U.S. DEPARTMENT OF ENERGY

Competitiveness and Commercialization of Energy Technologies

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

February 24, 2022

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About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- commercialization and competitiveness, and
- cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

Acknowledgments

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Nomenclature or List of Acronyms

CdTe	Cadmium telluride
DOE	U.S. Department of Energy
E.O. 14017	Executive Order on America's Supply Chains
HVDC	High-voltage direct current
IP	Intellectual property
IRR	Internal rate of return
LPO	Loan Programs Office
OEM	Original equipment manufacturer
OP	Office of Policy
OTT	Office of Technology Transitions
PGM	Platinum group metal
PSH	Pumped storage hydropower
PV	Photovoltaics
R&D	Research and development
RDD&D	Research, development, demonstration, and deployment
ROI	Return on investment
WACC	Weighted average cost of capital
WBG	Wide bandgap

Executive Summary

Competitive U.S.-based clean energy manufacturers and rapid commercialization of U.S.-developed technologies are critical to secure energy supply chains, generate high quality jobs, and meet the United States' national security, energy and climate objectives. The February 2021 "Executive Order on America's Supply Chains" (E.O. 14017) directs the U.S. Department of Energy (DOE) to evaluate supply chains that encompass the energy industrial base, focusing on technologies that are critical to meet U.S. decarbonization goals by 2050.

Understanding and analyzing the end-to-end supply chain through economic analysis is crucial to mitigating risks and identifying opportunities to enhance U.S. competitiveness in the clean energy industry. This insight will allow the Department of Energy (DOE) to leverage its research, development, demonstration and deployment (RDD&D) capabilities to most fully realize the objectives of E.O. 14017.

This report provides a six-step structured analytical approach to such an economic analysis of supply chains:

Step 1: Prioritization. For each technology, map the supply chain, and screen where the biggest vulnerabilities and opportunities are based on qualitative assessments of current supply and demand. Based on the assessment, prioritize where further detailed analysis is required.

Step 2: Create Supply Baseline. Create the supply chain baseline of the current and projected global asset footprint, which includes location, costs, and volumes of assets (such as manufacturing plants), considers the impact of new technologies.

Step 3: Create Demand Forecast. The demand forecast includes the prices the market is willing to bear, given the component's value proposition across applications, and the likely volumes demanded by the marketplace.

Step 4: Assess U.S.-based Economics of Production. Understand what it would cost to build U.S.-based assets and the unit economics to manufacture in the United States in the context of potential new technology commercialization opportunities and other market dynamics. Given that, understand where in the current supply chain stack potential U.S. assets would reside, and understand for which applications the U.S.-based output would be competitive.

Step 5: Policy Analysis. Given the supply/demand scenarios and U.S. cost competitiveness, lay out policy options that would catalyze the building of a U.S.-based supply chain.

Step 6: "War Gaming" and Scenario Analysis. The marketplace is dynamic, so any new policies or changes to the supply stack will elicit competitive responses. Use scenario analysis and simulate potential outcomes in the supply stacks, demand stacks, and global and domestic markets.

A systematic analysis for the most at-risk supply chains based on the above approach should guide decision-making across DOE and the U.S. government. The approach will be challenging to implement due to significant data gaps, difficult-to-model system dynamics, and complex interactions between companies and governments; thus, sufficient resources, multiple agencies, and central coordination will be required over the long term. This report describes the establishment of a hub-and-spoke model for analytics capabilities that will significantly augment the current capacity within DOE to execute these analyses.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1.1 Introduction

In February 2021, President Biden signed the "Executive Order on America's Supply Chains" (E.O. 14017), directing four executive agencies to evaluate the resilience and security of the nation's critical supply chains and to craft strategies for six industrial bases that underpin America's economic and national security. As part of the one-year response to E.O. 14017, the U.S. Department of Energy (DOE), with support from DOE national laboratories, conducted evaluations of the supply chains that encompass the energy industrial base, with a particular focus on technologies required to decarbonize the U.S. economy by 2050, which have identified challenges and opportunities across critical technology areas. Beyond this initial analysis, a systematic economic analysis requires a full demand-side analysis across applications, as well as an understanding of market structure and dynamics for each component. This report provides a 6-step analytical approach to such an analysis and provides a framework for implementing the analysis across the technology areas of the energy industrial base to help guide the establishment of US manufacturing assets.

This report uses a few terms throughout, that are worth defining at the outset:

- **Competitiveness.** While this term is used in economic and business language to refer to a number of different, but related, concepts, this report uses the term to describe the ability of a nation's industry, or a specific domestic firm within that industry, to gain a competitive advantage over foreign competitors (Porter, 1990). This report is concerned with the competitiveness of domestic industries to support clean energy supply chains.
- **Technology Commercialization.** In this report, we define technology commercialization as the process by which new technologies are transferred from the laboratory to full commercial scale, through the Research, Development, Demonstration, and Deployment (RDD&D) process.
- **Supply Chain.** A supply chain is the system of stakeholders, technologies, activities, information, and resources involved in moving materials, goods, and services throughout the production process from raw material and intermediate components to the final product, end customer, or end-of-life management. A resilient supply chain is designed, managed, and operated to effectively prepare for and adapt to change, with the ability to sustain manufacturing operations or rapidly recover from anticipated and unanticipated disruptions.

1.2 Economic Analysis Is Essential to Understanding Supply Chain Competitiveness in the Energy Industrial Base

The Biden Administration has set 2030 climate goals aimed at ambitious and achievable reductions in greenhouse gases (White House, 2021). Reaching these goals will require a sweeping transformation of the U.S. energy industrial base. While efficient decarbonization technologies are available to pursue these goals, they often rely on raw materials bought and sold in opaque and volatile global markets concentrated in geopolitically sensitive areas. Midstream supply chain stages, such as material processing and component manufacturing, are often concentrated in foreign countries with complicated geopolitical relationships with the United States or may face other issues that make them susceptible to disruption.

One strategy for improving the resilience of supply chains for decarbonization technologies is increasing domestic production of raw materials, components, and energy technologies through onshoring overseas manufacturing, scaling up existing manufacturing, increasing materials recycling, and encouraging new manufacturing by commercializing technologies developed in the United States. Increased domestic manufacturing requires domestic industries that have the potential to be competitive relative to global competitors. A domestic manufacturing industry may not be competitive for various reasons, such as challenging market or supply chain dynamics, natural resource endowment, domestic or international policies, or technology and workforce gaps. If a domestic industry is not competitive relative to other countries at present, and the United States wishes to establish supply chain resiliency through onshoring, policy interventions will be required to help the U.S. industry establish an economically competitive position.

