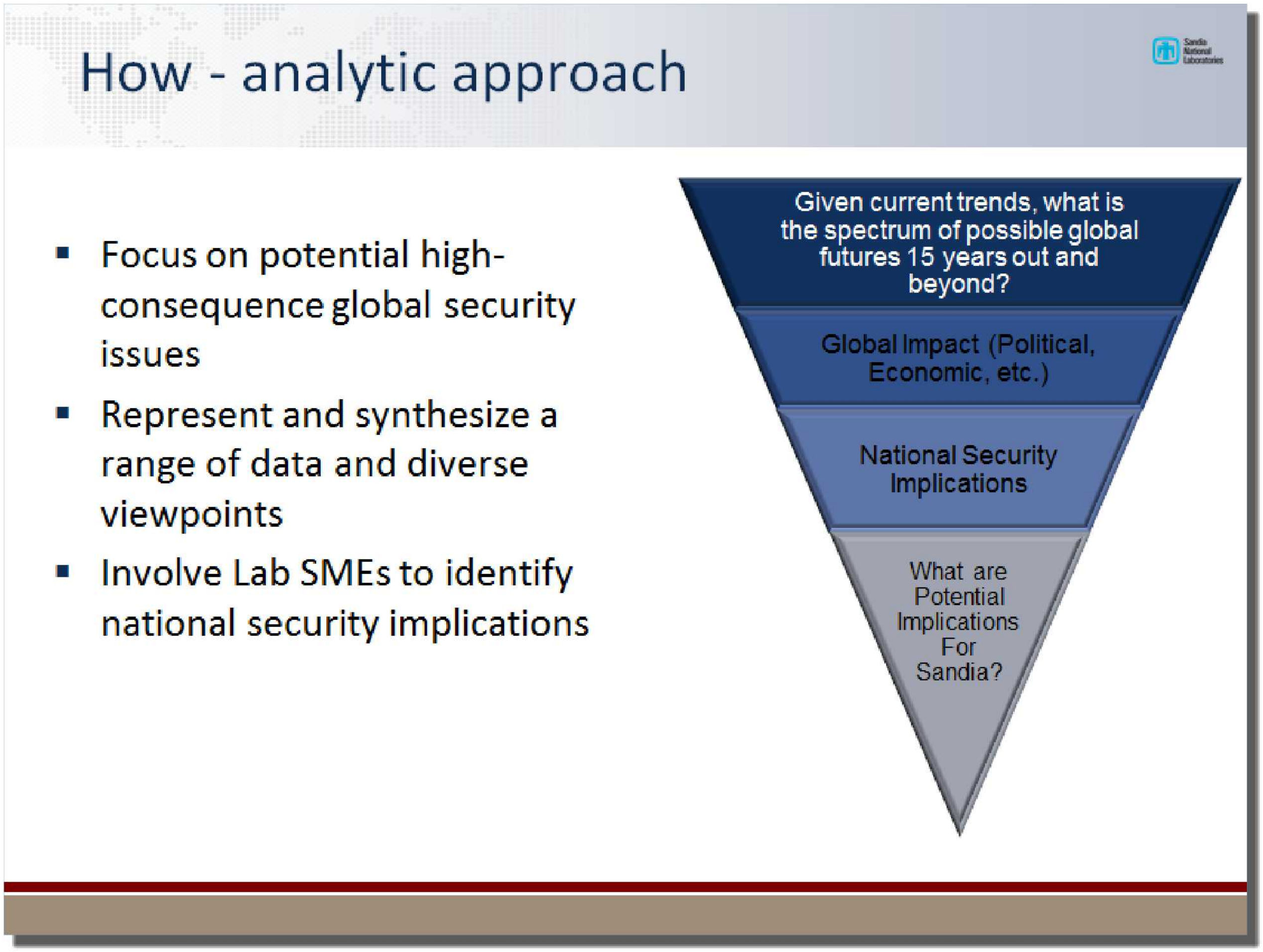


Figure 3. Sandia's Analytic Approach to Global Security

1.1. Introduction to Global Security: Nonrenewable Resources

Figure 4. Study of the Risk to Accessing Nonrenewable Resources

This annotated report examines the future of nonrenewable resources and the impact that those resources may have on global security in the next 15 to 25 years. This GF study was motivated by the fact that historically resources have been a driver of geopolitical tension, hence our desire to better understand how resources may help shape geopolitics in the future.

The past several decades have been a time of increasing globalization, where countries like the United States (U.S.) have been increasingly dependent on importing resources from around the world. As this report will discuss, this globalization has had tremendous benefits—especially in a geopolitically stable world as we have experienced recently—but also entails some risk.

This study focused on nonrenewable natural resources like oil[5] and uranium.[6] These resources are usually at the beginning of supply chains that are often long and complex. Nonrenewable

[5] The image is the upper right is an oil pumpjack. (By Flcelloguy at the English language Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2351321.)

resources are special for two reasons. First, they are extremely concentrated geographically so that no one country can have access to all possible resources without engaging in trade (Lamy, 2010, p. 3). This uneven distribution helps drive global geopolitics uniquely since other resources historically are distributed with population (e.g., civilization required food and water to grow, and supply chains are driven by labor and capital that exist where people live). Second, nonrenewable resources are continuously depleting. The known resources that are easiest to extract are extracted today, while those extracted tomorrow are either harder to extract or harder to find. This dynamic adds to geopolitical stress, especially as demand for nonrenewables is increasing rapidly through population growth and the spread of industrialization.

This study's framework and security drivers also apply to other resources, such as renewable natural resources like food and water and resources produced by supply chains. Our original motivation for focusing on nonrenewables was driven by the natural security community's frequent attention to nonrenewable resources; however, there is an increasing recognition that other resources are a source of national security risk—and in fact may generate an even bigger risk than nonrenewables (Parthemore and Rogers, 2010, p. 7).[7]

For this study, we define "resource security" as "the reliable and affordable access to the utility of resources." This definition is similar to other definitions[8] but emphasizes that what really matters is the "utility" of resources.[9] That is—with the exception of some rare, precious metals like gold—users do not care about an individual resource itself, but the services that it provides; if other resources provide similar services, then they provide effective substitutes that improve resource security. This definition also emphasizes that "access" to resources is of greatest importance over the next several decades. Most resources exist in sufficient reserves somewhere on earth to satisfy demands for several decades, but **access** to those resources could be at risk, particularly if geopolitical upheaval erodes globalism.[10]

As we mentioned earlier, the geopolitical consequences of nonrenewable resources are not a new issue. This study includes historic examples that have been relevant to U.S. national security since World War II (WWII). One particularly salient example was uranium supplies before and during WWII. Prior to the war, there was limited demand for uranium due to a lack of known applications. Uranium was a byproduct of radium mining. The richest source of uranium was the

---

[6] The image in the lower right is an open pit uranium mine in Namibia (By Ikiwaner - Own work, GFDL 1.2, https://commons.wikimedia.org/w/index.php?curid=8132735). Modern

[7] As we discussed, a key reason that the national security community is interested in nonrenewables is because they are finite. As we conducted this study, we quickly realized that there was no widespread risk of "running out" of nonrenewable resources in the next several decades. Even the most limited resources likely have several hundred years of exploitable supply left on earth. Contrast that to renewables like food, where less than a year of supply may exist, or supply chain products, where hours of supply exist in extreme cases like radiopharmaceuticals.

[8] We drew much of the definition's wording from Lee, et al. (2012, p. 2), "reliable access to the resources on which society and the economy depend, at affordable cost".

[9] This idea is similar to Simon (1996, pp. 61-62), who emphasized the importance of "resources as services". He cites several examples of how substitutes reduced copper use (e.g., fiber optics instead of copper wires, iron and aluminum cookware instead of copper, and PVC plumbing instead of copper).

[10] The United Kingdom Ministry of Defence (2010, p. 117) concludes strongly that the vulnerability is resource access, not the global availability of resources: "New discoveries allied to technological advances *will* provide sufficient reserves, such that accessibility, rather than availability, is the primary concern" (emphasis in original).

Shinkolobwe mine in the Belgian Congo, which was owned by Union Miniere du Haut Katanga, a Belgian company (Jones, 1985, p. 8). The company produced a cache of ore containing 65-percent uranium oxide and waste piles at 20-percent uranium oxide (Nichols, 1987, pp. 44-47)[11] before shutting down due to a lack of demand. Prior to the German invasion of Belgium, the company transferred all its radium and some of the uranium ore to the United States, where it was later sold and exported to Canada for processing (Jones, 1985, pp. 25, 64-65). After the German invasion, Belgium's colonies remained under the control of the Belgian government in exile in London. Nonetheless, there remained worries that Germany would try to get access to the mine or divert uranium shipments from the mine. Williams (2016) reviewed declassified sources from the Office and Strategic Services and concluded that a substantial U.S. clandestine effort was made to assure that the uranium did not fall into German hands—an effort she credits for assuring that the German atomic project could not succeed (pp. 247-248). In fact, immediately following WWII German atomic scientists cited a lack of uranium as a major reason for their failure (Frank, 1993, p. 78).

[11] By contrast, most other uranium mines have had concentrations of uranium oxide of a fraction of a percent.

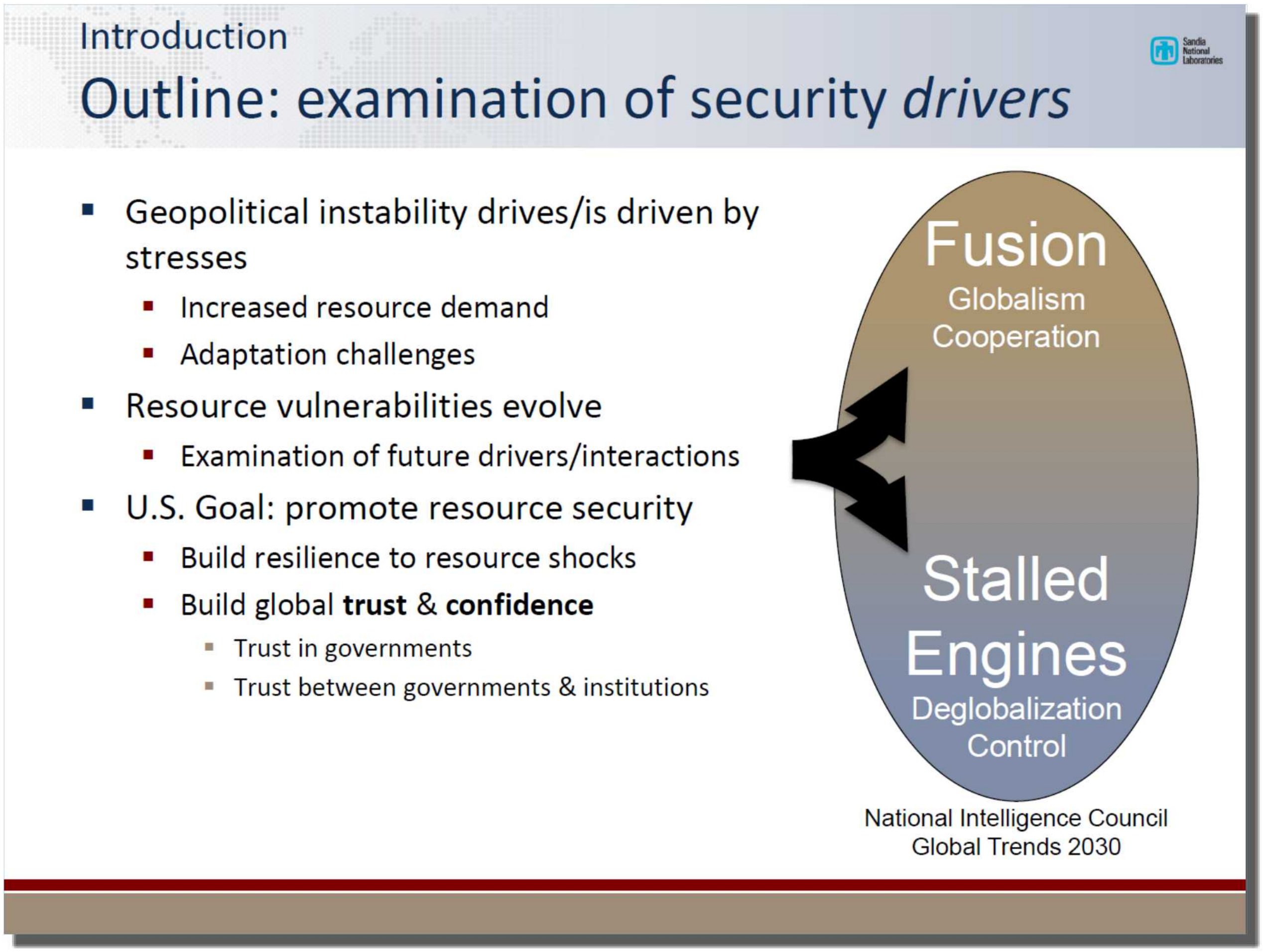


Figure 5. Overview of the Nonrenewable Resources Study

The principal conclusion of our study is that within the next 15 to 25 years, the future of nonrenewable resource security is likely to be dominated by geopolitics (Figure 5). In today's globalized work, the security of nonrenewable resources depends on the ability to obtain those resources from all corners of the world. An abrupt change in geopolitics could make it more difficult to obtain resources. Furthermore, resource shocks, for example, a disruption the supply of a resource or set of resources, could drive geopolitical impacts, especially if states enact counterproductive policies that increase global competition over resources.

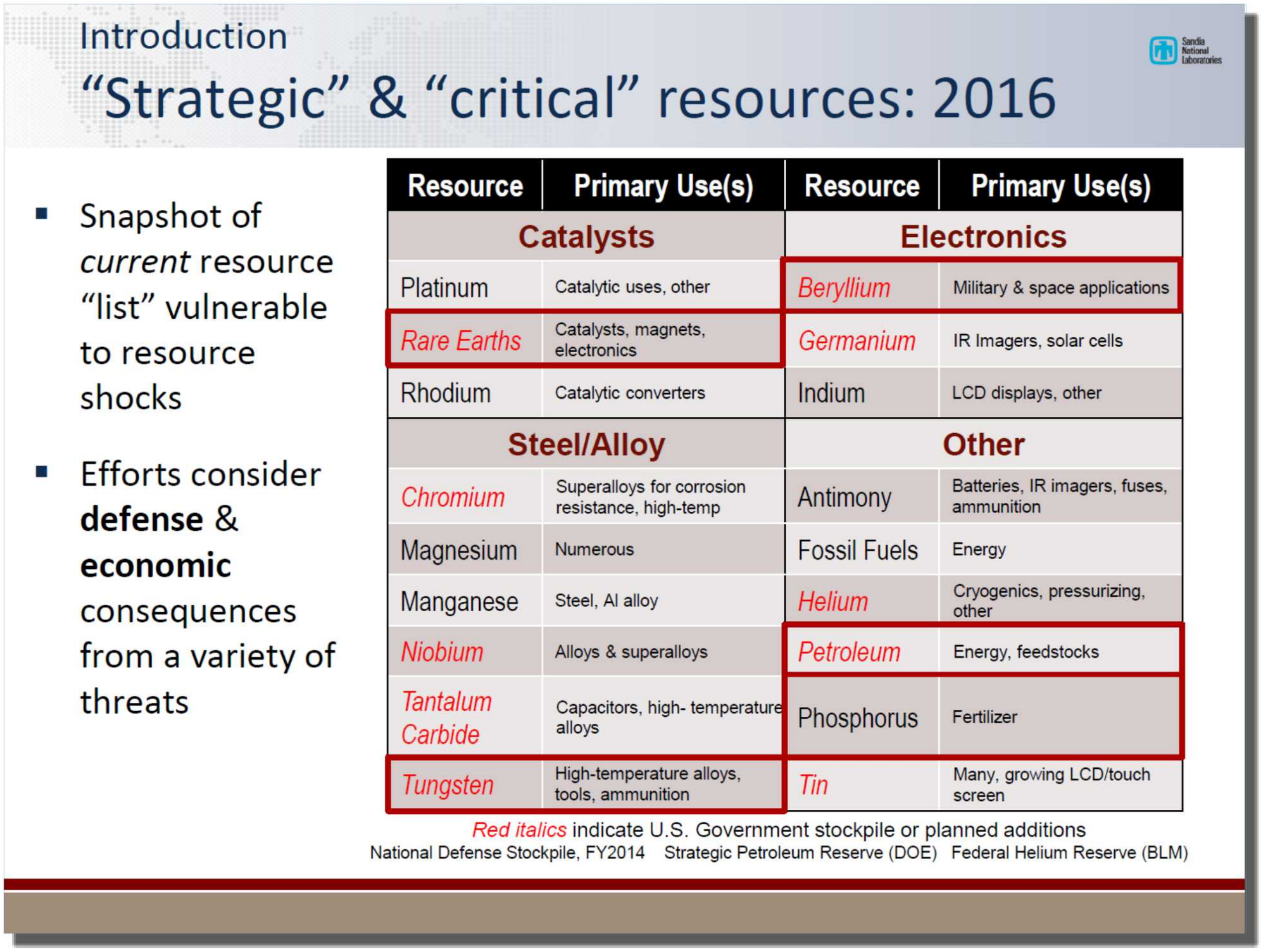
We identified two additional factors that could stress natural resource security and geopolitics. First, demand for resources is likely to continue accelerating. Second, the ability to adapt to resource vulnerabilities is likely to have limits.

