Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

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U.S. DEPARTMENT OF
ENERGY

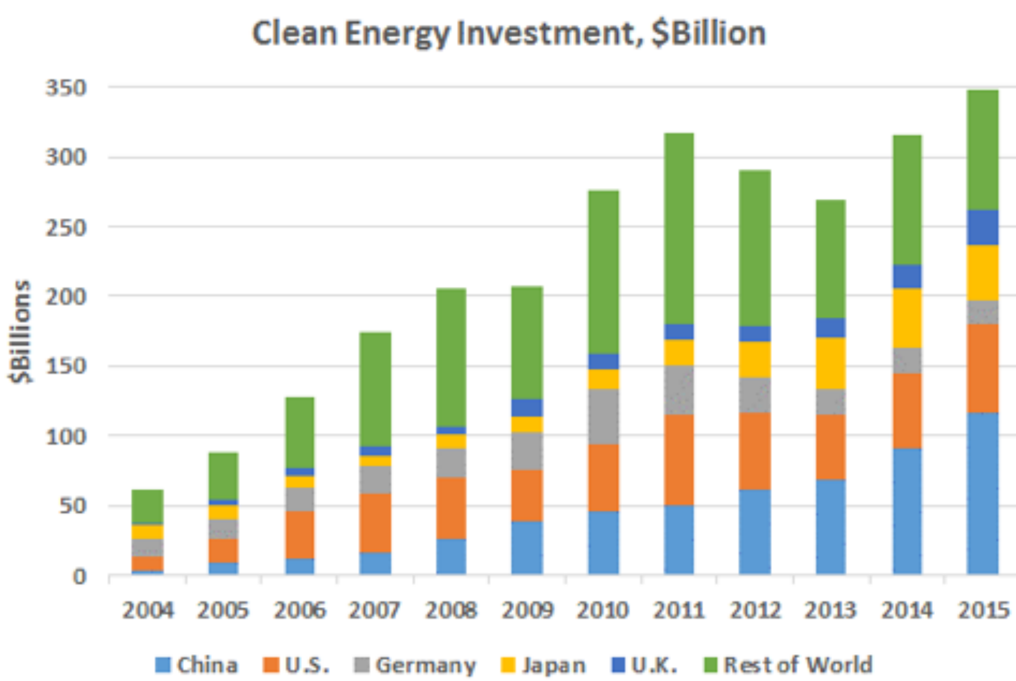
Quadrennial Technology Review 2015

Competitiveness Case Studies

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

The energy industry faces pressing security, economic, and environmental challenges, as described in the main Quadrennial Technology Review 2015 (QTR) report Chapter 1 and the Chapter 1 Supplemental Information appendix *Additional Information on Energy Challenges*.[1] Commensurate with the scale of these challenges is the scale of the opportunity for the clean energy industry. In 2015, global investment in clean energy was about $350 billion, with China the largest investor (Figure 1). Further, China announced a plan in January 2017 to invest $360 billion in renewable energy by 2020.[2] Going forward, the International Energy Agency (IEA) projects that, to 2040, the global market for clean energy technologies will total roughly $8 trillion for renewable energy supply and $23 trillion for energy efficiency, and that the total global energy supply and efficiency technology market will total over $60 trillion.[3] To assess the U.S. opportunity in these enormous global markets, this Supplemental Information appendix briefly explores some of DOE's initial analyses of the manufacturing competitiveness of U.S. clean energy technologies in global markets, and some of the implications of RDD&D efforts for U.S. economic competitiveness.[4]

Figure 1 Global clean energy investment 2004-2015.[5]



Chapters 3-8 of the QTR and its appendices identify opportunities for energy science and technology RDD&D to supply, distribute, and use energy more securely, cost-effectively, and cleanly in the power, buildings, industry, fuels, and transportation sectors,[6] and to reduce the environmental footprint of manufactured products across their lifecycles.[7] Clean, low-cost, stable production, delivery, and efficient use of energy can lead to reduced costs for domestic manufacturers and therefore improved competitiveness.[8] Further, the RDD&D opportunities identified in the QTR as well as other opportunities, if successfully developed, offer the potential to provide important clean energy technologies for both domestic and international markets.

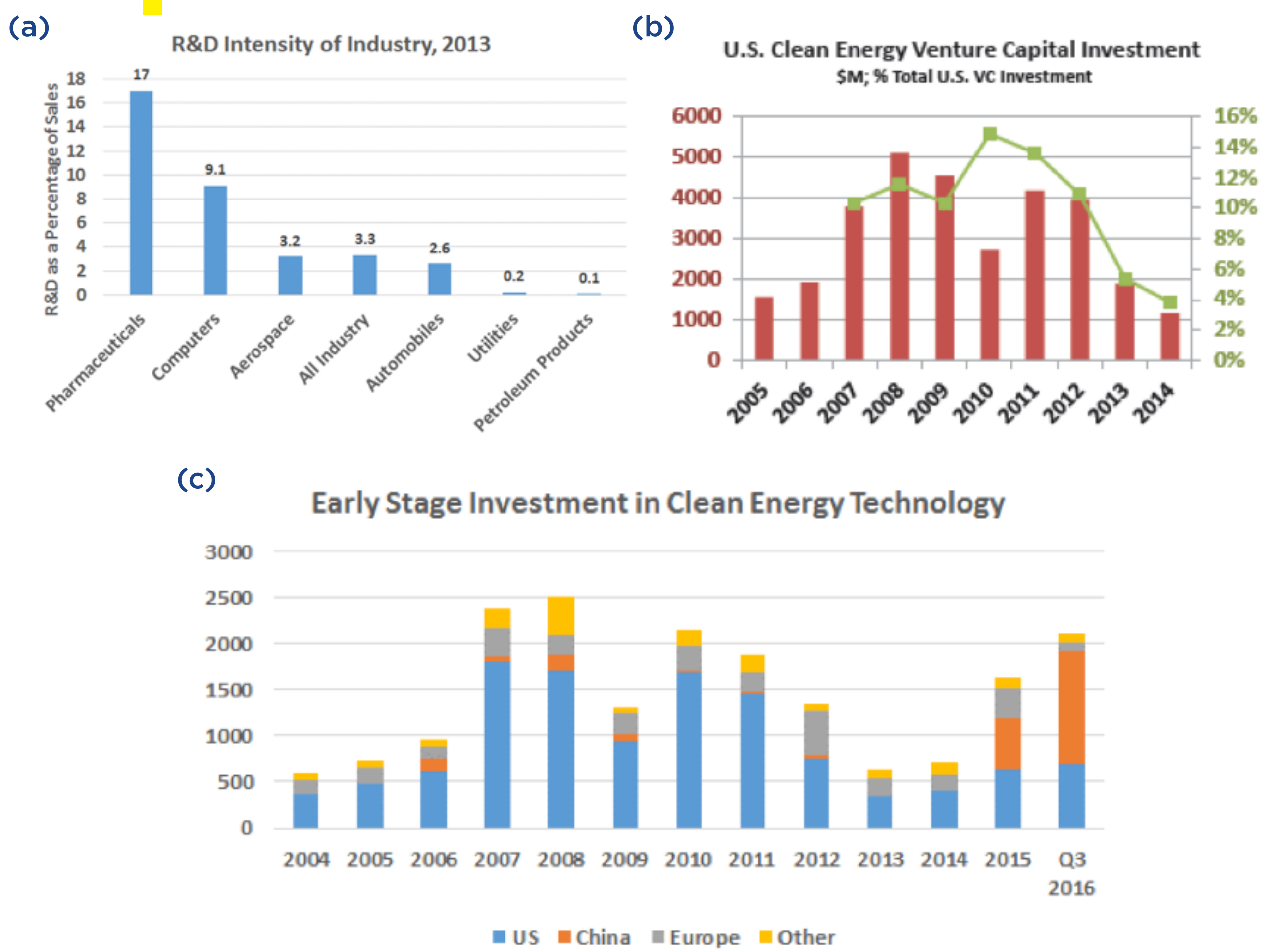
Many factors impact economic competitiveness, including the availability of investment capital, labor costs, tax structure, currency exchange rates, and import/export policies, to name only a few, but the focus here is on the key issue of technology innovation.[9] With global competition for market share in clean energy technologies and services, clean energy innovation and competitiveness will be important contributors to national economies in coming decades.[10] Indeed, the National Academies of Sciences, Engineering, and Medicine's National Research Council notes, "The capacity to innovate is fast becoming the most important determinant of economic growth and a nation's ability to compete and prosper in the 21st century global economy."[11] Advanced manufacturing is a critical part of this.[12]

Energy innovation requires investment, but as described in the QTR Chapter 1 appendix "*Additional Information on Energy Challenges*", private investment in clean energy RDD&D may be constrained by factors such as the following:

- Long gestation times for clean energy RDD&D can lead to long periods before there can be a return on investment for the company or investor.
- Risks of energy RDD&D activities—technical, managerial, financial, market (including energy market volatility), regulatory, policy, etc.—may be high for a company or investor.
- Appropriability of the energy RDD&D outputs (competitors could copy the technology or find alternative approaches) can reduce returns.
- High capital costs for supplying or saving low-margin commodity fuels or power can lead to long periods to earn a return.
- New energy infrastructure requirements may pose chicken-and-egg challenges requiring large investments over long periods.
- Externalities of security or the environment are often un-costed, voiding the market benefits for clean energy technologies that address them.
- Energy market failures and frictions—such as split incentives between the owner who purchases equipment and the renter who pays for the energy used—can limit market opportunities.

These pose substantial challenges for investors and contribute to observed low levels of private investment in energy RDD&D compared to that in other important sectors (Figure 2).[13]

Figure 2 (a) Private R&D investment as a percentage of sales for indicated technology sectors[14]; (b) Venture Capital (VC) investment in clean energy[15]; (c) Global early-stage clean energy technology investments.[16]



Venture capital funding in clean energy is also low, and has generally declined from its peak (in dollars) in 2008 (Figure 2b). Recent Bloomberg New Energy Finance data indicates that early stage clean energy investment has seen a small uptick in the U.S. in 2015 and through the third quarter of 2016, but that early stage investment by China has soared (Figure 2c). A recent review for the period 2006-2011 found poor returns for venture capital in clean energy and indicated that other financial structures may be better suited to the clean energy industry due to factors such as those listed above (see the text box "Venture Capital: The Wrong Model"[17]); they also found that venture capital was shifting away from capital intensive hardware and materials towards software where they had opportunities more in-line with their usual approach.

"Venture Capital: The Wrong Model"

"Cleantech companies commercializing innovative science and engineering were especially unsuited to the VC investment model for four reasons. First, they were illiquid, tying up capital for longer than the 3-5 year time horizon preferred by VCs, because working out the kinks in new science is time consuming. Second, they were expensive to scale, often raising hundreds of millions of dollars to build factories, even while the fundamental technology was still being developed. Third, there was little room for error because these companies competed in commodity markets with razor-thin margins—against cheap silicon solar panels or abundant oil and gas—making it difficult to invest in R&D while also operating a lean manufacturing operation. Finally, the likely acquirers—utilities and industrial giants—were unlikely to acquire risky start-ups and averse to paying a premium for future growth prospects when they did invest. For most cleantech start-ups, this meant that the sale price couldn't offer the outsize returns investors needed. These factors conspired to cost VC investors hundreds of millions of dollars before learning whether their cleantech bets had a chance of success—an order of magnitude greater than the equivalent software experiment."

Benjamin Gaddy, Varun Sivaram, Francis O'Sullivan, "Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation", MIT Energy Initiative Working Paper, July 2016.

The low rates of U.S. private sector energy technology R&D investment described above are insufficient to meet U.S. energy security, economic, and environmental challenges, as described in the QTR main report Chapter 1 and Supplemental. To address these challenges, public RDD&D investment is necessary. In fact, public investments in energy supply and end-use technology RDD&D have demonstrated large overall returns in many cases, including direct economic returns, public health benefits, and others. For example, a retrospective analysis by the National Academies of Sciences, Engineering, and Medicine found direct economic returns of about 20 to 1 for public investment in energy efficiency RDD&D for the portfolio they indicated.[18] Subsequent analyses across a wide range of energy RDD&D investments have also generally found large economic and environmental returns.[19] Such public RDD&D investments have catalyzed important advances in energy supply and end-use technologies such as oil and gas well drilling technology and shale oil and gas technology and have contributed to U.S. competitiveness in these and many other energy technologies.[20] Other key countries have seen the large opportunity for energy and particularly clean energy technology and are pursuing it aggressively, as noted above.[21]

A competitive clean energy industry also depends on a strong private sector manufacturing base that is efficient in energy use, production processes, and costs. Without this base, the competitive advantage gained through technology innovation and the associated learning gained through manufacturing innovation may be compromised. In recent decades, the U.S. has lost ground in manufacturing overall. As a fraction of U.S. GDP, manufacturing declined from 27% in 1957 to about 12% by 2013[22], the overall U.S. trade deficit in manufactured products tallied $7.5 trillion from 2000 to 2013[23], and there have been large job losses[24] due to a variety of factors, with some recovery since the recession., all due to a variety of factors. In contrast, Germany, a country with a higher wage in manufacturing than the U.S. (an average hourly compensation of $45.79 versus $35.67 for the U.S.)[25], has retained manufacturing at 22% of GDP.[26] Continued innovation in clean energy RDD&D will be a critical component of U.S. competitiveness in the huge global markets for energy technology noted above, and the use of advanced energy technologies to provide clean, cost-effective, reliable energy supplies is a basic contributor to U.S. manufacturing competitiveness broadly.

To better understand the worldwide manufacturing landscape in clean energy technologies, DOE initiated competitiveness analyses of several important technology areas, as described below, which can provide insights on RDD&D approaches that may help strengthen U.S. clean energy manufacturing competitiveness. These DOE analyses, as well as a significant and growing body of work in the literature, identified a number of market challenges to the demonstration, scale-up, and adoption of clean energy technologies.[27,28] For example, China-based solar photovoltaic (PV) manufacturers gained an advantage due to several factors, including access to scale-up capital, the development of and access to a robust supply chain, and others.[29]

Manufacturers in Asia have dominated lithium ion battery (LIB) production. These incumbents have gained significant experience building batteries for consumer electronics applications. They benefit from an additional competitive advantage derived from a mature supply chain and an experienced workforce that supports the consumer electronics battery industry, and in some cases, some manufacturers may receive various other direct and indirect supports.[30] The focus here, however, is on techno-economic-related factors that may impact U.S. manufacturing competitiveness; issues in trade are the purview of the U.S. Department of Commerce, the United States Trade Representative, and others.

To date, DOE has completed the evaluation of the manufacturing competitiveness of five clean energy technologies. These analyses seek to better understand techno-economic drivers associated with manufacturing, but cannot capture all manufacturing competitiveness factors that may affect any given firm. These studies can reveal opportunities for RDD&D to strengthen manufacturing, lower labor cost disadvantages, and reduce environmental and other costs, and can also help evaluate where RDD&D might help improve technological aspects of competitiveness, but do not examine macroeconomic competitiveness factors such as currency exchange rates or explicit or implicit supports.[31]

The following briefly examines several measures of national competitiveness and energy technology issues, followed by a discussion of results and lessons-learned from the aforementioned competitiveness analyses. The remainder of this appendix reviews case studies of U.S. manufacturing competitiveness in photovoltaics (PV), wind turbine blades, lithium ion batteries (LIB), light-emitting diodes (LEDs), and carbon fiber, and it concludes with a brief discussion of RDD&D opportunities that might help strengthen U.S. manufacturing competitiveness in clean energy technology as well as further analysis that would help better understand these issues.

1.1 Competitiveness of Clean Energy Technologies in Global Markets

There are many definitions and measures of competitiveness (Table 1), but a common thread is the productivity with which a nation utilizes its resources, measured by the value of goods and services produced per unit of its resource investment.[32]

Table 1 Competitiveness: A sampling of definitions and measures.

Definitions and Measures of Competitiveness	Source
"The United States is competitive to the extent that firms operating in the U.S. can compete successfully in the global economy while supporting high and rising living standards for Americans."	Porter & Rivkin[33]
"America's international competitiveness is based on its capacity to innovate and manufacture new services and high-technology products. Furthermore, the fundamental measure of competitiveness is quality jobs."	Rising Above The Gathering Storm[34]
"Competitiveness is the capacity to be attractive to businesses and to simultaneously create a more widely prosperous society."	Thomas Kochan[35]
"Competitiveness in a sector can be defined as the "capacity to sustain growth through either increasing productivity or expanding employment."	McKinsey Global Institute[36]

Table 1 Competitiveness: A sampling of definitions and measures, continued.

Definitions and Measures of Competitiveness	Source
"Competitiveness is the set of institutions, policies, and factors that determine the level of productivity of a country."	World Economic Forum (WEF)[37]
"When countries are competitive, have a "set of institutions, policies and factors" that are conducive to productivity growth—then businesses are positioned to grow and be effective competitors against other domestic and foreign firms."	Department of Commerce[38]
"Competitiveness is measured by productivity. Productivity depends both on the value of a nation's products and services, measured by the prices they can command in open markets, and the efficiency with which these products can be produced. Productivity supports high wages, a strong currency, and attractive returns to capital—and with them a high standard of living."	The Global Competitiveness Report[39]
"The true definition of competitiveness is the ability of a region to export more in value added terms than it imports."	Atkinson[40]

The availability of low-cost energy supplies within the U.S. can contribute to a market advantage for U.S. manufacturers, especially those producing energy-intensive products, such as chemicals or forest products. For example, due to low-cost natural gas, the chemicals industry increased ethylene production capacity by approximately 33% between 2008 and 2012, and manufacturers in the U.S. were estimated to realize cost savings of more than $11 billion annually from lower feedstock and energy costs.[41] Increases in ethylene production also impact a diverse mix of downstream products, especially those with high embodied energy, such as adhesives, coatings, and plastics.