Robust and resilient domestic supply chains require economics that encourage private sector investment at home. Highly complex, interdependent supply chains are the result of numerous investment and business decisions made over the course of many years. For example, in the pharmaceutical industry, many of the world's small molecule drug manufacturing facilities are located in Puerto Rico because of incentives that have led the private sector to build the majority of their manufacturing plants in that region.

Granular analysis that considers the market dynamics within critical supply chains, and that can be updated as worldwide manufacturing footprints evolve and country-level incentives and tariffs change, will help position the United States for the supply chain of the future -- building out domestic manufacturing, while commercializing new technologies.

1.3 The Department of Energy can Drive U.S. Competitiveness Through Its Impact on the RDD&D Pathways of Clean Energy Technologies

Among its many responsibilities, DOE directs funding for research, development, demonstration, and deployment (RDD&D) of technologies that may transform the U.S. energy industrial base over time. These activities include basic science research and discovery, applied science research and development (R&D), development of nascent technologies, and further efforts to accelerate the demonstration, deployment, and scale-up of new technologies to drive commercialization at scale. Technologies developed through funding from the U.S. Department of Energy and related federal agencies have the potential to drive U.S. manufacturing competitiveness in the rapidly expanding clean energy sector for decades to come, and their commercialization is an important part of a U.S. supply chain competitiveness strategy.

It is critical to align the identification and pursuit of RDD&D with market opportunities to support U.S. competitiveness and the growth of resilient and sustainable supply chains that could include domestic manufacturing to support clean energy technologies. This impact may occur over short-, medium-, and long-term timescales—supporting U.S. leadership in high-growth markets today, while strengthening the strategic positioning in markets that may emerge over the next five, ten, or twenty years.

The purpose of this report is to illustrate how economic and market analysis will inform a DOE strategy to enhance the competitiveness of domestic industries and accelerate the commercialization of new technologies.

1.4 Additional Considerations

This report was prepared in parallel with several DOE one-year energy domestic base deep dive assessments, particularly those relevant to decarbonization by 2050. These technologies include rare earth permanent magnets, platinum group metal (PGM) catalysts, semiconductors, wind turbines, solar photovoltaics (PV), nuclear energy, fuel cells and electrolyzers, hydropower, carbon capture materials, electric grid, and energy storage for grid applications. Due to the scale and complexity of interdependent supply chain networks, the robust economic analysis described in this report takes time, data, and capacity. This report describes an approach to continue and expand the analysis for all technology areas through a long-term approach that will guide decision-making on the establishment of US manufacturing assets and the continual updating of those analyses as market conditions evolve. As policy actions are undertaken, analysis capabilities should also monitor if the intended outcomes are being achieved.

According to E.O. 14017, it is important to “ensure integrity and public confidence in supply chain analyses” (Section 5E, E.O. 14017). This can be achieved by sharing analytical findings in ways that improve public understanding, including aspects of resiliency that increase public confidence.

Section 2 of this report describes the recommended 6-step economic analysis to evaluate supply chain competitiveness. Section 3 summarizes this report’s recommendations to implement the analysis across the energy industrial base.

2 An Analytical Framework to Evaluate Supply Chain Competitiveness and Drive Technology Commercialization

It is important to ground policy actions and strategies spurring domestic technology commercialization and competitiveness in the context of the industry's fundamental economics and an understanding of private sector decision making. The transition to a clean energy economy will require significant investment by the private sector, responding to market signals and government policies (IEA, 2021). The analytical framework articulated in this section describes steps that will be part of the overall DOE strategy to expand supply chain knowledge, inform decision making, and support the clean energy transition.

2.1 Definitions

This section uses several terms common in describing supply chains, defined below:

- **Node.** Throughout this section, *nodes* refer to physical nodes in a supply chain; that is, entities or assets that extract raw materials, manufacture components, and process, store, or distribute goods and services, and entities responsible for end-of-life activities, including recycling and waste management. The word "node" is also used in this report as a shorthand for a single raw material, component, or product made at a node in the supply chain.
- **Tiers.** A common way to group nodes and identify upstream and downstream relationships within the supply chain. For example, Tier 1 suppliers provide products or services to the integrator; Tier 2 suppliers provide products or services to Tier 1 suppliers; etc (FEMA, 2019).

2.2 Six-Step Analytical Approach

Below, we describe a six-step structured analytical approach to assessing a supply chain for vulnerabilities and opportunities.

Step 1: Prioritization. For each technology, map the supply chain, and screen where the biggest vulnerabilities and opportunities are based on assessments of a set of criteria at each node (for all tiers of the supply chain). Based on the assessment, prioritize where further detailed analysis is required.

Step 2: Create Supply Baseline. Create the supply chain baseline of the current and projected global asset footprint, which includes locations, costs, and volumes of assets (such as manufacturing plants), considers substitute technologies (e.g., polysilicon vs. CdTe), new manufacturing technologies (that could shift the cost curve), and disruptive technologies (e.g., additive manufacturing, 5G, autonomous vehicles).

Step 3: Create Demand Forecast by Application. The demand forecast includes the prices the market is willing to bear, given the component's value proposition across applications, and the likely volumes demanded by the marketplace. Understand how the supply curve intersects the demand curve.

Step 4: Assess U.S.-based Economics of Production. Understand what it would cost to build U.S.-based assets and the unit economics to produce/manufacture in the United States and potential opportunities for, and impacts of, new technology commercialization and other market dynamics. Given that, understand where in the current supply chain stack potential U.S. assets would reside, and understand for which applications the U.S.-based output would be competitive.

Step 5: Policy Analysis. Given the supply/demand scenarios from step 2 and step 3 and the assessment of U.S. cost competitiveness and opportunities from step 4, identify policy options that would catalyze the building of a U.S.-based supply chain and support other U.S. policy objectives.

Step 6: "War Gaming" and Scenario Analysis. The marketplace is dynamic, so any new policies or changes to the supply stack will elicit competitive responses. Use scenario analysis and simulate potential outcomes in the supply stacks, demand stacks, and global market dynamics.