The conclusion that nonrenewable natural resource issues are largely geopolitical issues is shared by many other researchers. For example, the Committee on Assessing the Need for a Defense Stockpile (2008, p. 2) concluded that threats to resource security were largely driven by geopolitical issues (i.e., the increased dependence on foreign sources and the increased risk from complex supply chain networks that have spread across the globe) plus increasing worldwide demand for resources. Notably absent from the assessments we reviewed was concern that resources would "run out." An insufficient supply of resources is a common worry, but the insufficiency is driven by challenges in responding to increased demand and/or supply disruptions driven by, or made worse by, geopolitical events.

A second principal conclusion of our study is that natural resource vulnerabilities will always exist, but they will evolve; in net, they could be easier to overcome or more difficult depending on geopolitically driven factors like globalism and global demand. Nonrenewable natural resources are valuable because they are scarce. Like anything that is scarce, they are governed by supply and demand. Because nonrenewables are a building block in most supply chains, they are especially vulnerable to demand shocks, for example, from the onset of rapid industrialization in developing countries. Since nonrenewables are so geographically concentrated, they are especially vulnerable to supply shocks from infrastructure and geopolitical disruptions.

The third principal conclusion is that the U.S. government will need to promote resource security in the next 15 to 25 years principally by building resilience to resource shocks and by building trust in governments, and between governments and institutions. We found that the National Intelligence Council (NIC) *Global Trends* 2030 bookend scenarios are particularly useful for illuminating the range of futures that the world may face. The "Fusion" scenario is a continued evolution of trends from the past few decades, where there is more globalism and more cooperation between countries and organizations around the world. Economic development would accelerate in a Fusion world, thus resource issues would likely be driven by increasing demand and demand shocks. Increased resilience would help the world foresee, withstand, adapt to, and recover from these shocks. In the "Stalled Engines" scenario, globalism retreats and it becomes more difficult to access resources from around the globe. This would drive countries to seek assured control of resources through domestic production or production from close allies. Resilience would also be important in the Stalled Engines world, driven by the need to find substitutes for resources that are too expensive to source domestically. Resource security would likely be substantially lower in the Stalled Engines world. The "offramp" from the Fusion world to the Stalled Engines world could be particularly painful because countries would need to adapt and adjust—perhaps suddenly—to a world of reduced resource ability. A rapid transition could outpace their ability to adjust. To avoid this offramp and remain in the Fusion world, countries would need to seek greater worldwide trust and cooperation.

1.1.1. Recent Studies Have Identified Resources at Risk



Resource	Primary Use(s)	Resource	Primary Use(s)
Catalysts		**Electronics**	
Platinum	Catalytic uses, other	*Beryllium*	Military & space applications
Rare Earths	Catalysts, magnets, electronics	*Germanium*	IR Imagers, solar cells
Rhodium	Catalytic converters	Indium	LCD displays, other
Steel/Alloy		**Other**	
Chromium	Superalloys for corrosion resistance, high-temp	Antimony	Batteries, IR imagers, fuses, ammunition
Magnesium	Numerous	Fossil Fuels	Energy
Manganese	Steel, Al alloy	*Helium*	Cryogenics, pressurizing, other
Niobium	Alloys & superalloys	*Petroleum*	Energy, feedstocks
Tantalum Carbide	Capacitors, high- temperature alloys	Phosphorus	Fertilizer
Tungsten	High-temperature alloys, tools, ammunition	*Tin*	Many, growing LCD/touch screen

Figure 6. Representative List of Strategic and Critical Resources

While conducting this study, we reviewed some of the many ongoing research efforts that governments have been conducting or funding on their behalf to mitigate risk by identifying nonrenewable resource vulnerabilities. Although the methodology in these studies varies, and the vulnerabilities identified vary (e.g., different countries have different vulnerabilities), they share a common risk-based framework. They measure the risk arising from a resource by the likelihood of a disruption occurring and by the consequences of a disruption should one occur. Consequences vary by study effort, but most often look at economic consequences (resources with a high level of economic risk are often called "critical resources") or defense and national security consequences ("strategic resources").

Figure 6[12] shows a representative list of some resources commonly found on these lists. This particular table was pieced together from the highest-risk resources identified by a number of sources:

---

[12] "Primary Use(s)" in the table are adapted from Office of the Under Secretary of Defense for Acquisition,

- In a seminal paper looking at absolute availability of resources, Goeller and Weinberg (1976) estimated the number of years of resources available until the world runs out based on abundance of resources in the earth's crust. Although their estimates are outdated by changes in demand, only the availability of phosphorus and fossil fuels stand out as being in particularly short supply (i.e., supplies measured in hundreds of years rather than thousands of years or longer).
- Researchers at the RAND Corporation (Silberglitt, et al. 2013) calculated a risk index for each resource based on its production concentration (within a particular country or countries) adjusted for the quality of governance in the countries that produced it. Their top risks are dominated by resources with production concentrated in China.
- Resources stockpiled by the U.S. government (as of 2014) are also included. Most of these resources are included in the National Defense Stockpile[13] (NDS) maintained by the Department of Defense (DoD), while petroleum is stockpiled in the Department of Energy's (DOE) Strategic Petroleum Reserve and helium is stockpiled in the Bureau of Land Management's Federal Helium Reserve.

Figure 6 is by no means complete; there are many studies considering many different types of risks and disruptions. More importantly, the list above is not a prediction of risks in the future; rather, it is a snapshot of current risks. Many of these resources are likely to be at risk 15 to 25 years from now, but others may drop off and others may be added as geopolitics, technology, and demand evolve.

Technology, and Logistics (2015a).

[13] These resources have positive inventory goals, as described by "Table 1: NDS Inventory and Goals" of Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (2015b). The NDS holds other resources that are a legacy of previous efforts, but for which DoD is now selling. DoD is in the process of updating its inventory goals over the next five years to include some of the resources listed in the table above as well as increasing inventories of manufactured items (e.g., lithium ion precursors and some types of explosives). See Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (2016) for details.

1.1.2. Future Risks Will Evolve and Cannot Be Predicted with Certainty

Figure 7. Possible Strategic and Critical Nonrenewable Resources in the Future

This study focused on identifying future stressors and drivers of resource security in the next 15 to 25 years. The study did not attempt to make predictions about what the "snapshot" table from the Figure 6 will look like. However, in conducting the study we came across many predictions from articles, researchers, and subject matter experts. In the graphic above, we include a sample of others' predictions to emphasize the breadth of future risks.

The first example is of rare earth elements (REE), which were listed in Figure 6. As we discuss in greater depth later in this report, there has been a rapid increase in technologies that use REEs, such as electronics and strong magnets used in wind turbines. DoD has also recognized the importance of REEs to defense applications, as evidenced by its recent decision to start acquiring yttrium[14] and dysprosium[15] in the NDS (Figure 7).

---

[14] Yttrium is not a true REE, but it is found alongside REEs, so it is usually considered a REE. Yttrium is used in industry in phosphors, ceramics, and automobile catalysts (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2015a). Image source: By Alchemist-hp (www.pse-mendelejew.de) - Own work, FAL, https://commons.wikimedia.org/w/index.php?curid=10793308.

The second example is phosphate. In Figure 7 the photo marked “Phosphate: no substitutes + limited” [16] shows the island nation of Nauru in the Pacific Ocean. Nauru was formerly a major source of phosphates that had been deposited over time by migrating birds, but little phosphate remains after extensive mining. Phosphate is used in fertilizer, so there is no substitute. Furthermore, phosphorus has been identified as a resource likely to run out the fastest (see Goeller and Weinberg, 1976). In a case study later in this report we examine phosphorus to see that recent worries about phosphorus depletion have been alleviated by new discoveries, but geopolitical risks may have been intensified by those discoveries.

The third example is topsoil. Farmers have long known that soil erosion is a problem that can impact crop production, which is why farmers have engaged in practices like terracing. However, in the past couple of decades researchers have begun understanding the magnitude of soil erosion globally. For example, the Food and Agriculture Organization (2015) of the United Nations estimates that a third of cropland soils globally “are moderately to highly degraded due to erosion, salinization, compaction, acidification, and chemical pollution” (p. XIX). Amundson et al. (2015) concludes that “human security over the next century will be severely threatened by unsustainable soil management practices.”

The final example is of sand. Sand is needed in large quantities as a component of mortar and concrete to build buildings and infrastructure. Only a small portion of sand is of suitable quality to be used for mortar and concrete; sand in deserts has been eroded by the wind and is too rounded to bond properly (Zhang et al., 2006). Sand is heavy and hard to transport, which means that local shortages of sand have the potential to increase construction costs (Beiser, 2016). This mismatch of supply and demand has the potential to lead to conflict; in India illegal sand mining has led to a black market, the emergence of “sand mafias,” and driven violence (Beiser, 2015).

[15] Dysprosium is used in industry in phosphors and permanent magnets (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2015a).
[16] Phosphate mining in Nauru: By Lorrie Graham/AusAID, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=32164905.

2. STATE OF THE SYSTEM

In this section we present three case studies that demonstrate the stressors we identified as impacting nonrenewable resource security in the next 25 to 35 years. To reiterate, we found that the future of nonrenewable resource security is closely tied to the future of geopolitics. The case studies in this section will demonstrate some ways in which geopolitics has impacted or may impact security in the future. (The next section goes a step farther and discusses the possibility that issues or disagreements surrounding resources could lead to geopolitical upheaval in the future.) The case studies also show how geopolitics interacts with increasing demand for resources and challenges to adaptation.

2.1. Case Study: Population and Industrialization Increase Resource Demand

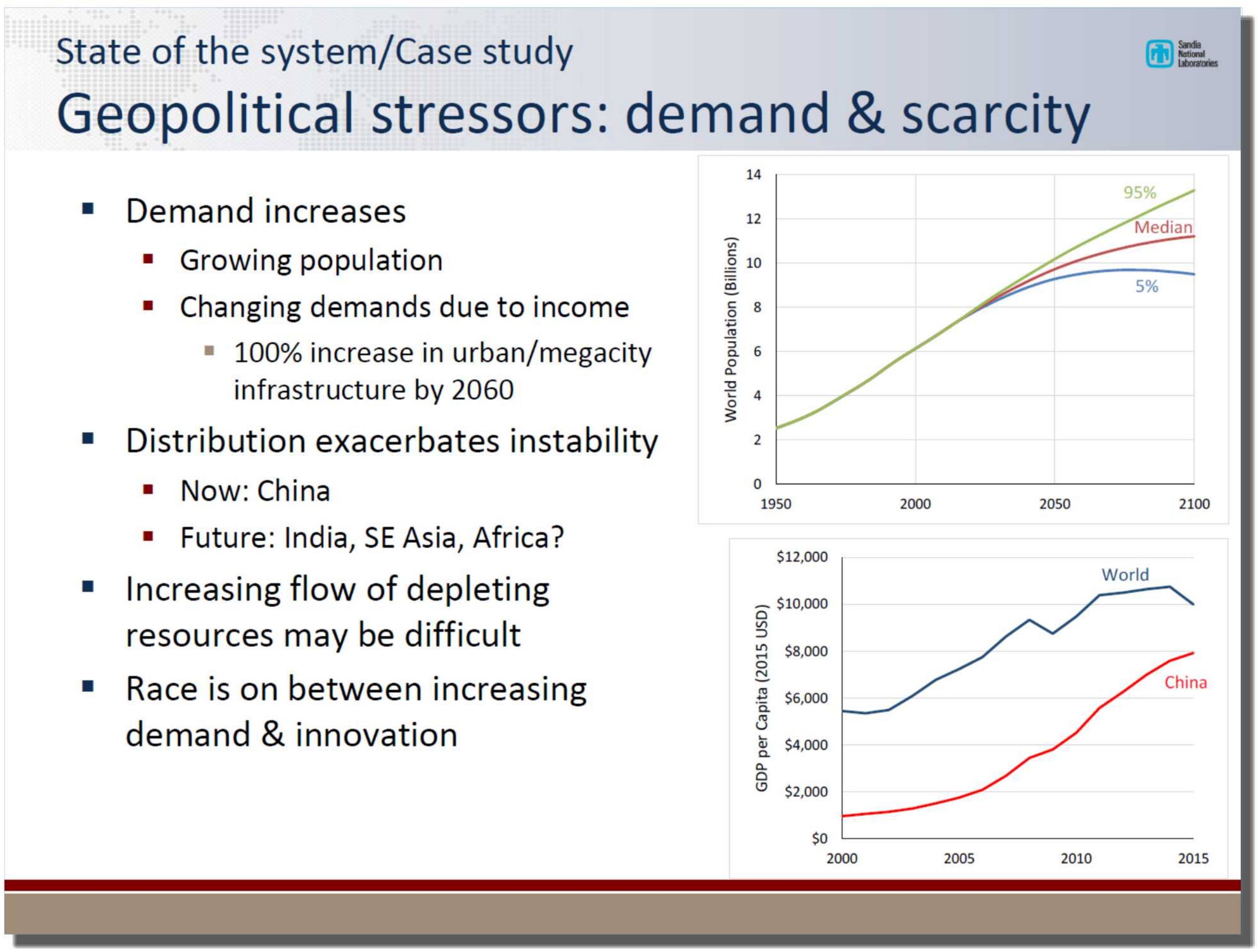


Figure 8. Geopolitical Stressors: Demand & Scarcity

A frequent theme across GF studies is that increasing population has driven, and will continue to drive, the evolution of global systems that impact human security. Since 1950 population has grown nearly threefold. United Nations population projections forecast continued increases in the next 15 to 25 years, with the median forecast reaching about 10 billion people by 2050.[17] This increase in population will drive increased demand for nonrenewable resources (Figure 8).

Two factors may lead to an even greater increase in resource demand. First, as explored in the GF study on urbanization and megacities (Passell et al., 2015), increased urbanization will likely lead to a large increase in demand for resources to build new infrastructure. Second, as countries industrialize and urbanize, they become more prosperous and their citizens demand more goods produced from resources. The bottom chart (Figure 8) shows China's growth in its gross domestic product (GDP) per capita over the past 15 years as it has industrialized.[18] China's GDP per capita has increased about 8-fold over that 15 years as its residents have become more productive and more prosperous, which has increased both China's demand for resources to produce exports and products for itself. A similar industrialization could occur in the future in places like India, Southeast Asia, and Africa, and could have similar impacts to resource demands.

Because nonrenewable natural resources are continuously depleting, without additional discoveries they become increasing difficult to extract. Coupled with rapidly increasing demand, this could be a recipe for increased scarcity, that is, higher prices and/or possible shortages. Resource optimists, like Simon (1996), have observed that throughout history "the continued development of technology… has more than made up for exhaustion" of nonrenewable resources (p. 30) and that short-term increases in scarcity often lead to "new developments [that] leave us better off than if the problems had not arisen" (p. 59).

There are two risks in the future that could temper this optimism. The first is the risk that these long-run innovations will eventually run into barriers that will lead to increasing scarcity in the long run.[19] The second, and probably more important risk in the next 15 to 25 years, is that innovations occur in the long run, but increased scarcity in the short- and medium-run can be painful and potentially lead to geopolitical turmoil. Even optimists like Simon (1996) acknowledge that these challenges exist, particularly when governments respond counterproductively to increased scarcity.[20] Although Simon emphasizes the need for short-run price increases to incentivize long-run innovation, most others find that price volatility can be harmful to long-term planning and investment by creating uncertainty while harming individuals (Lamy, 2010, p. 3).

---

[17] Population chart source data: United Nations, Department of Economic and Social Affairs, Population Division, *World Population Prospects, the 2015 Revision*, https://esa.un.org/unpd/wpp/Download/Probabilistic/Population/.

[18] GDP per capita chart data: World Bank, http://data.worldbank.org/indicator/NY.GDP.PCAP.CD.

[19] For example, Stern (1997) cites supply-side and demand-side barriers to innovation, adaptation, and substitution that could lead to long-run scarcity issues. On the supply-side, some resources have unique properties that ultimately cannot be substituted (p. 198). On the demand side, individuals often have minimal demands (e.g., for food and shelter) that cannot decrease despite increased prices (p. 207).

[20] Simon (1996, Chapter 5) argues that long-term forecasts of decreased food availability have never proven true, but shorter-term famines have occurred despite globally sufficient food supplies. He argues that government planning (e.g. in the Soviet Union and the People's Republic of China) have often led to famine, and poor governance in African countries continues to result in famine.