Manufacturing clean energy technologies for global markets offers large opportunities, as described above, with the IEA forecasting over $60 trillion to be invested in energy technology to 2040, and Bloomberg New Energy Finance tracking roughly $350 billion of investment in clean energy technology in 2015 (Figure 1). The IEA forecasts that global energy demand will grow about 37% by 2040, with most growth outside the Organization for Economic Cooperation and Development (OECD) (as seen in QTR Figure 1-5).[42]

1.2 Importance of Competitiveness in Clean Energy Manufacturing

The manufacturing sector makes an important contribution to the U.S. economy, accountable for about 12.3% of U.S. GDP (down from 27% in 1957).[43] The manufacturing sector supports U.S. economic growth and U.S. employment, providing well-paid jobs – 21% more than the average hourly compensation in private sector service industries.[44] The manufacturing sector also provides large employment multiplier effects: each manufacturing job supports an additional 1.6 jobs, and each advanced manufacturing job supports as many as 4.9 other jobs.[45] The manufacturing sector also contributes to the Nation's exports.[46]

On average, over 30% of U.S. manufacturing firms reported an innovation between 2008 and 2010 compared to only 13% for other U.S. businesses.[47] National Science Foundation data, among others, indicates that U.S. manufacturing firms demonstrate almost three times the rate of innovation as U.S. services firms.[48]

It has been well documented[49] that a competitive manufacturing sector contributes to sustained economic growth and energy security. Research is also finding that there are important feedbacks from manufacturing to the invention and discovery phases.[50] Manufacturing strength is tightly linked to the innovative potential and competitiveness of nations via R&D investments, and manufacturing accounts for 70% of U.S. private sector R&D investment.[51] Manufacturing also helps sustain and build an industrial commons, a term that describes the ecosystem of complex and enduring partnerships among manufacturers, universities, technical colleges, firms, research institutes, financing entities, and other links in the supply chain.[52] An example is Germany's industrial commons, which is comprised of suppliers, trade associations, industrial collective research consortia, industrial research centers, Fraunhofer Institutes, universities, industry collaboratives, and technical advisory committees.[53] Another example is the biomedical and drug research ecosystem concentrated in Boston stimulated by the regional knowledge networks comprised of universities, biotechnology firms, and related equipment and service providers.[54] A Supplemental Information appendix for Chapter 6, "*Public Private Consortia and Technology Transition Case Studies*", describes eight examples of U.S. public-private consortia and their technology transition activities.

The iterative innovation cycle between engineering and production is responsible for a range of breakthrough technologies. Research from the Massachusetts Institute of Technology's (MIT's) study "Production in the Innovation Economy (PIE)" has indicated firms are increasingly recognizing the connection of production with development and design.[55]

2. Manufacturing Competitiveness Analysis Case Studies

Recommendations to examine manufacturing competitiveness of U.S. clean energy technologies are not new; for example, the Congressional Office of Technology Assessment (OTA) recommended that Congress consider directing the Departments of Commerce and Energy to expand efforts to better understand specific strengths and weaknesses of the U.S. RDD&D system, including "… scale-up of manufacturing that captures significant economies-of-scale and learning."[56] While DOE included competitiveness factors in some technology evaluations in the past, it has recently initiated detailed manufacturing competitiveness analysis case studies to better inform assessments of clean energy technologies in a global context. Informed by technology- and process-based cost modelling, including that published in the literature,[57] the analysis methodology considers the costs of producing clean energy products in the U.S. compared to other nations. Other factors such as availability of investment capital, availability and requirements of low-cost labor, policy, ease of transportation, and supply chains are also considered. The methodology also includes an assessment of competitiveness factors, and how competitiveness is changing in domestic and global markets.[58,59] This type of manufacturing competitiveness analysis offers additional information to better inform RDD&D technology roadmaps and investments, and identifies efforts needed to address key barriers to U.S. clean energy manufacturing competitiveness in the global marketplace.

DOE has supported development of an analysis methodology and the conduct of manufacturing competitiveness analyses of several clean energy technologies with participation from leading industry experts.[60] These analyses include global supply chain and trade flow overviews, comparative cost assessments, strategic factors, and sensitivity analyses. The analyses include an assessment of published market studies, findings from detailed bottom-up cost modeling of different regional production scenarios, and an overview of qualitative factors that can influence factory location decisions. Cost models are based on detailed, bottom-up accounting of the total cost to manufacture; costs captured include all capital, fixed, and variable costs in each regional production scenario. The analyses identify key trends, cost considerations, and other market and policy developments that can influence manufacturing of clean energy technologies.[61] For DOE, the findings of these case studies on market challenges faced in these sectors can help inform future RDD&D funding.

2.1 Photovoltaics Case Study

Background

To analyze manufacturing costs, the National Renewable Energy Laboratory (NREL) developed a bottom-up model for wafer-based silicon PV. NREL validated this model with extensive anonymized industry feedback and review, and sought inputs on historical and future factory-location decisions from the perspective of a multinational corporation, with particular attention on China.[62] Through this approach, NREL quantified the conditions of China's PV price advantage during the study period, examined if these conditions could be reproduced elsewhere, and evaluated the role of innovative technology on potential future global manufacturing costs.[63] The analysis indicated that the price advantage of a China-based factory relative to a U.S.-based factory was driven mainly by China's ability to access scale-up capital (as opposed to the cost of capital) and to achieve large economies-of-scale and related advantages including the development of and access to a robust supply chain, contributing to a price advantage, at the time of the analysis, of \$0.22/W, as seen in Figure 3a.[64] The PV industry has advanced rapidly since this analysis. PV installations have nearly doubled since 2011, to 57 GW in 2015, and costs have dropped as shown in Figure 3b. However, there remain labor cost and supply chain—materials and equipment—advantages for China.

Figure 3a Comparison of U.S. and Chinese PV manufacturing costs in 2012. Based on NREL's bottom-up model for wafer-based silicon PV, indigenous factors, such as low labor cost, were not primary drivers of China's price advantage at the time of this study. The analysis assumes 2-GW per year Chinese PV factory (23%) and a 500-MW U.S. factory.[65]

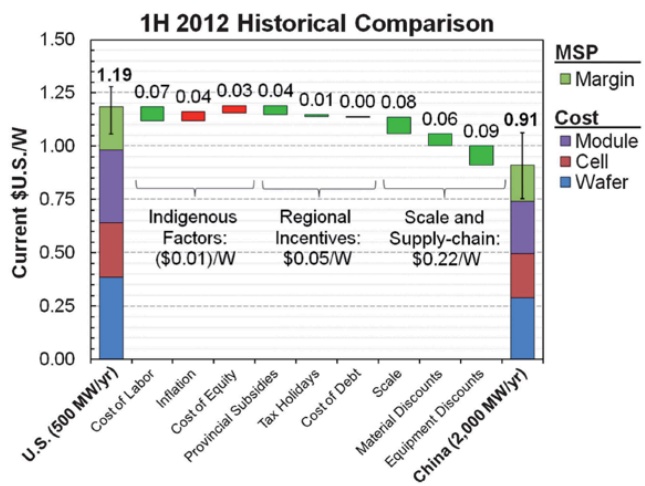


Figure 3b Manufacturing costs and sustainable prices for standard silicon PV modules as of August, 2015, showing the cost breakout by activity for major PV producing countries and regions. Note the dramatic price reductions from Figure 3a to Figure 3b.[66]

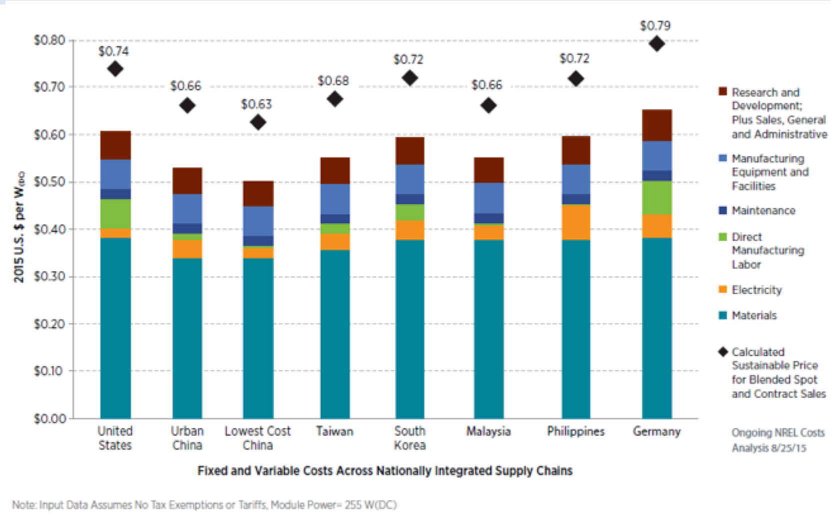
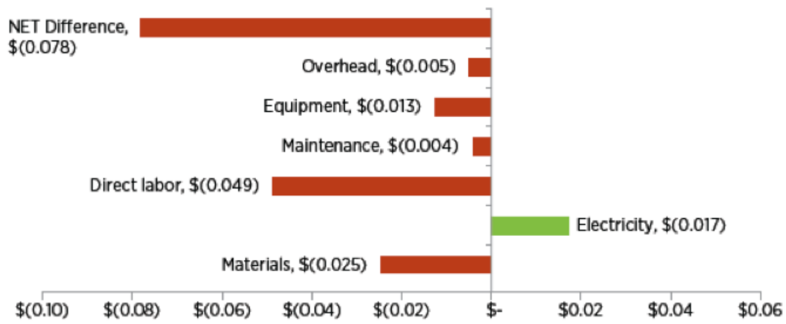


Figure 3c U.S. vs urban China silicon PV module production cost difference by factor, as determined by ongoing NREL cost analysis, 2015. The United States had an advantage with low cost electricity, but China had an advantage with low cost labor and supply chain cost advantages for materials and equipment.[67]



China and Taiwan accounted for about 40 GW of global PV module production in 2015, up from roughly 0.05 GW in 2004. Regional incentives, including provincial subsidies, tax holidays, and low-cost debt, may have been key enablers for this rapid scaling by Chinese PV manufacturers, and scale can be an important factor in driving costs down.[68] Of course, the price advantage could be disrupted by technology innovations, where U.S. firms could have an advantage, if the innovation could be manufactured and marketed at scale.[69] However, intense price competition from abroad, whether driven by manufacturing advantages or the lack of a level playing field, reduces margins and the ability of U.S. companies to invest in R&D. From 2009 through 2014, some 112 solar energy companies, primarily in the United States and the European Union, were identified as bankrupt, closed, or acquired by competitors under suboptimal conditions.[70] Without domestic manufacturing of solar PV, the benefits of scaling and development of robust supply chains are lost, and the accompanying manufacturing innovation of next generation solar technologies may be compromised.

Factors that impede private investment in clean energy technology RDD&D are summarized above and briefly examined in the QTR Chapter 1 SI appendix, "Additional Information on Energy Challenges". Public-private RDD&D support can then help address this private investment shortfall.[71] This is done with high leverage by requiring cost-sharing of the research, ensuring strong private engagement and investment; and the most important RDD&D can be identified and efficiently developed through competitive solicitations. Areas of RDD&D include advancing the basic materials and technologies, improving manufacturing processes, supporting independent performance validation, assisting manufacturing scale-up, addressing balance-of-system costs, and others, as detailed elsewhere.[72] These activities help drive costs down and make the clean energy benefits of PV more broadly available to the public; they may also help the competitiveness of U.S. manufacturing.

2.2 Wind Turbine Blades Case Study

Background

DOE conducted a manufacturing competitiveness analysis of wind turbine technology. Over the past decade, significant wind manufacturing capacity has been built in the United States to capture an increasing domestic market.[73] The cost model was developed by NREL in collaboration with experts from Sandia Laboratories, with validation by industry, to understand the factors impacting the manufacturing of wind turbine technology to meet this demand.[74] The cost model incorporated insights from past DOE-funded programs like the Wind Partnerships for Advanced Component Technology,[75] in addition to more recent National Laboratory led efforts such as the Clean Energy Manufacturing Analysis Center,[76] and other collaborative work with industry. The analysis also included an overview of qualitative factors that can influence factory location decisions.[77]

Findings

The analysis indicated that the manufacturing costs, as calculated at the factory gate, vary regionally, depending on the material and labor cost, with labor cost being the most significant factor. The cost of capital also influenced disparities in factory gate prices, but to a lesser extent than materials and labor. In addition, as the blade size increases, the labor costs became a smaller proportion of factory gate price while transportation considerations became more significant (Figure 4a).[78] As blade sizes have grown, so have the challenges for highway shipping and logistics due to the additional transport complications caused by tunnels, overpasses, and available turning radius areas (Figure 4b).[79]

Figure 4a Cost components of wind turbine blades as they are made larger. Note that the labor component becomes a smaller share of the total as blade length increases.[80]

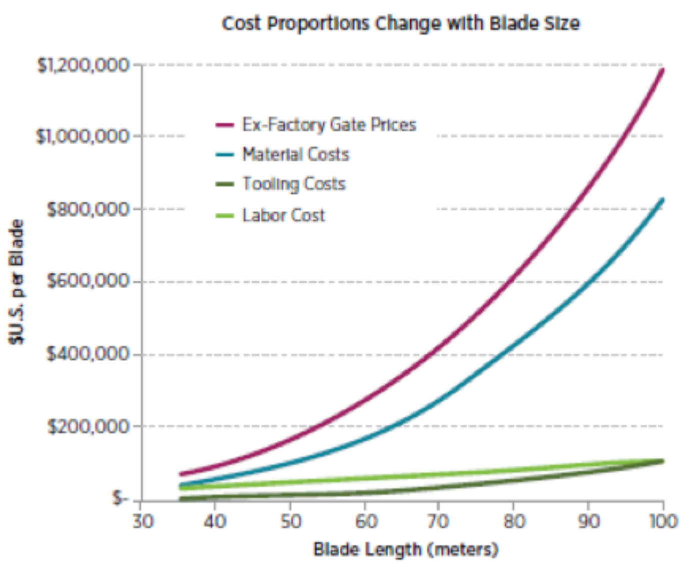
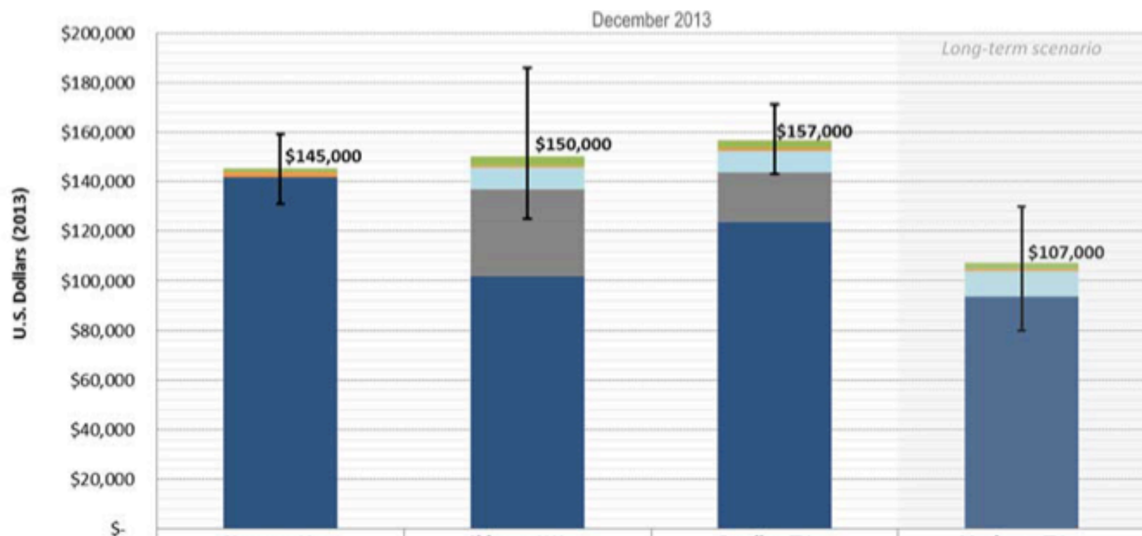


Figure 4b Transport of an 80-meter blade to a 7-MW test turbine in Scotland illustrates logistics challenges.[81]

For manufacturers of large wind turbine components such as the wind blade and towers, proximity to end markets is a key consideration, as evidenced by the influence of manufacturing costs and transportation on factory location decisions, as indicated by the scenario analysis shown in Figure 5. It is worth noting that the analysis found that Mexico's close proximity to the U.S. and good rail connections could reduce transport costs compared to China and Brazil, leaving it with a potential labor cost advantage. A range of qualitative factors, like policy uncertainty and ease of doing business, also influences decision-making.[82]

Figure 5 Analysis indicates that long-distance shipping costs could exceed benefits of manufacturing in lower cost labor regions for deployment locations in the U.S. mid-west. Mexico's proximity to the U.S. and good transportation connections largely eliminated shipping costs in the scenario analysis, leaving a labor cost advantage.[83]



	Newton, IA to Massena, IA	China to WA to Massena, IA	Brazil to TX to Massena, IA	Mexico to TX to Massena, IA
Total Handling Costs	$1,500	$3,500	$3,500	$2,500
Trucking	$1,980	$900	$900	$900
Rail	$0	$8,750	$8,750	$10,063
Overseas Shipping	$0	$35,000	$20,000	$0
Ex-factory Gate Price	$142,000	$102,000	$124,000	$94,000
TOTAL (rounded)	$145,000	$150,000	$157,000	$107,000

Current DOE Activities to Increase U.S. Wind Turbine Blade Competitiveness

In order to meet the domestic demand for clean wind power[84] with its corresponding public benefits, DOE identified approaches that would streamline the blade manufacturing process for conventional wind turbines.[85] Some examples of innovations include new component handling systems to aid in the installation of large, cumbersome parts and 3D-projected blueprints that reduce the time for workers to identify the correct location for the installation of fixtures, and connecting hardware approaches that reduced costs and improved time-to-market. These and other advances also enable the construction of longer blades and taller towers, which can allow the cost-competitive placement of wind turbines in areas with lower wind speeds but closer to large urban load centers, with corresponding savings by avoiding the cost and difficulty of installing long distance power transmission lines. These advantages provide substantial public benefits, and have the further advantage of enhancing the competitiveness of the U.S. wind-energy manufacturing sector.

2.3 Lithium Ion Batteries Case Study[86]

Background

DOE had a competitiveness analysis of lithium-ion batteries (LIBs) technology done by leading national labs, industry, and technology experts.[87] The analysis centered on a single LIB technology that couples lithium-nickel-manganese-cobalt (NMC) cathodes, with graphite anodes (Gr) and carbonate electrolytes. The NMC-Gr combination is representative of LIBs being manufactured for the electric vehicles (EV) industry today.

The analysis included an assessment of published market studies, findings from bottom-up cost modeling of regional production scenarios, with validation by industry and technology experts, and an overview of qualitative factors that can influence factory decisions.

Findings

Manufacturers in Asia have historically dominated LIB production. The U.S. had 17% of the global LIB manufacturing capacity for automotive applications at the end of 2014 and 7% of total global LIB manufacturing capacity, while China, Korea, and Japan accounted for nearly all the rest of the global LIB manufacturing capacity (Table 2).[88] China, Japan, and Korea have gained significant experience building batteries for consumer electronics applications. The manufacturing processes developed for the consumer products are directly applicable to EVs. However, it is important to note that LIBs for the consumer market predominantly contain lithium-cobalt oxide as the cathode material, whereas the automotive industry has preferred alternative cathode materials due to the high cost of cobalt and safety-related considerations.[89] The experience, mature supply chain, and existing workforce from the consumer electronics battery industry can largely be applied to automotive specific LIB production using these alternative cathode materials. In contrast, the U.S. LIB supply chain is less mature,[90] and most U.S. cell and battery plant operators are relatively new to the industry.[91] In an effort to increase factory utilization, U.S. LIB capacity is targeting both the emerging automotive market and stationary energy storage for electric grid applications.