Figure 1 summarizes this six-step approach.

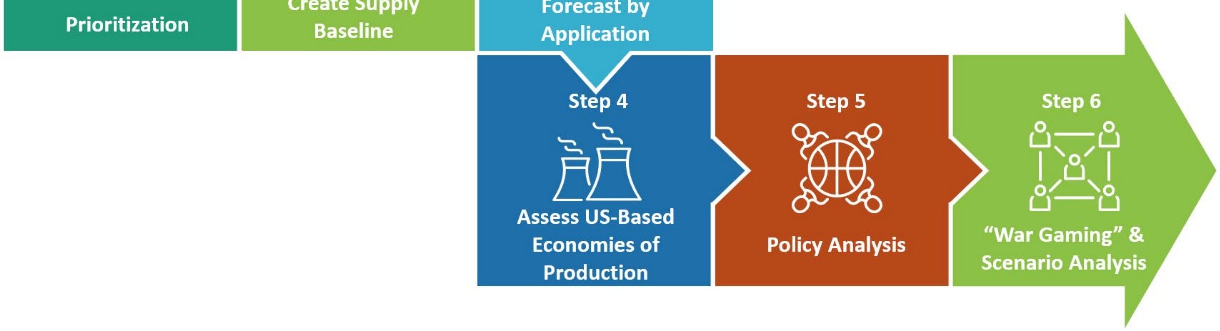


Figure 1: Steps to Evaluate Competitiveness of US Based Footprints

This type of detailed analysis is required to drive analytically informed decision making to ensure that strategic moves made by the United States are sustainable. This analysis should be updated on a regular basis given the dynamic nature of the marketplace.

2.3 Step 1: Prioritization

Understanding supply chain dependencies and vulnerabilities starts with systems-level visibility. The first step in the analytical process is to screen the supply chains across a technology for the greatest vulnerabilities and opportunities, based on qualitative assessments of the existing supply and demand situation. This qualitative assessment informs the development of a prioritized list of critical supply chain nodes and maximizes the impact of economic analysis on important strategic decisions.

A few prioritization criteria important to consider in this assessment include:

- **Greater market concentration**, both geographically and in terms of the number of individual firms competing in the market (fewer firms means greater market concentration), can increase the risk to supply by reducing the number of points of failure needed to threaten a supply chain. The existence of high market concentration may also allow existing producers to act to undercut new entrants to the market, especially if existing producers have the excess production capacity to flood the market and depress prices temporarily.

- **Geopolitical stability** where current supply is located, as well as geopolitical and trade relationships with the United States, will impact the likelihood of supply disruptions faced by U.S. buyers.
- **Price volatility** can be an important indicator of supply reliability. Note that suppliers that can provide a stable source of supply at contracted prices may be able to command a premium.

Additional prioritization criteria may be developed to augment those listed above.

Figure 2 provides an illustrative screening analysis completed for solar photovoltaics (PV). First, assemble a list of the product components across all nodes (including all tiers) of the supply chain, from raw materials (quartz, polysilicon, aluminum, etc.) through to end products (modules/inverters/systems, etc.), accounting for the end-of-life stage. For each of the components, a series of questions about their demand and supply can then provide, in aggregate, a qualitative assessment of risk. For each component, questions may include:

- Is there a significant domestic market for this product/component? Is the projected domestic demand significant?
- Is there a significant global market? Is the projected global demand significant?
- Is there a competitive domestic market? Are U.S. suppliers competitive in the global market?
- Is foreign supply source significant? Is it secure?

Depending on the security and commercial criticality of the overall technology, we can then establish a threshold for advancing nodes to the more detailed analysis in Steps 3-6.

Supply chain segments to meet the demand of the final product	Product/ Components	Significant domestic suppliers	Significant domestic demand	Projected significant domestic demand	Significant global market	Projected significant global demand	Cost competitive among US suppliers	Cost competitive between US suppliers vs. global suppliers	Is foreign supply source significant secure?
Raw materials	Quartz	Yes	Yes	Yes	Yes	Yes	No	Maybe	Yes
	Bauxite	No	Yes	Yes	Yes	Yes	No	Maybe	Yes
	Iron	Yes	Yes	Yes	Yes	Yes	Maybe	Maybe	Yes
	Silver	Yes	Yes	Yes	Yes	Yes	Maybe	Maybe	Yes
	Copper	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	Yes
	Cadmium	Yes	Yes	Yes	No	No	No	Maybe	Yes
	Tellurium	Yes	Yes	Yes	No	No	No	Maybe	Yes
Processed material	Polysilicon	Yes	Maybe	Yes	Yes	Yes	Maybe	No	No
	Aluminum	Yes	Yes	Yes	Yes	Yes	No	Maybe	Yes
	Rolled Glass	No	Yes	Yes	Yes	Yes	No	No	Yes
	Float Glass	Yes	Yes	Yes	Yes	Yes	Maybe	No	Yes
Subcomponents	Ingots	No	No	Yes	Yes	Yes	No	No	No
	Wafers	No	No	Yes	Yes	Yes	No	No	No
	Cells	No	Yes	Yes	Yes	Yes	No	No	Yes
	Supports	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
End products	Modules	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
	Inverters	No	Yes	Yes	Yes	Yes	No	No	Yes
	Systems	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	Yes

Figure 2: Solar PV Example of Screening Process for Competitiveness Analysis (DOE, 2022)

Example Data Required for Step 1:

- *Comprehensive list of supply chain nodes (across all tiers)*
- *Time series price and quantity information on all nodes/product components*
- *Market information for each node, including measures of market concentration/competitiveness (e.g., Herfindahl index, lists, and sizes of incumbents)*

Comprehensive analysis across multiple, complex supply chains is data and labor intensive and will require increased resources and capacity. Over time, best practices may be implemented to develop standardized approaches to qualitative and quantitative analyses of prioritization criteria.

2.4 Step 2: Create Supply Baseline

For each prioritized nodes/product components (e.g., "Bauxite" in the example from Step 1), a mapping of current global assets, their location, transportation, suppliers, production volumes, and unit cost economics provides an important basis for understanding how any U.S.-based assets would fit into the global marketplace.