2.2. Case Study: Phosphate Rock Adaptation Challenges

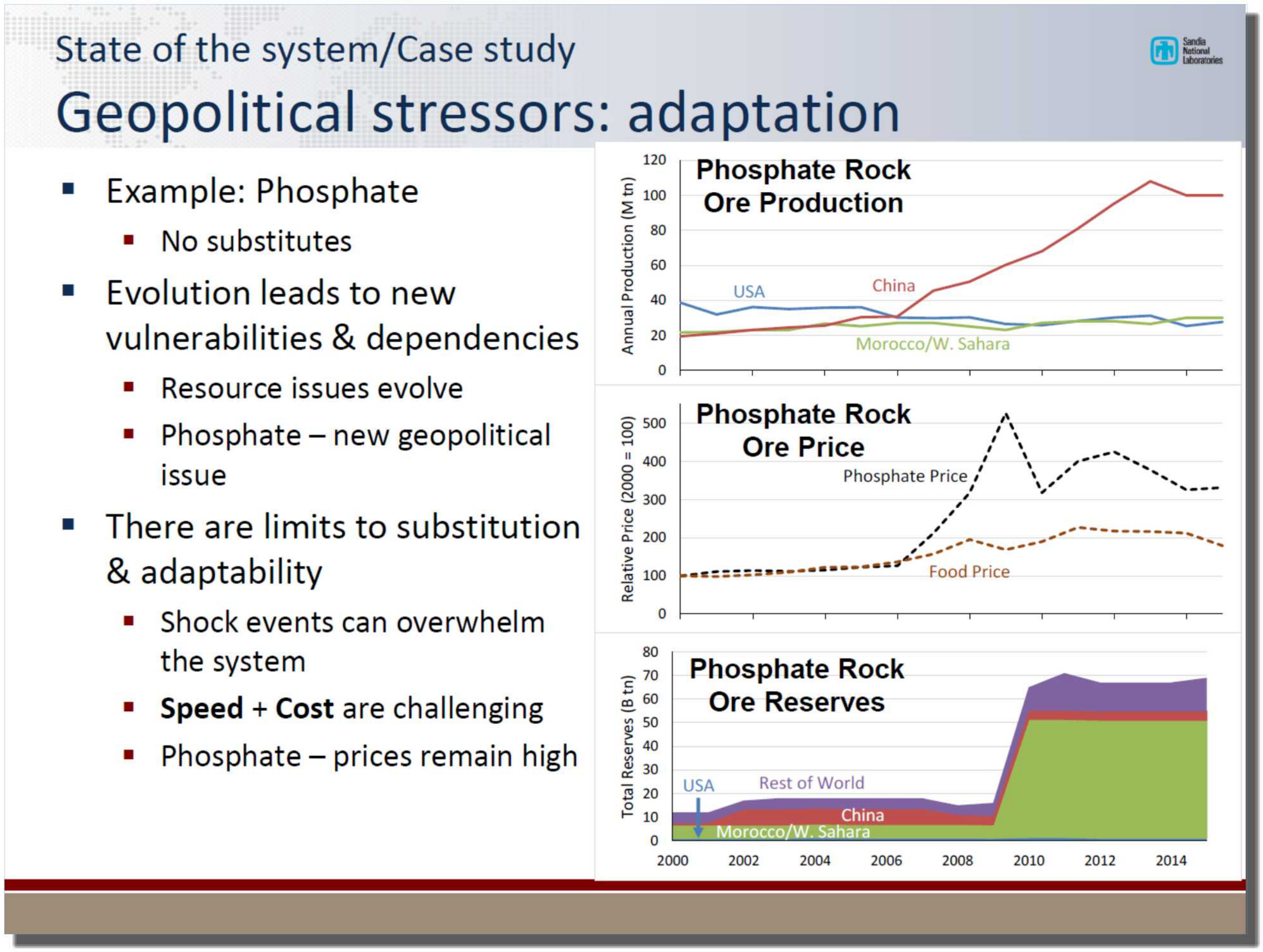


Figure 9. Geopolitical Stressors Example: Phosphate

We looked into many case studies of resource scarcity and found a common pattern of adaptation solving scarcity issues in the long-run, but with short-term and medium-term adjustment difficulties and heightened geopolitical risk. The second case study looks at phosphate rock production, which was chosen as a timely exemplar of these findings.

Phosphorus is an important nutrient that is supplemented with fertilizer. It is a great example of the limits to long-run adaptation cited by researchers like Stern (1997). There are supply-side limits to substitution since humans (and livestock) need phosphorus and nothing else can substitute. There are demand-side limits to substitution since people need a minimal amount of food to survive. Few other scarce resources are this technically constrained. In addition, as mentioned earlier, the availability of phosphorus is relatively constrained compared to other resources, as Goeller and Weinberg (1976) showed in their analysis that concluded phosphorus as the resource that the world would run out of first.

The Figure 9 charts show production of phosphate rock since 2000, prices of phosphate rock and food during that time, and proven reserves.[21] In 2000, the United States was the world's dominant producer of phosphate (with about 30% of global production), but as China industrialized it rapidly increased its production and now provides 45% of the world's production. For many other commodities, this would be a story of increased geopolitical risk due to the concentration of production in China (the next case study looks at two examples of this risk). In 2007 through 2009, as the price of phosphate increased by over 300% led by the China-fueled commodity boom, this looked to be the case.

The increased phosphate price spurred mining efforts, and a huge source of reserves in Morocco and the Western Sahara were added to the world's reserves. The U.S. Geological Survey (USGS) now estimates that Moroccan/Western Saharan reserves (now over 70% of the world's identified reserves) alone could supply 225 years of world production at 2015 rates.[22] It would seem that the potential crisis is averted; however, a new geopolitical vulnerability has emerged. First, Morocco could potentially suffer from spillover from other Arab countries. (Protests in Morocco during the Arab Spring helped lead to government reforms.) This could potentially increase the risk of future supplies. Second, the Western Sahara is a disputed region with a relatively high risk of conflict that could potentially lead to supply disruptions. Like most countries, the United States does not recognize Morocco's sovereignty over the Western Sahara. Furthermore, even today the risk of armed conflict between Morocco and an independence movement seems to be growing (United Nations, 2016).

During the time that the price of phosphate rock spiked, food prices also increased, although to a lesser degree. We were not able to find any research that could link the two increases, but they are likely to be related since phosphate fertilizer is an input to food. Spikes in food prices have been found to increase violence in Africa (van Weezel, 2016) and many observers blame the recent instability in the Middle East and North Africa on food price increase, which has been supported with quantitative research (Lagi, et al. 2011). Conversely, a geopolitical disruption in the region could lead to a spike in phosphate prices that could create upward pressure on food prices with geopolitically destabilizing impacts.

The phosphate case study also demonstrates some limits to adaptation. Following the spike in prices that peaked in 2011, prices decreased somewhat but remained well above their historic levels. Discoveries of reserves in Morocco, the Western Sahara, and the rest of the world likely helped temper long-term prices, but production in these regions has yet to ramp up significantly. Historic disruptions have sometimes required decades of adjustment. Perhaps the most well-known example, which we touch upon towards the end of this presentation, is the price and availability of petroleum. Shortages spurred by the Organization of the Petroleum Exporting Countries (OPEC) embargo of 1973 initially led to a wider exploration of supplies and

---

[21] All data about phosphate rock in the charts is from the United States Geological Survey (USGS) annual *Mineral Commodity Survey* from 2002-2016 (http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/). The food price index is from the International Monetary Fund (https://www.imf.org/external/np/res/commod/External_Data.xls).

[22] In the even longer-run, other adaptations would likely expand the life of phosphate reserves and help economies absorb the impact of increasingly hard-to-find phosphate. For example, phosphate could be used more efficiently and with less waste. Goeller and Weinberg (1976) speculate that in the extreme long-run, the lack of phosphorus availability means that bones will be recycled and agriculture and animal wastes will need to be returned to farm soil (p. 684).

technological changes that increased fuel efficiency, but longer-term technological advances like hydrologic fracturing took decades to mature.

2.3. Case Study: Industrialization and Concentration in China

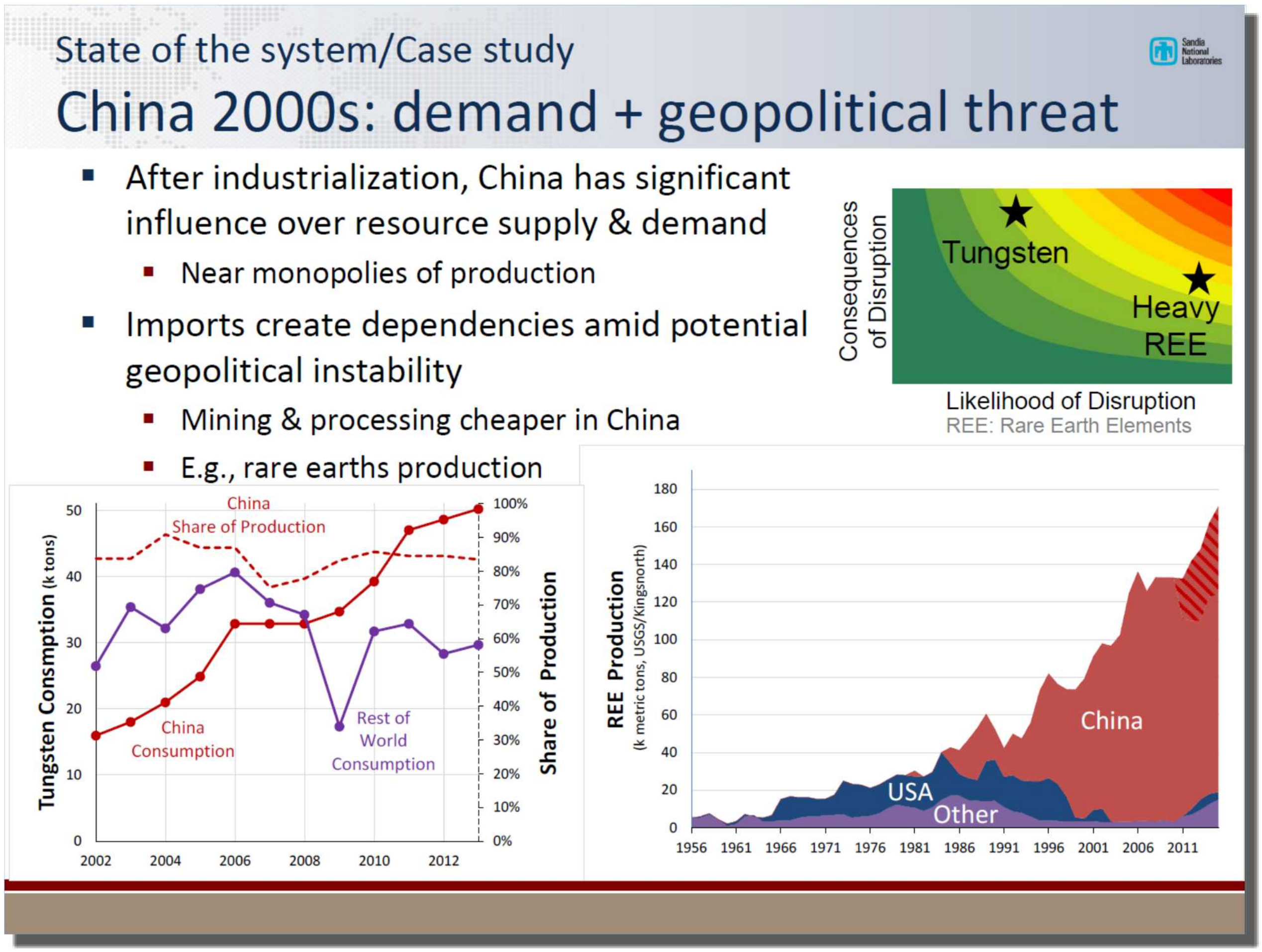


Figure 10. Geopolitical Stressors Example: Industrialization of China Since 2000

The third case study is that of the industrialization of China since 2000. Industrialization increased China's demand for resources and increased China's production dominance in many resources. We look at two resources in particular, tungsten and REEs, whose production is concentrated in China and which frequently emerge as two of the minerals with the highest risk in the studies shown previously. In Figure 10 the chart in the upper right is adapted from a study that looks at risks of supply disruptions and economic impacts to Europe (Gloser et al., 2015, p. 43).

China has historically been a major producer of tungsten, overtaking the Soviet Union in 1979 as the world's largest producer.[23] China further expanded production in the late 1990s to increase its

[23] Tungsten statistics are from annual USGS *Mineral Commodity Survey*

share of world production to above 80%, where it has generally remained. China is naturally endowed with a large share of tungsten reserves, with about 60% of global reserves. Despite this production dominance and natural abundance of tungsten, researchers like Silberglitt et al., (2013) assess that even without production from China "the world's existing reserves would appear to be sufficient for decades to come" (p. 18). Although long-term supplies of tungsten seem assured due to worldwide reserves, in the short- and medium-term term there are two concerns. First, the production concentration in China could create a large disruption if supplies from China were to be disrupted. Second, as it has industrialized, China has rapidly increased its demand for tungsten. China is now a net importer of tungsten ore and concentrates that it processes into products and intermediate products (for export to foreign manufacturers) (Silberglitt et al., 2013, p. 24). By dominating both the supply and demand sides of the tungsten market, China has tremendous market power that could take "at least several years" to reconstitute outside of China (Silberglitt et al., 2013, p. 25). Furthermore, if China were to experience a production disruption it seems possible that China could choose to prioritize shipments to domestic users of tungsten rather than exporting to the global market.

Perhaps the most widely recognized import dependency of the past decade is that of REEs from China. Despite the word "rare," REEs "are relatively abundant in the Earth's crust" although fewer concentrations of REE mean that there are relatively few places they can be mined profitably (USGS, 2016, p. 135). China has, by far, the largest identified reserves (over 40% of global reserves in 2015), but many countries have reserves. Global reserves identified by the USGS would be sufficient for over 1,000 years of global production at 2015 production rates. For many years, the United States was the dominant producer of REE.[24] In the late 1990s demand for REEs grew quickly as demand for their applications increased.[25] In the late 1990s U.S. production, which was located at a mine in Mountain Pass, California, quickly drew down, and then disappeared completely when the mine ceased REE operations. At the same time, mining activity in China increased to meet growing demand for REE, eventually producing nearly all of the world's REE.

In 2010 China's dominance in REE began to weaken—temporarily. Following an altercation between the Japanese Coast Guard and a Chinese fishing boat in the disputed Senkaku/Diaoyu Islands, China allegedly brandished a REE "weapon" by withholding REE exports to Japan (Strauss, 2014 and Gholz, 2014). During that time, REE prices spiked, with year-end prices increasing by as much as 500% (for europium) between 2010 and 2011. These price increases led to explorations for new mines and the reopening of previously shuttered mines, like the one in Mountain Pass. Additionally, they led to new efforts at efficiency (e.g., using less REE in magnets), substitution (e.g., production of a "dysprosium-free magnet that works at relatively

(http://minerals.usgs.gov/minerals/pubs/commodity/tungsten/).

[24] Historic data for REE are from Tse (2011) and from annual USGS *Mineral Commodity Survey* (http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/). Hatched areas in the red are estimates from Kingsnorth (2016) of production in China beyond official quotas (USGS uses the quotas in their data, but observers like Kingsnorth believe that China's production exceeds those quotas).

[25] For example, the growth of many clean-energy applications have increased demand for REE, such as lanthanum used as a catalyst in petroleum refineries, neodymium and dysprosium used in permanent magnets in wind turbines and electric vehicle motors, and europium, terbium, and yttrium used as lighting phosphors in fluorescent lights (U.S. Department of Energy, 2011, pp. 4-5).

high temperatures”), demand reduction from users who did not require the performance levels of rare earth magnets, and new recycling efforts (Strauss, 2014). The largest U.S. users of REE are gasoline refineries that use them in catalysts, some of whom stopped using REE because the performance degradation from not using REE was relatively minor (Gholz, 2014). Although the episode likely strengthened long-term economic resilience to REE disruptions, short-term risks remain high. China still dominates production, and as prices have fallen to a fraction of their 2011 levels (e.g., prices for europium were down about 95% between 2011 and 2015) efforts have become uneconomical—for example, the Mountain Pass mine stopped producing REE again in 2015. China seems likely to regain its past production share.

3. GLOBAL IMPLICATIONS

The past several decades have been a time of geopolitical stability. Even during the last decades of the Cold War, the geopolitical landscape was relatively stable, with few surprises. Toward the end of the Cold War and especially in the two decades afterward, globalization began to accelerate as labor, capital, and product markets began to grow increasingly interconnected.

This section focuses on the global, geopolitical implications of nonrenewable resource security. Although resource security has generally benefited from globalism and geopolitical stability in the recent past, this study identified three areas where globalism has increased geopolitical risk or could erode resource security in the future. Moreover, resource security issues have the potential to lead to future geopolitical risk and upheaval (Figure 11).