Table 2 Manufacturing Capacity for Lithium-Ion Batteries Cells by Country/Region (2014)

	Manufacturing Capacity for Lithium-Ion Batteries Cells by Country/Region (2014)*				LIB Manufacturing Capacity (MWh) for Automobiles, Plant Status, 2016*			
	Total LIB Manufacturing Capacity (MWh)	Share of Total Capacity (%)	Automotive LIB Manufacturing Capacity (MWh)	Share of Automotive Capacity (%)	Fully Commiss-ioned	Partially Commiss-ioned	Under Con-struction	Announced
China	39,010	51	11,240	41	11,152	3,038	16,244	19,246
Japan	11,978	16	5,750	21	13,623	--	--	--
Korea	16,059	21	4,600	17	6,570	--	--	--
U.S.	4,970	7	4,600	17	8,925	8,750	26,250	150
EU	1,798	2	1,300	5	--	--	---	--
Rest of World	2,440	3	0	0	3,380	--	--	120
Total	76,255	100	27,490	100	43,660	11,788	42,494	19,516

*Data Source: Bloomberg New Energy finance (2014)
*Data Source: Bloomberg New Energy finance Desktop Portal, 201692

Migration of LIB Manufacturing

Asia's rise as a leader in LIB production is built on the consumer electronics industry shift of labor-intensive low-margin production to Asia.[93] Battery companies and suppliers to the consumer electronics industry (NiCad, NiMH) then located to be close to their corporate customers. The disruptive lithium ion suppliers followed and displaced the incumbent battery companies.

The concentration of LIB cell and upstream processed materials suppliers in Japan grew from sustained investments in LIB technology by both consumer electronics companies in the 1990s that were bolstered by Japanese government support in the form of R&D and low cost capital to establish manufacturing plants. These investments were made despite the long commercialization cycle of LIB technologies, and the low returns on the LIB business itself because the technology enabled competitive advantages in portable consumer electronics end applications – the primary Japanese corporate investors in the technology were the consumer electronics companies themselves.[94] Korea and China followed Japan's lead in investing in LIB cell and battery pack production for consumer electronics. Korea's concentration of upstream materials suppliers is a result of more recent governmental and industry efforts (beginning in the 2000s) to build up this portion of the supply chain within Korea.[95,96]

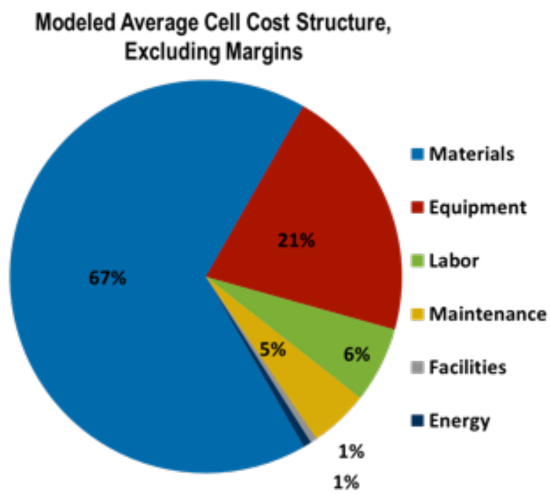
The analysis segmented LIB production cost into three categories: processed materials (representing 45% of battery pack cost for a 40-mile range plug-in hybrid electric vehicle (PHEV) and up to 70% of cost for a 300-mile range EV), electrode and cell manufacturing, and pack integration and assembly. The U.S. is well positioned in the pack integration and assembly segment given that this activity will either be conducted by (or near) the vehicle manufacturer.

Quantifiable drivers of competitiveness for electrode and cell production can be generalized into two categories: regional cost drivers and firm-specific characteristics. The major regional cost factors influencing location decisions include labor, facilities (including capital cost), and materials costs. These costs tend to be lower in China and Korea than in the U.S.

In the near term, firm-specific characteristics influencing costs favor incumbent companies that have gained experience building LIB cells for consumer electronics applications and have existing manufacturing plants that can be redirected to manufacture EV batteries. Current consumer electronics cell format is focused on producing small 18650 cylindrical cells or small flat prismatic cells having a capacity of 0.5-3 amp-hours. However, EV manufacturers prefer much larger prismatic type cells (20-60 amp-hours) in order to increase the ratio of active- to non-active materials.[97]

Cost analysis indicates that materials costs dominate the total cell cost (Figure 6). For a given electrochemistry, materials costs tend to be a function of cell manufacturing company characteristics, in that pricing is determined in part by purchasing volume, as well as the nature of the relationships between LIB manufacturers and their suppliers. Currently, Asian manufacturers tend to have well established, close relationships with regionally co-located input materials suppliers that appear to confer pricing advantage beyond volume-based discounts. Analysis indicates that, after U.S. manufacturers develop trusted relationships based on favorable experience with suppliers such that material prices become equalized with materials cost leaders like Korea and China, regional factors such as labor and facility cost will become competitive factors that favor lower cost regions. U.S. advantage in reduced shipping costs can offset some of the Asian labor and facility advantages. U.S.-based manufacturing also faces difficult challenges due to relative immaturity of the U.S. supply chain and market participants.[98]

Figure 6 Materials are the largest single cost component for LIB cells. Equipment and labor are the next largest cost components.[99]



These existing relationships will be less important as new lithium ion or other electrochemistries are developed that have the potential to significantly reduce the cost of EV batteries and increase market penetration of these vehicles. A large potential impact could result from new manufacturing technologies, and U.S.-based manufacturing advances in the automotive battery manufacturing sector in the U.S. would likely impact the consumer electronics battery manufacturing. As the unit cost, energy density, and power density specifications come in line with the EV needs, the gains made in manufacturing electric vehicle batteries become directly recoverable in producing batteries for consumer electronics.

Current DOE Activities to Increase U.S. LIB Competitiveness

To capture the national energy security and economic benefits of reducing our oil dependence, as well as the corresponding environmental benefits, advances are needed in battery technology to significantly reduce the cost of EVs and increase the market penetration of these vehicles (QTR, Chapter 8). The potential RDD&D opportunities to realize these advances may also help U.S.-based automotive battery manufacturing competitiveness. The potential impacts of these RDD&D opportunities on lowering the costs of EVs and their associated potential benefits on future U.S. competitiveness in this area include:

- **Advanced materials technologies** – these will offset some advantages currently held by established foreign producers. DOE is currently supporting R&D in a number of key battery technology opportunities.
- **Advanced manufacturing processes** – new automotive battery designs and new manufacturing processes can allow U.S. manufacturers to enter markets that have been the domain of Asian manufacturers who have advantages in small consumer electronics batteries, and offer the potential to eclipse companies. Process scale-up R&D can help bridge the gap between small-scale laboratory research and high-volume battery manufacturing, and lead to progress in the development, validation, and commercialization of advanced battery chemistries. In order to increase the yield of LIB production, DOE has efforts underway focused on real-time metrology to enable rapid quality control/quality assurance (QC/QA) of LIB raw materials and fabricated components, as well as a cost effective R&D tool for next generation LIB chemistry.
- **High level of automation** – large-scale LIB cell manufacturing plants have a high degree of automation due to the manufacturing precision and quality required to meet the durability, life, and safety requirements of EV components. This reduces the impact of labor cost differences to the point where shipping costs can offset labor costs differences.
- **Market Scale-up** – although beyond DOE's purview, this is critical for success of LIB technology. Factory utilization is a function of market demand and a key driver of battery manufacturing cost. U.S.

manufacturers need an expanding market for automotive batteries in order to scale-up production to get economies-of-scale and to be able to drive down the learning curve.

Tesla is currently constructing and has started production at a large-scale battery manufacturing facility in Nevada that can potentially demonstrate that a manufacturing facility in the U.S. can be competitive through economies-of-scale and learning, and technology advancements. Tesla expects a 30% battery cost reduction attributable to economies-of-scale at this factory.[100] Recent studies indicate that the learning rate (the cost reduction following a cumulative doubling of production) is between 6% and 9%, in line with earlier studies on vehicle battery technology.

2.4 Light Emitting Diodes Case Study

Background

DOE has been assessing the competitiveness of Light Emitting Diode (LED) manufacturers responsible for producing sapphire and silicon-carbide (SiC) substrates, LED die, LED packages, and LED lamps/luminaires. U.S. LED manufacturers have remained competitive by integrating across the value chain to maximize their margins. Many of these manufacturers started as materials companies, developing strong LED die and package manufacturing businesses. They then expanded their business model to include lamp and luminaire manufacturing, and more recently, control systems. This puts them in direct competition with other vertically integrated solid-state lighting (SSL) manufacturers such as Philips and OSRAM. The move to higher value-added products has tended to offset the declining profit margins from the die and packages, and has produced significant revenue growth.[101] Increasingly intense offshore competition with low labor cost high-volume production, however, is forcing U.S. manufacturers to move to higher-end products.[102]

Findings

The benefits of LED lighting include very long lifetimes, potentially very high efficiencies, and lifetime financial savings for consumers. Manufacturers, however, are most concerned about minimizing price even if it means producing LEDs with lower efficiencies. DOE's focus has been to partner with manufacturers to achieve higher efficiencies and improved color through cost-shared R&D, and drive costs down in order to enable larger market deployment.[103]

Manufacturing efficiency can impact competitiveness in emerging markets. LED adoption in the developed world remains sensitive to price, and costs can significantly limit uptake in emerging markets. Companies can employ many strategies to grow market share in emerging markets, including establishing effective distribution channels and introducing local manufacturing facilities, but low cost is likely to be the most important factor for the individual purchasing the product with efficiency and the associated public benefits difficult for the individual to ascertain or evaluate and therefore of much less concern in the investment decision.[104]

Current DOE Activities to Increase U.S. SSL Competitiveness

Since launching its SSL manufacturing initiative in 2009, DOE has competitively awarded 17 SSL manufacturing R&D projects, covering much of the value chain of SSL production, including process improvements, manufacturing equipment, materials, testing, and designs for low cost. Work has also included flexible manufacturing of state-of-the-art LED modules, light engines, and luminaires, as well as development of manufacturing processes for practical OLED (organic LED) panels. Other projects included improving the metal organic chemical vapor deposition (MOCVD) epitaxial tools, developing wafer inspection equipment, and improving phosphor deposition processes.[105] These variously focus on achieving higher efficiencies, improved color, manufacturing scale-up, and lower costs to realize the largest possible public benefit. At the same time, this RDD&D can enhance U.S. competitiveness in the global LED industry.

2.5 Carbon Fibers Case Study[106]

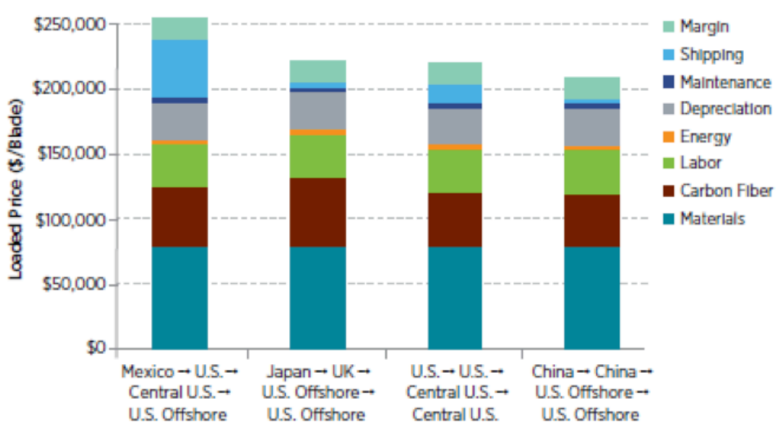
Background

DOE's Oak Ridge National Laboratory (ORNL) is currently conducting a competitiveness analysis of carbon fiber and its application in analysis of carbon fiber and its application in composites manufactured with carbon fiber reinforced plastics (CFRPs) for the wind energy, compressed gas storage, aerospace, and automotive industries.[107] For each application, the analysis considers competitiveness barriers, current and anticipated supply chains, and factors that influence manufacturing location decisions. The goal is to identify key opportunities in the CFRP supply chain where the U.S. can achieve or maintain a competitive advantage if CFRPs are to be successfully developed to meet future demands.[108]

Findings – CFRPs for Wind Turbine Blades

For wind energy, longer blades on taller towers offer access to winds further above the earth, which provide higher, steadier wind speeds. This is important to enable use of wind turbines in areas with otherwise lower wind-speeds that are closer to large urban loads in the U.S., as noted above. Higher stiffness resulting from the use of carbon fibers motivates the use of CFRPs for wind turbine blades. The lighter weight of CFRPs reduces weight on the turbine hub and tower. In addition to technical challenges related to manufacturing comparatively larger-tow[109] industrial grade carbon fibers for better compressive strength, cost-effectiveness is a major barrier to U.S. market growth of CFRPs for wind energy. With materials, including carbon fiber, contributing the largest share of total wind turbine blade cost, as shown in Figure 7, pathways to low-cost carbon fiber as well as alternative high-throughput manufacturing methods, such as an automated 3-D weaving and fiber replacement processes, can improve cost-effectiveness.[110]

Figure 7 Cost of manufacturing a 61.5 meter carbon fiber spar cap wind turbine blade by supply chain locations, as modeled by CEMAC.[111]



Findings – CFRPs for Aerospace Applications

The aerospace industry is a mature field of CFRP applications and is the largest source of carbon fiber demand by monetary value in addition to being a major source of demand by weight today. A large share of aerospace carbon fiber demand is driven by premier wide-body jet projects by Boeing and Airbus.[112] CFRP is also important for military aerospace applications. Competitiveness in aerospace-grade carbon fiber manufacturing does not require collocation with manufacturers of carbon fiber based aerospace components due to an insignificant share of shipping cost to carbon fiber cost. However, as carbon fiber composites are used in larger parts and in greater volumes, new manufacturing techniques will be required that increase the pace and efficiency of production.

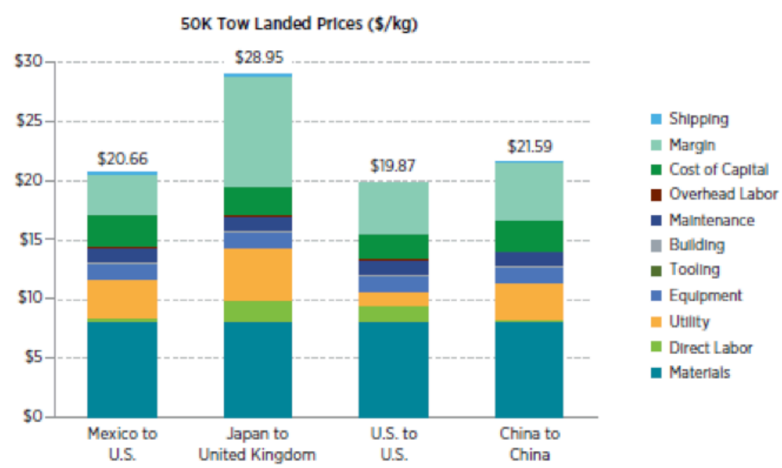
Findings – CFRPs for Automobile Applications

Due to high costs, long manufacturing cycle times, and uncertain supply chains, carbon fiber usage by the automotive industry has largely remained confined to ultra-expensive, low production volume models.[113] CFRPs are now attracting much more attention by the automotive industry as lightweighting becomes an increasingly important pathway to achieve corporate average fuel economy (CAFE) standards. However, before CFRPs can achieve widespread adoption, very efficient, fast, and cost-effective manufacturing operations need to be developed to meet the needs of automotive production. For example, CFRP parts require relatively long manufacturing cycle times compared to conventional steel stamping operations. One option is the use of resin transfer molding (RTM) processes, but one bottleneck is in the labor-intensive and costly dry fiber preform step that is required before the resin matrix material is injected into the mold. RDD&D opportunities include new manufacturing processes such as high-pressure resin transfer molding (HPRTM) and carbon fiber reinforced thermoplastics (CFRTP) that have the potential to reduce cycle time, labor requirements, and costs.

Findings – Overall U.S. CFRP Competitiveness Assessment

The regional competitiveness analyses show the U.S. is currently in a competitive position for CFRPs for the clean energy market sectors. A significantly smaller share of material shipping cost, as compared to the final product cost, has contributed to a worldwide supply chain distribution in the industry today. Factors contributing to U.S. competitiveness in carbon fiber production include, for example, low utility costs (that offset higher U.S. labor costs) compared to those in China or Japan (Figure 8). For wind energy, proximity to the location of deployment may affect future final-product manufacturing locations as projected future wind energy generation requires large blades and transportation requirements would present cost and logistical challenges, as discussed earlier. Factors such as matured supply chains, an established workforce/labor pool, and regional (tax) incentives have influenced regional competitiveness to date. Zoltek, one of the largest carbon fiber suppliers to the wind energy industry, has locations in Hungary, Mexico, and the U.S., and supplies worldwide to meet the demands of GE Energy, Vestas, and Gamesa today.[114]

Figure 8 Cost of manufacturing 50K Tow carbon fiber, as modeled by CEMAC and Oak Ridge National Laboratory.[115]



Activities to Increase U.S. Carbon Fiber Competitiveness

U.S. competitiveness has been bolstered by its advantage in skilled production labor, engineering expertise, low energy prices, and by long-term contracts with specific end users, but still faces substantial challenges requiring further RDD&D to lower costs and improve performance, and to further scale-up production to realize economies of scale and learning, but facing the chicken-and-egg problem of having high costs with limited volume but needing low costs to get high volume.[116] To strengthen U.S. competitiveness in carbon fiber manufacturing through RDD&D activities, DOE launched a Clean Energy Manufacturing Innovation Institute for Composites Materials and Structures to address the challenges faced by this industry.[117]

2.6 Key Lessons Learned from the Clean Energy Manufacturing Competitiveness Analyses

These case studies highlight market challenges and competitiveness factors influencing manufacturing location decisions, which can provide insight for strategic investments in RDD&D of clean energy technologies. This can help decision-makers understand the overall situation facing U.S. manufacturers in global markets, beyond what any one individual manufacturer, especially a small, innovative new company, can potentially do by itself. Specific lessons learned from the PV and LIB competitiveness studies emphasize the critical roles that an industrial commons, mature supply chain, and access to capital serve for a technology to rapidly scale-up and achieve economies-of-scale.[118] In addition, most of the five case studies note that scale-up financing for production is a particular problem for clean energy technologies.[119] These studies also underscore the importance of a skilled, robust workforce. All the case studies highlight the need for advanced manufacturing technology to enable rapid scale-up and drive down production costs, while increasing the manufacturing efficiency (in both energy use and production processes). It is also necessary to pay attention to materials and component supply chain development, including reliance on foreign sources for specific materials that are in short supply in the U.S.[120] and the various associated risks. Finally, there is a need for general awareness of clean energy RDD&D activities around the world to identify important areas for development, opportunities for collaboration, and competitiveness threats. It is important to note that the case studies presented in this Supplemental Information appendix represent a limited set from a large range of energy technologies, including clean energy and energy efficiency technologies, as well as technologies that cut across many sectors, (see Technology Assessment appendices to QTR Chapters 3 through 8) that could benefit from similar market and competitiveness analyses. Additional studies could provide further insight into factors that affect U.S. energy technology competitiveness.