Step 2 in this analytical approach is to map out the current status of supply (by node) in a supply stack, where every individual asset's (e.g., refinery, manufacturing plant) high-level unit costs (e.g., $/kg or $/part) are modeled at its steady-state volume. Assets, including those owned by the same company, may have different costs depending on the production technology they use; labor, electricity, or other location-dependent costs; or in the case of mines, on the type and grade of ore being processed. Production of substitutes that provide similar value to the original product should also be included.

Figure 3 provides a simplified example of a hypothetical supply stack, in which each bar is an individual asset. In this example, firms A and B own low-cost, high-capacity assets in the generally low-cost Location 1, while firms C and D own intermediate-cost assets in two other locations. Finally, Firm E owns high-cost, low-volume assets in high-cost Location 4.

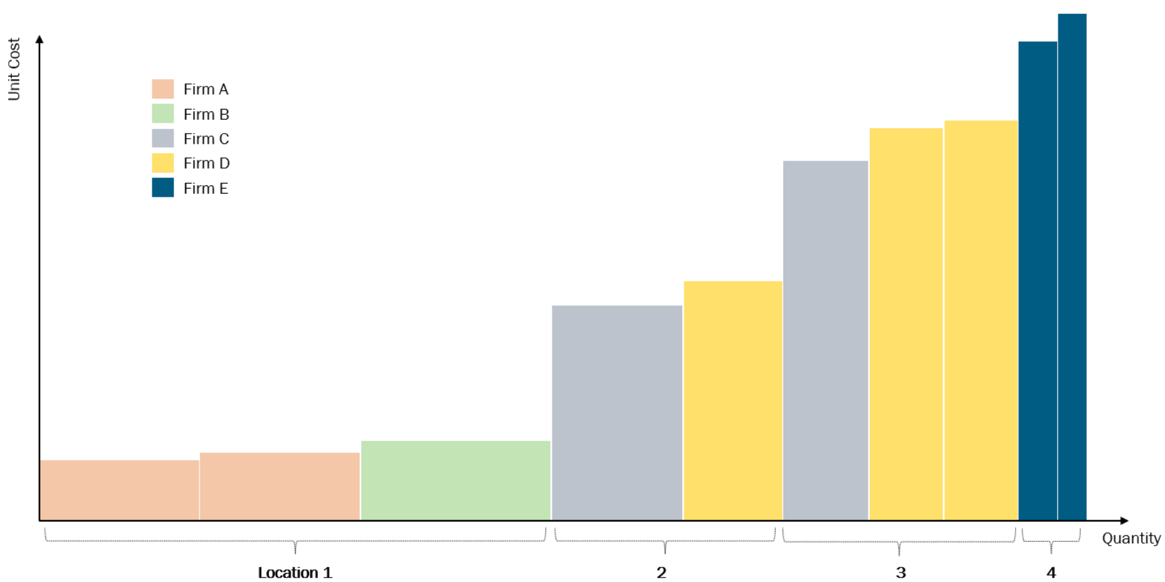


Figure 3: Illustrative Supply Stack Example

Understanding where potential U.S. assets would fall in the supply stack is critical to understanding their competitiveness in the market. Building the supply stack and identifying where potential new assets would fall in the stack requires analysis of an array of costs, including manufacturing costs, material input costs, and transportation costs. See below for an in-depth discussion of these cost components.

Assessing Costs

Competitiveness of U.S. suppliers depends on their costs relative to global suppliers, controlling for quality and product differentiation. Understanding cost factors can help inform overall competitiveness and identify effective approaches to improve competitiveness.

Manufacturing Costs include labor, materials, waste treatment, utilities, capital depreciation, capital investments and plant maintenance, and support services and supplies. They vary depending on the production process used, as different production processes may use different amounts of materials, labor, and capital. For example, the use of the grain boundary diffusion process in the manufacturing of neodymium-iron-boron magnets allows magnet manufacturers to reduce their use of heavy rare earth elements by nearly 50 percent, but the technology is not available to all producers due to expensive equipment and intellectual property constraints (Smith and Eggert, 2018).

The competitiveness of domestic firms also depends on regional differences in these costs. For example, labor costs are lower in many countries than they are in the United States—a significant consideration, given the importance of maintaining strong labor standards and family-supporting wages for American workers. The differences are greater for jobs that require less skill or training than for more skilled positions (Chung, Elgqvist, Santhanagopalan, CEMAC, 2015). U.S. producers may be able to make up for higher labor costs per worker with improved worker productivity, through improved production technologies, more capital-intensive processes, or better worker training. Thus, investments in workforce development can be critical to making a sector domestically competitive. However, if labor makes up a high portion of costs in an industry, it may be difficult for U.S. production to be cost-competitive.

Energy costs can also be important drivers of total production costs in some industries and may vary significantly by location. Average electricity and natural gas prices in the United States are relatively low by global standards (Chung, Elgqvist, Santhanagopalan, CEMAC, 2015), though prices vary by location within a country and over time. Electricity-intensive manufacturing may be able to reduce costs by locating near a large hydropower plant, or other source of cheap electricity. The efficiency of energy consumption, coupled with the costs of raw materials, can be key drivers of manufacturing costs.

Material Costs needed for production can also be a major driver of costs, and material availability can be a key vulnerability. If materials are less expensive or more easily available in one country or region, this can push companies to locate their production there. China's dominance in rare earth markets, for example, combined with reductions in Chinese export quotas and a temporary cut-off of rare earth metal shipments to Japan in 2010, led to significant price volatility in rare earth markets as well as price differentials between internal Chinese prices and export prices. This, in turn, led rare earth magnet companies from Japan and Germany to establish new production facilities in China where the supply of needed rare earth materials was more secure. Differences in material prices by location can therefore be a key indicator of potential competitiveness of U.S. suppliers. If material prices are volatile, it may be advantageous to establish strong relationships or contracts with suppliers. This may be easier to do if suppliers are domestic or located in allied countries.

Transportation costs and other transaction costs such as tariffs are key to determining when it makes sense for different stages of the supply chain to be located near each other. If a product's transportation costs are high, it may make sense for enough domestic production to exist to meet domestic demand, but not more. Policies to increase demand for the product may then spur new domestic production. Examples of products with high transportation costs include wind turbine blades and towers, because of their size, and rare earth magnet powders (specifically neodymium-iron-boron) because they are pyrophoric (at risk of igniting if exposed to air). Non-domestic manufacturers would find it challenging to compete in these product categories since their transportation costs would lead to a higher landed and all-in cost to the customer.