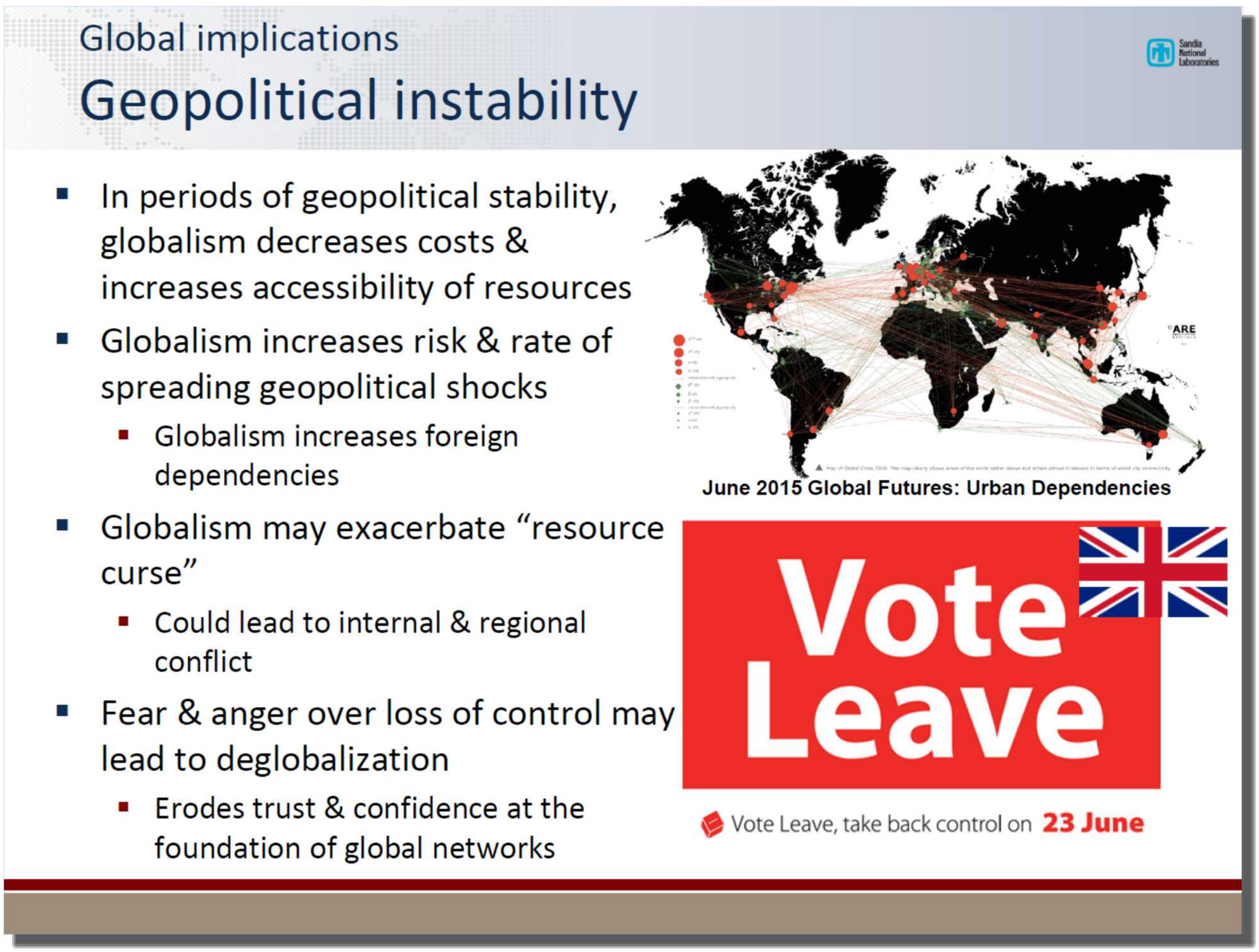


Figure 11. Sources of Geopolitical Instability

3.1. Geopolitical Stability and Globalism have Bolstered Nonrenewable Resource Security

In net, most economists believe that globalization has resulted in increased prosperity (e.g., poor workers especially have much increased purchasing power—about triple of purchasing power without international trade [The Economist, 2016d]), although most observers also recognize many challenges created by globalization, such as displaced workers who cannot find new work (The Economist, 2016d).

The combination of globalism and geopolitical stability has helped to bolster global resource security. Globalism as allowed countries around the world to obtain a greater variety of nonrenewable resources for lower prices. As the previous case study showed, China dominates production because China can produce more cheaply than other countries, even though many other countries have significant reserves. This efficiency provides consumers with greater purchasing power to purchase other items.

3.2. Current Risk: Globalism Increases Risk of Foreign Dependencies

Globalism increases foreign dependencies and can potentially increase the risk of the spread of geopolitical instability. A highly connected, globalized world means that "any local disruptions—whether resulting from extreme weather or labour unrest—can rapidly translate into higher prices in international markets" (Lee, et al., 2012, p. 128).[26] In a well-functioning global market, these price effects should be beneficial, in net, because they help allocate scarce resources to the place they are needed most following a disruption. The side effect is that events occurring beyond a country's borders, that the country has no control over, can negatively impact that country. This phenomena is similar to the movement of global capital; most of the time capital mobility is widely beneficial, but occasionally can be a disaster for a country in the short term (The Economist, 2016e).[27]

Furthermore, in many cases globalization is beneficial because creates a wider variety of producers that can serve as backup in case of a local disruption. However, as we showed in the case studies with nonrenewable resource production concentration, this can create a situation of "all the eggs in one basket", where the entire basket is subject to the events in a single, foreign country.

3.3. Current Risk Globalism Exacerbates the Resource Curse

Second, globalism may exacerbate the "resource curse" where countries that specialize in resource production suffer "low growth and high unemployment, leading in turn to inequality and increased risks of conflict and instability" (Lee, et al., 2012, p. 136). Researchers have long identified the resource curse as detrimental to economies that specialize in resource production rather than diversify across industries that leverage human capital. Three reasons often cited as driving the resource curse are "Dutch Disease" (resource production leads to an appreciation in the local currency, which means that manufacturers in the country are uncompetitive and fail to

---

[26] This connectivity was a major theme in the previous Global Futures study on urbanization and megacities (Passell et al., 2015). The map of interconnected cities is from ARE Architectural Research, "Global Cities in Harmonious Development", http://www.lboro.ac.uk/gawc/visual/globalcities2010.pdf.

[27] The Economist (2016e) reasons that "Markets for capital are error prone in a way that markets for goods are not. Stocks, bonds and property are subject to wild swings in value." Similarly, nonrenewable resources are subject to wild swings in value that the prices of final goods can largely absorb.

grow), revenues from resources that are often diverted to fuel corruption and weakening institutions, and that resource proceeds can be diverted to fund civil wars (Lamy, 2010, p. 9). Globalism helps intensify Dutch Disease because global markets reduce the need for domestic manufacturers. Other than during periods of high volatility, globalism has generally been linked to falls in resource prices, which have had "disastrous consequences for Third World development" (Deudney, 1990, p. 471). Globalism also likely increases overall volatility of resource prices since resource markets are more volatile than long-term forward contracts,[28] which has been difficult for exporters to manage since "few have been able to successfully implement revenue stabilization funds" (Lee, et al., 2012, p. 136).

3.4. Future Risk: Globalization Could Reverse

There is an increasing threat that globalization has stalled and will reverse. A decrease in globalism would make it more expensive and more difficult to obtain widely dispersed resources from around the globe, which would harm resource security. Furthermore, if deglobalization happened rapidly it would be difficult to adjust and onshore production, which would result in painful resource shortages in the near- and medium-term—particularly if imports of a wide variety of resources were halted simultaneously (as the case might be if trade with China were halted). The United Kingdom Brexit referendum on June 23, 2016 to leave the European Union, was one glaring sign that globalization may be reversing. Another sign of the potential retreat of globalism may be the realignment of Western politics, which is increasing moving from a left-right divide to a pro-anti globalism divide ("drawbridge down" vs. "drawbridge up" [The Economist, 2016b]).

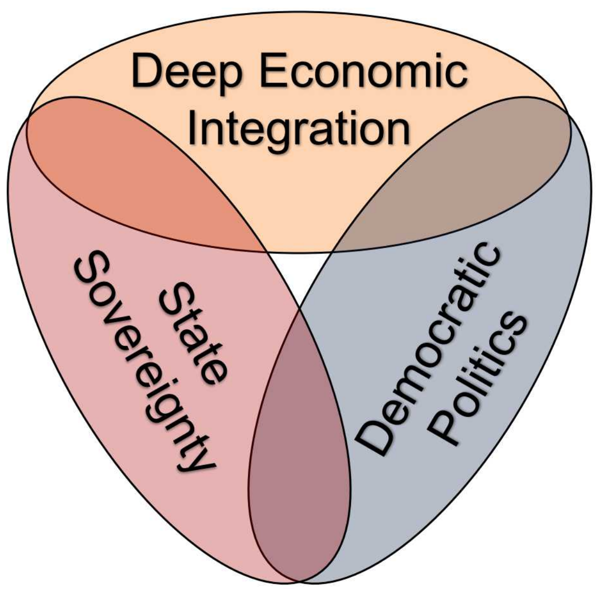


Figure 12. World Economic Trilemma (Rodrik, 2007)

[28] For example, prior to the OPEC embargo, countries and oil companies would engage in long-term oil contracts that lasted between 10-20 years (Lamy, 2010, p. 62). After the embargo, spot and futures markets developed where most petroleum is traded; however, these prices are volatile.

This would not be the first time that globalization reversed. An earlier era of globalization in the 1800s led to geopolitical strife toward the late 1800s and early 1900s; World War I proved to be the end of that era of globalization (The Economist, 2016a). Dani Rodrik, a macroeconomist at Harvard who specializes in trade issues, observed that countries face a trilemma—deeper economic integration means an erosion in state sovereignty or in democracy (Rodrik, 2007, see Figure 12). As an example, Apple was recently fined billions of dollars by the European Union for tax avoidance in Ireland, a decision that Irish politicians viewed as eroding Ireland's sovereignty over their tax policy (The Economist, 2016c). The charge that integration erodes democracy—Britain's laws are being made by bureaucrats in Brussels—was brought up frequently by "leavers" during the campaign for the Brexit referendum.[29]

3.5. Future Risk: Resource Insecurities Could Lead to Geopolitical Upheaval

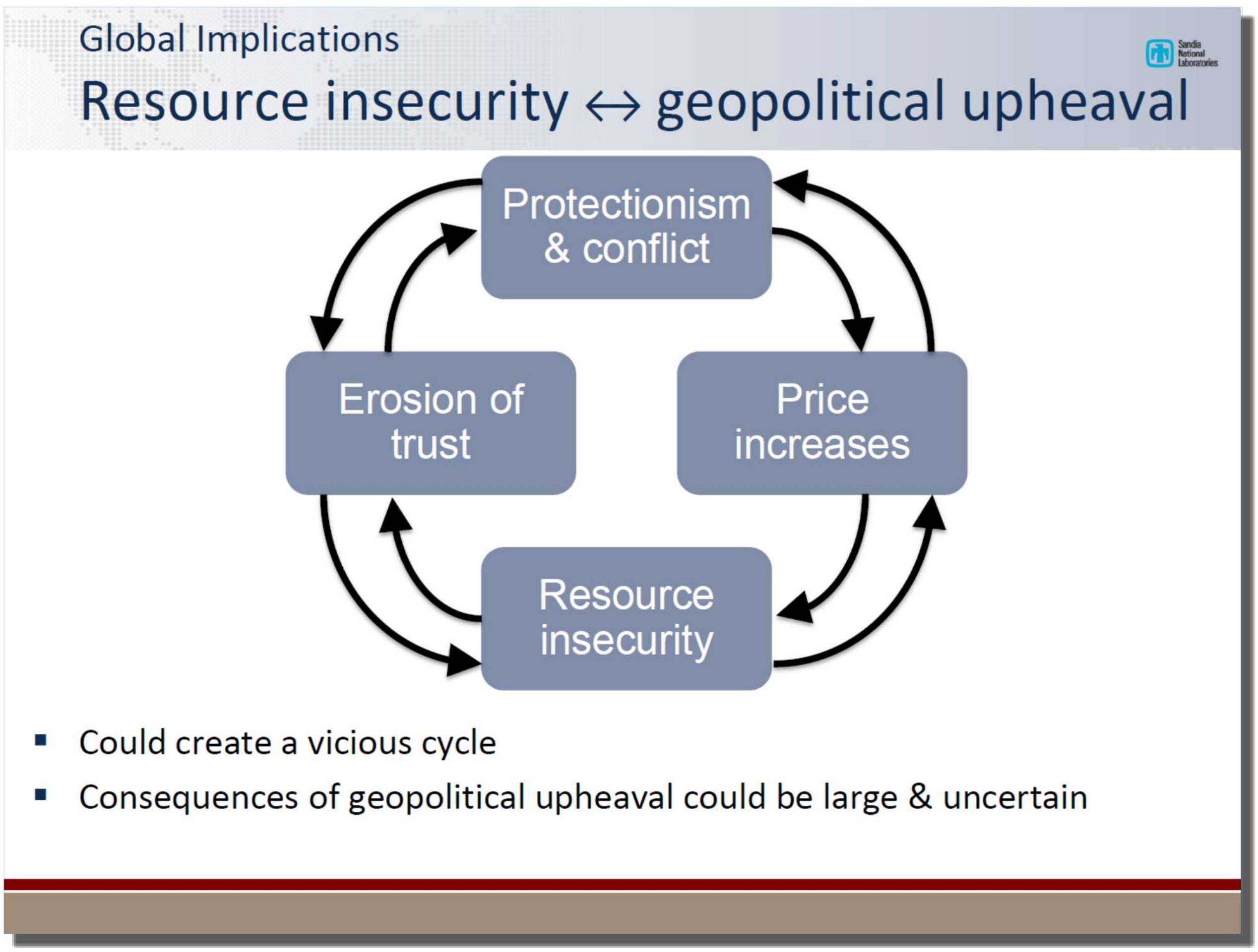


Figure 13. Cycle of Resource Insecurity and Geopolitical Upheaval

[29] The "Print at Home Vote Leave Posters" are from http://www.voteleavetakecontrol.org/assets-d3n8a8pro7vhmx.cloudfront.net/voteleave/pages/2318/attachments/original/1464168270/vl_tbc.png, accessed October 10, 2016.

The discussion in Figure 11 focused mainly on the possible impacts that a geopolitical upheaval could have on resource security. To recap, globalism bolsters resource security throughout the world by increasing access to nonrenewable natural resources and decreasing the prices of resources, in net. A reduction of globalism would likely harm resource security because it would lead to shortages and higher prices. The geopolitical upheaval that marks the transition to a deglobalized world could be particularly painful due to dependencies on foreign sources of resources. It could be difficult to adjust to a sudden, rapid loss of many resources.

Figure 11 discussed some of the signs that are emerging that globalization might be reversing. But resource issues, for example, vulnerabilities, fears, and shortages, could also help to create that geopolitical upheaval.

Before discussing the possibility that resource fears could help trigger a geopolitical upheaval, it is important to recognize that geopolitics—particularly in a globalized world—is fairly stable. For example, following the OPEC embargo in 1973, governments instituted many policies that appeared to be counterproductive and driven by fear. For example, the United States instituted price controls, a petroleum export ban, and governments of resource-rich countries nationalized resources.[30] Nevertheless, the system showed a remarkable degree of resilience by leveraging globalism; oil markets were created and alternate sources of petroleum emerged on these global markets (Lamy, 2010, p. 62). Similarly, many researchers and observers caution that resource issues usually do not lead to war (Simon, 1998, Chapter 29) and that conflict over resources is merely "possible" but not likely (United Kingdom Ministry of Defence, 2010, pp. 115-117).

Many argue that resource fears have driven conflict and geopolitical upheaval in the past, and may do so in the future. A commonly cited example is that of World War I, which marked the reversal of the first wave of globalization and led governments to seek "secure access" to resources—a trend that was not reversed for a half century (Lamy, 2010, p. 64). Lee et al. (2012) describe the possibility of a vicious cycle (a "spiral of insecurity" [p. 152]) where governments respond to resource scarcity by implementing counterproductive policies[31] that "typically make things worse, not better," (p. 8) "erode trust and undermine multilateralism," (p. 8) and can lead to "the militarization of resources in response to perceived threats and therefore create the conditions for conflict" (p. 2) (Figure 13). They find that the challenge for governments is a lack of proven solutions to harmful price volatility; countries attempt measures to reduce the negative impacts, but "there have been no credible international policy responses to volatile resource prices" (p. xiv) and past attempts have been "costly and largely unsuccessful" (p. xii).[32]

---

[30] In 1978 international companies controlled 70% of oil and gas resources, but resource nationalism decreased that to 20% by 2010 (United Kingdom Ministry of Defence, 2010, p. 115).

[31] Lee et al. (2010, Chapter 5) list a variety of different counterproductive policies that are "adding fuel to the fire" and accelerating the vicious cycle. They include: resource subsidies, strategic reserves of resources, expropriation/nationalization of resources, foreign direct investments from state-owned enterprises to secure resources, long-term contracts, land acquisitions, expanding to utilize sources that are more costly (both financially and ecologically), imposing trade restrictions, and banning resource exports.

[32] Lee et al. (2012) recommend policies that "manage perceptions, expectations and fears of resource scarcity in a collaborative manner", "mitigate excessive politicization of resource markets and trade that could bring about worst-case scenarios" (p. xiv), and "driv[e] down resource intensity and encouraging sustainable use" (p. xii).