3. Representative Manufacturing Competitiveness Factors Needing Further Evaluation

The manufacturing competitiveness challenges illuminated by the analyses described above can provide useful factors for consideration as strategies are developed for RDD&D. However, insights gained from analyses have also revealed information gaps needed to better understand the opportunities for clean energy technologies in global markets. While analyses to date have considered emerging markets, supply chain, labor, critical materials, industrial commons, economies-of-scale, and time-to-market, future manufacturing competitiveness analyses could benefit from an evaluation of additional factors, such as:

- **Global Benefits Analysis.** The analysis of U.S.-based production in domestic and global markets to identify risks and RDD&D opportunities that contribute to domestic benefits as well as provide foundational capabilities for competing in global markets while also providing benefits for those countries.
- **Technology/Labor Dynamic.** Low-cost labor has often been argued as a primary factor driving U.S. companies to transfer large-volume, low-margin manufacturing to offshore producers and focus instead on high-end, high-margin production. This strategy, however, has not worked well in some cases, such as consumer electronics.[121] One challenge is that, having honed the manufacturing processes, offshore producers are then able to climb the value chain to higher-end products; U.S. producers are then hard-pressed to push back, given that they may have lost legacy manufacturing capabilities and supply chains, and did not adequately develop new manufacturing capabilities to compete against low-margin, high volume competitors.[122] The analyses described above found low cost labor was an issue in some cases but not in others. Regardless, clean energy technologies must reduce costs to be competitive in U.S. markets if they are to broadly penetrate markets to provide large public benefits. This requires a better understanding of the dynamics of technology and labor, such as the impacts of lower manufacturing labor costs through RDD&D on flexible automation, design for manufacturing, and improved

metrology to improve yield and quality, among others, with an emphasis on platform technologies that have the potential for pervasive impacts on manufacturing.[123]

- **Supply Chain Constraints.** Some clean energy technologies may depend on critical materials that are at risk of being constrained by supply chain pinch points. This motivates an R&D strategy focused on improved capture and use of critical materials, including those now produced as side products such as tellurium which is a side product of copper mining, more efficient use of critical materials (e.g., thinner layers of CdTe in solar cells), and elimination of materials that are subject to supply disruptions and development of substitute materials, including through computational materials development (see QTR Chapter 6 and Chapter 9).[124] The Critical Materials Institute (CMI) Energy Innovation Hub at Ames National Laboratory is targeting these issues.[125]
- **Industrial Commons.** Offshoring has eroded the industrial commons that enable the U.S. to manufacture advanced technology products.[126] These industrial commons include not just suppliers of advanced materials, production equipment, and components, but also R&D knowhow, advanced process development, engineering skills, and manufacturing competencies, as illustrated in the LIB analysis. These are largely outside the purview of any single company. A recent MIT study notes that in new technologies, such as those in energy, biotechnology, and batteries, there must be a closer integration between research, development, design, product definition, and production.[127] RDD&D strategies to advance clean energy technologies will need to consider approaches to strengthen this industrial commons, and drive down the production cost while increasing manufacturing efficiency.[128]
- **Economies-of-Scale.** The PV case study underscores the importance of economies-of-scale, economies-of-learning, and supply chain efficiencies.[129] This suggests the need for further analysis of these issues on cost reductions, and on RDD&D that enables such cost reductions. In addition, the analysis highlighted the impact of economies-of-scale to enable development of specialized equipment for high-throughput, high-performance manufacturing, as well as the location where the economies-of-scale are to be developed. For example, large single-piece wind turbines blades are better suited to local production because of high transportation costs,[130] whereas segmented blades produced in high quantity may benefit from centralized production. Finally, analysis is needed on the extent to which scale is important in generating larger revenues that can be reinvested in RDD&D.[131]
- **Time-to-Market.** Reducing the time required to get a product to market is important in domestic as well as international markets. It may be possible to reduce the costs of demonstrations and scale-up by utilizing advanced simulations, and to utilize 3D printing technology, for example, to replace some production steps. Some of these may be foundational RDD&D needs across industry sectors. Many small- to mid-size companies may not have the resources to support dedicated efforts in these capabilities and may find access to such capabilities of particular value.[132]
- **Emerging Markets.** As seen in QTR Chapter 1 Figure 1-5, energy technology markets will increasingly be outside the OECD countries. As many clean energy technologies can realize significant economies-of-scale and economies of learning, the extent to which U.S. producers can remain competitive without being significant players in these international markets is an open question. Opportunities span energy supply and end-use technologies in every sector.[133] Particular conditions need to be considered in some countries, such as the lack of infrastructure, lack of operations and maintenance capabilities, wide voltage and frequency excursions on the grid, and much more.[134] Particular opportunities include the development of applications that can generate income for users in rural and outlying urban areas.[135] Analysis of transportation and supply chain logistics costs also needs to be incorporated. Factors like these are currently not addressed in competitiveness analysis.

In totality, these evaluation factors will contribute to an understanding of DOE's impact on the global value chain[136] of U.S. clean energy technology; in turn, this may be useful to help inform decisions that may strengthen the future manufacturing competitiveness of the U.S. clean energy industry.

4. Strengthening Clean Energy Technology & Manufacturing[137]

DOE supports clean energy manufacturing-related RDD&D in partnership with industry, universities, national laboratories, non-profit organizations, and others through a variety of mechanisms, particularly competitively awarded public-private cost-shared awards in various forms. This manufacturing-related RDD&D supports national goals of advancing clean energy technology and manufacturing to realize security, economic, and environmental benefits for the American public, while also contributing to U.S. manufacturing competitiveness through some of the factors listed in the earlier section. These efforts include the following:

- **Engaging with industry, academia, national laboratories, and others.** The Clean Energy Manufacturing Initiative (CEMI) co-hosted under a partnership[138] with the Council on Competitiveness three national and four regional summits in the past several years as well as a number of fora focused on specific topics. These activities have involved nearly 2,000 leaders in manufacturing RDD&D from industry, academia, national laboratories, government, and others. This engagement serves a critical role by tapping the extensive knowledge of the broad community to help identify key clean energy manufacturing challenges, opportunities, and potential pathways forward.
- **Establishing Clean Energy Manufacturing Innovation Institutes.**[140] A Federal government-wide effort was launched in 2011 by the President to rebuild U.S. manufacturing competitiveness—Manufacturing USA, the National Network for Manufacturing Innovation (NNMI).[141] In support of NNMI, DOE has established Manufacturing Innovation Institutes to focus on technology development, address challenges of manufacturing scale-up, and help develop the next-generation workforce.[142] These Institutes include the Next Generation Power Electronics National Manufacturing Innovation Institute—PowerAmerica,[143] the Institute for Advanced Composites Manufacturing Innovation,[144] and the Smart Manufacturing Innovation Institute.[145] Further, DOE launched the Rapid Advancement in Process Intensification Deployment (RAPID) Manufacturing Institute Modular Chemical Process Intensification Institute[146] in December 2016, and launched the Recycling and Remanufacturing Innovation Institute (Reducing Embodied Energy and Decreasing Emissions—REMADE)[147] in January, 2017. DOE is also collaborating with other agency-led NNMIs, such as the Department of Defense's (DOD's) National Additive Manufacturing Innovation Institute—America Makes,[148] Lightweight Innovations for Tomorrow—LIFT,[149] and the Digital Manufacturing and Design Innovation (DMDI) Institute.[150]
- **Accelerating Materials Development.** Discovery, development, validation, scale-up, and other steps in commercializing new materials at scale typically takes 10 to 20 years or more and is very expensive. To address this challenge, the Administration launched the Materials Genome Initiative in 2011 to cut this time in half or less and to do the work at a much lower cost.[151] The Administration also launched the Advanced Manufacturing Partnership 2.0 (AMP 2.0).[152] In support of these efforts, among other activities described here, DOE has launched the Energy Materials Network (EMN) to substantially accelerate and reduce the cost of developing new, affordable, high-performance materials for clean energy technologies.[153] Current consortia include: the Electrocatalysis Consortium (ElectroCat)[154] to develop high performance fuel cells that do not require expensive platinum group metals; the Caloric Materials Consortium (CaloriCool)[155] to develop solid state materials to provide cooling in air conditioners and refrigerators; and the Lightweight Materials National Lab Consortium (LightMat)[156] to develop lightweight materials for vehicles and other applications. Additional consortia are being examined, such as for solar module materials.[157]
- **Aiding Technology Innovation and Scale-up with DOE.** Some applied energy offices support the establishment of shared facilities for manufacturing R&D and demonstration or pilot facilities for demonstrating manufacturing processes at scale.[158] Examples include the Critical Materials Institute (CMI) Energy Innovation Hub,[159] the Vehicle Systems Integration Laboratory (VSI),[160] Oak Ridge National Laboratory's (ORNL's) Manufacturing Demonstration Facility (see below),[161] DOE's Materials

Engineering Research Facility (MERF),[162] and the Joint Center for Energy Storage Research.[163] DOE is also a partner in the U.S. Advanced Battery Consortium (USABC).[164]

- **Demonstrating Manufacturing.** DOE has established Manufacturing Demonstration Facilities (MDFs) to leverage national lab capabilities to support the demonstration of new manufacturing processes, reduce technical risks, and encourage collaborations. To support entrepreneurs that are moving new inventions into manufactured products, DOE has launched the Build4Scale initiative to provide training on manufacturing fundamentals such as selecting materials, designing for assembly, selecting production processes, and working with production partners.[165] DOE has a number of the top supercomputers in the world, so DOE's Lawrence Livermore National Laboratory is leading the effort to use supercomputers to model, simulate, and analyze key industrial products and processes in order to sharply reduce the costs of new clean energy technologies and the time required to get them to market.[166] An MDF at Oak Ridge National Laboratory is focused on additive manufacturing, carbon fiber, and other manufacturing innovations.[167]
- **Assisting Manufacturing.** DOE has several significant clean energy manufacturing assistance programs. These efforts include Loan Programs;[168] and technical assistance to manufacturers to facilitate the commercialization, acceptance, and adoption of energy efficiency in manufacturing—examples include the Superior Energy Performance® (SEP™)[169] Program, Technology Assistance Partnerships (TAPs),[170] Better Plants Program,[171] and Industrial Assessment Centers.[172] Assistance programs also include the Small Business Vouchers program to provide assistance using National Laboratory resources;[173] and others.
- **Collaborating in Partnerships.** In addition, DOE collaborates with the U.S. DRIVE partnership on hydrogen and fuel cell R&D, electrochemical energy storage, and advanced powertrains[174] for passenger vehicles and with the 21st Century Truck Partnership on heavy-duty engines for commercial vehicles. There is also active collaboration on combustion research as well as hydrogen and fuel cell research and manufacturing with several countries through the IEA.
- **Accelerating Technology Transition to Markets.** DOE's technology-to-market efforts are aimed at enhancing the industrial impact of the national laboratories. Activities include DOE's National Clean Energy Business Plan Competition (DOE NCEBPC),[175] National Incubator Initiative for Clean Energy, and Small Business Innovation Research/Small Business Technology Transfer Programs (SBIR/STTR).[176] DOE is also facilitating training of researchers from national laboratories to transition high-impact national laboratory-invented technologies into the marketplace. Efforts to help address this include the Lab-Embedded Entrepreneurship Program to help national lab researchers advance technologies towards commercial systems,[177] and the Technologies in Residence Program.[178] Within this Program are the following three centers: Cyclotron Road at Lawrence Berkeley National Laboratory,[179] Chain Reaction Innovations (CRI) at Argonne National Laboratory,[180] and Innovation Crossroads at Oak Ridge National Laboratory.[181]

All of these examples illustrate strategies to strengthen U.S. competitiveness in clean energy manufacturing to lower costs, improve performance, and help enable U.S. companies to be competitive globally, while also providing job, income, and other benefits at home.

5. Conclusion

Analyses of U.S.-based manufacturing competitiveness of select clean energy technologies (Section 2) have revealed useful insights for factors including emerging markets, supply chains, labor, industrial commons, economies-of-scale, and time-to-market, among others. Equally important gaps have been identified that need further evaluation (Section 3). These analyses and insights can help inform U.S. public and private understanding of the global manufacturing landscape, the RDD&D required to strengthen the manufacturing competitiveness of U.S. clean energy technologies for domestic and global markets, and strategies for strengthening the U.S. position. Some of these factors and areas for further analysis are listed in Table 3.

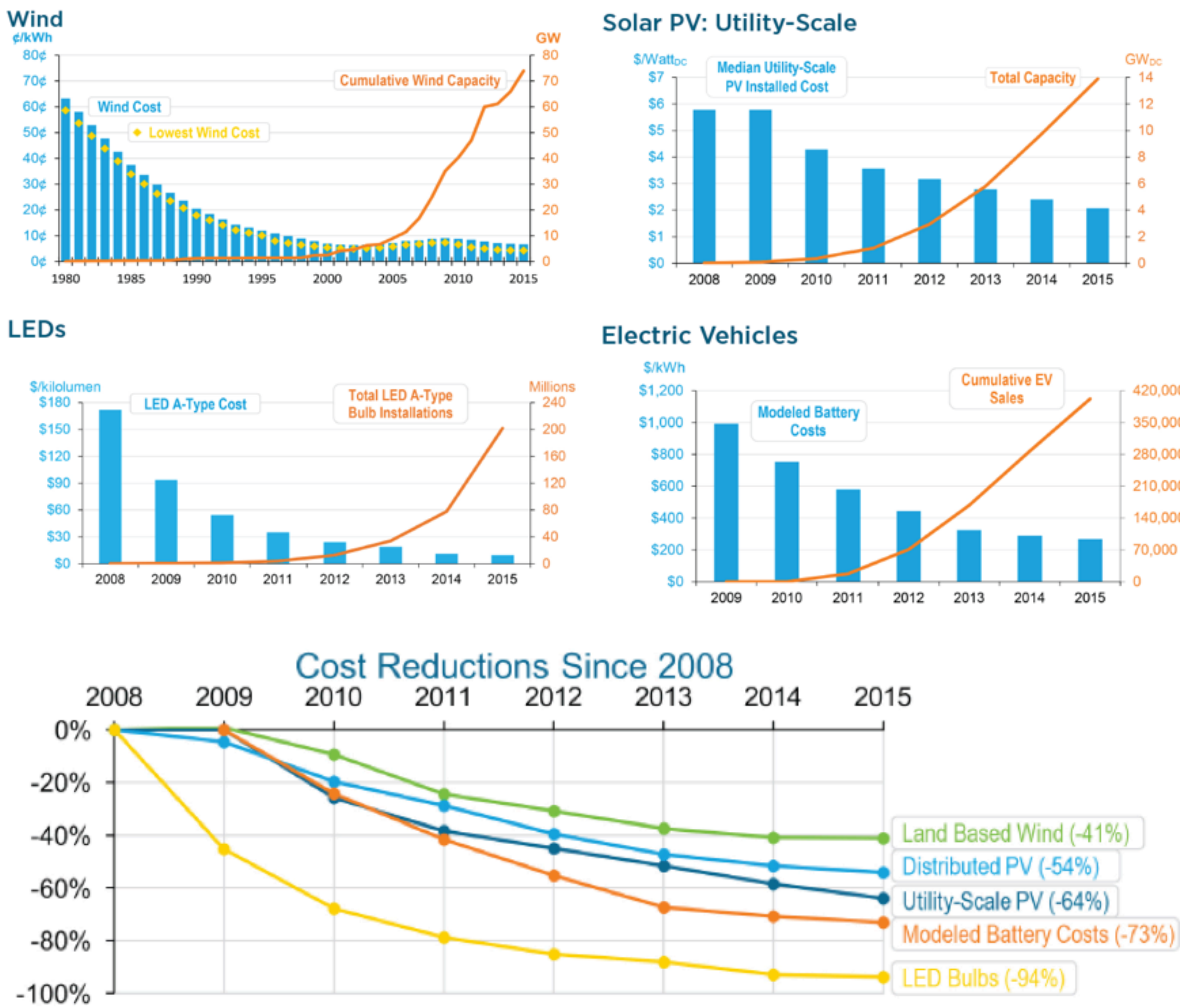
Table 3 Potential analyses to help inform future DOE RDD&D strategies to enhance competitiveness of U.S. clean energy technologies in global markets.

Focus Area	Steps for Consideration
Analysis	Analyze U.S.-based production in domestic and global markets to identify risks and RDD&D opportunities that contribute to advancing clean energy technologies.
Flexible Automation	Examine ways to lower high-volume manufacturing labor costs through RDD&D on flexible automation, design for manufacturing, and improved metrology to improve yield and quality.
Critical Materials	Identify RDD&D strategies to improve capture of materials now produced as side products, increase efficient use of critical materials, eliminate the need for materials that are subject to supply disruptions, and develop substitute materials.
Industrial Commons	Develop RDD&D strategies to advance clean energy technologies while strengthening U.S. clean energy manufacturing through the industrial commons.
Economies-of-Scale	Analyze: (1) issues of economies-of-scale, economies of learning, and supply chain efficiencies and impacts on cost reductions: (2) the impact of achieving economies-of-scale for enabling development of specialized equipment for high-throughput, high-performance manufacturing; and (3) the extent to which scale is important in generating increasing revenues in support of RDD&D and the resulting impact on cost reduction and on competitiveness.
Time-to-Market	Design RDD&D strategies that reduce the time required to get a product to market.
Emerging Markets	Develop RDD&D strategies that target energy technology markets outside the OECD countries.

The clean energy technologies identified above and others have rapidly improving performance and plummeting costs, as indicated in Figure 9. If the U.S. falls behind in a particular technology area, the rapid advances shown could quickly result in U.S. companies being effectively locked out of these markets. Innovation is critical, and so are manufacturing capabilities and competitiveness.

The competitiveness factors discussed above indicate some of the issues that need to be addressed to help support U.S. competitiveness in global markets. Further case studies and additional analyses can help identify particularly important RDD&D opportunities and mechanisms to improve U.S.-based manufacturing competitiveness in domestic and global markets, building on the approaches identified in Section 4, and strategies for going forward.

Figure 9 For (a) Wind, (b) Utility-Scale Solar photovoltaics (PV), (c) white Light-Emitting Diodes (LEDs), and (d) Electric Vehicle Batteries, the bars indicate the reduction in cost over time, and the line going up indicates the sales of equipment. Finally, (e) indicates percentage reductions in costs since 2008.[182]



Endnotes

[1] U.S. Department of Energy, "Quadrennial Technology Review 2015", http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015 and http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus

[2] Meng Meng and Josephine Mason, "China to plow $361 billion into renewable fuel by 2020", Reuters, January 5, 2017

[3] International Energy Agency, "World Energy Outlook 2016", OECD/IEA, Paris, France, 2016. See text page 22, "A cumulative $44 trillion in investment is needed in global energy supply in our main scenario, 60% of which goes to oil, gas and coal extraction and supply, including power plants using these fuels, and nearly 20% to renewable energies. An extra $23 trillion is required for improvements in energy efficiency.

[4] For a more complete review and analysis, see: Clean Energy Manufacturing Analysis Center, "2015 Research Highlights", NREL/BR-6A50-65312, March, 2016; http://www.manufacturingcleanenergy.org/ and http://www.nrel.gov/docs/fy16osti/65312.pdf Clean energy technology and manufacturing competitiveness are rich topics, where many stakeholders have efforts underway. This Supplemental Information appendix focuses primarily on DOE analyses, and taps into some of the many assessments and studies conducted by industry, academia, and others that explore U.S. competitiveness.

[5] Bloomberg New Energy Finance Clean Energy Investment Fact Pack, accessed January 9, 2017.

[6] U.S. Department of Energy, "Quadrennial Technology Review 2015", http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015 and http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus

[7] In particular, see: QTR, 6L "Sustainable Manufacturing - Flow of Materials through Industry", http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus

[8] The European Council for an Energy Efficient Economy describes energy efficiency as the most powerful and quickest way to cut the energy costs of European businesses, and thereby boost their competitiveness. See:

- "European competitiveness and energy efficiency: Focusing on the real issue, A discussion paper," the European Council for an Energy Efficient Economy, 21 May 2013. http://www.eceee.org/all-news/press/2013/the-real-issue-on-energy-and-competitiveness/ee-and-competitiveness.
- European Council for an Energy Efficient Economy, "Energy Efficiency and Competitiveness," http://www.eceee.org/policy-areas/competitiveness.

The impact of energy efficiency on energy security and economic security is also discussed in, for example:

- "Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements", International Energy Agency, 2012. http://www.iea.org/publications/insights/ee_improvements.pdf.

[9] Energy innovation may include technologies that help users of energy, technologies that help production of energy, and technologies that help producers of energy products.[10] See, for example,

- Miller, M.; Perry, T.D.; et al; "Clean Energy Innovation: Sources of Technical and Commercial Breakthroughs," National Renewable Energy Lab, March 2011; National Renewable Energy Laboratory, NREL/TP-6A20-50624. http://www.nrel.gov/docs/fy11osti/50624.pdf.
- President's Council of Advisors on Science and Technology, "Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing," July 2012. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf.

[11] The National Research Council's "*Rising to the Challenge*", National Academies Press, 2012, https://www.nap.edu/catalog/13386/rising-to-the-challenge-us-innovation-policy-for-the-global

[12] Executive Office of the President, President's Council of Advisors on Science and Technology, "Report to the President: Accelerating U.S. Advanced Manufacturing", October 2014, https://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf

[13] See also: Gregory F. Nemet, Daniel M. Kammen, "Energy research and development: Declining investment, increasing need, and the feasibility of expansion", Energy Policy 35 (2007), 746-755.

[14] National Science foundation, National Center for Science and Engineering Statistics, 2017. Business R&D and Innovation: 2014. Detailed Statistical Tables (forthcoming). Arlington, VA. Will be available at: http://www.nsf.gov/statistics/industry/ See also: Gregory F. Nemet, Daniel M. Kammen, "Energy research and development: Declining investment, increasing need, and the feasibility of expansion", Energy Policy 35 (2007), 746-755. https://thefoodenergywaternexus.files.wordpress.com/2015/10/nemetkammen_ep07.pdf

[15] American Energy Innovation Council, "Catalyzing American Ingenuity: The Role of Government in energy Innovation", "Figure 3: Total R&D Spending as a Share of Sales". http://americanenergyinnovation.org/ ; Benjamin Gaddy, Varun Sivaram, Francis O'Sullivan, "Venture Capital and Cleantech: The Wrong model for Clean Energy innovation" MIT Energy Initiative Working Paper, July 2016. http://energy.mit.edu/publication/venture-capital-cleantech/

[16] Data drawn by DOE from Bloomberg New Energy finance and includes VC-Tech/Early Spinoff, VC-SeriesB/Second Round, VC-Series A/First round, VC-Seed/Angel. Note that China's growth is substantially due to a few very big deals, but China has many fewer deals than in the U.S.

[17] Benjamin Gaddy, Varun Sivaram, Francis O'Sullivan, "Venture Capital and Cleantech: The Wrong model for Clean Energy innovation", MIT Energy Initiative Working Paper, July 2016. http://energy.mit.edu/publication/venture-capital-cleantech/

[18] Board on Energy and Environmental Systems, "Was It Worth It: Energy Efficiency and Fossil Energy Research 1978-2000", National Research Council; National Academies of Science, Engineering, and Medicine; National Academy Press, Washington, DC, 2001. http://www.nap.edu/catalog/10165/energy-research-at-doe-was-it-worth-it-energy-efficiency This study examined an R&D portfolio in energy efficiency of about $1.6 billion, roughly one-fifth of the total Federal expenditure on energy efficiency R&D for the period examined, and found a net economic benefit attributable to the public sector of about $30 billion.

[19] See, for example, the retrospective benefits studies listed at: http://www.energy.gov/eere/analysis/program-evaluation-eere-planned-and-completed-evaluations and http://www.energy.gov/eere/analysis/policy-and-analysis-publications

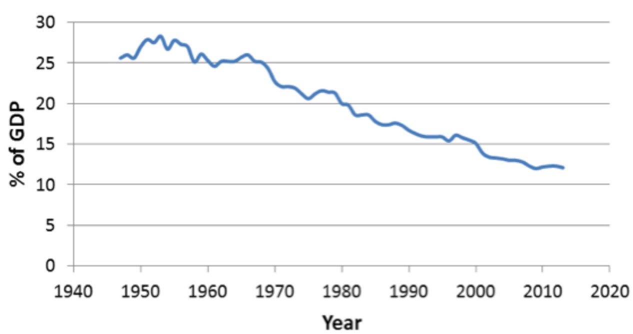
[20] See, for example:

- "Where the Shale Gas Revolution Came From: Government's Role in the Development of Hydraulic Fracturing in Shale," The Breakthrough Institute, May 2012. http://thebreakthrough.org/blog/Where_the_Shale_Gas_Revolution_Came_From.pdf.
- Boyd, G.A. and J. X. Pang, "Estimating the linkage between energy efficiency and productivity," Energy Policy, 28 (2000) 289-296. http://www.sciencedirect.com/science/article/pii/S0301421500000161.
- Worrell, E., J. A. Laitner, M. Ruth, and H. Finman, "Productivity benefits of industrial energy efficiency measures", Energy, 28 (2003) 1081–1098. http://www.sciencedirect.com/science/article/pii/S0360544203000914.
- National Research Council, "Energy Research at DOE: Was it Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000", National Academy Press, Washington, DC, 2001. http://www.nap.edu/catalog/10165/energy-research-at-doe-was-it-worth-it-energy-efficiency See page 23, Table 3-2 for the DOE energy efficiency expenditures analyzed, which total about $1.6 B, and page 29, Table 3-4 showing net realized benefits of ~$30B in economic benefits, ~$3-20B in environmental benefits, and ~$0.2-1B in security benefits.
- Numerous retrospective benefits studies can be found at: http://www.energy.gov/eere/analysis/program-evaluation-eere-planned-and-completed-evaluations and http://www.energy.gov/eere/analysis/policy-and-analysis-publications

[21] For example, the levels of R&D described in the reports below can be compared on a per capital and GDP basis by country.

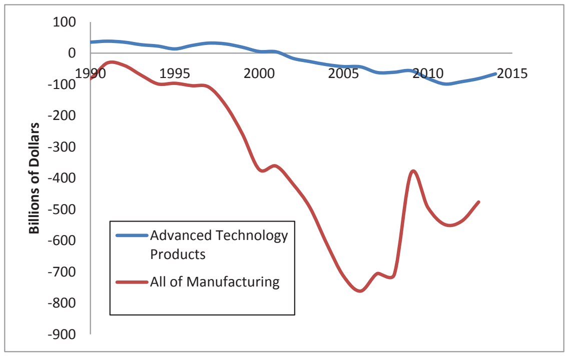
- GDP data from The World Bank, World Development Indicators. http://databank.worldbank.org/data/home.aspx.
- Japan, Canada, South Korea, and U.S. RD&D data is available from the Organization for Economic Cooperation and Development (OECD) Library http://www.oecd-ilibrary.org/energy/data/iea-energy-technology-r-d-statistics_enetech-data-en.
- China's RD&D data can be derived from: State and Science Technology Commission, China Statistical Yearbook on Science and Technology (2009), as cited in: Gallagher, K.S., et al., "Trends in investments in global energy research, development, and demonstration," Wiley Interdisciplinary Reviews: Climate Change, Volume 2, Issue 3, pages 373–396, May/June 2011. http://www.researchgate.net/publication/229925882_Trends_in_investments_in_global_energy_research_development_and_demonstration.

[22] Time series manufacturing value-added as a percentage of GDP for the U.S. can be seen in the graphic below, developed from data available from the Bureau of Economic Analysis, GDP-by-Industry Data 2013. http://www.bea.gov/iTable/iTable.cfm?ReqID=51&step=1#reqid=51&step=51&isuri=1&5114=a&5102=5.



U.S. manufacturing value added as a percentage of GDP.

[23] The graphic below is developed from data available from the U.S. Census Bureau, Foreign Trade Division. For Trade in Goods with Advance Technology Products, see https://www.census.gov/foreign-trade/balance/c0007.html. For "All of Manufacturing", see https://www.census.gov/foreign-trade/statistics/historical/gands.pdf. The "high-tech" portion of the domestic manufacturing sector is also on the decline. The balance of trade for advanced technology products, which includes biotechnology products, computers, semiconductors, and robotics, was in surplus from 1988 until 2002, when it turned negative.



U.S. trade balances for high-tech and all manufactured products. The U.S. trade deficit in manufactured products tallied to $7.5 trillion from 2000 to 2013.

[24] See, for example, Justin R. Pierce, Peter K. Schott, "The Surprisingly Swift Decline of US Manufacturing Employment", American Economic Review 2016, 106(7), 1632-1662.

[25] "Table 1. Manufacturing (ISIC C, NAICS 31-33), Hourly compensation costs, U.S. Dollars, 2008-2012," Bureau of Labor Statistics, July 2014, www.bls.gov/fls/ichccindustry.htm#C.

[26] Parilla, J., J. L. Trujillo, and A. Berube, "Skills and Innovation Strategies to Strengthen U.S. Manufacturing: Lessons from Germany," The Brookings Institution, 2015. http://www.brookings.edu/~/media/research/files/reports/2015/02/25-germany/lessonsfromgermany.pdf.

For detailed information on industrial comparisons by country, see BLS hourly compensation costs (2012 data) here: http://www.bls.gov/fls/ichccindustryreport.htm#chart03.

For further discussions of Germany's approach to sustain a strong manufacturing sector, see: MIT Production in the Innovation Economy Commission. "*Production in the Innovation Economy*", MIT Press, 2013.

[27] See, for example: Goodrich, A. C., D. M. Powell, T. L. James, M. Woodhouse, T. Buonassisi, "Assessing the drivers of regional trends in solar photovoltaic manufacturing," Energy & Environmental Sciences, 2013. http://pubs.rsc.org/en/Content/ArticleLanding/2013/EE/c3ee40701b#!divAbstract.

[28] In addition, there is also extensive literature on the challenges of technology demonstration, manufacturing scale-up, and market adoption. See, for example:

- The Committee on America's Energy Future. "America's Energy Future: Technology and Transformation: Summary Edition," National Academy of Sciences, 2009. http://www.nap.edu/catalog/12710/americas-energy-future-technology-and-transformation-summary-edition
- Berger, S., et al, "*Making in America*", MIT Press, 2013.
- "Restoring American Energy Innovation Leadership: Report Card, Challenges, & Opportunities", American Energy Innovation Council, February 2015. http://bipartisanpolicy.org/wp-content/uploads/2015/02/AEIC_Energy_Innovation.pdf.

[29] Goodrich, A. C., D. M. Powell, T. L. James, M. Woodhouse, T. Buonassisi, "Assessing the drivers of regional trends in solar photovoltaic manufacturing," Energy & Environmental Sciences, 2013. http://pubs.rsc.org/en/Content/ArticleLanding/2013/EE/c3ee40701b#!divAbstract This analysis showed that supply chain development and the ability to scale-up manufacturing provided a more significant competitive advantage for the Chinese PV industry than labor cost advantages.

In October 2012, U.S. Department of Commerce (DOC) issued final determinations in the solar antidumping (AD) and countervailing duties (CVD) investigation. The DOC affirmed its preliminary finding that Chinese-origin crystalline-silicon cells are subject to antidumping (AD) and countervailing duties (CVD) when imported into the U.S. See, for example http://enforcement.trade.gov/download/factsheets/factsheet_prc-solar-cells-ad-cvd-finals-20121010.pdf. Also, http://www.usitc.gov/press_room/news_release/2015/er0121ll329.htm.

[30] Chung, D., T. James, E. Elgqvist, A. Goodrich, and S. Santhanagopalan, "Automotive Lithium-ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations," National Renewable Energy Laboratory, August 22, 2014. http://energy.gov/eere/cemi/downloads/automotive-lithium-ion-battery-supply-chain-and-us-competitiveness

In 2011, Energy Secretary Steven Chu testified to the House Energy and Commerce Committee about the China Development Bank offering more than $34 billion in credit lines to China's solar companies. See http://energy.gov/articles/my-testimony-house-energy-and-commerce-committee.

In 2012, a Senate report indicated that China's National People's Congress approved the Twelfth Five-Year Plan in March, 2011, which established spending and preferential tax and procurement policies designed to promote Chinese industries related to solar, biomass, and wind energy technology. See, Wyden, Senator Ron, "International Trade in Environmental Goods, 2012 Report, Losing the Environmental Goods Economy to China", February 28, 2012. https://www.wyden.senate.gov/download/staff-report-losing-the-environmental-goods-economy-to-china. See also, Melton, Oliver, "China's Five-Year Planning System: Implications for the Reform Agenda", Testimony for the U.S.-China Economic and Security Review Commission, April 22, 2015. http://www.uscc.gov/sites/default/files/Melton%20-%20Written%20Testimony.pdf.

31 See, for example:

- President's Council of Advisors on Science and Technology, "Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing," Executive Office of the President, July 2012. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17,_2012.pdf
- President's Council of Advisors on Science and Technology, "Report to the President: Accelerating U.S. Advanced Manufacturing", Executive Office of the President, October 2014, https://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf

32 Porter, M. E., "The Competitive Advantage of Nations," Harvard Business Review, 1990. https://hbr.org/1990/03/the-competitive-advantage-of-nations.

33 See:

- Porter, M.E. and J. W. Rivkin, "The Looming Challenge to U.S. Competitiveness," Harvard Business Review, March 2012, https://hbr.org/2012/03/the-looming-challenge-to-us-competitiveness/ar/1.
- See also: "Can America Compete? Strategies for economic revival," Sept-Oct 2012, Harvard Magazine. http://harvardmagazine.com/2012/09/can-america-compete.

34 *Rising Above The Gathering Storm, Revisited*, by Members of the 2005 "Rising Above the Gathering Storm" Committee, National Academy of Sciences, 2010. http://www.nap.edu/catalog/12999/rising-above-the-gathering-storm-revisited-rapidly-approaching-category-5.

35 Kochan, T., "Jobs Compact for America's Future," Harvard Business Review, 2012. https://hbr.org/2012/03/a-jobs-compact-for-americas-future/ar/1.

36 Manyika, J., et al., "Manufacturing the future: the next era of global growth and innovation," Washington, DC: McKinsey & Company, 2012. http://www.mckinsey.com/insights/manufacturing/the_future_of_manufacturing.

37 World Economic Forum, "Global Competitiveness Report, 2011–2012", http://www3.weforum.org/docs/WEF_GCR_Report_2011-12.pdf

38 *The Competitiveness and Innovative Capacity of the United States*, Washington, DC: U.S. Department of Commerce, 2012. http://www.esa.doc.gov/reports/competitiveness-and-innovative-capacity-united-states.

39 *The Global Competitiveness Report 2008-2009*, 2008 World Economic Forum. http://www.weforum.org/reports/global-competitiveness-report-2008-2009.

40 Atkinson, R.D., "Competitiveness, Innovation and Productivity: Clearing up the Confusion," ITIF, August 2013. http://www2.itif.org/2013-competitiveness-innovation-productivity-clearing-up-confusion.pdf.

41 Shale Gas: Reshaping the US Chemicals Industry, Price Waterhouse Cooper, October 2012. Accessed on March 20, 2015 at: http://www.pwc.com/en_US/us/industrial-products/publications/assets/pwc-shale-gas-chemicals-industry-potential.pdf. Estimates are based on PWC cost models and use EIA data and forecasts for natural gas prices.

42 "International Energy Agency. World Energy Outlook 2014 Factsheet," International Energy Agency. http://www.worldenergyoutlook.org/media/weowebsite/2014/141112_WEO_FactSheets.pdf.

Turner, G., "Global Renewable Energy Market Outlook," Bloomberg New Energy Finance, 2013. http://about.bnef.com/content/uploads/sites/4/2013/04/Global-Renewable-Energy-Market-Outlook-2013.pdf

43 Gross Domestic Product-by-Industry Data, New Quarterly Gross Domestic Product by Industry Statistics, Survey of Current Business (SCB), Bureau of Economic Analysis, May 2014. https://www.bea.gov/scb/pdf/2014/05%20May/0514_gdp-by-industry.pdf.

44 National Science and Technology Council, "*A National Strategic Plan for Advanced Manufacturing*", Executive Office of the President, 2012. https://www.whitehouse.gov/sites/default/files/microsites/ostp/iam_advancedmanufacturing_strategicplan_2012.pdf.

45 For a discussion on employment multipliers for the U.S. economy, see:

- Bivens, J., "Updated Employment Multipliers for the U.S. Economy," Working paper No. 268, Economic Policy Institute, August 2003, 23.
- Moretti, E., "Local Multipliers," American Economic Review, Papers & Proceedings 100, May 2010. http://emlab.berkeley.edu/~moretti/multipliers.pdf.
- Ezell, S.J. and R. D. Atkinson, "The Case for a National Manufacturing Strategy," ITIF, 2011. http://www2.itif.org/2011-national-manufacturing-strategy.pdf.
- National Science and Technology Council, "A National Strategic Plan for Advanced Manufacturing", Executive Office of the President, 2012. https://www.whitehouse.gov/sites/default/files/microsites/ostp/iam_advancedmanufacturing_strategicplan_2012.pdf.

46 For additional discussion on the role of manufacturing sector in supporting U.S. exports/imports, see:

- President's Council of Advisors on Science and Technology, "Report to the President on Capturing Domestic Competitive Advantage in

Advanced Manufacturing," Executive Office of the President, July 2012. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf

- Executive Office of the President, President's Council of Advisors on Science and Technology, "Report to the President: Accelerating U.S. Advanced Manufacturing", October 2014, https://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf

[47] An NSF analysis found that the manufacturing industries in aggregate (NAICS 31–33) exhibited a considerably higher overall incidence of innovation than did the population of companies as a whole. About 22% of all the companies in manufacturing industries reported one or more product innovations in the 2006–08 period and about 22% reported process innovations. Boroush, M., "NSF Releases New Statistics on Business Innovation," National Science Foundation, October 2010. http://www.nsf.gov/statistics/infbrief/nsf11300/.

[48] See:

- Tassey, G., "Rationales and Mechanisms for Revitalizing US Manufacturing R&D Strategies," Journal of Technology Transfer 35, no. 3 (2010): 283-333. http://www.nist.gov/director/planning/upload/manufacturing_strategy_paper.pdf.
- Boroush, M., "NSF Releases New Statistics on Business Innovation," National Science Foundation, October 2010. http://www.nsf.gov/statistics/infbrief/nsf11300/.

[49] Helper, S. and H. Wial, "Strengthening American Manufacturing: A New Federal Approach," Brookings Institution, September 2010. http://www.brookings.edu/~/media/research/files/papers/2010/9/27-great-lakes/0927_great_lakes_manufacturing.pdf.

[50] A growing number of analysts argue the importance of the linkages between R&D and manufacturing and the extent to which feedback from production helps guide R&D. This is especially true for industries where product development and innovation are tightly-coupled with manufacturing processes. An overview of this concept can be found in:

- Bonvillian, W., "Advanced Manufacturing Policies and Paradigms for Innovation", Science, V.342, 6 Dec. 2013.
- "The Role of Manufacturing Collaborations in a 21st Century Innovation Economy," 113th Congress, Testimony of Dr. Martin A. Schmidt, 2013.

A case study in the optoelectronic industry can be found in

- Fuchs, E. and R., Kirchain, "Design for Location? The Impact of Manufacturing Offshore on Technology Competitiveness in the Optoelectronics Industry," Management Science, Volume 56, Issue 12, 2010. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1545027.

[51] National Science Board, Science and Technology Indicators, 2014. http://www.nsf.gov/statistics/seind14/.

[52] These industrial commons include not just suppliers of advanced materials, production equipment, and components, but also R&D know-how, advanced process development and engineering skills, and manufacturing competencies. See:

- Pisano G. and W. Shih, "Restoring American Competitiveness," Harvard Business Review, July 2009. https://hbr.org/2009/07/restoring-american-competitiveness/ar/1.
- Berger, S., *"Making in America"*, MIT Press, 2013.
- Gertner, J., "Does America Need Manufacturing?", NY Times, 8 2011 28, http://www.nytimes.com/2011/08/28/magazine/does-america-need-manufacturing.html.
- Pisano, G.P., "The U.S. Is Outsourcing Away Its Competitive Edge," Harvard Business Review, October 1, 2009, https://hbr.org/2009/10/the-us-is-outsourcing-away-its/.
- Hayes, R.H., Outsourcing Is High Tech's Subprime-Mortgage Fiasco, Harvard Business Review, October 7, 2009, https://hbr.org/2009/10/outsourcing-is-high-techs-subprime/.

[53] The Fraunhaufer institute is discussed in, for example:

- Berger, S., *"Making in America"*, MIT Press, 2013.
- Berger S. and MIT Industrial Performance Center, *"How We Compete: What Companies around the World Are Doing to Make It in Today's Global Economy"*, New York: Currency Doubleday, 2005.
- Pisano, G.P. and W. C. Shih, "Does America Really Need Manufacturing?" Harvard Business Review, March 2012, https://hbr.org/2012/03/does-america-really-need-manufacturing/ar/1.

[54] The competitiveness advantage from an industrial commons is discussed in, for example:

- Porter, M. E., *"The Competitive Advantage of Nations"*, Free Press, 1990.
- The Council on Competitiveness, Michael E. Porter, Monitor Group, "On the Frontier, Clusters of Innovation Initiative: Regional Foundations of U.S. Competitiveness," October 2012. http://www.hbs.edu/faculty/Publication%20Files/COI_National_05202014_ad0fe06c-674c-494b-96f6-6882db4e6aaf.pdf.

[55] The researchers at the MIT Production in the Innovation Economy Commission interviewed multiple firms to explore their approach to connecting production with development and design. Firms such as Toyota, Honeywell, Johnson & Johnson, and UTC all cited the need for the close relationship between product development and manufacturing. Toyota indicated the importance of collocating development with manufacturing. Johnson & Johnson described the importance of having manufacturing close to research and development. However, for Honeywell and UTC, the importance of the development-to-manufacturing linkage varied depending on the product line. See, "*Production in the Innovation Economy*", MIT Production in the Innovation Economy Commission, 2013.

[56] See, for example:

- U.S. Congress, Office of Technology Assessment, *"Renewing Our Energy Future,"* OTA-ETI-614 (Washington, DC, September 1995. See pages 257-258. https://www.princeton.edu/~ota/disk1/1995/9552/9552.PDF
- For a historical review of the Federal government contribution to increase U.S. innovation and competitiveness, see Atkinson, R.D., "Understanding the U.S. National Innovation System," ITIF, June 2014. http://www.itif.org/publications/2014/06/30/understanding-us-national-innovation-system.

[57] For solar energy, see, for example:

- Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research, *"Optics and Photonics - Essential Technologies for Our Nation"*, National Academy of Sciences, 2013. http://www.nap.edu/catalog/13491/optics-and-photonics-essential-technologies-for-our-nation.
- Curtright, A. E., M. G. Morgan and D. W. Keith, "Expert Assessments of Future Photovoltaic Technologies," Environmental Science & Technology 42: 9031-9038, 2008. http://pubs.acs.org/doi/abs/10.1021/es8014088.

For wind energy, see, for example:

- Siler-Evans, K., I.L. Azevedo, M. G. Morgan, and J., Apt, "Regional variations in the health, environmental, and climate benefits of wind and solar generation", PNAS, 2013 110: 11768-11773. http://www.pnas.org/content/110/29/11768.shorts.
- Lam, L., L. Branstetter, and I. L. Azevedo, "Too Fast, Too Soon? The Rise of the Chinese Wind Turbine Manufacturing Industry," Working Paper, Department of Engineering and Public Policy, Carnegie Mellon University, June 20, 2014. http://cedmcenter.org/wp-content/uploads/2014/06/Lee-Branstetter.pdf.
- Apt, J. and P. Jaramillo. *"Variable Renewable Energy and the Electricity Grid"*. 2014. RFF Press.

For Li-Ion batteries, see, for example:

- Sakti, A., J. E. Michalek, E. Fuchs, and J. Whitacre, "A techno-economic analysis and optimization of Li-ion batteries for personal vehicle electrification," Journal of Power Sources. 273: January 2015 pp. 966-980. http://www.cmu.edu/me/ddl/publications/2014-JPS-Sakti-etal-Techno-Economic-EV-Battery.pdf.

For LEDs, see, for example:

- Min, J., I.L. Azevedo, and P. Hakkarainen, "Net carbon emissions savings and energy reductions from lighting energy efficiency measures when accounting for changes in heating and cooling demands: a regional comparison," Applied Energy, Volume 141, 1, March 2015, Pages 12–18. http://cedmcenter.org/net-carbon-emissions-savings-and-energy-reductions-from-lighting-energy-efficiency-measures-when-accounting-for-changes-in-heating-and-cooling-demands-a-regional-comparison/.
- Min, J., I. L. Azevedo, J. Michalek, and W. Bruine de Bruin, "Labeling energy cost on light bulbs lowers implicit discount rates," 2014, Ecological Economics, 97: 42–50. http://www.sciencedirect.com/science/article/pii/S092180091300325X.

For carbon composites, see, for example:

- Fuchs, E., F. Field, R. Roth, and R. Kirchain, "Plastic Cars in China? The Significance of Production Location over Markets for Technology Competitiveness", International Journal of Production Economics, 132(2011): 79-92., 2011. http://www.sciencedirect.com/science/article/pii/S0925527311001290
- Fuchs, E., F. Field, R. Roth, and R. Kirchain, "Strategic Materials Selection in the Automotive Body: Economic Opportunities for Polymer Composite Design", Composite Science and Technology, 68(9): 1989-2002, 2008. http://www.sciencedirect.com/science/article/pii/S0266353808000316.

[58] The following factors are considered in the competitiveness analysis: technology innovation potential, manufacturing experience, learning by doing, intellectual property, cost of energy, cost of manufacturing, availability of investment capital, low-cost labor requirements and availability, skilled labor requirements and availability, tax policy, currency fluctuations, import and export policies, automation/advanced manufacturing, raw material availability, ease of transportation, existing supply chains, synergistic industries, existing or growing market, ease of doing business, safety, and regulations, and others. Technical Discussions, National Renewable Energy Laboratory, 2014 and 2015.

[59] Ibid, Technical Discussions, National Renewable Energy Laboratory, 2014 and 2015.

[60] See: Clean Energy Manufacturing Analysis Center, Joint Institute for Strategic Energy Analysis, U.S. Department of Energy Clean Energy Manufacturing Initiative, http://www.manufacturingcleanenergy.org/ ,

[61] The methodology on clean energy competitiveness analysis is quantitative and technology-specific. See case studies described in the text.

[62] For detailed discussions on the cost model, see Powell, D. M., M. T. Winkler, A. Goodrich and T. Buonassisi, "Modeling the Cost and Minimum Sustainable Price of Crystalline Silicon Photovoltaic Manufacturing in the United States," IEEE Journal of Photovoltaics, 2013, 3, 662–668. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=6407638

[63] See, for example, Goodrich, A., T. James, and M. Woodhouse, "Solar PV manufacturing cost analysis: U.S. competitiveness in a global industry." Washington, DC: National Renewable Energy Laboratory, 2011.

[64] See, for example:

- Goodrich, A.C., D. M. Powell, T. L. James, M. Woodhouse, and T. Buonassisi, "Assessing the drivers of regional trends in solar photovoltaic manufacturing," Energy & Environmental Sciences, 2013. http://pubs.rsc.org/en/Content/ArticleLanding/2013/EE/c3ee40701b. Key examples of regional incentives are provincial/state subsidies and tax holidays.

- U.S. Department of Commerce, International Trade Administration, Fact Sheet, "Commerce Finds Dumping of Imports of Certain Crystalline Silicon Photovoltaic Products from China and Taiwan and Countervailable Subsidization of Imports of Certain Crystalline Silicon Photovoltaic Products from China" http://www.finance.senate.gov/imo/media/doc/Certain%20Crystalline%20Silicon%20Photovoltaic%20Products%20Factsheet1.pdf
- United States, International Trade Commission, "U.S. ITC Votes to Continue Cases on Certain Crystalline Silicon Photovoltaic Products from china and Taiwan", February 14, 2014, http://www.usitc.gov/press_room/news_release/2014/er0214mm1.htm.

65 Goodrich, A.C., D. M. Powell, T. L. James, M. Woodhouse, and T. Buonassisi, "Assessing the drivers of regional trends in solar photovoltaic manufacturing," Energy & Environmental Science, 2013. http://pubs.rsc.org/en/Content/ArticleLanding/2013/EE/c3ee40701b

66 Clean Energy Manufacturing Analysis Center, "2015 Research Highlights", NREL/BR-6A50-65312, March, 2016; http://www.manufacturingcleanenergy.org/ http://www.nrel.gov/docs/fy16osti/65312.pdf

67 Ibid

68 Goodrich, A.C., D. M. Powell, T. L. James, M. Woodhouse, and T. Buonassisi, "Assessing the drivers of regional trends in solar photovoltaic manufacturing," Energy & Environmental Sciences, 2013. http://pubs.rsc.org/en/Content/ArticleLanding/2013/EE/c3ee40701b.

69 Woodhouse, M., A. Goodrich, R. Margolis, T. L James, M. Lokanc, and R. Eggert, "Supply-Chain Dynamics of Tellurium, Indium and Gallium within the Context of PV Module Manufacturing Costs," IEEE Journal of Photovoltaics, April 2013, and http://www.nrel.gov/docs/fy13osti/56883.pdf.

70 Eric Wesoff, "Rest in Peace: The Fallen Solar Companies of 2014", December 6, 2014, http://theenergycollective.com/eric-wesoff/2165821/rest-peace-fallen-solar-companies-2014.

71 O'Connor, A., R. Loomis, F. Braun, "Retrospective Benefit-Cost Evaluation of DOE Investments in Photovoltaic Energy Systems", 2010, http://www.energy.gov/sites/prod/files/2015/05/f22/solar_pv.pdf http://www.energy.gov/eere/analysis/downloads/retrospective-benefit-cost-evaluation-doe-investments-photovoltaic-energy and http://www.energy.gov/eere/analysis/program-evaluation-eere-planned-and-completed-evaluations

72 The 2014 SunShot Initiative Portfolio Book includes overviews of each of SunShot's five subprogram areas, as well as a description of every active project in the SunShot's project portfolio as of May 2014. See: "Tackling Challenges In Solar: 2014 Portfolio, SunShot Initiative," Solar Energy Technologies Office, U.S. Department of Energy. http://energy.gov/eere/sunshot/downloads/2014-sunshot-initiative-portfolio-book-tackling-challenges-solar-energy

73 By 2015, there were more than 75 gigawatts of total installed wind power, as compared to one gigawatt in 2005. See: U.S. Department of Energy, "Revolution Now: The Future Arrives for Five Clean Energy Technologies – 2016 Update", http://energy.gov/eere/downloads/revolutionnow-2016-update

74 The analysis by Sandia National Laboratory estimated the bill of materials for a 61.5 meter blade design (Johanns and Griffith 2013). While the inputs were validated by industry, it should be noted that the results do not necessarily represent the costs for all manufacturers and blade designs. The NREL cost model also incorporated insights from past DOE-funded programs like the Wind Partnerships for Advanced Component Technology (Berry, et al. 2003), in addition to more recent National Laboratory led efforts such as the Advanced Manufacturing Initiative (AMI) and other collaborative work with industry (Johanns and Griffith 2013). See:

- Johanns, W. and D.T. Griffith, "User Manual for Sandia Blade Manufacturing Cost Tool: Version 1.0." Sandia National Laboratories Technical Report. SAND2013-2733. April 2013. http://energy.sandia.gov/energy/renewable-energy/wind-power/offshore-wind/offshore-wind-sandia-large-rotor-development/.
- Berry, D., S. Lockard, K. Jackson, M. Zuteck, C. Van Dam, T. Ashwill, T. and P. Veers, "Case Study for Large Wind Turbine Blades," WindPACT Blade System Design Studies. SAND2003-1428. May 2003. http://windpower.sandia.gov/other/031428.pdf.

75 The Wind Partnerships for Advanced Component Technology (WindPACT) studies were conducted to assist industry by testing innovative components, such as advanced blades and drivetrains, to lower the manufacturing and deployment cost.

See, for example: Berry, D., S. Lockard, K. Jackson, M. Zuteck, C. Van Dam, T. Ashwill, T. and P. Veers, "Case Study for Large Wind Turbine Blades," WindPACT Blade System Design Studies. SAND2003-1428. May 2003. http://windpower.sandia.gov/other/031428.pdf.

76 Clean Energy Manufacturing Analysis Center, http://www.manufacturingcleanenergy.org/

77 James, T. and A. Goodrich, "Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry," National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/60063.pdf.

78 This NREL analysis was completed using Sandia's NuMAD-based modeling and is focused on vacuum assisted resin transfer molding processes. Scaling factors are from an industry-validated modeling project led by Sandia National Laboratories. The starting mass for the model's 5 MW blade point design is 20% higher than some of today's commercial product. See James, T. and A. Goodrich, Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry, National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/60063.pdf

79 James, T. and A. Goodrich, Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry, National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/60063.pdf

80 Clean Energy Manufacturing Analysis Center (CEMAC), "2015 Research highlights", 2015. http://www.nrel.gov/docs/fy16osti/65312.pdf

81 U.S. DOE, "Wind Vision: A New Era for Wind Power in the United States." March 2015, see Chapter 2. https://energy.gov/eere/wind/wind-vision

82 For a discussion of policy impact on renewable energy deployment, see Bredehoeft, G., "The Outlook for Renewable Electricity in the United States: Assessing the Role of Policy and Other Uncertainties," 2014 EIA Energy Conference, July 14, 2014, Washington, DC. http://www.eia.gov/conference/2014/pdf/presentations/bredehoeft.pdf.

83 James, T. and A. Goodrich, Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry, National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/60063.pdf

84 The Wind Technologies Market Report describes the status of the U.S. wind energy industry in 2013; its trends, performance, market drivers and future outlook. "2013 Wind Technologies Market Report," Department of Energy, Wind and Water Technology Office, April 2014. http://energy.gov/eere/wind/downloads/2013-wind-technologies-market-report.

85 "2013 Wind Technologies Market Report," Department of Energy, Wind and Water Technology Office, April 2014. http://energy.gov/eere/wind/downloads/2013-wind-technologies-market-report

86 For a more complete discussion, see: Clean Energy Manufacturing Analysis Center, "2015 Research Highlights", Joint Institute for Strategic Energy Analysis, 2016, National Renewable Energy Laboratory NREL/BR-6A50-65312, March 2016, http://www.nrel.gov/docs/fy16osti/65312.pdf , and references cited within.

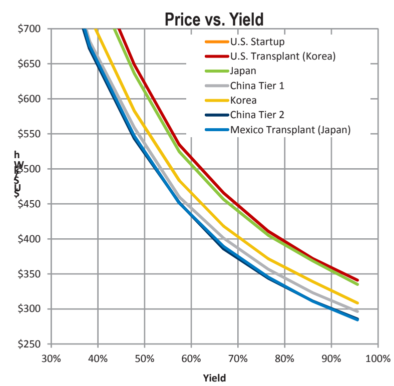
87 Donald Chung, Emma Elgqvist, Shriram Santhanagopalan, "Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations", National Renewable Energy Laboratory, NREL/TP-6A20-66086, April 2016, http://www.nrel.gov/docs/fy16osti/66086.pdf and

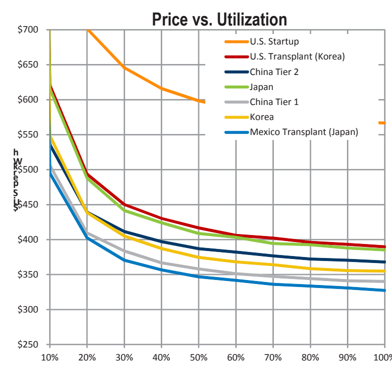
Donald Chung, Emma Elgqvist, Shiriram Santhanagopalan, "Automotive Lithium-ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations", National Renewable energy Laboratory, NREL/PR-6A50-63354, June 2015, http://energy.gov/eere/cemi/downloads/automotive-lithium-ion-battery-supply-chain-and-us-competitiveness and http://energy.gov/sites/prod/files/2015/06/f23/Lithium-ion%20Battery%20CEMAC.pdf

88 Ibid

89 Some safety related considerations include the nature of the material in enhanced stability and safety of alternative materials under EVs' more abusive conditions of high vibration, temperature extremes, and car crashes.

90 There are two mechanisms by which NREL postulate this immaturity may manifest: utilization and yield, as seen below.





Interviews conducted by NREL with industry suggest yields for large format automotive LIB cells range from 70-90%. For a Korean manufacturing facility, this represents a difference in modeled price of between ~$400 and ~$325/kWh, or about a 23% difference. See: Donald Chung, Emma Elgqvist, Shiriram Santhanagopalan, "Automotive Lithium-ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations", National Renewable Energy Laboratory, NREL/PR-6A50-63354, June 2015, http://energy.gov/eere/cemi/downloads/automotive-lithium-ion-battery-supply-chain-and-us-competitiveness and http://energy.gov/sites/prod/files/2015/06/f23/Lithium-ion%20Battery%20CEMAC.pdf

91 For additional discussion, see: Donald Chung, Emma Elgqvist, Shiriram Santhanagopalan, "Automotive Lithium-ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations", National Renewable energy Laboratory, NREL/PR-6A50-63354, June 2015, http://energy.gov/eere/cemi/downloads/automotive-lithium-ion-battery-supply-chain-and-us-competitiveness and http://energy.gov/sites/prod/files/2015/06/f23/Lithium-ion%20Battery%20CEMAC.pdf

92 Chung, D., Emma Elgqvist, Shriram Santhanagopalan, "Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations", Clean Energy Manufacturing Analysis Center (CEMAC), National Renewable Energy Laboratory, NREL/TP-6A20-66086, April 2016, http://www.nrel.gov/docs/fy16osti/66086.pdf

93 U.S. Congress, Office of Technology Assessment, "The Big Picture: HDTV and High-Resolution Systems", OTA-BP-CIT-64 (Washington, DC: U.S. Government Printing Office, June 1990), https://www.princeton.edu/~ota/disk2/1990/9007_n.html

94 Brodd, R. J., "Cost Comparison of Producing High-Performance Lithium-ion Batteries in the U.S. and in China," Journal of Power Sources, 22 December 2012. http://www.researchgate.net/publication/257225636_Cost_comparison_of_producing_high-performance_Li-ion_batteries_in_the_U.S._and_in_China.

[95] Bae, Andy, "Lithium-ion Battery Materials: Japan Dominates in the EV Era," February 4, 2011, Navigant Research. http://www.navigantresearch.com/blog/articles/lithium-ion-battery-materials-japan-dominates-in-the-ev-era.

[96] "Electric Vehicle Batteries, Lithium Ion Batteries for Hybrid, Plug-in Hybrid, and Battery Electric Light Duty Vehicles: Market Analysis and Forecasts," Pike Research, 2013.

[97] DOE/NREL identified a list of key LIB incumbent advantages including: greater cumulative production experience, manifested in part as higher yields; volume purchasing discounts for materials; established supply chain relationships that support further discounted materials costs; amortization of some fixed costs across greater volumes/end markets; potential cross-utilization of some capacity; greater ability to withstand large market fluctuations; and greater credibility and track record with respect to stringent automotive OEM requirements.

[98] This is the conclusion of NREL's "future" scenario. If input material prices could be equalized, and a lower cost of capital could be realized, the U.S. can potentially host cost-competitive LIB cell production. How lower materials costs are realized offshore appears to be partially due to scale and volume purchases, partially due to some degree of backwards integrations, and partially due to possible national incentives favoring domestic supplier/producer transactions. See: Donald Chung, Emma Elgqvist, Shriram Santhanagopalan, "Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations", Clean Energy Manufacturing Analysis Center (CEMAC), National Renewable Energy Laboratory, NREL/TP-6A20-66086, April 2016, http://www.nrel.gov/docs/fy16osti/66086.pdf .

[99] Materials costs tend to be a function of cell manufacturing company characteristics, in that pricing is determined in part by purchasing volume, but also by the nature of the relationships between LIB manufacturers and their suppliers. Asian manufacturers tend to have well established, close relationships with regionally collocated input materials suppliers that appear to confer pricing advantage beyond volume-based discounts. Further, some degree of vertical integration across Asian market participants drives lower effective material costs for certain cell producers. While these advantages manifest as regional in nature, they are not necessarily impossible to reproduce in other geographies as there do not appear to be endemic, region-specific characteristics that contribute to this advantage. See: Donald Chung, Emma Elgqvist, Shriram Santhanagopalan, "Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations", Clean Energy Manufacturing Analysis Center (CEMAC), National Renewable Energy Laboratory, NREL/TP-6A20-66086, April 2016, http://www.nrel.gov/docs/fy16osti/66086.pdf

[100] Tesla's construction and initial operations described at: https://www.bloomberg.com/news/articles/2017-01-04/tesla-flips-the-switch-on-the-gigafactory
Cost reductions can be found at: Nykvist, B. and M. Nilsson, "Rapidly falling costs of battery packs for electric vehicles", Nature Climate Change published online 23 March 2015, v.5, April 2015, pp. 329-333. http://www.nature.com/nclimate/journal/v5/n4/full/nclimate2564.html.

[101] Brodrick, J., Technical Discussions, Department of Energy, Building Technologies Office, 2014.

[102] DOE's effort is focused on continued reduction of manufacturing costs to accelerate adoption, and to ensure products meet the levels of quality and reliability demanded by the markets. 2014. See: "Manufacturing Roadmap: Solid-State Lighting Research and Development," U.S. Department of Energy, Buildings Technology Office, August 2014. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf.

[103] "Manufacturing Roadmap: Solid-State Lighting Research and Development," U.S. Department of Energy, Buildings Technology Office, August 2014. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf.

[104] Brodrick, J., Technical Discussions, Department of Energy, Building Technologies Office, 2014.

[105] See:

- "Manufacturing Roadmap, Solid-State Lighting Research and Development," U.S. Department of Energy, Buildings Technology Office, August 2014. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf.

DOE's Building Technologies Office's (BTO's) is focused on improving the efficiency of existing and new buildings in both the residential and commercial sector through the development of high-impact energy efficiency technologies and practices. In addition to solid-state lighting, BTO is also funding R&D activities to reduce installed and manufacturing costs in order to increase the likelihood of mass-market adoption of the energy efficiency technologies. See:

- "R&D Roadmap for Emerging Window and Building Envelope Technologies," U.S. Department of Energy, Building Technologies Office, February 2014. http://energy.gov/sites/prod/files/2014/02/f8/BTO_windows_and_envelope_report_3.pdf.
- "Research & Development Roadmap for Emerging Water Heating Technologies," U.S. Department of Energy, Building Technologies Office, September 2014. http://energy.gov/sites/prod/files/2014/09/f18/WH_Roadmap_Report_Final_2014-09-22.pdf.

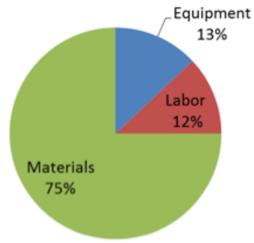
[106] For a more complete discussion, see: Clean Energy Manufacturing Analysis Center, "2015 Research Highlights", Joint Institute for Strategic Energy Analysis, 2016, National Renewable Energy Laboratory NREL/BR-6A50-65312, March 2016, http://www.nrel.gov/docs/fy16osti/65312.pdf , and references cited within.

[107] For additional information on ORNL's competitive analysis of carbon fiber, please see, for example, QTR Chapter 6, Appendix 6E: "Technology Assessment: Composite Materials and their Manufacture", http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus

[108] Recognizing both carbon fiber (CF) and carbon fiber reinforced polymer (CFRP) as materials critical for several DOE initiatives (e.g., transportation lightweighting and wind turbine blade), this analysis seeks to identify key opportunities in the CF supply chain where U.S. can achieve or maintain a competitive advantage. See: Das, S., J. Warren, D. West, and S. M. Schexnayder, "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis," Oak Ridge National Laboratory, Technical Report ORNL/SR-2016/100 and NREL/TP-6A50-66071, May 2016, http://www.nrel.gov/docs/fy16osti/66071.pdf

[109] ORNL defines a large-tow bundle as an untwisted bundle of greater than or equal to 24K filaments.

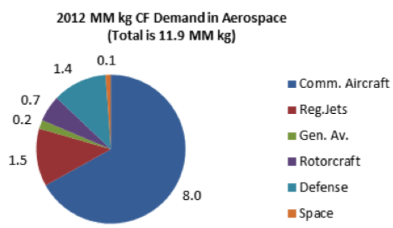
[110] A recent cost analysis of 100m carbon spar cap with foam blade using Vacuum Assisted Resin Transfer Molding (VARTM) infusion with several preform components indicates that materials account for 75% of total blade cost, as shown below.



Cost breakdown of a 100m carbon spar blade. See, Griffith, D. T. and W. Johanns "Large Blade Manufacturing Cost Studies Using the Sandia Blade Manufacturing Cost Tool and Sandia 100-meter Blades," SAND2013-2734, Sandia National Laboratories, Albuquerque, NM, Apr 2013. http://energy.sandia.gov/energy/renewable-energy/wind-power/offshore-wind/offshore-wind-sandia-large-rotor-development/.

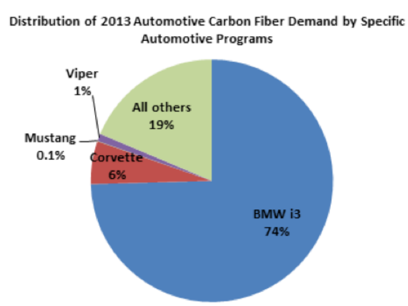
[111] Clean Energy Manufacturing Analysis Center, "2015 Research Highlights", Joint Institute for Strategic Energy Analysis, 2016, National Renewable Energy Laboratory NREL/BR-6A50-65312, March 2016, http://www.nrel.gov/docs/fy16osti/65312.pdf

[112] Commercial aircraft is a strong driver of this increase in demand within the aerospace sector, and its two dominant companies, Boeing and Airbus, as can be seen in figure below.



Breakdown of aerospace CF demand by sector. See: "Growth Opportunities in the Global Carbon Fiber Market: 2013-2018," Lucintel, Irving, TX Nov 2012. http://www.lucintel.com/reports/chemical_composites/growth_opportunities_in_china_carbon_fiber_market_2013-2018_trend_forecast_and_competitive_analysis_august_2013.aspx

[113] The distribution of automotive CF demand with respect to these key automotive programs is seen below. The BMW i3 electric vehicle program and the three North American programs account for more than 80% of present CF demand by the automotive industry. The "All others" category contains the Volkswagen Group, owner of many of the luxury brands (Lamborghini, Porsche, Bentley, Bugatti, Ducati) who were among the first to use CF for automotive applications. See for example, Sloan, J., "Carbon Fiber 2013 Report, Part 2: Automotive", http://www.compositesworld.com/blog/post/carbon-fiber-2013-report-part-1-automotive.



Distribution of 2013 automotive carbon fiber demand by specific automotive programs (Sloan 2013).

[114] Das, S., J. Warren, D. West, and S. M. Schexnayder, "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis," Oak Ridge National Laboratory, Technical Report ORNL/SR-2016/100 and NREL/TP-6A50-66071, May 2016, http://www.nrel.gov/docs/fy16osti/66071.pdf

[115] Clean Energy Manufacturing Analysis Center, "2015 Research Highlights", Joint Institute for Strategic Energy Analysis, 2016, National Renewable Energy Laboratory NREL/BR-6A50-65312, March 2016, http://www.nrel.gov/docs/fy16osti/65312.pdf

[116] Historically, a combination of publicly-funded R&D, direct grants to industry, and public-private partnerships have helped enable the development of a strong domestic carbon fiber manufacturing in Japan. On the other hand, the U.S. Commerce Department restricts the export of goods and technology that could contribute to military potential or nuclear proliferation of other nations, including carbon fiber. Carbon fiber precursors, including manufacturing equipment are export-controlled today even with the anticipated large growth in the non-defense sector in the future. Das, S., J. Warren, D. West, and S. M. Schexnayder, "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis," Oak Ridge National Laboratory, Technical Report ORNL/SR-2016/100 and NREL/TP-6A50-66071, May 2016, http://www.nrel.gov/docs/fy16osti/66071.pdf

[117] For additional information, see QTR Chapter 6 and the associated technical appendices at: http://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015-omnibus

[118] The term "Valley of Death" describes the challenge of transitioning a technology from the drawing board to commercial deployment. Two "Valleys of Death" are discussed. The first "Valley of Death" describes the period of transition of a promising developing technology to demonstration stage, showing the promise of commercial deployment. The second "Valley of Death" describes the period transitioning from the demonstration stage to commercial scale.

- For analyses of the Valley of Death phenomenon, see:
  - Branscomb, L. and P. Auerswald, "Valleys of Death and Darwinian Seas: Financing the Invention to Innovation Transition in the United States," The Journal of Technology Transfer 28(3-4), August 2003. http://link.springer.com/article/10.1023%2FA%3A1024980525678.
  - Tassey, G., "Rationales and Mechanisms for Revitalizing US Manufacturing R&D Strategies," Journal of Technology Transfer 35, no. 3 (2010): 283-333. http://www.nist.gov/director/planning/upload/manufacturing_strategy_paper.pdf.
  - Boroush, M., "NSF Releases New Statistics on Business Innovation," National Science Foundation, October 2010. http://www.nsf.gov/statistics/infbrief/nsf11300/.
- DOE supports RDD&D where the second "D" refers to demonstration. As such, the first valley of death is to some extent addressed through technology demonstrations while the second valley of death is addressed to an extent by the DOE Loan Programs Office that finances scale up and commercialization efforts.

[119] The second volume of the MIT "*Production in the Innovation Economy*" report has an important study on the problem faced by startups, including in energy startups, of obtaining financing for production scale up in non-IT/software sectors; volume one discusses the problem that manufacturing SMEs have in getting financing for this stage.

[120] Critical Materials Institute (CMI) Energy Innovation Hub is working to assure supply chains of materials critical to clean energy technologies. See: https://cmi.ameslab.gov/.

[121] Many U.S. consumer electronics companies opted to transfer large-volume, low-margin manufacturing to offshore producers as early as 1950s. The appeal ranged from incentives by the host country (e.g., tax breaks, low-cost or free land) to low labor cost. A growing number of analysts have presented case studies on companies that showed that once manufacturing activity moves overseas, so do the required skills, networks, and supply chains; and once offshore the manufacturing activities, and the learning they engender, are difficult to recover.

For example:

- Locke, R. M. and R. L. Wellhausen, Editors, *"Production in the Innovation Economy"*, The MIT Press, 2014.
- Berger, S., Making In America, MIT Press, 2013.
- Pisano, G. P., and W. C. Shih, "Restoring American Competitiveness," Harvard Business Review, July-August 2009. https://hbr.org/2009/07/restoring-american-competitiveness/ar/1.
- Rappaport, A., "Outsourcing isn't a Problem for Silicon Valley but is for Detroit," Harvard Business Review, October 9, 2009. https://hbr.org/2009/10/outsourcing-isnt-a-problem-for/.
- Ezell, S. J., and R. D. Atkinson, "The Case for a National Manufacturing Strategy," Information Technology and Innovation Foundation, April 2011. http://www2.itif.org/2011-national-manufacturing-strategy.pdf.

[122] For an example:

- Tassey, G., "The Manufacturing Imperative," in *"Strengthening American Manufacturing: The Role of the Manufacturing Extension Partnership"*, National Research Council, 2013. http://www.nap.edu/catalog/18329/strengthening-american-manufacturing-the-role-of-the-manufacturing-extension-partnership.
- Tassey, G., *"The Technology Imperative"*, Edward Elgar, 2009.
- Pisano, G. P. and W. C. Shih. "Does America Really Need Manufacturing?" Harvard Business Review 90(3), March 2012. https://hbr.org/2012/03/does-america-really-need-manufacturing/ar/1.

For discussion on the impact of a weakened supply chain onto U.S. competitiveness, see:

- Tassey, G., "Rationales and Mechanisms for Revitalizing U.S. Manufacturing R&D Strategies," The Journal of Technology Transfer, January 29, 2010. http://www.nist.gov/director/planning/upload/manufacturing_strategy_paper.pdf.

[123] New tools, technologies, and platforms are making it faster and cheaper to prototype products, creating novel opportunities for entrepreneurship in manufacturing in the United States. For example:

- Additive manufacturing can reduce the cost of designing and prototyping automobile components by as much as 99%.
- New online communities can help entrepreneurs rapidly assemble the appropriate workforce.
- New technologies and computer aided design tools can dramatically lower the cost of prototyping in manufacturing.

For example:

- Ford Press Release, "Ford's 3D-Printed Auto Parts Save Millions, Boost Quality," December 12, 2013." https://media.ford.com/content/fordmedia/fna/us/en/news/2013/12/12/ford_s-3d-printed-auto-parts-save-millions--boost-quality.html.
- "Making in America: U.S. Manufacturing Entrepreneurship and Innovation," The Executive Office of The President, June 2014. https://www.whitehouse.gov/sites/default/files/docs/manufacturing_and_innovation_report.pdf.

[124] "The Role of the Chemical Sciences in Finding Alternatives to Critical Resources: A Workshop Summary," NAP, 2012. http://www.ncbi.nlm.nih.gov/books/NBK97332/. Chapter 6, Critical Materials in Large-Scale Battery Applications, provides extensive discussion of the dependence of batteries and other energy storage technology on critical materials.

[125] For a detailed discussion on trends in advanced materials and integrated computational materials engineering, see Shipp, S. S., "Emerging Global Trends in Advanced Manufacturing," Institute for Defense Analysis, March 2012. http://www.wilsoncenter.org/sites/default/files/Emerging_Global_Trends_in_Advanced_Manufacturing.pdf

For the current and future outlook for critical materials used in sustainable energy applications, and a research and development agenda across the supply chain to mitigate the effects of material criticality on achieving a sustainable energy future, see:

- "Critical Materials for Sustainable Energy Applications," Resnick Institute Report, California Institute of Technology, September 2011. http://resnick.caltech.edu/docs/R_Critical.pdf.
- "Critical Materials Strategy," U.S. Department of Energy, December 2011. http://energy.gov/epsa/initiatives/department-energy-s-critical-materials-strategy.

The Critical Materials Institute (CMI) Energy Innovation Hub is working to assure supply chains of materials critical to clean energy technologies. https://cmi.ameslab.gov/.

[126] Industrial commons is a term that describes the complex and enduring partnerships among manufacturers, universities, technical colleges, firms, research institutes, financing entities, and other links in the supply chain. To remain competitive, companies require an industrial commons that includes not just suppliers of advanced materials, production equipment, and components, but also R&D know-how, advanced process development and engineering skills, and manufacturing competencies.

- For example:
  - Pisano, G.P., "The U.S. is Outsourcing Away its Competitive Edge," Harvard Business Review, October 1, 2009, https://hbr.org/2009/10/the-us-is-outsourcing-away-its/.
  - Augustine, N.R., Chair, *Rising Above the Gathering Storm Committee, Is America Falling Off the Flat Earth?* National Academy of Sciences, National Academy of Engineering, and Institute of Medicine of the National Academies, 2007. http://www.nap.edu/catalog/12021/is-america-falling-off-the-flat-earth.
- This was originally called "industrial clusters. In "The Competitive Advantages of Nations", Michael Porter makes the case that industrial clusters have the potential to affect competition in three ways: by increasing the productivity of the companies in the cluster, by driving innovation in the field, and by stimulating new businesses in the field. See Porter, M.E., *"The Competitive Advantage of Nations"*, New York: The Free Press. 857 pgs. 1990.

[127] This is in contrast to Apple, Qualcomm, and Cisco where they took full advantage of the "modularity" of the global economy. They focused their business model on the design of their products and associated information systems; offshoring the industrial work did not leave them at a disadvantage.

See:

- Berger, S., *"Making In America"*, MIT Press, 2013.
- Fuchs, E., "Global manufacturing and the future of technology," 1 August 2014 Science, Vol 345 Issue 6196. http://www.sciencemag.org/content/345/6196/519.
- Bonvillian, W., "Advanced Manufacturing Policies and Paradigms for Innovation", Science, V.342, 6 Dec. 2013. http://www.sciencemag.org/content/342/6163/1173.

[128] Additional discussions on the importance of the industrial commons on manufacturing competitiveness, see MIT "*Production in the Innovation Economy*", MIT Press 2013.

[129] Goodrich, A.C., D. M. Powell, T. L. James, M. Woodhouse, and T. Buonassisi, "Assessing the drivers of regional trends in solar photovoltaic manufacturing," Energy & Environmental Sciences, 2013. http://pubs.rsc.org/en/content/articlelanding/2013/ee/c3ee40701b#!divAbstract.

[130] Economists refer to this concept as the tradability of a product. Tradability is the property of a product that can be sold in another location distant from where it was produced. See for example, M. Macintyre et al. (eds.), *Service Design and Delivery*, Springer Science+Business Media, LLC, 2011.

Discussions on the tradability of PV can be found in, for example, Woodhouse, M., A. Goodrich, R. Margolis, T. L James, M. Lokanc, and R. Eggert, "Supply-Chain Dynamics of Tellurium, Indium and Gallium Within the Context of PV Module Manufacturing Costs," IEEE Journal of Photovoltaics, April 2013. http://www.nrel.gov/docs/fy13osti/56883.pdf.

Discussions on the tradability of wind turbine blades can be found in, for example, James T., and A. Goodrich, "Supply Chain and Blade Manufacturing Considerations in the Global Wind Industry," National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/60063.pdf.

[131] Additional discussion can be found in "*Global Trade and Conflicting National Interests*", where Gomory and Baumol note that, in a world of capital mobility and economies of scale, once capital is established in a country it tends to remain in that country. In other words, once an industry is captured by a country that industry is "retainable." Once an industry is developed in a country, new competitors have difficulty entering that market since they cannot take advantage of scale economies. The corollary is also true, once an industry reaches scale at a country, it is unlikely to leave that country. Gomory, R.E. and W. J. Baumol, "*Global Trade and Conflicting National Interests*", MIT Press, 2001.

[132] New technologies for rapid prototyping – from laser cutters to CNC routers to 3D printers – have dramatically lowered the cost of developing a prototype. See, "Making in America: U.S. Manufacturing Entrepreneurship and Innovation," The Executive Office of the President, June 2014. https://www.whitehouse.gov/sites/default/files/docs/manufacturing_and_innovation_report.pdf.

[133] Forums such as Sustainable Energy for All (SE4All) Forum, 4-6 June 2014, attendees from the European Union, China, Iceland, and Sierra Leone emphasized the need for innovative technical and investment solutions to provide universal access to sustainable energy. See, "Report on Sustainable Energy for All (SE4All) Forum, 4-6 June 2014", United Nations, 2014. http://www.se4all.org/se4all-forum/.

[134] Technological developments alone will not be sufficient to transform the energy harnessing landscape. New business models, capital, etc. Moreover, a collaborative innovation approach is needed. Many technologies that could be game changing need to be developed in different areas, ranging from advances in computational management to advanced materials and marketization. See: King, Sir David and C. Grey, "Energy Harnessing: New Solutions for Sustainability and Growing Demand," World Economic Forum 2013. http://www.weforum.org/reports/energy-harnessing-new-solutions-sustainability-and-growing-demand.

[135] Of the 1.5 billion people that have no access to electricity, 85% live in rural areas or on the fringes of the cities. The United Nations estimates that an average of $35-$40 billion a year needs to be invested until 2030 so everyone on the planet can cook, heat and light their premises, and have energy for productive uses.

See:

- The Secretary-General's Advisory Group on Energy and Climate Change (AGECC), "Energy for a Sustainable Future, Report and Recommendations," United Nations, 28 April 2010 New York. http://www.un.org/wcm/webdav/site/climatechange/shared/Documents/AGECC%20summary%20report%5B1%5D.pdf.
- "Energy in the Developing World: Power to the People," The Economist, September 2, 2010. http://www.economist.com/node/16909923.

[136] OECD defines the Global Value Chain as "the full range of activities that are required to bring a product from its conception, through its design, its sourced raw materials and intermediate inputs, its marketing, its distribution and its support to the final consumer," as defined by Duke University's Global Value Chains Initiatives. http://www.globalvaluechains.org/concepts.html.

See:

- Gereffi, G. and K. Fernandez-Stark, "Global Value Chain Analysis: A Primer, Center on Globalization, Governance & Competitiveness (CGGC)," Duke University, May 31. http://www.cggc.duke.edu/pdfs/2011-05-31_GVC_analysis_a_primer.pdf.
- Donofrio, N.M. and K. S. Whitefoot, Editors, *"Making Value for America: Embracing the Future of Manufacturing, Technology, and Work"*, National Academy of Science, 2015. http://www.nap.edu/catalog/19483/making-value-for-america-embracing-the-future-of-manufacturing-technology.

[137] A more extensive review is provided by: U.S. DOE, "The Clean Energy Manufacturing Initiative: Strengthening American Manufacturing and Clean Energy Innovation", DOE/EE-1462, http://www.energy.gov/eere.cemi, and http://www.energy.gov/sites/prod/files/2016/10/f33/CEMI%20Publication-WebR.pdf

[138] The partnership with the Council on Competitiveness is the American Energy and Manufacturing Competitiveness (AEMC) Partnership and is described at: http://www.compete.org/programs/compete-energy-manufacturing/aemc

[139] U.S. DOE, "The Clean Energy Manufacturing Initiative: Strengthening American Manufacturing and Clean Energy Innovation", DOE/EE-1462, http://www.energy.gov/eere.cemi, and http://www.energy.gov/sites/prod/files/2016/10/f33/CEMI%20Publication-WebR.pdf

[140] "Manufacturing USA – the National Network for Manufacturing Innovation", https://www.manufacturing.gov/nnmi/

"National Network for Manufacturing Innovation", http://energy.gov/eere/amo/national-network-manufacturing-innovation

[141] "National Network for Manufacturing Innovation: A Preliminary Design," Executive Office of the President National Science and Technology Council, Advanced Manufacturing National Program Office, Executive Office of the President, January 2013. http://www.manufacturing.gov/docs/nnmi_prelim_design.pdf.

"Manufacturing USA—the National Network for Manufacturing Innovation", https://www.manufacturing.gov/nnmi/

[142] As indicated in "National Network for Manufacturing Innovation: A Preliminary Design", there are gaps that separate American inventions, research discoveries, and ideas from the development and scale-up of domestic manufacturing. Examples of gaps are

- Market failures that deter private-sector investment in advanced technologies.
- Technology development time horizons driven by investor expectations for realizing returns.
- The challenges in scale-up, as technologies and products become ever-more complex and their life cycles shrink.
- The lack of network of organizations—from suppliers of equipment, parts, and services to schools, colleges, and training programs to utilities and other infrastructure systems.
- Increased innovation to remain globally competitive.

The NNMI program is designed to address these gaps to bring together industry; universities (including community colleges); and local, State and Federal governments to spur manufacturing innovation. Each institute will focus on building clusters of advanced manufacturing capabilities that join expertise from industry, academia, and government; in essence forming an industrial commons.

See also,

- "Capturing Domestic Competitive Advantage in Advanced Manufacturing," AMP Steering Committee Report, President's Council of Advisors on Science and Technology, Executive Office of the President, July 2012. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf.
- "A National Strategic Plan for Advanced Manufacturing," President's Council of Advisors on Science and Technology, Executive Office of the President, February 2012. https://www.whitehouse.gov/sites/default/files/microsites/ostp/iam_advancedmanufacturing_strategicplan_2012.pdf
- http://www.manufacturing.gov/.

[143] The Next Generation Power Electronics National Manufacturing Innovation Institute (PowerAmerica) is focused on making wideband gap (WBG) power electronics cost-competitive within five years. PowerAmerica activities are focused on device manufacturing, WBG specific power module development and electronics to exploit the attributes of WBG devices. http://www.ncsu.edu/power/.

[144] The Institute for Advanced Composites Manufacturing Innovation works to develop new low-cost, high-speed, and efficient manufacturing and recycling process technologies that will promote widespread use of advanced fiber-reinforced polymer composites. http://energy.gov/eere/amo/institute-advanced-composites-manufacturing-innovation.

[145] "President Obama Announces Winner of New Smart Manufacturing Innovation Institute and New Manufacturing Hub Competitions", White House, Office of the Press Secretary, June 20, 2016, https://www.whitehouse.gov/the-press-office/2016/06/20/fact-sheet-president-obama-announces-winner-new-smart-manufacturing

"Clean Energy Smart Manufacturing Innovation Institute", https://smartmanufacturingcoalition.org/

[146] "Energy Department Announces American Institute of Chemical Engineers to Lead New Manufacturing USA Institute", December 9, 2016, https://energy.gov/articles/energy-department-announces-american-institute-chemical-engineers-lead-new-manufacturing

[147] "Energy Department Launches New Manufacturing USA Institute Focused on Recycling and Reusing Materials", January 4, 2017, https://energy.gov/articles/energy-department-launches-new-manufacturing-usa-institute-focused-recycling-and-reusing

[148] "America Makes", https://www.americamakes.us/about/overview

[149] "LIFT—Lightweight Innovations for Tomorrow", http://lift.technology/

[150] A summary of on-going NNMIs can be found at http://manufacturing.gov/welcome.html.

[151] Materials Genome Initiative, https://www.whitehouse.gov/mgi

[152] "Report to the President: Accelerating U.S. Advanced Manufacturing", Executive Office of the President, President's Council of Advisors on Science and Technology, October 2014. https://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf

[153] Energy Materials Network, http://www.energy.gov/eere/energy-materials-network/energy-materials-network

[154] "Electrocat: ElectroCatalysis Consortium", http://www.electrocat.org/

[155] "CaloriCool", https://www.caloricool.org/

[156] "LightMAT: Lightweight Materials Consortium", https://lightmat.org/

[157] Energy Materials Network Workshop, http://energy.gov/eere/sunshot/downloads/energy-materials-network-workshop

[158] These activities help remove the capital cost barrier in laboratory and testing equipment that would have prevented a clean energy technology from being demonstrated and validated. Furthermore, drawing upon the idea of the industrial commons, these facilities help foster collaboration between national laboratories, universities, and companies (small, medium, and large alike).

[159] Critical Materials Institute (CMI) Energy Innovation Hub is working to assure supply chains of materials critical to clean energy technologies. https://cmi.ameslab.gov/. Additional efforts within DOE include projects related to the batteries and magnets in electric vehicles (Vehicles Technologies Office, VTO) and the recovery of lithium from geothermal brines (Geothermal Technology Office, GTO).

[160] Vehicle Systems Integration Laboratory (VSI), a collaboration between DOE's VTO and ORNL, enables integrated testing of vehicle powertrain technologies, including hybrid systems. http://www.ornl.gov/science-discovery/clean-energy/research-areas/transportation/vehicle-systems.

[161] ORNL's Manufacturing Demonstration Facility provides industry with affordable and convenient access to facilities, tools and expertise to facilitate rapid deployment of advanced manufacturing technologies to enhance the competitiveness of U.S. manufacturing, with particular focus on additive manufacturing, composites manufacturing, carbon fiber manufacturing, and battery manufacturing. http://web.ornl.gov/sci/manufacturing/mdf/.

[162] DOE's Materials Engineering Research Facility (MERF) at Argonne National Laboratory (ANL) and DOE's Battery Manufacturing R&D Facility at ORNL aid in moving innovations from the lab to the marketplace. The MERF develops processes and scales up battery materials from the gram quantities in the lab to the tens of kilograms quantities needed for evaluation by industry. The Battery Manufacturing R&D Facility develops and demonstrates advanced manufacturing processes that reduce the cost of battery manufacturing. http://www.anl.gov/energy-systems/facilities/materials-engineering-research-facility.

[163] The Joint Center for Energy Storage Research is the Energy Innovation Hub for Battery and Energy Storage within Basic Energy Sciences. It aims to enable next generation batteries and energy storage for the grid and for transportation by delivering electrical energy storage with five times the energy density and one-fifth the cost of today's commercial batteries within five years. www.jcesr.org.

[164] The collaboration with U.S. Advanced Battery Consortium (USABC) supports clean energy manufacturing by conducting battery manufacturing R&D on advanced battery technologies that reduce lithium-ion battery materials costs and manufacturing process costs. http://www.uscar.org/guest/index.php.

[165] "Build4Scale: Training Cleantech Entrepreneurs for Manufacturing Success", http://energy.gov/eere/articles/build4scale-training-cleantech-entrepreneurs-manufacturing-success

"DOE Announces Manufacturing Training for Cleantech Entrepreneurs", http://energy.gov/eere/articles/doe-announces-manufacturing-training-cleantech-entrepreneurs

[166] High Performance Computing for Manufacturing (HPC4Mfg), Accelerating Innovation, https://hpc4mfg.llnl.gov/

[167] Oak Ridge National Laboratory Manufacturing Demonstration Facility, http://web.ornl.gov/sci/manufacturing/

[168] Investments by the U.S. Department of Energy's Loan Programs Office (LPO) has supported the deployment of innovative clean energy projects and advanced vehicle-manufacturing facilities across the United States. To date, LPO supports a diverse portfolio of more than $30 billion in loans, loan guarantees, and commitments, covering more than 30 projects across the country. The current projects focus on Advanced Fossil Energy, Renewable Energy and Energy Efficiency, and Advanced Nuclear Energy. http://energy.gov/lpo/loan-programs-office.

[169] The Superior Energy Performance® (SEP™) Program is an example of technical assistance to manufacturers focused on implementing energy efficiency technologies. SEP utilizes the ISO 50001-energy management system standard as its foundation and is designed to help facilities improve their energy performance. http://www.energy.gov/eere/amo/superior-energy-performance.

[170] Technology Assistance Partnerships (TAPs), in working with national laboratories and companies, focus on the deployment of energy efficiency technologies such as combined heat & power (CHP) and waste heat to power. http://energy.gov/eere/amo/chp-technical-assistance-partnerships-chp-taps.

[171] Better Plants, http://energy.gov/eere/amo/better-plants

[172] Industrial Assessment Centers, http://energy.gov/eere/amo/industrial-assessment-centers-iacs

[173] Small Business Vouchers Program, https://www.sbv.org/about.html

[174] U.S. DRIVE (United States Driving Research and Innovation for Vehicle efficiency and Energy), is a government-industry partnership focused on accelerating the development of pre-competitive and innovative technologies to enable a full range of affordable and clean advanced light-duty vehicles. http://www.uscar.org/guest/partnership/1/us-drive.

[175] http://techportal.eere.energy.gov/commercialization/natlbizplan.html.

[176] Information on activities such as SBIR/STTR can be found at http://energy.gov/eere/about-us/technology-market-team.

[177]U.S. DOE, "The Clean Energy Manufacturing Initiative: Strengthening American Manufacturing and Clean Energy Innovation", DOE/EE-1462, http://www.energy.gov/eere.cemi, and http://www.energy.gov/sites/prod/files/2016/10/f33/CEMI%20Publication-WebR.pdf

[178] "Technologist in Residence Program, http://energy.gov/eere/cemi/technologist-residence-program

[179] Cyclotron Road, "Where breakthrough energy technologies are born", http://www.cyclotronroad.org/

[180] Chain Reaction Innovations, http://chainreaction.anl.gov/

[181] Innovation Crossroads, http://innovationcrossroads.org/

[182] U.S. Department of Energy, "Revolution Now: The Future Arrives for Five Clean Energy Technologies – 2016 Update", http://energy.gov/eere/downloads/revolutionnow-2016-update

Acronyms

AMP 2.0	Advanced Manufacturing Partnership 2.0
ANL	Argonne National Laboratory
CAFÉ	Corporate Average Fuel Economy
CaloriCool	Caloric Materials Consortium
CEMAC	Clean Energy Manufacturing Analysis Center (DOE/NREL)
CEMI	Clean Energy Manufacturing Initiative (DOE)
CFRP	Carbon Fiber Reinforced Plastic
CFRTP	Carbon fiber Reinforced Thermoplastic
CMI	Critical Materials Institute
DMDI	Digital Manufacturing and Design Innovation Institute
DOC	Department of Commerce
DOD	Department of Defense
DOE	U.S. Department of Energy
ElectroCat	Electrocatalysis Consortium
EMN	Energy Materials Network
EV	Electric vehicles
GDP	Gross domestic product
Gr	Graphite anodes (in LIBs)
GW	Gigawatts
HPRTM	High-pressure Resin Transfer Molding
IAC	Industrial Assistance Center
IEA	International Energy Agency
LED	Light emitting diode
LIB	Lithium ion battery
LIFT	Lightweight Innovations for Tomorrow
LightMAT	Lightweight Materials National Laboratory Consortium
LPO	Loan Program Office of DOE
MDF	Manufacturing Demonstration Facility

MERF	Materials Engineering Research Facility (MERF)
MIT	Massachusetts Institute of Technology
MOCVD	Metal Organic Chemical Vapor Deposition
MWh	Megawatt hours
NCEBPC	National Clean Energy Business Plan competition (DOE)
NiCad	Nickel-cadmium battery
NiMH	Nickel-metal hydride battery
NMC	Nickel-manganese-cobalt (cathodes in LIBs)
NNMI	National Network for Manufacturing Innovation
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
OECD	Organization for Economic Cooperation and Development
OLED	Organic LED
ORNL	Oak Ridge National Laboratory
OTA	U.S. Congress Office of Technology Assessment (de-funded)
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
QC/QA	Quality control/quality assurance
QTR	Quadrennial Technology Review 2016
RDD&D	Research, development, demonstration, and deployment
REMADE	Recycling and Remanufacturing Innovation Institute (Reducing embodied Energy and Decreasing Emissions)
RTM	Resin Transfer Molding (For CFRPs)
SBIR/STTR	Small Business Innovation Research/Small Business Technology Transfer Program
SiC	Silicon-carbide (Substrates for LEDs)
SSL	Solid state lighting
SEPTM	Superior Energy Performance®
TAP	Technology assistance partnership
USABC	U.S. Advanced Battery Consortium

VSI	Vehicle Systems Integration Laboratory
VTO	Vehicle Technologies Office of DOE