Beyond the "hard" costs listed above, other **hidden costs** may play an important role in determining a U.S. supplier's competitiveness relative to global suppliers. These costs may include lead time, poor quality and communication, the potential for continuous improvement, and geopolitical and climate risks. Addressing these risks within their business model may enable a U.S. firm to increase their customer value proposition and increase their global competitiveness (Gray et al, 2020).

In addition to mapping the current status of supply, the analysis should consider scenarios for how the supply stack may change over the time period of interest. For example, could there be a shift in the costs of some assets due to changes in energy or labor costs? Are there new disruptive manufacturing technologies being developed that could lead to the building of new assets that would dramatically shift the cost curve? Are there new substitute technologies that could make parts of the existing supply stack obsolete (e.g., a new material that could displace an incumbent one for certain applications)?

Example Data Required for Step 2:

- *Global asset data (location, unit cost, volume)*
- *Unit costs of new substitute/replacement technologies*
- *List and assessment of new manufacturing technologies (that would shift the cost curve)*
- *Global supply curve by asset (y-axis is unit cost; x-axis is manufacturing volume)*

Similar to step 2, completing this step will require additional data and analysis resources and capacity. In particular, unit costs of substitute technologies may be challenging to project, and intelligence on potential facility builds may be difficult to obtain.

2.5 Step 3: Create Demand Forecast by Application

For each node of the supply chain at which we are conducting the analysis, Step 3 constructs a demand stack. This information complements the supply stack developed in Step 2 to complete our understanding of the market segment at each node. Because the willingness to pay for a component may vary by application, the demand stack may include buyers outside of the industry we are studying. Taking the example from Section 2.3, suppose we prioritized for analysis the market for "Bauxite" in Step 1 (and completed the supply stack for "Bauxite" in Step 2), Step 3 would identify all the current and potential applications of "Bauxite," including those not part of the supply chain for solar PV. End uses for bauxite, for example, include steel, cement, and chemicals (USGS, 2016). The analysis should also anticipate potential uses in new applications that may appear over time, and applications that may begin using the product should its cost change with the introduction of new supply. There also are situations where applications may be willing to be pay more for higher quality product and/or other "softer" benefits (e.g., ability to tailor a solution, fast response time) and understanding which applications those are can also help the US with their competitive positioning.

The quantity demanded and willingness to pay for different applications informs our understanding of the potential addressable market at different cost points and, in conjunction with our supply stack from Step 2, can help us predict the potential market dynamics for hypothetical new domestic entrants into the market, and the impact of policy interventions. Figure 4 illustrates a simplified hypothetical demand stack, and the below discussion addresses further considerations when evaluating demand.

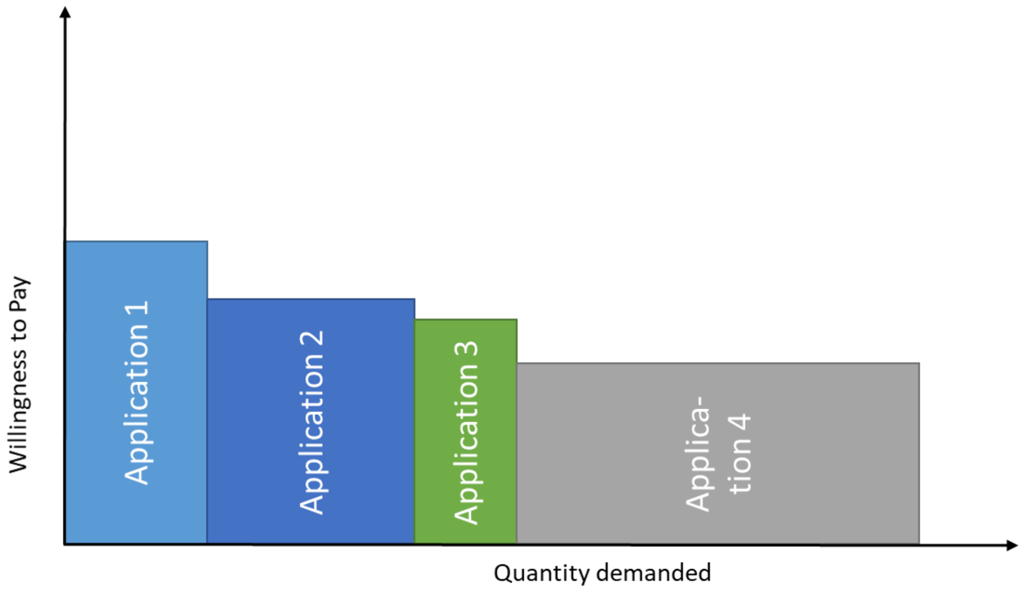


Figure 4: Illustrative Demand Stack Example

Demand-side Considerations for Potential U.S. Suppliers

To evaluate the competitiveness of a potential supplier, it is important to understand what market or market applications they plan to address, the size of those market applications, and the pricing they would likely face in each application.

Evaluating Market Size. Suppliers may aim to sell in domestic markets only or aim to compete in global export markets. The total size of the domestic market, as well as transportation costs for a product, may determine whether U.S. producers can be supported by domestic sales or if they will have to compete on global export markets. The size of the global market is also important because if it is small, each new production facility can have a significant impact on global supply, which may make it more challenging to add new production unless there is significant demand growth. The size of these markets will also determine how much impact the development of a new industry is likely to have on job creation and growth of the U.S economy. Industries with larger expected market size, in dollar terms, have the potential for larger economic impacts.

Suppliers with products that are differentiated from the products of their competitors may also focus on sub-markets for applications in which their products offer greater advantages. For example, wide bandgap (WBG) semiconductors may never compete for the entire semiconductor market but can compete for sub-markets such as those for transformers in the electric grid, grid integration of wind and solar power, data centers, and industrial motors (U.S. DOE, 2013), where their higher cost is justified by the higher performance needed in these applications. The cost-benefit calculation may be different for each potential application.

Price Premiums. Companies with higher costs can still compete on quality or reliability or in regional markets when prices differ by location. Distinct markets by location can exist when transportation costs, tariffs, or other costs of sales between regions are high. Products that have significant price differentials depending on quality may also be better suited for domestic manufacturers that are not able to compete on price, but that can optimize their production to develop a higher-quality product than competitors. For example, U.S.-produced nuclear reactors are known for their quality and safety, which may be more important to buyers than small differences in production costs.