3.5.1. Case Study: Japan's Need for Petroleum Triggers U.S. Entry into WWII

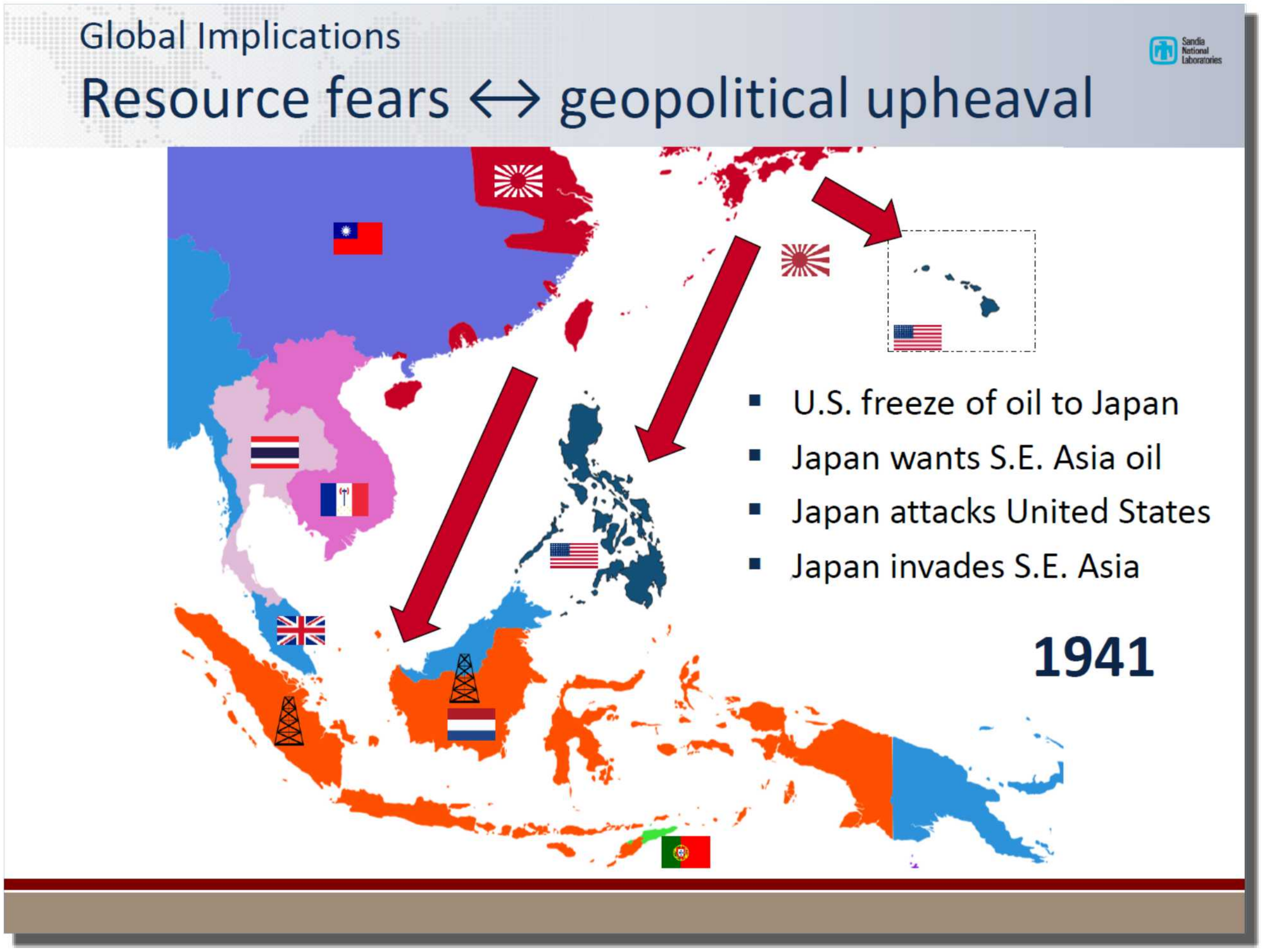


Figure 14. Resource Fears Have Led to Geopolitical Upheaval

WWII, which occurred during between the two waves of globalism, provides a number of salient examples of conflict driven by nonrenewable resources. In addition to the earlier uranium example are petroleum examples as both Germany and Japan lacked domestic supplies of petroleum to fuel their war efforts. The Japanese example is particularly interesting because it is widely agreed (e.g., Miller, 2007) that Japan's petroleum shortage was a trigger to the United States entering WWII (Figure 14). At the beginning of WWII, the United States was the world's primary exporter of oil. Japan relied upon U.S. supplies of oil because it lacked resources at home or in the areas it controlled. In July 1941 Vichy France agreed to a Japanese occupation of Indochina, which was followed by a U.S. freeze of Japanese assets and an embargo on U.S. petroleum exports (as well as British and Dutch oil from Southeast Asia). Japan decided to invade Southeast Asia to secure access to its oilfields, but feared that the attack would draw the United States into the war, so Japan invaded the Philippines (a U.S. commonwealth at the time) and attacked the U.S. Pacific Fleet at Pearl Harbor to provide Japan with breathing room to occupy Southeast Asia in early 1942.

Japan's decision to attack the United States was a clear case of resource fears driving a militarized response to increase resource security. It is difficult to know how WWII would have proceeded differently had the petroleum issues not existed—the United States had been preparing for entry to WWII and Japan was allied with Germany, so the result may have been similar—but it could have turned out very differently given U.S. isolationism and reluctance to enter war (see The Economist, 2013).

3.5.2. South China Sea Is a Possible Site of Future Resource Conflict

Figure 15. Resource Fears May Lead to Future Geopolitical Upheaval

It is impossible to predict the future, especially on complex issues like resource security. With these complex issues, it can be difficult to understand what happened even after the fact. As we have shown, few people *expect* that resource issues could spiral into geopolitical upheaval, but many think that it could be *possible*. Given current geopolitics and natural resource dependencies, it seems like one of the biggest risks in the future could be a conflict driven by controversy over the South China Sea.[33] China considers the South China Sea, as bordered by the

[33] By comparison, Lee et al. (2012, p. xix) also consider the South China Sea to be a possible flashpoint for resource

"nine-dash line"[34] (Figure 15), to be its sovereign territory (U.S. Department of State, 2014). The South China Sea may have important resources, for example, the China National Offshore Oil Corporation introduced lease blocks off of Vietnam (U.S. Department of State, 2014, pp. 16-17). Perhaps more importantly, the South China Sea is a key trade route from Africa and the Middle East to Asia, with a third of global crude oil and half of liquefied natural gas passing through (U.S. Energy Information Administration, 2013). A conflict in the region could be driven by resource fears, and could have large repercussions on global resource security given China's dependence on energy imports and global dependence on China for minerals.

---

competition, but also add the East China Sea, the South Atlantic, the Arctic Ocean and East Africa.
[34] Recent maps, like the one pictured here based on U.S. Department of State (2014, p. 4) have a tenth dash east of Taiwan.

4. NATIONAL SECURITY IMPLICATIONS

4.1. Possible Futures

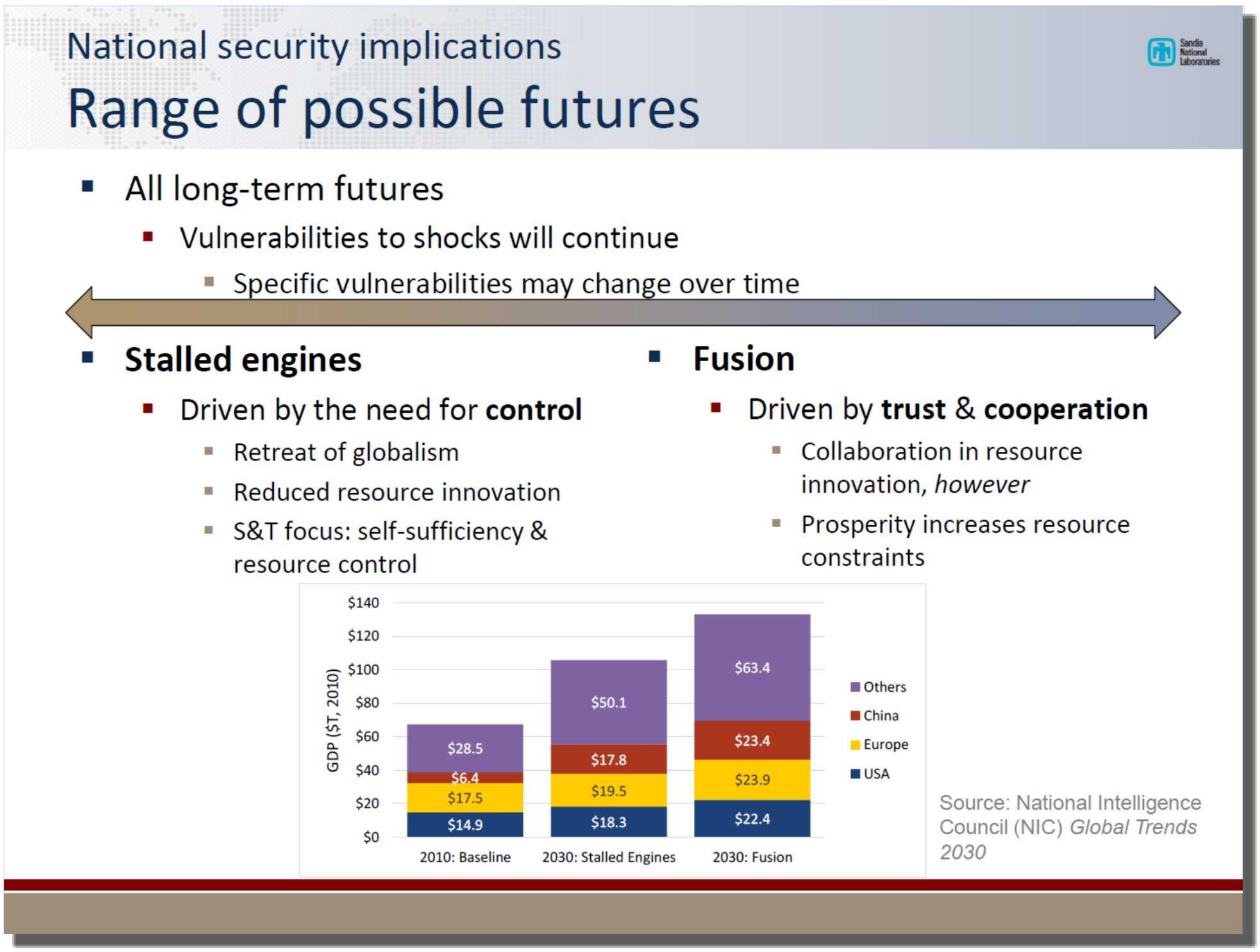


Figure 16. Range of Possible Futures

As mentioned earlier in this report, we leveraged the two bookend[35] scenarios from the NIC's (2012) *Global Trends 2030* scenarios to help illuminate the national security implications of nonrenewable natural resource security over the next 15 to 25 years. The NIC releases a Global Trends study every four years after the presidential election. This particular study was released after the 2012 presidential election. We found this study useful because the future of globalism underlies the two *Global Trends 2030* bookend scenarios as well as future nonrenewable resource security risks (Figure 16).

---

[35] By "bookend" the NIC (2012) means "the most plausible worst case" (p. 110) and "the most plausible best case" (p. 116). More extreme scenarios are possible but of low likelihood. The actual future is likely to include some mix of the two bookend scenarios.

The “Fusion” scenario is characterized by a continued evolution of globalism, where there is more cooperation and greater global prosperity. Overall GDP is highest in the Fusion future, but this can also trigger resource constraints similar to how the China’s industrialization increased resource prices in the 2000s. U.S. GDP in this world is higher than in the “Stalled Engines” scenario, but U.S. GDP is lower than China’s and relatively worse compared to “Others.” In the Fusion world, globalized innovation focuses on “innovation to deal with resource issues and climate change” (NIC, 2012, p. 116), “new technologies [that] are replacing or making available resources go farther” (p. 119), and “technological innovation [that] is also critical to the world staying ahead of the rising resource constraints that would result from the rapid boost in prosperity” (p. 120).

The Stalled Engines scenario is characterized by a retreat of globalism, although not a complete reversal of globalization (which happened following World War I, but is unlikely). The focus of this world is global competition, rather than global cooperation. Without globalism to enable the global accessibility of nonrenewable natural resources, self-sufficiency becomes more important. This assured access to resources can be through direct control of resources or through innovation and research that seeks ways to adapt to reduced resource accessibility. However, the retreat of globalism hampers global research, which leads to “slower-than-anticipated technological improvements in extraction efficiency and deposits” (NIC, 2012, p. 111).

	Stalled engines: Fear of insecurity	Fusion: Increasing cooperation
Drivers	Fears of resource insecurity drive resource insecurity • Resource nationalization • Resource militarization	Cooperation increases prosperity, intensifying global resource demands
E.g.	Colonies, mercantilism, OPEC	U.S. federalism, globalization, China 2000s
Values	Control of resources • Quest for secure access to resources in connected world	Innovators empowered • Challenges regions overly dependent on resource exports
Conflict	Risk of near-peer conflict • Retreat of globalism, but not completely	Regional conflict driven by resource “losers”

Figure 17. Impact Analysis of Range of Possible Futures

The two bookend scenarios differ in stark ways, but also share some similarities (Figure 17).

Drivers: Both scenarios are driven by positive feedback processes. Stalled Engines has "spirals of insecurity" (Lee et al., 2012, p. 152) where counterproductive government policies lead to increases in resource security. For example, the NIC sees countries in the Stalled Engines world "creating export bans, exacerbating food shortages and price spikes" (NIC, 2012, p. 112). In the Fusion world, prosperity and cooperation build on each other. Prosperity also increases scarcity, which creates new problems that can be solved with global cooperation. However, this scarcity also produces opportunities for resource shocks to create an "off ramp" from the Fusion world to the Stalled Engines world.

Examples: Colonies are the classic example of countries trying to develop assured sources of resources under their control. Mercantilism was an economic system that existed before globalism in which countries tried to maximize the resources under their control; colonies were a natural outgrowth. The OPEC embargo and its immediate response of counterproductive policies was an example of resources being used as a weapon. However, as we explained earlier, the long-term response to the OPEC embargo was a strengthening of globalism. The U.S. Constitution is an early example of moving toward a Fusion world as the individual U.S. states integrated economically, but had to sacrifice a large degree of their individual sovereignty. Globalization and the industrialization of China during the 2000s are also examples of greater global cooperation, but—as we have shown throughout this presentation—introduce new risks that might lead to off ramps to the Stalled Engines world.

Values: The Stalled Engines world most values control of resources in order to secure access to those resources. A lack of global trade means that resources, on average, are relatively expensive. In the Fusion world, innovators—that is, human capital—is most valued. In the Fusion world it is relatively easier to gain access to resources, hence they have lower prices. This becomes a challenge to countries dependent upon exports who are unable to diversify their economies to grow human capital (NIC, 2012, p. 122). Innovation will also remain important in the Stalled Engines world to find workarounds for resources that are no longer accessible. However, innovation is constrained by a reduction in global cooperation.

Conflict: The biggest upside to the Stalled Engines world is that it reduces foreign dependencies. However, cooperation and dependencies are two sides of the same coin in a geopolitically stable world. Instead of dependencies and cooperation, the Stalled Engines world increases the risk of near-peer conflict between the most prosperous, powerful countries. It encourages alliances because they help assure access to resources, so some degree of global cooperation is likely to remain. The Fusion world encourages global cooperation to reduce this global competition. Conflict remains from the resource "losers" who are too dependent on resource exports and have failed to diversify, and this conflict can be an impetus for even greater cooperation between major powers to help bring peace and prosperity to these regions.

4.2. National Security Organizations Will Need To Foster Global Resilience to Resource Shocks

Figure 18. National Security Resource Strategies Will Emphasize Resilience

A previous GF study on the future of technology (Warren, et al., 2015) described the evolution of national security goals. Traditionally national security institutions have focused on either preventing bad things from happening or defeating bad things when they cannot be prevented. For example, deterrence and diplomacy are ways of preventing wars, while capabilities to win wars are important to defeating adversaries. Capabilities in both areas are needed, and they clearly complement each other (i.e., the ability to defeat an adversary can prevent war in the first place). A common theme across the GF studies is that the world is becoming increasingly complex. In the national security world, this complexity (e.g., a proliferation of potential adversaries with enhanced capabilities) means that not all threats can be prevented or defeated. Bad things will happen, hence national security institutions, as well as societies as a whole, need to be resilient (Figure 18). That is, they must withstand, adapt, and recover from challenges (Vugrin, et al., 2010). A resilient system will have technical features (e.g., backup stockpiles, substitution possibilities, agility) and have a resilient governance system (e.g., a system that encourages learning, understanding, and foresight to anticipate and respond effectively to stressors) (Schoon and Saltzberg, 2016).

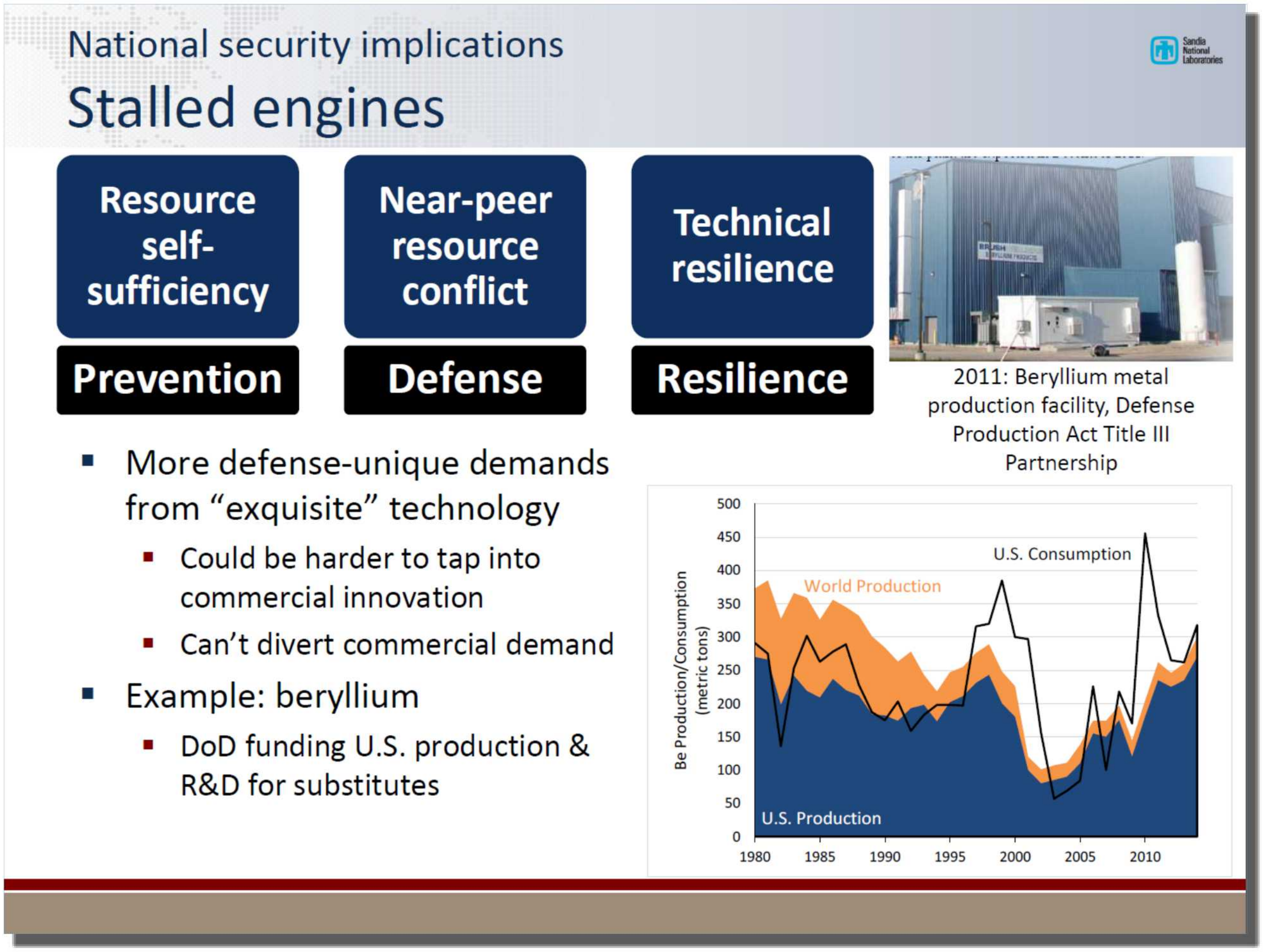


Figure 19. National Security Strategies for a Stalled Engines World

In the Stalled Engines world, the primary way to prevent resource insecurity is through assured access to resources, that is, resource self-sufficiency. However, because resources are distributed unevenly across the globe, complete self-sufficiency is not be achievable. Some resources will be inaccessible, while other resources will be too expensive to access for many applications. Therefore, technical resilience will be necessary to reduce the consequences of inaccessible resources. This technical resilience involves innovations that increase substitution possibilities and increase efficiency to reduce the need for hard-to-access resources (Figure 19). Another common source of technical resilience is likely to be stockpiles that can help a country withstand temporary disruptions, which are likely to be more frequent in the Stalled Engines world (e.g., an ally may decide to withhold resource exports for political reasons).

As long as the United States invests in exquisite technologies that provide a technological advantage over its adversaries, there will cases of resources where U.S. national security organizations dominate demand and—potentially—supply. The previous GF study on the future of technology (Warren, et al., 2015) found that the defense industry is increasingly diverging from commercial industry, which will tend to create more defense-unique resource dependencies. This uniqueness creates additional defense risk for two reasons. First, if the defense sector has unique demands, it will be unable to leverage the research, innovation, and adaptability of commercial industry. Industry is incentivized to discover ways to adjust to resource shocks; if defense and commercial industry use the same resources, the adaptations of commercial industry can be leveraged by defense. Second, Title I of the Defense Production Act allows DoD and the Department of Commerce to prioritize deliveries of goods and services to national security needs, rather than commercial needs (Committee on Assessing the Need for a Defense Stockpile, 2008, p. 84). In many cases, demand from the defense sector is a relatively small portion of domestic demand. For example, "well under 10 percent of U.S. demand" for REEs is from defense (Gholz, 2014, p. 10), which means the defense industry has the ability to commandeer REE from the commercial sector, even after a substantial supply disruption.

Case Study: Beryllium

Beryllium is a prominent example of a nonrenewable resource upon which U.S. national security organizations depend to produce exquisite systems (which would be more in demand in the Stalled Engines world due to increases in near-peer competition), but have limited commercial demand. Beryllium has several technical properties (e.g., it is strong yet light) that help produce exquisite[36] performance in defense systems like aircraft, space vehicles, satellites, guidance systems, and nuclear weapons (U.S. DOE, 2011). However, beryllium is expensive to produce and potentially dangerous, which has discouraged commercial demand. Exposure to beryllium can lead to Chronic Beryllium Disease, a chronic lung disease (U.S. DOE, 2011). These health risks have led to an increasingly high degree of regulation of beryllium production, which has helped to drive up the cost of components made of beryllium (over $500,000 a pound of DoD components [Tozer, 2015].)

As could happen for many resources in the Stalled Engines world, the United States has been self-sufficient for supplies of beryllium for several decades.[37] Following the Cold War, U.S. beryllium consumption has often exceeded global production, which is possible due to the existence of stockpiles. Even the 1950s and 1960s resembled a Stalled Engines world for beryllium as the United States consumed a large portion of the world's beryllium production, and relied on a handful of allies and neighbors for its supply.[38] Sometime between 1968 and 1980[39] the United States became the dominant producer of beryllium ore. In 2000, the only primary beryllium facility—that is, a plant that converts beryllium ore into beryllium metal—in the United States closed, which led to a sharp downturn in ore production (USGS, 2013). To assure future supplies of beryllium, DoD entered into a Defense Production Act, Title III agreement to

---

[36] A core U.S. national security strategy is providing U.S. forces with "technological superiority" as an asymmetric advantage over potential adversaries. Former Secretary of Defense Robert Gates called these technologies "exquisite." (See http://www.defense.gov/transcripts/transcript.aspx?transcriptid=4396 and http://www.defense.gov/transcripts/transcript.aspx?transcriptid=4404.)

[37] Chart data source: USGS, "Beryllium Statistics", January 28, 2016, http://minerals.usgs.gov/minerals/pubs/historical-statistics/ds140-beryl.xlsx

[38] For example, in 1963 the major sources of beryllium ore for the United States were from Brazil, Argentina, and British colonies in Africa (Eilertsen, 1964). The United States imported a small amount of processed beryllium metal from Western Europe.

[39] USGS data on beryllium prior to 1980 has many gaps or instances where data has been withheld.

invest in a public-private partnership to build a new facility in Ohio, which was opened in 2011 (USGS, 2013).[40] DoD is also trying to reduce its dependence on beryllium by developing new materials to substitute for beryllium in DoD weapons systems (Tozer, 2015). A Stalled Engines world would likely lead to more examples like beryllium that required domestic investments to assure access to resources, and greater research and development efforts to overcome increased local scarcity.

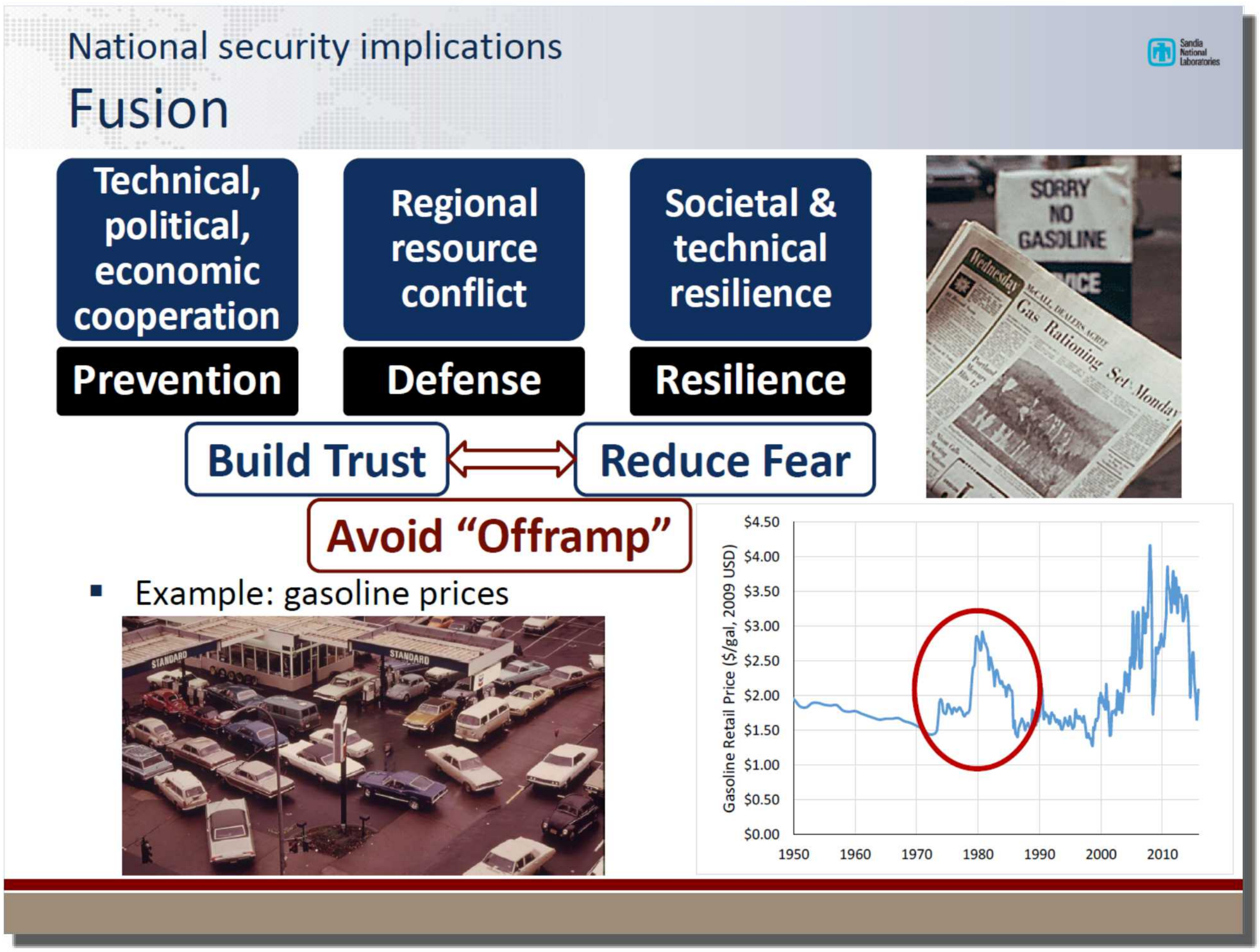


Figure 20. National Security Strategies for a Fusion World

In the Fusion world, the primary way to avoid resource shocks and respond effectively when the resource shocks occur is to engage in cooperation. This cooperation can span across domains (Figure 20). For example, government laboratories might engage in technical cooperation with commercial industry, both inside the United States and abroad. National security organizations might cooperate with other countries over regional resource conflicts. This cooperation helps

---

[40] The image of the building is of the Materion Corporation's "Pebbles Plant" in Elmore, Ohio (DoD, Manufacturing and Industrial Base Policy, 2012, p. 10).

build trust, which is important for avoiding the off ramp from the Fusion world to the Stalled Engines world.

Since resource vulnerabilities will always exist and resource shocks will always occur, resilience is need to more effectively absorb, adapt to, and recover from these shocks. As in the Stalled Engines world, technical resilience (e.g., substitution and efficiency) can help increase resilience to resource shocks. But social resilience, that is, the resilience of people and society, is necessary to reduce fears from resource shocks and prevent counterproductive policies. By reducing fear, off ramps to the Stalled Engines world may be avoided. Social resilience is perhaps more difficult to manage than technical resilience, since societies are complex and difficult to influence, while technical innovations are often more straightforward.[41]

[41] Rosenberg, et al., 2016 recommend a range of policies aimed at increasing resilience to energy vulnerabilities that are applicable to nonrenewable natural resources. They recommend that the United States use resource issues to "pursue shared interests on foreign policy goals" with other countries, particularly China (p. 32), promote trade and efficient markets (p. 42), invest in efficiency and alternatives (p. 42), and improve cooperation across the Pacific (pp. 46-50).

Case Study: U.S. Resilience to Oil Shocks

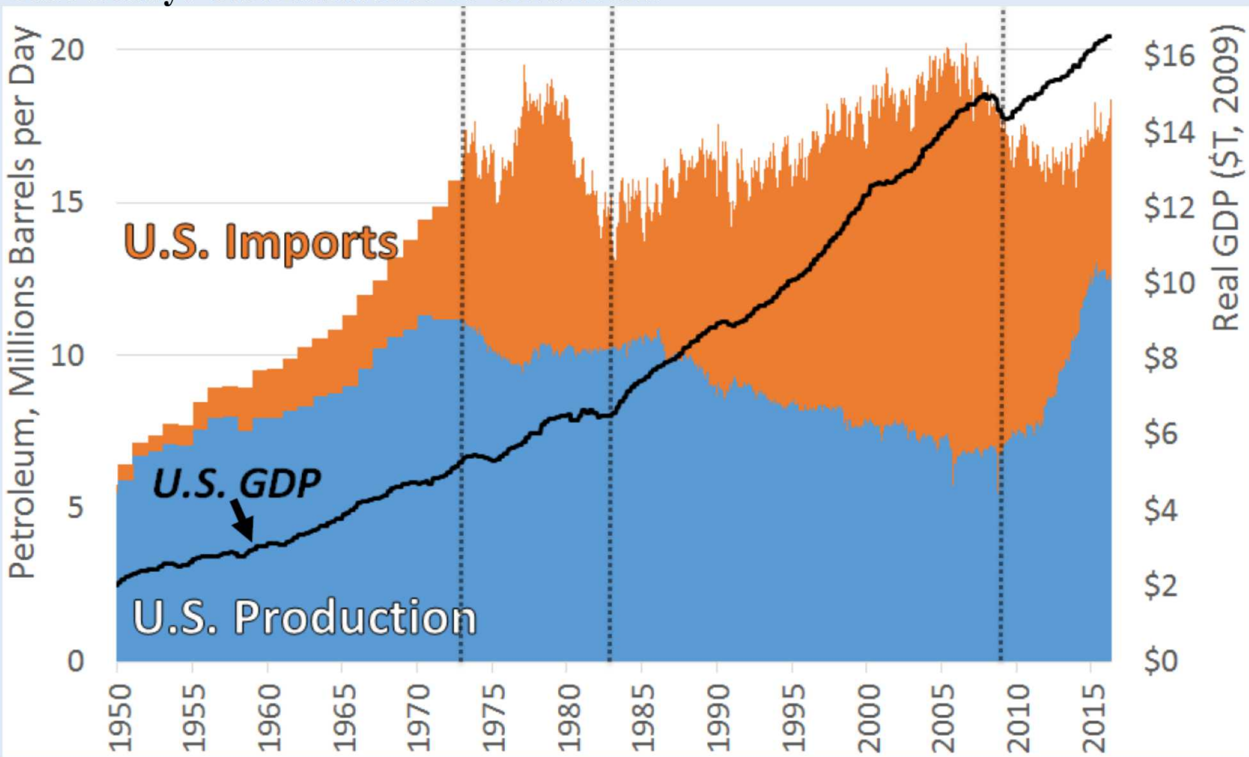


Figure 21. U.S. Petroleum Consumption, Sources, and Real Gross Domestic Product

U.S. reactions to oil shocks provide interesting case studies of social resilience. The OPEC embargo was a shock to Americans, who were accustomed to reliable availability of gasoline and steady prices (the inflation adjusted price of gasoline decreased steadily over time).[42] The spike in gasoline prices during the 1973 OPEC embargo was relatively small (prices increased by about a third), but limited by price controls. As the photos in Figure 20 show,[43] society showed little resilience to gasoline shortages; fear and panic seemed to dominate. Although the initial reaction to the oil shock led to counterproductive policies and threatened to push the United States toward a Stalled Engines world (U.S. production of oil actually declined after the 1973 embargo, see Figure 21[44]), in the long run society built resilience through a combination of technical and societal changes. Cars achieved greater fuel economy, which led to greater efficiency,[45] and new sources of petroleum were found. New markets for oil were created, which

[42] The gasoline price chart is based on the author's calculations using monthly and annual data from the U.S. Energy Information Administration, August 2016 Monthly Energy Review (https://www.eia.gov/totalenergy/data/browser/xls.cfm?tbl=T09.04&freq=m). Nominal prices were converted to 2009 dollars using the Bureau of Economic Analysis deflators (http://www.bea.gov/national/xls/gdplev.xls).
[43] The image of the gas line is by David Falconer, Photographer (NARA record: 1427627) - U.S. National Archives and Records Administration, Public Domain, https://commons.wikimedia.org/w/index.php?curid=17173611. The "SORRY NO GASOLINE" image is by David Falconer, Photographer - Public Domain, https://commons.wikimedia.org/w/index.php?curid=3575687.
[44] Oil production data is from Table 3.1, "Petroleum Overview" of the U.S. Energy Information Administration, May 2016 Monthly Energy Review, May 25, 2016. GDP data is from the U.S. Bureau of Economic Analysis, "Current-Dollar and 'Real' Gross Domestic Product," http://www.bea.gov/national/xls/gdplev.xls, August 26, 2016.

in turn helped to incentivize behavior to change. In the past 20 years, gasoline prices have been extremely volatile relative to the 1970s, but society has been highly resilient to oil shocks.[46]

This increased U.S. resilience to petroleum shocks points to another potential off ramp from the Fusion world to the Stalled Engines world. Now that the United States is evolving into an energy exporter, it can potentially wield these resources to coerce its adversaries on non-resource issues (Gompert and Binnendijk, 2016, pp. 20-21). Observers caution that such a strategy is not "well rooted in international norms" and would likely fail in the long run (Gompert and Binnendijk, 2016, p. 21) and would undermine opportunities for U.S. leadership of global cooperation (Rosenberg, et al., 2016).