If products are produced in geopolitically sensitive regions, buyers may be willing to pay a premium for additional reliability of supply. For some industries and technologies, the reliability of supply may be more important than costs, if material costs are low but the availability of the material is crucial to the manufacturing process. For example, rare earth metals make up a small part of the cost of manufacturing a vehicle, but if rare earth metals become unavailable, this could disrupt the vehicle production supply chain.

Example Data required for Step 3:

- *List of applications the technology can address, including current and potential future applications*
- *Bottoms-up cost analysis of price that market will bear given value proposition, by application*
- *Global demand curve by application (y-axis is unit price; x-axis is volume)*
- *Global demand curve by customer/end-user (y-axis is unit price; x-axis is volume)*

2.6 Step 4: Assess U.S.-based Economics of Production

Once the market data in steps 2 and 3 have been collected and analyzed, Step 4 assesses the economics of potential U.S.-based production: its cost components, competitive advantages, and barriers to entry.

First, construct the **unit costs of potential U.S.-based assets**. For hypothetical combinations of location, scale, and quality/product differentiation, estimate the steady-state operational fixed and variable costs of production, and divide by production volume for an estimate of unit costs. These cost components are described in detail in Section 2.4. These estimates provide an understanding of where any U.S.-based assets would fall in the cost stack we constructed in Step 2.

Next, approximate **start-up costs** (i.e., initial capital investments). These can constitute a substantial barrier to entry for new firms entering the market or for existing firms that are looking to build new manufacturing facilities. In addition to the cost of equipment, the costs of learning a new manufacturing process, including material and time lost while optimizing the process, are important components of start-up costs. Semiconductor fabrication is an example of an industry with high start-up costs, including both high capital costs and significant expertise and learning-by-doing involved to establish an efficient production facility. There may also be knock-on start-up costs when introducing a new technology into an ecosystem where Tier Ones, Tier Twos, and OEMs may need to establish new work processes to adopt a new technology. For example, with carbon fiber products, new recycling processes had to be established when first introduced.

As part of both start-up and operating costs, construct an understanding of labor and **workforce development** costs. Firms will not make large capital investments in a manufacturing asset without being assured that they will have access to a ready workforce with the skills they need in that location, or the ability to quickly attract and develop such a workforce. The analysis should consider both the initial investments in talent acquisition and training, as well as the costs of maintaining an on-going talent pipeline.

China's long dominance as the "world's workshop" may continue. In terms of manufacturing costs, although China's labor costs have risen quickly recently, over 30% from 2016-2022, they are still substantially lower than the US. This has driven some manufacturing to lower wage countries such as Vietnam, but other factors keep China attractive. Specifically, its large labor pool, networked business ecosystem, and controlled currency exchange rate give it advantages that make manufacturing in China sticky. Deeper analysis will need to guide the United States' strategy to drive toward competitiveness.

To understand if private sector capital will be sufficient to establish U.S.-based production assets, use the unit cost and start-up cost estimates in conjunction with the market data from steps 2 and 3 to conduct **analyses of investment returns** (e.g., WACC/IRR). The policy implications may be different depending on whether start-up costs or steady-state operating costs are the key factor limiting domestic competitiveness. If U.S. companies have the potential to be competitive once they have overcome the initial start-up costs, a set of policies focused on supporting companies through the initial start-up phase, such as supporting capital investments and workforce development, may be sufficient. If their steady-state operating costs are likely to be too high to be competitive and their products have no source of differentiation, long-term policy support may be needed to drive down domestic operating costs, e.g., through investment in superior manufacturing technologies or next-generation technologies that give domestic producers a competitive advantage.

Finally, thoroughly assess industry **barriers to entry** and a domestic entrant's potential sources of **competitive advantage** that may allow them to overcome such barriers. These considerations are discussed in further detail below.

Understanding Barriers to Entry & Sources of Competitive Advantage

New U.S. companies and assets may face different barriers to entry depending on the market dynamics of each industry.

Economies of scale are a fundamental quality of production that may shape industry dynamics. Firms that have economies of scale are able to lower unit costs by spreading fixed costs over a larger number of goods produced. Those with increasing returns to scale experience reductions in the average cost of producing additional units of output as more goods are produced.

In industries with companies with economies of scale, new companies may find it hard to enter the sector or survive as their manufacturing asset may need to reach a minimum production volume to be cost-competitive. For example, Infinium, a rare earth metal refiner, ran into this problem when it attempted to refine metals at a small scale for domestic stockpiles and research needs.

The **market structure** of the existing markets is also important when considering new entrants. The number of companies selling a particular product, and the relative size and market share of each, contribute to the amount of market power held by market participants. A company with large market share can often influence market prices and may use that power to try to limit entry of new players. On the other hand, it can also be difficult to be profitable in a highly competitive commodity market with many smaller players, as the competition keeps prices low.

Also important is the level of vertical integration in the supply chain. A vertically integrated company that produces products at multiple stages of the supply chain has the ability to either use their products internally or sell to other buyers, making it difficult for a new entrant occupying a thinner slice of the supply chain to find suppliers and/or buyers for their products. Vertically integrated companies can also reap benefits from improved security, visibility, and coordination. While potentially acting as a barrier to entry for new firms, vertical integration can also serve as a strategy for standing up a new industry where existing suppliers and buyers do not exist.

Opportunities for **technological disruption** may arise when innovations create a new market or are able to displace an existing market or value chain. U.S. companies may be able to establish a foothold in an industry by introducing new, disruptive technologies.

Firms with a technological value proposition that is protected by intellectual property have a significant advantage over their competitors. For example, Hitachi owns patents on standard techniques for producing neodymium-iron-boron magnets, which creates challenges for new entrants into the market. However, technological advantages erode over time, as patent protection expires and other producers are eventually able to replicate production techniques. Domestic producers may need to continue innovating to maintain their technological advantage, or find markets where they can compete on cost and quality in a mature industry. In some situations, where copying is easy and there is little patent protection, the advantage might be to the second mover, who can take advantage of the new technology without bearing the R&D costs needed to develop the new technology.