---

[45] As Figure 21 shows, between 1950 and 1973 U.S. petroleum consumption and U.S. GDP increased at a nearly identical pace (about 160% increase). However, since 1973 U.S. petroleum consumption has increased about 10% while U.S. GDP has increased about 210%.

[46] Many researchers note that some caution must be taken when comparing the 1970s with the 2000s. Oil shocks during the 1970s were driven by supply cuts from OPEC, whereas oil shocks in the 2000s were driven by demand shocks from China's industrialization. Demand shocks may be easier to adjust to since they are driven by booming economies (Lamy 2010, p. 97).

5. CONCLUSION

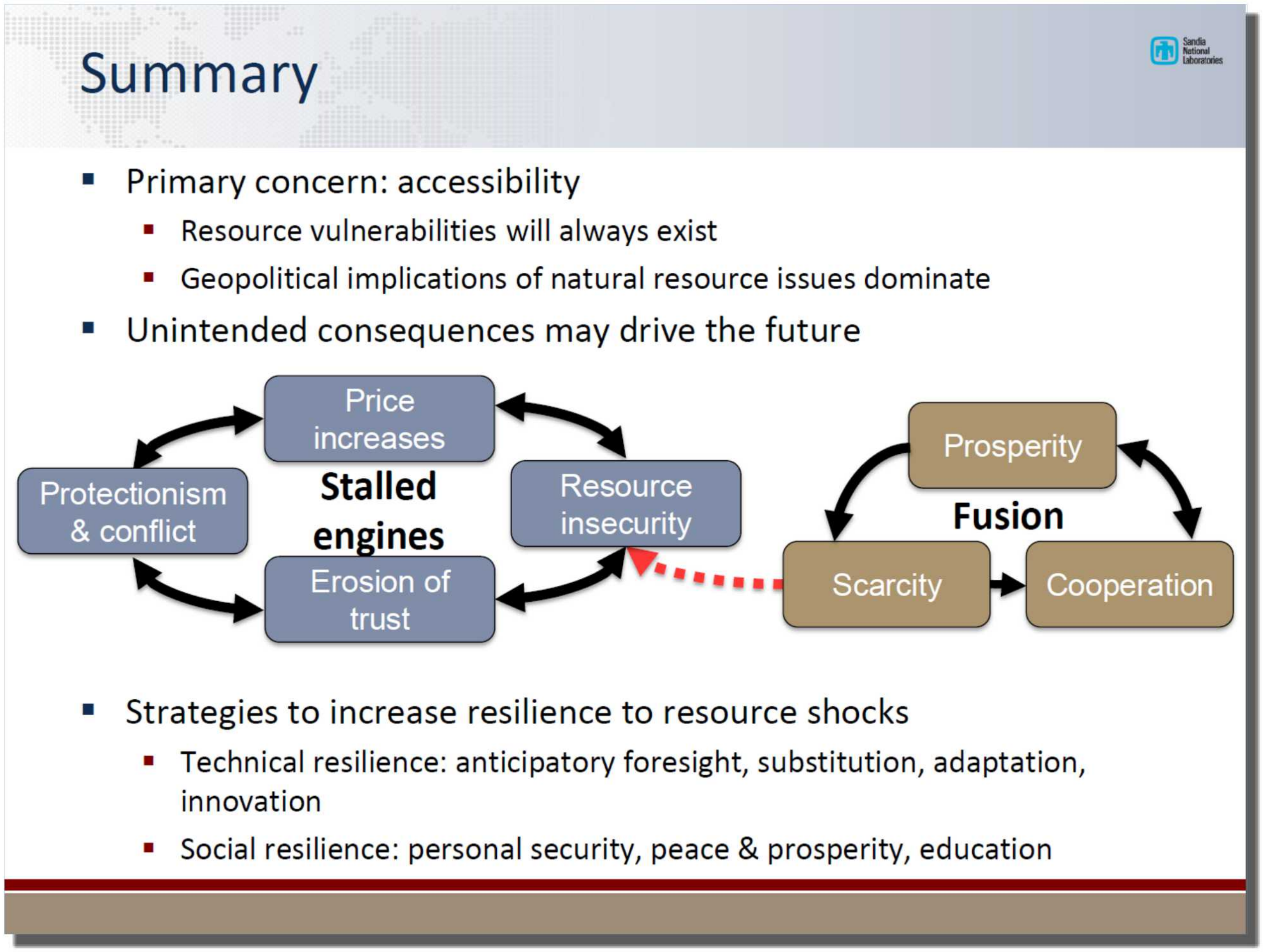


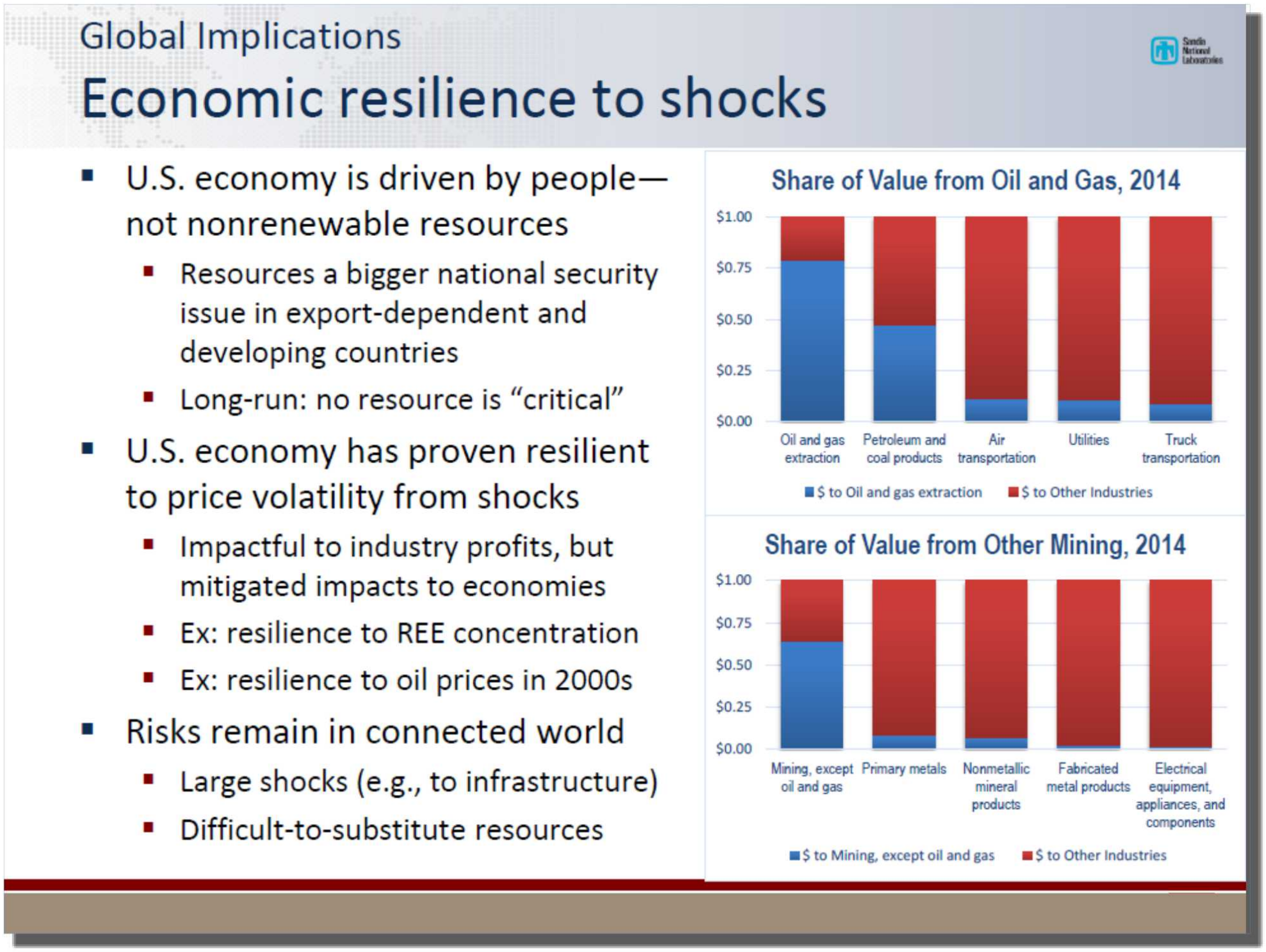
Figure 22. Resource Accessibility Is Primary Concern

This GF study has found that the dominant nonrenewable natural resource security issue over the next 15 to 25 years will be the accessibility of these resources. Given the uneven distribution of nonrenewable resources, resource vulnerabilities (e.g., infrastructure dependencies and single points of failure) will always exist (Figure 22). The world's ability to overcome resource shocks is dependent on the ability to trade resources globally and engage in global innovation systems. A reduction in globalism, brought upon by a geopolitical upheaval, would reduce global resource security by making resources and innovation less accessible. Furthermore, a sudden geopolitical upheaval could be especially damaging since it would challenge countries' and societies' abilities to adjust; for example, the United States is highly dependent upon foreign sources for many of its resources, so the adjustment period could be long and painful.

The study has shown how unintended consequences may drive the future of resource security in the next 15 to 25 years. In the Fusion world with high degrees of trust and cooperation between countries and institutions, prosperity and cooperation build upon each other. However, this increase prosperity increases demands for resources, thus increasing scarcity. Resource constraints often motivate additional cooperation and prosperity. But, historic examples exist where scarcity has led to off ramps from a Fusion world to a Stalled Engines world with eroded trust where countries engage in counterproductive policies that erode resource security. There are currently many signs—most notably the Brexit referendum in the United Kingdom—that the possibility of an off ramp is increasing.

A key goal of the United States in the next 15 to 25 years will be to increase the resilience of institutions and society to natural resource vulnerabilities. Technical resilience is needed to anticipate resource vulnerabilities and find substitutions, adaptations, and innovations that increase the ability to absorb, adapt to, and recover from resource shocks, which are inevitable in any future. To avoid the potentially painful off ramp from the Fusion world to the Stalled Engines world, social resilience may help reduce fears generated by resource shocks and avoid counterproductive policies and conflict.

APPENDIX: ECONOMIC AND DEFENSE IMPACTS OF SHOCKS TO NONRENEWABLE RESOURCES



Section 1.1 described some of the nonrenewable resources that recent studies have identified as critical or strategic. The studies show that these materials have a high likelihood of a disruption or some other type of shock impacting them and would have a high level of consequences if disrupted. These studies usually focus on economic consequences (i.e., materials that are economically important) or defense/national security consequences (e.g., materials that defense institutions need). This appendix discusses economic and defense consequences in more detail.

The economic and defense risks that these studies identify are real and can be impactful. However, the study team found that in today's world of globalism these risks are manageable. The big risk is that globalism recedes (especially if it is a sudden change), which will magnify all of these individual risks and could potentially increase the likelihood of many resource shocks occurring at once.

When the study team first began examining economic consequences, we looked at how dependent different sectors of the economy are on nonrenewable natural resources. The graphs in the figure above calculate measures of dependence on oil and gas extraction (North American

Industry Classification System [NAICS] 211) and mining (except oil and gas) (NAICS 212).[47] This measure uses data from the Bureau of Economic Analysis (BEA) to estimate the share of value added in each sector of the economy that comes from these two nonrenewable resource industries. Value added is a useful economic measure since Gross Domestic Product is the sum of all the value added produced by a country's economy. For each sector, the five sectors that are most dependent upon the nonrenewable sector are listed.

As the graphs show, the nonrenewable sectors are most dependent on themselves. Most of the value added created in the nonrenewable sectors originates from the rents they pay to landowners and the wages they pay their employees. However, some of the value added is due to other industries (e.g., purchasing equipment to extract the resources), which is why the shares are less than 100%. Other industries have a relatively low level of economic dependence on nonrenewable resource sectors. The highest is for petroleum and coal products (e.g., gasoline). This is consistent with historic experience—at least in recent history, the only nonrenewable resource shocks that have had an appreciable macroeconomic impact are those to oil, which is a major input to gasoline, and which is a major expenditure of both consumers and other production industries.

Table 1. Top shares of each dollar of value added for oil and gas extraction

	Oil and Gas Extraction	*Compensation*
Oil and gas extraction	**$0.79**	**$0.20**
Petroleum and coal products	**$0.47**	**$0.22**
Air transportation	**$0.11**	**$0.50**
Utilities	**$0.10**	**$0.30**
Truck transportation	**$0.09**	**$0.54**

[47] To calculate these metrics, we used BEA data for 2014 that included 71 industries (accessed April 6, 2016): BEA Use Table: IOUse_Before_Redefinitions_PRO_1997-2014_Summary.xlsx.
BEA Total Requirements (Industry by Industry): IxI_TR_1997-2014_Summary.xlsx. We used the Use table to as an estimate of the share of output for each industry that is value added (i.e., wages, rents, profits, and taxes). We then multiplied the total requirements matrix by these output shares. For any industry's output, the value added provided by the entire supply chain should equal the value of the output, but this relationship sometimes does not hold for a number of reasons. Therefore, we make a simple linear adjustment across the supply chain so the value added throughout the supply chain equals the output. As an example of a calculation in the table, $1 of output in Air Transportation requires $0.19 of output from Oil and Gas Extraction (using the Total Requirements table). On average, 71% of Oil and Gas Extraction output is value added it has provided (using the Use table). This means that $1 of output in Air Transportation requires $0.19 x 71% = $0.13 of value added from Oil and Gas Extraction. However, across all industries these calculations lead to $1 of output in Air Transportation requiring $1.19 of value added, thus we adjust all values to sum to $1, i.e., $0.13/$1.19 = $0.11, as Table 1 shows.