In mature industries, relative factor costs of inputs such as labor, materials, and equipment may play a more important role in determining which producers are most successful. Technological developments in these industries may focus on improving production processes to reduce cost, leading to a relative cost advantage over competitors.

Example Data required for Step 4:

- *Bottoms-up costs to build assets in the United States and major cost sensitivities*
- *Upstream and downstream costs/prices for U.S.-built facilities*
- *Modeling and analysis of project economics: internal rate of return (IRR), weighted average cost of capital (WACC)*
- *Sensitivity analysis of cost/price changes up and down the supply chain and identification of major risks*
- *Analysis of barriers to entry and sources of competitive advantage*

Similar to previous steps, completing this step will require additional data and analysis resources and capacity. In particular, establishing cost components and completing a full analysis of project economics will require drawing on private sector insights and expertise.

2.7 Step 5: Policy Analysis

Analyses of the supply chain risks and vulnerabilities, opportunities, potential competitiveness of domestic industries form the foundation for government policy and investment decisions and strategies to support strong domestic supply chains and the clean energy transition. This capability can be used to inform a wide range of decisions, including annual research and development investments, technology deployment strategies, manufacturing strategies, intellectual property and licensing policy, tax policy, climate, and environment policy, international development activities and strategies, trade policy and export strategy, and high-level national security strategies and objectives.

Understanding policies of the various types listed above will require additional analyses built on the foundational market assessment in Steps 1-4. For example:

- Financial modeling and analysis of the potential impact of policy changes that affect project economics or company financials
- Modeling the potential impact of new policies on supply chain stacks and potential competitive responses

- Estimating the incentive size required to shift investment decisions
- Analysis of policies that could be proposed or implemented internationally as a response to U.S.-based policies
- Analysis of labor market responses to workforce development programs

While many of the items listed above exist in some form or another, the development of systematic approaches and strategies to analyze the interplay of highly dynamic markets and policy environments is needed at a greater scale than what is currently available.

2.8 Step 6: "War Gaming" and Scenario Analysis

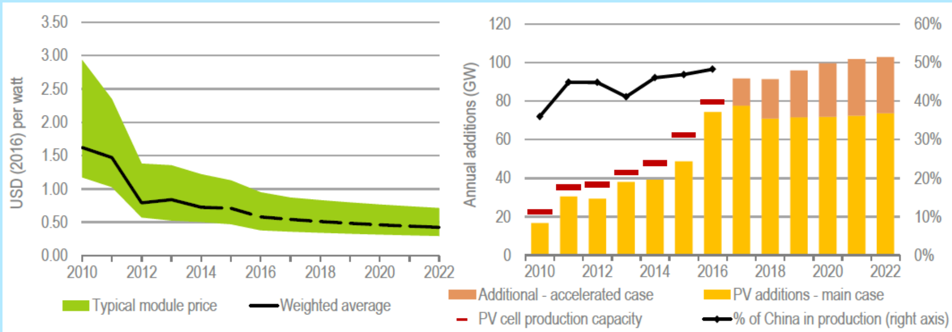
Finally, Step 6 reconciles the findings from the supply-side analysis (Step 2) and the demand-side analysis (Step 3) and evaluates the impacts of the proposed policies on the decision-making of individual actors in the context of market dynamics. Markets change rapidly due to demand shocks, macroeconomic shifts, policy changes in other countries, investor appetite, new company strategies, and other factors. An understanding of supply chain and manufacturing economics is only robust when it includes the ability to game out various scenarios and feedback loops.

Scenario analysis is useful for evaluating market outcomes over time, and in response to external market factors such as other governments' policies and strategic behavior by market actors. Scenario analysis can include the use of dynamic simulation models (e.g., agent-based models, computational general equilibrium models) that can model the ability of firms to compete in the broader market over time. For example, observable country- or company-level strategies can be modeled and explored to assess ways that markets and supply chains may evolve. In these models, customers respond to options in the market; companies respond to customer behavior and shifting preferences.

Case Study: Industry Dynamics in the Solar PV Market

Many, if not most, of the early technology breakthroughs in photovoltaics (PV) occurred in the United States. In 1962, Bell Labs launched Telstar which included solar cells that could generate 14 watts. By 1972, PV was widely used in outer space applications where there were few, if any, alternatives to generate electricity. In 1980, ARCO Solar, an American firm, was the first company to produce over 1 MW of PV modules in a year.1 In 1985, researchers at Stanford University were the first to demonstrate a PV cell that was 25% efficient. In 2000, First Solar began producing thin-film PV panels in Perrysville, Ohio. With a capacity of over 100 MW annually, it was the largest PV manufacturing plant in the world at the time. (DOE, 2022)

Policies and investments in other countries accelerated market activities. Germany introduced a feed-in tariff to spur demand for renewable energy, including solar, in 2000. This led to strong performance by German manufacturers to meet domestic demand. Over time, the increased cost competitiveness and market opportunity for solar technologies led to greater investments by countries around the world, particularly coming out of the Great Recession. (IEA, 2020) The increase in investment led to further cost reductions due to access to low-cost capital, economies of scale, and continued technological innovations in PV cells and manufacturing processes.



Sources: SPV Market Research (2017a), "Photovoltaic manufacturer capacity, shipments, price and revenues 2016/17"; SPV Market Research (2017b), *The Solar Flare – Issue 1.*

Figure 5: PV module prices (left) and manufacturing capacity and net annual additions (right) (IEA, 2017)

China, in particular, was aggressive in the use of policy mechanisms to drive increased solar manufacturing.1 By 2012, 45% of global solar manufacturing was located in China, due in large part to the use of low-wage labor and low-cost financing. American and European firms were unable to compete with their Chinese counterparts based on price in such an environment. By 2017, Chinese manufacturing capacity represented over 50% of the global supply (IEA, 2017).

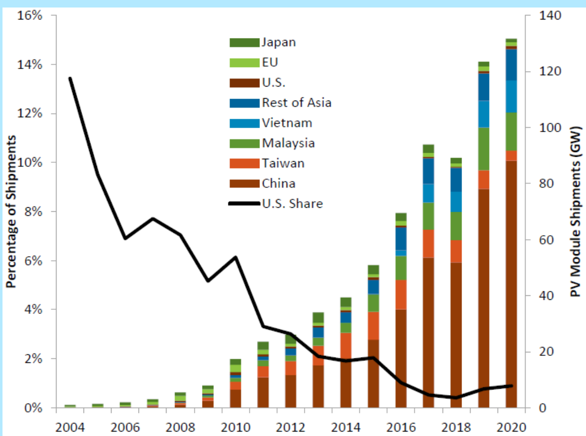


Figure 6: Global Annual PV Shipments by Region (right axis), U.S.-manufactured percentage of global PV shipments, left axis (NREL, 2021)

Despite decades of U.S. leadership in the research and development of solar technologies, the United States is not the leader in global PV manufacturing currently. Yet, solar remains a highly dynamic, high-growth sector with continued economic opportunities that arise from the research, development, and deployment of new technologies. Expanded economic analysis of new energy technologies can support a strategy to spur domestic manufacturing and maximize the benefits of high-growth technology sectors to the American people.

Simulations can also be used to explore scenarios with specific observed strategic behaviors. The case study on the solar PV market below describes industry dynamics that require policy responses informed by scenario analysis.

Scenario analysis can inform a wide range of investment and policy decisions. For example, as clean energy markets grow and mature, country-level strategies will continue to evolve and adapt. Nimble, quick-turnaround scenario analysis is an important tool to inform U.S. government and private-sector investment decisions.

3 Next Steps

3.1 Undertake a Systematic Analysis for the Most At-risk Supply Chains to Guide Decision Making

The analytical approach described in this report is an essential tool in supporting "[r]esilient American supply chains [that] will revitalize and rebuild domestic manufacturing capacity, maintain America's competitive edge in research and development, and create well-paying jobs" called for in the President's Executive Order (White House, 2021). DOE will build on the work included in the 100-day and one-year reports in response to Executive Order 14017 to continue toward a systematic economic analysis of supply chains that face risks and present opportunities, as described in Section 2. This analysis will complement already completed work to further enhance U.S. leadership and competitiveness in clean energy technologies, resulting economic and jobs benefits to the American people.

The economic analysis described above can dovetail with an analytically driven planning process for DOE's RDD&D investment strategies to maximize the benefit of federal investments to the American people. DOE's Office of Technology Transitions (OTT) is developing a commercialization adoption-risk framework that allows program offices to evaluate not just the technology risk, but the market risk of the technologies in their portfolios. The framework tracks these risks over time and ensures market risk is being mitigated at the same time as technology risk, bringing the technologies closer to commercialization. Faster commercialization of new technologies will speed the pursuit of national economic, security, and climate goals.

The output of these analyses will inform complementary activities by interagency partners in support for U.S. exports, scale-up of small businesses, increasing competitiveness for U.S. manufacturing, and reduction in global emissions through the deployment of U.S.-developed low-emissions technology around the world.

3.2 Significantly Augment the Analytical Horsepower Needed to Execute on These Analyses

The clean energy sector faces rapidly changing global markets; the emergence of numerous new technologies, rapid policy development, and implementation in countries around the world to address climate change and support domestic economies; and increased action by companies to respond to this dynamic environment. Accomplishing the detailed analyses described in this report at the speed, scale, and rigor necessary, and in an ongoing manner, requires an expansion on already existing capabilities. To provide a sense of the scope of work — each of the companion reports' eleven technology areas are looking at 20 to 56 different supply chain stages — the number of different supply chain stages to evaluate is large. When asked what proportion of the analysis described in Section 2 has been completed in each of these areas to date, many of the technology areas self-assessed in the range of 25-75%, due to limitations in available data and analytical capabilities. Additional supply chains not covered in these reports may also require evaluation.

Analytical capabilities exist within the DOE, including at the Office of Technology Transitions, the Office of Policy, the Loan Program Office, within the various technology offices, and across the DOE national laboratory complex and in other federal agencies. However, analysis capabilities with a deep understanding of markets are too few, their work is largely uncoordinated, and the requisite data are far from sufficient.

Hub-and-Spoke Analysis Model

Coordination across relevant offices within DOE, the national laboratory complex, and its interagency partners is essential for the efficient and effective use of resources to develop the kind of analytical capacity described above. A hub-and-spoke model could be implemented in which a central office at DOE develops and maintains shared data and analysis tools that can be applied across multiple economic analysis contexts. The central office could provide access to data sets, "off-the-shelf" models for common analyses, such as unit costs from a production facility, analysts capable of quick-turn and longer-term analysis tasks, and contract mechanisms to engage external subject matter experts. Additionally, the hub could develop baseline economic analyses for cross-cutting supply chain topics, such as upstream materials relevant to multiple downstream markets and common assumptions that offices should use (e.g., projected cost of labor).

Creating and maintaining an energy supply chain office as well as database and analytical decision modeling capabilities is described in *policy action #22* in the accompanying capstone report. This office will facilitate a centralized consortium for market and supply chain research and analysis, to provide a forum for federal, national laboratory, academia, and industry to address crosscutting issues. Benefits to this type of approach include establishing consistency for data standards and frameworks, validation and sharing, addressing and overcoming data gaps, and identifying research needs. A central function could create end-to-end supply chain analysis capabilities through linking existing capabilities and provide easily digestible resources and tools across the federal government and to private-sector stakeholders.

The energy supply chain office will also play a guiding role in the aggregation of relevant supply chain data. In addition to analytical capacity, access to reliable supply chain data and comprehensive supply chain maps is essential to the success of any economic analysis of supply chain competitiveness. Many data sources are not adequately designed to perform supply chain analysis at present. Partial data about supply chains can be assembled from publicly available sources; some data is compartmentalized or incomplete. Efforts should be made to assemble public (federal, state, and local) and private, historical, and near-real-time raw data, including data that covers environmental and social vectors. The government has a role to play in coordinating data collection (through voluntary or compulsory reporting), while protecting the sensitive information of individual companies (such as costs and production volumes).

4 Conclusions

A deep understanding of supply chain economics in key technology areas, enabled by the six-step analysis outlined in this report, will allow the Department of Energy (DOE) to leverage its research, development, demonstration, and deployment (RDD&D) capabilities to most fully realize the objectives of E.O. 14017. The Office of Technology Transitions, and the DOE offices in the technical areas covered in the accompanying reports, will continue to coordinate on deepening the department's understanding of supply chain resilience and competitiveness, using the self-assessments completed to-date as a starting point for further analysis.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

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