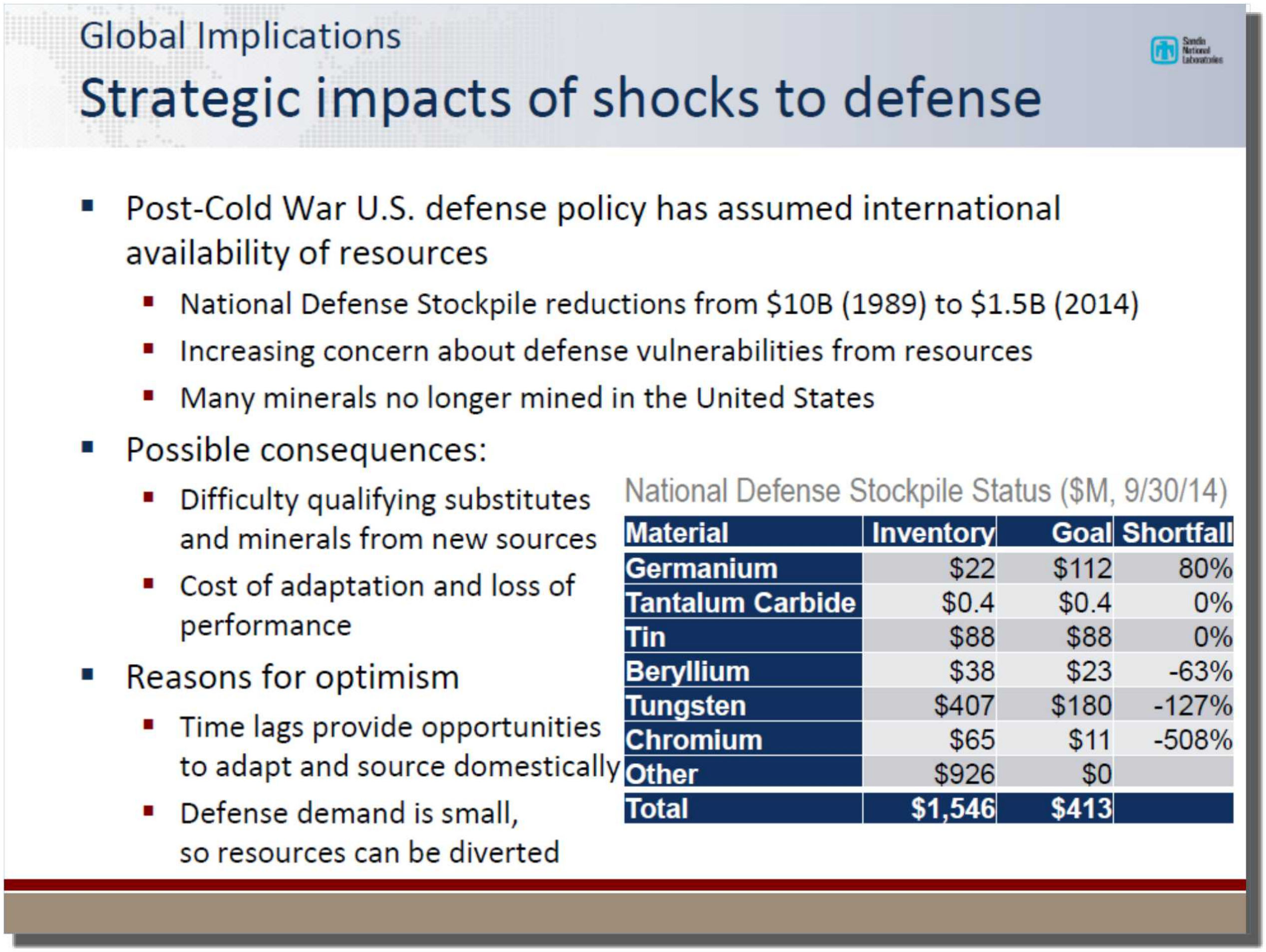
Table 2. Top shares of each dollar of value added for mining (except oil and gas)

	Mining (except oil and gas)	*Compensation*
Mining, except oil and gas	**$0.64**	**$0.36**
Primary metals	**$0.09**	**$0.51**
Nonmetallic mineral products	**$0.07**	**$0.54**
Fabricated metal products	**$0.02**	**$0.59**
Electrical equipment	**$0.02**	**$0.57**

Tables 1 and 2 show the data from charts numerically, but also added the share of value added in each sector due to compensation to employees. These data illustrate an important feature of the U.S. economy—even in sectors that are highly dependent on nonrenewable resources, the dependence on human capital—that is, the people who earn the compensation—is usually several times higher. People often recognize this fact for emerging industries (e.g., those in Silicon Valley), but it also holds true for the older, manufacturing industries that are most dependent on nonrenewable natural resources. This points to supply chains, which are dependent on specialized human capital, as being potentially higher risk and worthy of a future Global Futures study.

The lack of economic dependence on nonrenewable natural resources increases the resilience of the U.S. economy to shocks. As the numbers show, industries are able to absorb large increases in the prices of resources without having a major impact on the overall costs that consumers pay. For example, a doubling of oil prices would be expected to lead to about an 11% increase in the cost of airline tickets (an industry that is especially susceptible to oil shocks). This could be very painful for airlines' profit margins, but it is relatively manageable for consumers. As the case studies in this report show, U.S. resilience to resource shocks seems to be growing as the U.S. economy matures.

There remain economic risks that cannot be measured by these metrics. For example, if an industry is dependent on a particular, hard-to-substitute resource, a supply disruption to that resource could have a magnified effect by halting economic activity in that sector. Even if a small percentage of the value added in such a sector was due to that resource, if workers were put out of work the net result could be a large impact. We were not able to find any examples of such impacts at an aggregate level, which is likely because increases in prices incentivize conservation and innovation to find substitutes. Nonetheless, large shocks (e.g., due to infrastructure or due to a rapid change in geopolitical conditions) when coupled with difficult-to-substitute resources could potentially lead to economic pain.



Material	Inventory	Goal	Shortfall
Germanium	$22	$112	80%
Tantalum Carbide	$0.4	$0.4	0%
Tin	$88	$88	0%
Beryllium	$38	$23	-63%
Tungsten	$407	$180	-127%
Chromium	$65	$11	-508%
Other	$926	$0	
Total	$1,546	$413	

The table above shows, however, that in the current state of the system national security and defense organizations probably have more resource security than they had during the Cold War. By the end of the Cold War, the National Defense Stockpile had amassed an inventory valued at $9.6B, with a shortfall of $12.5B (Committee on Assessing the Need for a Defense Stockpile, 2008, p. 28). Following the Cold War, a recognition of the increased availability of materials worldwide, coupled with less risk of a long-term conflict involving mobilization (e.g., converting commercial industry to defense production as occurred during WWII) led to a rapid decrease in stockpile goals (Committee on Assessing the Need for a Defense Stockpile, 2008, Chapter 6).[48] Much of the inventory was liquidated, and as the table above shows, the stockpile goals were reduced to $413M across six materials by 2014 (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2015b, Table 1).

[48] Following the Cold War, the perceived need for an increase in mobilization decreased. Perhaps more importantly, there was an increased recognition that the decreased size of the defense sector and the decreasing speed of defense production meant that there was plenty of time to deal with resource shocks. If any shocks persisted over a long period, resources could ultimately be commandeered from the commercial sector (Gholz, 2014, p. 10)—which now dwarfs the defense sector—through the Defense Priorities and Allocations System administered by the Department of Commerce.

As this report discusses (especially Section 4.2), there is reason to worry about strategic impacts of nonrenewable resource shocks to national security and defense institutions, especially as these institutions diverge from commercial industry. Furthermore, the recognition of the growing magnitude and degree of offshoring U.S. resource needs has led to a reevaluation of the stockpile and an expansion of the materials stocked (see Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2016), as discussed in Section 1.1.2.

6. REFERENCES

Amundson, R., A.A. Berhe, J.W. Hopmans, C. Olson, A.E. Sztein, D.L. Sparks. 2015. "Soil and human security in the 21st century," *Science* Vol. 348, Issue 6235.

Beiser, Vince, 2015. "The deadly global war for sand," March 26, *Wired*. https://www.wired.com/2015/03/illegal-sand-mining/.

Beiser, Vince, 2016. "The world's disappearing sand," *New York Times*, June 23, 2016.

Biringer, Betty, Eric Vugrin, and Drake Warren, 2013, *Critical Infrastructure System Security and Resiliency*, Boca Raton: CRC Press.

Committee on Assessing the Need for a Defense Stockpile, 2008, *Managing Materials for a Twenty-first Century Military*, Washington, D.C.: The National Academies Press.

Deudney, Daniel, 1990, "The Case Against Linking Environmental Degradation and National Security," *Millennium Journal of International Studies*, v. 19(3), pp. 461-476.

Eilertsen, Donald E., 1964, "Beryllium," Mineral yearbook metals and minerals (except fuels) 1963, v. 1, Washington, D.C.: Bureau of Mines, pp. 301-309.

Frank, Charles (ed.), 1993, *Operation Epsilon: The Farm Hall Transcripts*, Berkeley: University of California Press (English translation of British transcripts declassified on February 6, 1992 of German scientists captured following WWII).

Food and Agriculture Organization of the United Nations. 2015, *Status of the World's Soil Resources (SWSR) – Main Report*. Rome, Italy: Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils.

Gholz, Eugene, 2014, *Rare Earth Elements and National Security*, New York: Council on Foreign Relations, Energy Report, October 2014.

Gloser, Simon, Lujis Tercero Espinoza, Carsten Gandenberger, and Martin Faulstich, 2015, "Raw Material Criticality in the Context of Classical Risk Assessment," *Resources Policy*, v. 44, pp. 35-46.

Gompert David C., and Hans Binnendijk, 2016, *The Power to Coerce: Countering Adversaries Without Going to War*, Santa Monica: RAND Corporation, RR1000.

Goeller H.E., and Alvin M. Weinberg, 1976, "The Age of Substitutability: What Do We Do When the Mercury Runs Out?" *Science*, v. 191(4228), pp. 683-689.

Jones, Vincent C., 1985, *Manhattan: The Army and the Atomic Bomb*, Washington, D.C., Washington, D.C., United States Army, Center for Military History.

Kingsnorth, Dudley J., 2016, "Rare earths exports from China will cease someday — and we need to prepare, says Kingsnorth", 5th Annual Cleantech and Technology Metals Summit, Toronto, May 10-11, 2016, https://www.youtube.com/watch?v=TWulwQjYUF8, published June 1, 2016.

Lagi, Marco, Karla Z. Bertrand, & Yaneer Bar-Yam, 2011, "The Food Crises and Political Instability in North Africa and the Middle East". New England Complex Systems Institute: http://necsi.edu/research/social/foodcrises.html, August 10, 2011.

Lamy, Pascal, 2010, *World Trade Report 2010: Trade in Natural Resources*, Geneva: World Trade Organization.

Lee, Bernice, Felix Preston, Jaakko Kooroshy, Rob Bailey, and Glada Lahn, 2012, *Resources Futures*, London: Chatham House.

Miller, Edward S., 2007, *Bankrupting the enemy: The U.S. financial siege of Japan before Pearl Harbor*, Annapolis, MD: Naval Institute Press.

National Intelligence Council, 2012, *Global Trends 2030: Alternative Worlds*, Washington, DC: National Intelligence Council, NIC 2012-001.

Nichols, Kenneth D., 1987, *The Road to Trinity: A Personal Account of How America's Nuclear Policies Were Made*, New York: Morrow.

Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2015a, *Strategic and Critical Materials 2015 Report on Stockpile Requirements*.

Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2015b, *Strategic and Critical Materials Operations Report To Congress: Operations under the Strategic and Critical Materials Stockpiling Act during Fiscal Year 2014*.

Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, 2016, *Strategic and Critical Materials Operations Report To Congress: Operations under the Strategic and Critical Materials Stockpiling Act during Fiscal Year 2015*.

Parthemore, Christine and Will Rogers, 2010, *Sustaining Security: How Natural Resources Influence National Security*, June 2010, Washington, D.C.: Center for New American Security.

Passell, Howard D., Thomas R. Nelson, Mark R. Ackermann, George A. Backus, Celeste A. Drewien, Chad Haddal, Elizabeth James Kistin Keller, Alexander Stevenson, Drake Edward Warren, 2015, *Urbanization, Megacities, and National Security*, SAND2016-7897 PE.

Rodrik, Dani, 2007, "The inescapable trilemma of the world economy", Dani Rodrik's weblog, June 27, 2016, http://rodrik.typepad.com/dani_rodriks_weblog/2007/06/the-inescapable.html.

Rosenberg, Elizabeth, David Gordon, Ellie Maruyama, and Alexander Sullivan. 2016. *The New Great Game: Changing Global Energy Markets, The Re-Emergent Strategic Triangle, and U.S. Policy*, Center for a New American Security, June 2016.

Schoon, Michael and Edward Saltzberg, 2016, "Applying Resilience Thinking: Seven Principles for Building Resilience in Social-Ecological Systems," March 2, 2016, Security & Sustainability Forum, https://vimeo.com/157642643.

Silberglitt, Richard, James T. Bartis, Brian G. Chow, David L. An, and Kyle Brady, 2013, *Critical Materials: Present Danger to U.S. Manufacturing*, Santa Monica: Rand Corporation: RAND-RR133.

Simon, Julian L., 1996, *The Ultimate Resource 2*, Princeton: Princeton University Press.

Stern, David I., 1997, "Limits to Substitution and Irreversibility in Production and Consumption: A Neoclassical Interpretation of Ecological Economics," *Ecological Economics*, v. 21, pp. 197-215.

Strauss, Mark, 2014, "How China's "Rare Earth" Weapon Went From Boom To Bust," io9, November 2, 2014, http://io9.gizmodo.com/how-chinas-rare-earth-weapon-went-from-boom-to-bust-1653638596, accessed May 26, 2016.

The Economist, 2013, "That special relationship: Why America dithered about joining the war," *The Economist*, April 27, 2013.

The Economist, 2016a, "Globalisation backlash 2.0," *The Economist*, Buttonwood's notebook, July 27, 2016, http://www.economist.com/blogs/buttonwood/2016/07/economics-and-politics-0.

The Economist, 2016b, "Drawbridges up: The new divide in rich countries is not between left and right but between open and closed," *The Economist*, July 30, 2016.

The Economist, 2016c, "Upsetting the Apple cart: Europe's most Europhile country is on the warpath with Brussels over tax," *The Economist*, September 10, 2016.

The Economist, 2016d, “Coming and going: Truth and myth about the effects of openness to trade.” *The Economist*, October 1, 2016.

The Economist, 2016e, “The good, the bad and the ugly: foreign direct investment is mostly welcome, but large short-term flows spell trouble,” *The Economist*, October 1, 2016.

Tozer, Jessica, 2015, “Seeking Alternatives for Beryllium in DoD Weapon Systems,” Armed With Science: The Official U.S. Defense Department Science Blog, February 17, 2015, http://science.dodlive.mil/2015/02/17/seeking-alternatives-for-beryllium-in-dod-weapon-systems/.

Tse, Pui-Kwan, 2011, *China's Rare-Earth Industry*, Washington, D.C.: U.S. Geological Survey Report 2011-1042.

United Kingdom Ministry of Defence, Strategic Trends Programme, 2010, *Global Strategic Trends—Out to 2040*, 4th Edition.

United Nations, 2016, “Ban 'deeply concerned' over tensions in south-western Western Sahara.” August 28, 2016, http://www.un.org/apps/news/story.asp?NewsID=54770.

United States Department of Defense, Manufacturing and Industrial Base Policy, 2012, *Defense Production Act Title III: Advancing the Industrial Base to Defend the Nation*, http://www.dpatitle3.com/Title_III%202012%20Brochure.pdf.

United States Department of Energy, 2011, *Critical Materials Strategy*, https://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

United States Department of Energy, 2016, “About Beryllium”, Accessed September 12, 2016, http://energy.gov/ehss/about-beryllium.

United States Department of State, Bureau of Oceans and International Environmental and Scientific Affairs, Limits in the Seas No. 143: China: Maritime Claims in the South China Sea, Washington, D.C.: Office of Ocean and Polar Affairs.

United States Energy Information Administration, 2013, “The South China Sea is an important world energy trade route,” Today in Energy, April 4, 2013, http://www.eia.gov/todayinenergy/detail.php?id=10671.

United States Geological Survey, 2013, “Beryllium”, *Mineral Commodity Summaries*, January 2013, Washington, D.C.

United States Geological Survey, 2016, “Rare Earths,” *Mineral Commodity Summaries*, Washington, D.C.

van Weezel, Stijn, 2016, “Food imports, international prices, and violence in Africa,” *Oxford Economic Papers*, v. 68(3), pp. 758-781.

Vugrin, Eric D., Drake E. Warren, Mark A. Ehlen, and R. Chris Camphouse, 2010, “A Framework for Assessing the Resilience of Infrastructure and Economic Systems,” in *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering*, Kasthurirangan Gopalakrishnan and Srinivas Peeta, eds., Berlin, Heidelberg: Springer-Verlag, Inc., pp. 77-116.

Warren, Drake, George Backus, Wendell Jones, Thomas Nelson, Russ Skocypec, 2015, Technology Empowerment: Security Challenges, SAND2016-7898 PE

Williams, Susan, 2016, *Spies in the Congo: America's Atomic Mission in World War II*, New York: Public Affairs.

Zhang, G., J. Song, J. Yang, X. Liu. 2006. “Performance of mortar and concrete made with a fine aggregate of desert sand,” *Building and Environment,* v. 41, pp. 1478-1481.

Distribution

1	MS0159	George Backus	0154 (electronic copy)
1	MS0159	Wendell Jones	0159 (electronic copy)
1	MS0159	Tom Nelson	0159 (electronic copy)
1	MS0159	Howard Passell	0159 (electronic copy)
1	MS0159	Drake Warren	0159 (electronic copy)
1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories