2015 RESEARCH HIGHLIGHTS

CEMAC Clean Energy Manufacturing Analysis Center

Operated by the Joint Institute for Strategic Energy Analysis

New Organization, New Insights for a New Energy Economy

In September 2015, I was honored to speak at the American Manufacturing and Competitiveness Summit in Washington, D.C. The event, co-hosted by the U.S. Department of Energy and the Council on Competitiveness, brought together leaders from industry, academia, labor, the U.S. national laboratories, government, and media to address critical energy and manufacturing issues. But the event was more than that for us at the Clean Energy Manufacturing Analysis Center (CEMAC)—the event served as our official "launch party." Dr. David Danielson, Assistant Secretary of Energy for Energy Efficiency and Renewable Energy, introduced CEMAC in his opening remarks, and various participants expressed their enthusiasm for CEMAC's work.

As Dr. Danielson said, the tent is big when it comes to clean energy manufacturing. The scope is broad and the opportunity is huge. Global investment in clean energy surged to more than $300 billion in 2015.

Investment in energy systems—and particularly clean energy systems—presents opportunity in the strategic area of clean energy manufacturing. Who will benefit from that investment? CEMAC aims to help governments, industries, and investors gain insights into clean energy manufacturing supply chains, drivers of factory location decisions, and country-specific opportunities to capture value from clean energy manufacturing. As these collected highlights from our initial works demonstrate, CEMAC is making strides in its mission to provide new data, new analytics, and new insights that are needed to inform policy and investment decisions today and for decades to come.

I am excited that CEMAC is an integral part of the portfolio of the Joint Institute for Strategic Energy Analysis (JISEA). Thank you for your interest in CEMAC and JISEA. Together, we can envision and realize a cleaner, more resilient energy future.

Doug Arent, MBA, Ph.D.
Executive Director
Joint Institute for Strategic Energy Analysis
U.S. Department of Energy's National Renewable Energy Laboratory

Growing Markets, Growing Opportunity

One of the key challenges of the 21st century is meeting growing energy needs while stewarding our local and global environment and contributing to a healthier economy.

The shift to clean power generating capacity over the next 25 years is being accelerated by increasing economic competitiveness of wind, solar and other clean energy technologies. Electrification of transportation and increasing efficiency of vehicles is helping lower carbon impact while extending opportunities for mobility. Carbon fiber and other advanced materials and manufacturing processes are creating new ways to create goods more efficiently.

This market-driven shift creates a unique economic opportunity. Public and private investments in energy research, design, development, and deployment have catalyzed important advances in energy technology that can contribute to economic competitiveness and energy production.

This report is CEMAC's first research highlights publication, compiling the exciting findings from our first studies in 2015. Using detailed bottom-up cost analysis, CEMAC examines the dynamics and health of the full supply chains for clean energy technologies and from that gains insights to help policymakers, industry, and investors better understand the global market for clean energy technologies. CEMAC analysis illuminates why certain countries or regions lead in production of these technologies, and how or if those circumstances can be replicated elsewhere. Technologies spotlighted here—solar photovoltaics, wind turbines, automotive lithium-ion batteries, and carbon fiber manufacturing—represent work completed by CEMAC and DOE's National Laboratory network. Over time, CEMAC analysis will expand to encompass a more complete suite of clean energy technologies.

Thank you for your interest in CEMAC. We look forward to engaging with you in a prosperous, clean energy future.

Jill Engel-Cox, Ph.D.
Director
Clean Energy Manufacturing Analysis Center
U.S. Department of Energy's National Renewable Energy Laboratory

IMPORTANCE OF CLEAN ENERGY MANUFACTURING ANALYSIS

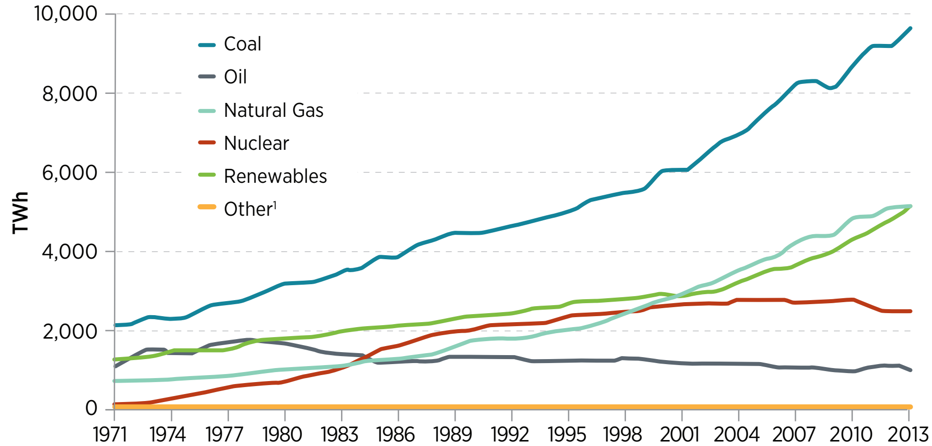
Global primary energy demand is likely to grow by more than 30% over the next 20 years, with much of the increased demand driven by emerging markets (Citi GPS 2015; REN21 2015; IEA 2015). Much of that demand is likely to be met with clean energy resources. Globally, annual investment in clean energy is approximately $300B and anticipated to grow from that level for many decades.

Meeting Growing Energy Demand with Clean Energy Technologies

CEMAC defines clean energy technologies as those that produce or deliver energy or energy services with fewer environmental impacts than conventional technologies, or enable existing technologies to operate more efficiently.

Traditional fossil fuel sources like coal and oil remain in abundant supply but are facing increasing competition from cleaner energy technologies due to a convergence of technology innovations, ongoing concerns over energy security, environmental impacts associated with traditional energy use, and dramatic cost declines of renewable energy. Many of these factors are pushing even traditional fossil-based generation to adopt efficiency and technology innovations that reduce the total system impact. With the historic Conference of Parties (COP21) agreement in Paris in late 2015, countries around the world, both developing and developed, made national commitments to cleaner power that could accelerate trends toward decarbonization.

In 2015, CEMAC focused on four technologies: solar photovoltaic modules, wind turbines, automotive lithium-ion batteries, and carbon fiber. The studies on these technologies are summarized in the following section. During these more detailed analyses of our inaugural year, we gained preliminary insights into clean energy manufacturing overall; specifically related to its adaptation to global economic dynamics and the factors influencing the location of manufacturing facilities in a global world.



[1] Includes non-renewable wastes, electricity from chemical heat and other sources (e.g. fuels cells)

Figure 1. Increase in global power generation, by source (1971–2013). Data source: International Energy Agency

Insight: Clean energy manufacturing is entering a new era—one that reflects the legacy of the past as well as new global dynamics.

The influences of these drivers, combined with finance and business model innovations, are driving the growth of clean energy technologies, opening the market to new producer and consumer segments globally (Stark et al. 2015). The 21st Century Power Partnership, a Clean Energy Ministerial initiative, lists innovations in business models and entrepreneurship, policy making, planning processes, operational practices, finance, regulation, and stakeholder engagement among additional forces helping drive the transformation to cleaner power systems (Miller et al. 2015).

Between 2004 and 2014, U.S. Energy Department data show that tumbling prices coincided with dramatic U.S. uptake across a range of technologies, including land-based wind, solar photovoltaic modules, electric vehicles, and A-type LED lighting. In some cases, expansion approached 100-fold, and cost reductions were on the magnitude of 50%–90% (DOE 2015). In a similar timeframe, renewables and cleaner technologies like natural gas captured larger shares of global power plant markets (Figure 1). Through 2040, levelized costs of wind and solar energy are expected to continue to fall while the costs of coal and gas remain stable (Citi GPS 2015).

Because many clean energy technologies, such as renewables and efficiency, do not require fuel for operations, the location and cost of the technology manufacturing and supporting operating costs become a larger factor in their contribution to the economy. Clean energy manufacturing analysis helps illuminate how and where the growing demand for clean energy technologies will likely be met.

Credible, objective, and geographically neutral data and insights can help governments and industries harness the opportunity provided by these market trends to inform investment strategies, policy, and other decisions to promote economic growth and competitiveness in the transition to a clean energy economy.

Insight: Multiple factors guide corporate strategy regarding factory location (Text Box 1), as CEMAC research has shown. These factors include indigenous factors (e.g., low labor costs, energy costs, resource availability), policy differences (e.g., taxes, tax incentives, interest rates, low-interest loans), existing infrastructure (e.g., transportation), existing supply chains, synergistic industries, and market characteristics (location, growth rate, competing products). Evaluating technologies at the research, development, demonstration, and deployment stages within the context of these factors can help to identify opportunities to target areas of high value-add manufacturing along the supply chain, and inform product and market strategies.

In the 1990s and 2000s, a trend toward locating manufacturing facilities overseas was largely driven by a desire to reduce costs by securing low-cost manufacturing labor (da Silveira 2014; Immelt 2012; Tate et al 2014; Booth 2013). For some manufacturers, low-cost labor continues to strongly influence location decisions. For others, labor savings may not justify costs associated with longer supply chains, transportation, and quality control. Figure 2 shows that for a range of clean energy technologies manufactured in the United States (and discussed in detail in this report), labor costs are a roughly equal share of normalized costs. However, the normalized cost of shipping, equipment, energy, and materials can vary greatly.

These are the types of insights that robust clean energy manufacturing analysis can provide. As we expand our technology analysis portfolio in future years, we can continue to inform and elevate the discussion of key factors related to the manufacture of clean energy technologies.

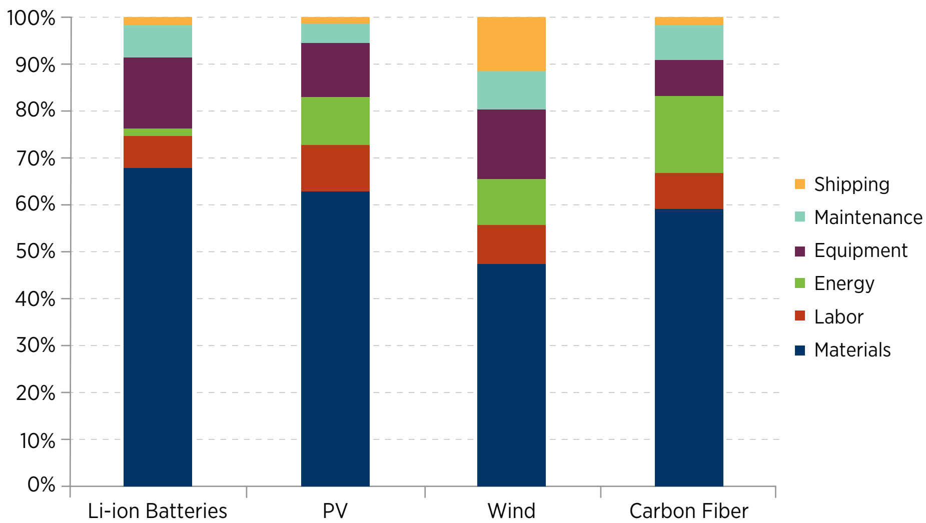


Figure 2. Normalized cost components for select clean energy technologies in the United States. Data source: CEMAC

Text Box 1. Factors Affecting Manufacturing Location Decisions

- Intellectual property protection
- Cost of energy
- Energy consumption
- Cost of manufacturing
- Availability of investment capital
- Low-cost labor requirements & availability
- Skilled labor requirements & availability
- Product quality
- Tax policy
- Currency fluctuations
- Import and export policies
- Automation/advanced manufacturing
- Raw material availability
- Transportation costs
- Existing supply chains
- Synergistic industries and clustering
- Existing or growing market
- Ease of doing business
- Safety
- Regulations
- Inventory costs and supply chain delays

MANUFACTURING ANALYSIS: Findings and Opportunities

CEMAC has conducted four major studies on the manufacturing of clean energy technologies. Three of these focused on the end product: solar photovoltaic modules, wind turbines, and automotive lithium-ion batteries. The fourth area focused on a key material for manufacturing clean energy technologies, carbon fiber.

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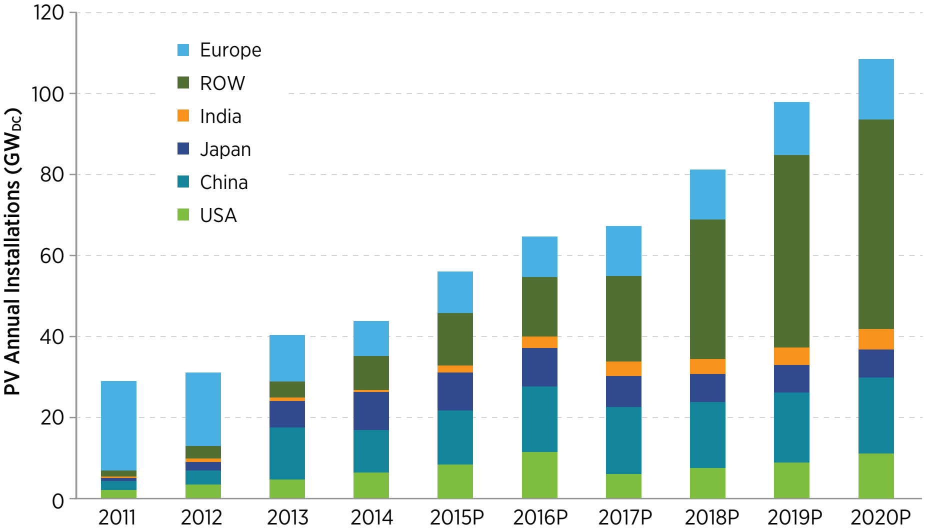
Solar Photovoltaic Modules

Michael Woodhouse, lead analyst for chapter

CEMAC analysts have undertaken thorough analysis of the manufacturing cost of PV technologies. This section will focus on silicon-based cells, although analysis has also been performed on other technologies such as cadmium telluride (CdTe), Copper indium gallium diSelenide (CIGS), and multi-junction and will be summarized in future studies. In 2015, 57 GW of PV was installed globally, an increase of nearly 30% from 2014 (BNEF 2016). This demand is roughly split between Europe, China, Japan, the United States, and emerging markets. With solar prices continuing to fall,



Note: P = Projection.

Figure 3. Historical, current, and projected global installations of photovoltaics. Data sources: Data displayed represents the median figures from the following sources: Henbest and Giannakopoulou 2015, Osborne, Boyes, and Sutton 2015, Shah and Booream-Phelps 2015, GTM 2015, Labastida and Gauntlett 2015.

SNAPSHOT: Solar PV Market

- In Q1 2015, the United States installed 1.3 GWDC of PV, the 6th consecutive quarter of 1GW+ installations.
- Total expected U.S. installations in 2015: 8 GW.
- Commissioned global installations in 2015: 57 GW.
- Announcements for new capacity to manufacture innovative PV products, including kerfless wafers and high efficiency cell designs, totaled 4.8 GW in 2015
- Several Chinese manufacturers report module costs of \$0.44-\$0.48/W—still a large range in module average selling prices but global average reported around \$0.67/W.
- 6–24 months: gap between a decision to invest in PV manufacturing capacity expansion and subsequent commissioning. Nominal average time is 12 months.

Data from Solar Energy Industry Association, Bloomberg New Energy Finance, Feldman, Margolis, and Boff, forthcoming and Basore, Chung, and Buonassisi 2015.

solar electricity is now cost competitive with many conventional sources, and is a preferred option for bringing clean, off-grid power to remote locations. Going forward, the "rest of the world (ROW)" segment of the market is expected to drive demand growth through 2020 (Figure 3, Snapshot text box). Global demand is projected to grow to 85 GW per year in 2019 with some analysts expecting more than 100 GW of demand. ROW will account for approximately half of demand by 2019 (Feldman, Margolis, and Boff).

According to Securities and Exchange Commission filings by leading PV manufacturers and integrators, average gross margins for manufacturing and installations have been less volatile since 2013. Top performers are consistently

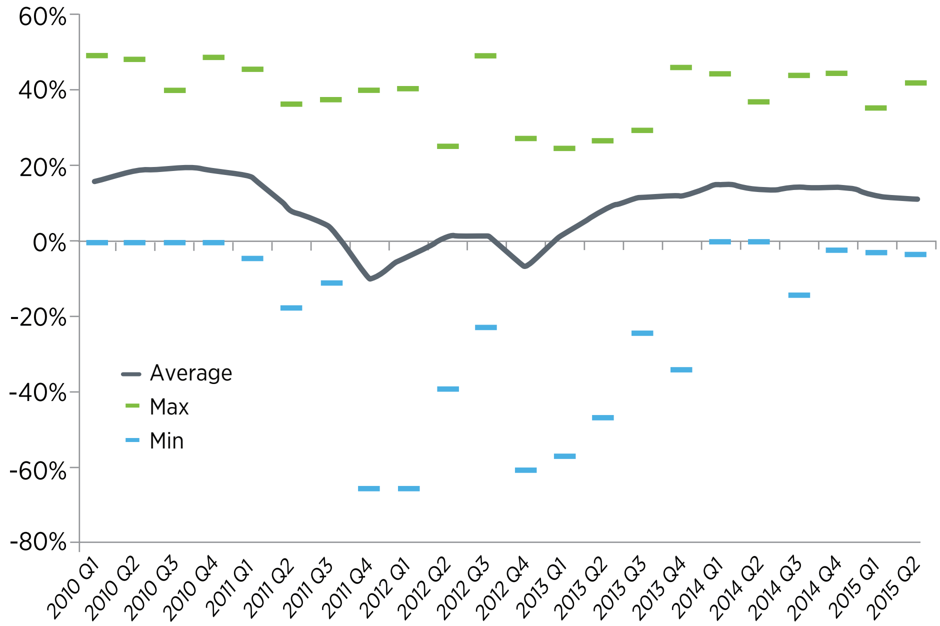


Figure 4. Average and range of gross margins across a sample of today's 20 largest solar photovoltaics manufacturing and installation firms. Data source: Bloomberg L.P. (2015). Operational results for companies included in Bloomberg Solar Energy industry coverage, 3rd Quarter 2004–1st Quarter 2015.

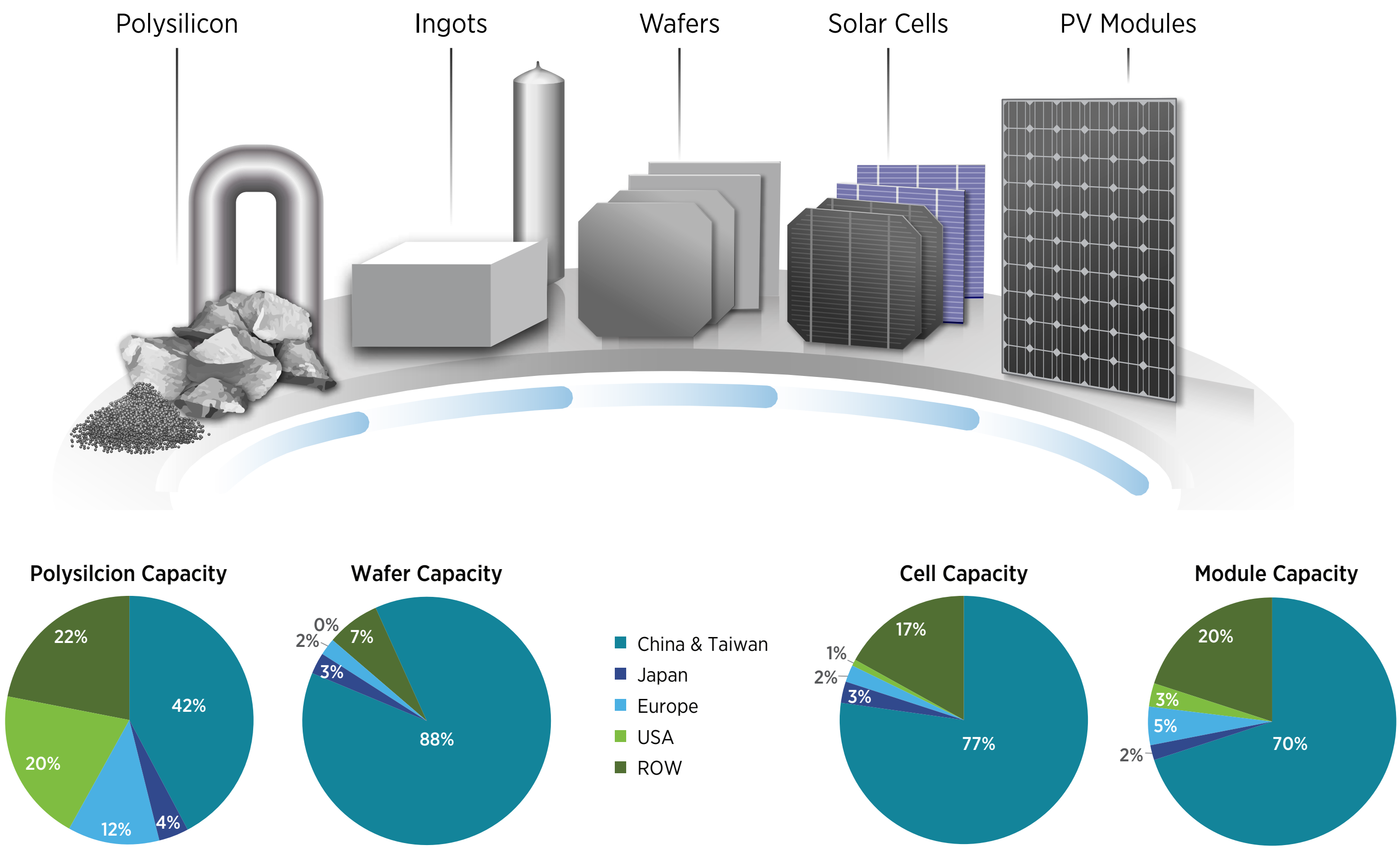


Figure 5. The wafer-based multi- and mono-crystalline silicon PV value chain and manufacturing capacity by country/region for each segment. Data source: NREL Solar Database

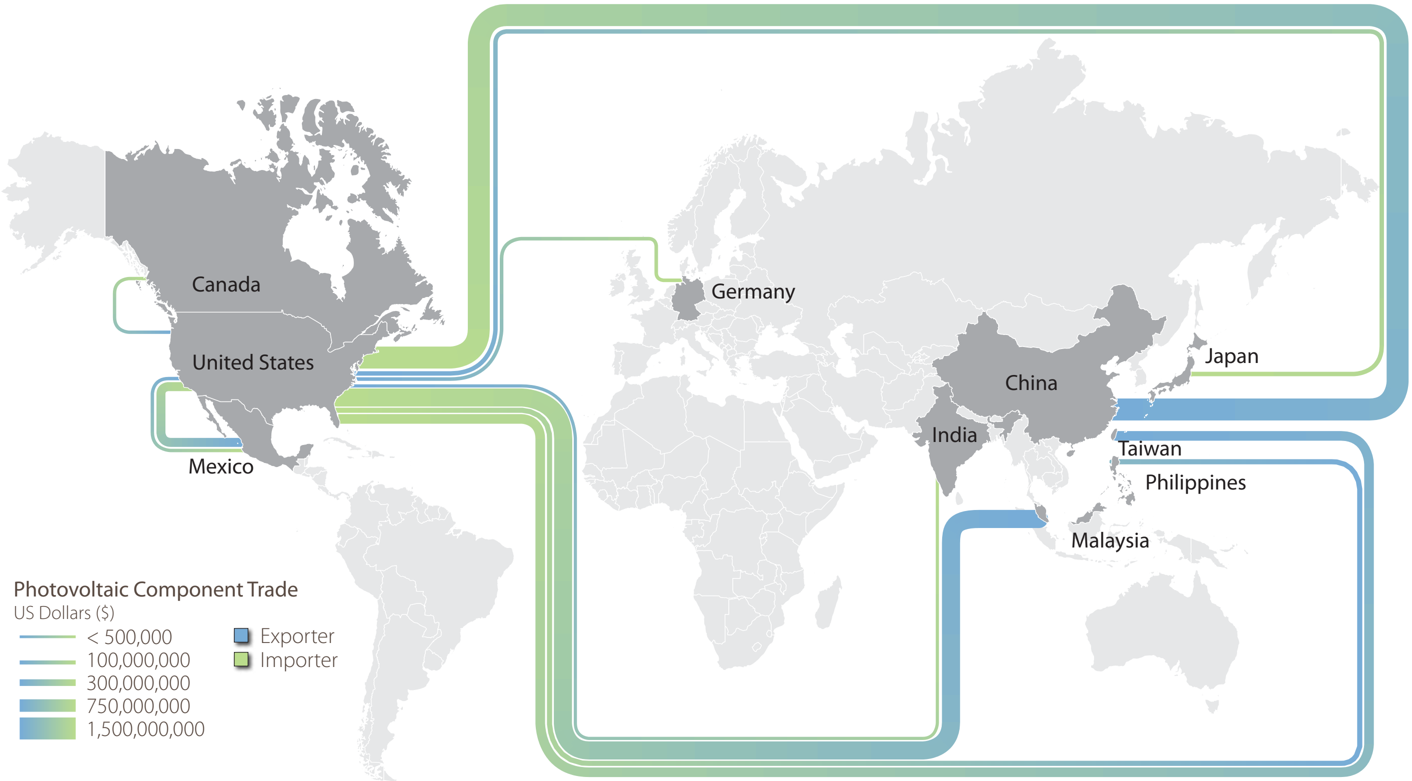


Figure 6. Value of trade in solar photovoltaic components between the United States and top five export markets and top five import sources, 3-year average (2012-2014)

obtaining gross margins near 40 percent while averages remain at approximately 16 percent in Q12015, after being in negative territory in 2011 and 2012 (Figure 4).

Manufacturing Today

Global PV manufacturing can be treated as an integrated value chain from polysilicon production through module assembly. Silicon-based PV modules are manufactured modularly via the discrete steps of polysilicon, wafer, cell, and module (Figure 5), all of which have relied on relatively standard product sizes and processes. These factors have facilitated commerce of intermediate products and the geographic diffusion of product and manufacturing-process technologies (Basore, Chung, and Buonassisi 2015).

PV modules are primarily a commodity product, and the industry and supply chains are global. Today, China is home to the majority of PV manufacturing capacity. Figure 6 and Figure 7 reflect China's dominance in each stage of the crystalline silicon (c-Si) PV module value chain: polysilicon, wafers, cells, and modules. Polysilicon production is the segment most equally distributed around the world. Several additional countries currently have wafer, cell, and module manufacturing production, including: China, Germany, India, Japan, Malaysia, Philippines, Singapore, South Korea, Taiwan, and the United States. In the thin-film arena, the dominating countries for manufacturing are Japan, China, Malaysia, and the United States. Emerging economies such as India have also become major draws for PV, and some are enacting policies to couple their growing demand with manufacturing (e.g., domestic content requirements). Going forward, innovative, high efficiency products are expected to grow in demand, and so the growth of the industry may center on facilities that have this focus. Several such additions have been announced within the United States in 2015.

Globally, factories have access to similar manufacturing technology, and the vast majority of manufacturers produce "off-the-shelf" technology. Although some manufacturers may differentiate their products based on performance, reliability, and appearance, price is the basis of competition between most manufacturers. Figure 8 shows the regional distribution of PV manufacturing activity in Asia. The distribution across Chinese provinces is driven by a balance between province-specific cost drivers, including local electricity and labor rates, and other manufacturing siting considerations (e.g., transportation infrastructure and access to skilled labor).

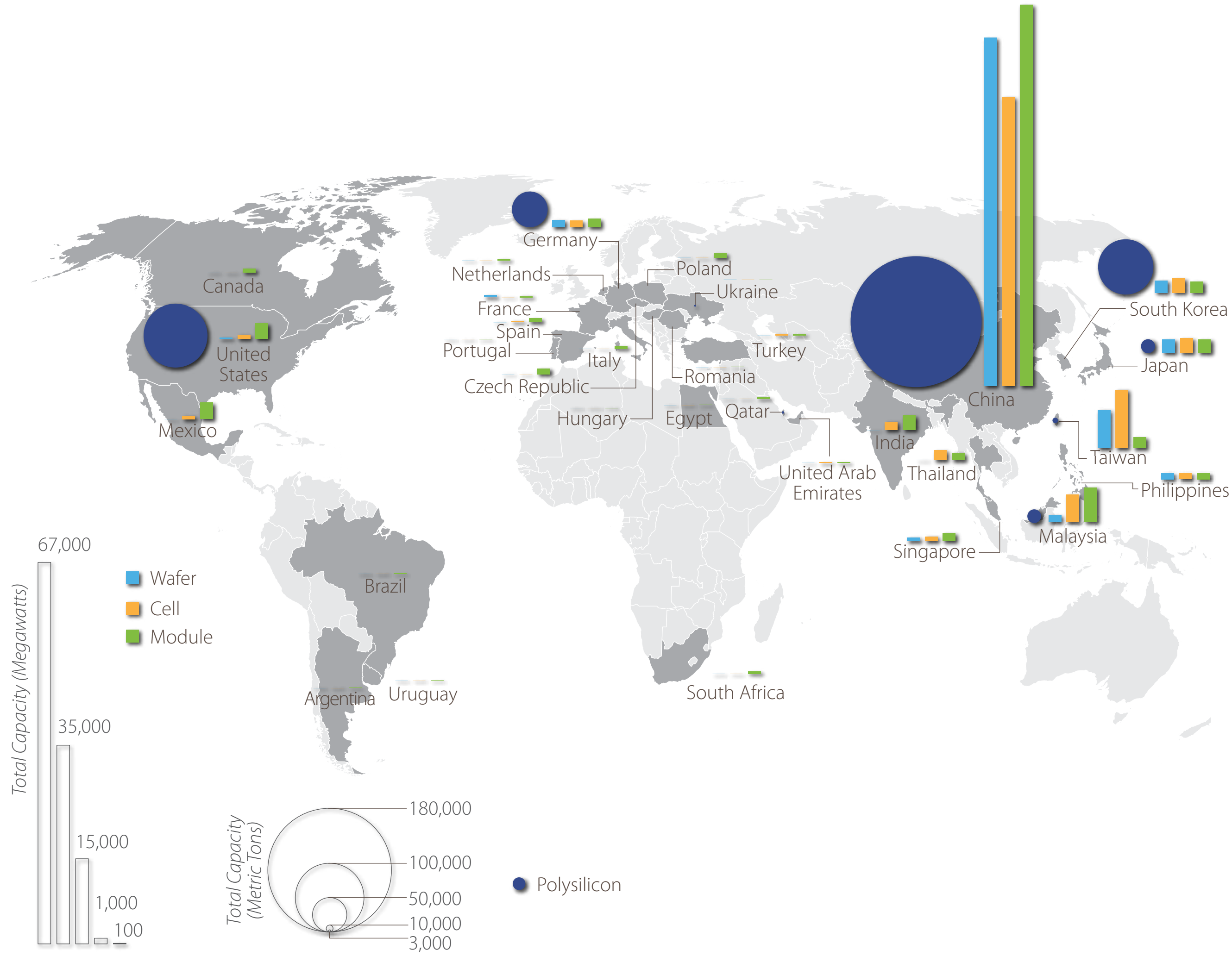


Figure 7. Distribution of photovoltaic component manufacturing (top 500 firms in 2015). Data source: CEMAC analysis of Bloomberg New Energy Finance and Greentech Media data.

China Dominates PV Manufacturing. Why?

The sheer scale of production, in addition to lower labor costs, drives China's current advantage in manufacturing solar PV modules. The growth of the Chinese PV manufacturing sector has been dramatic, moving from being very small ten years ago to dominating global markets today. China's scale advantage may have been enabled, in part, through preferred access to capital (indirect government subsidies) and additional incentives to create jobs within its provinces. As the domestic ecosystem for PV manufacturing grew within China, so too did the clustering benefits associated with the specialized production of materials within the supply chain. Reduced logistics costs and, oftentimes, preferential pricing afforded to other domestic manufacturers appear to have conveyed economically significant benefits to China-based factories. The cost of manufacturing equipment also varies greatly. Production machines available almost exclusively in China from domestic vendors can also be less expensive than competing machines that are sold globally.

The price for PV modules varies widely across the globe, from \$0.55/W to \$0.95/W, depending on quality and brand. This range can be attributed to varying scales of purchase, different pricing for modules having different efficiencies and from different suppliers, and in some cases because of tariffs. When examining the costs and minimum sustainable prices (Figure 9), note that the NREL results are for all new manufacturing capacity. In practice, many manufacturers may be able to realize lower equipment and facilities costs, for example, because they may be using older equipment and facilities that have been paid for over time. Today manufacturers are also able to acquire cheaper equipment

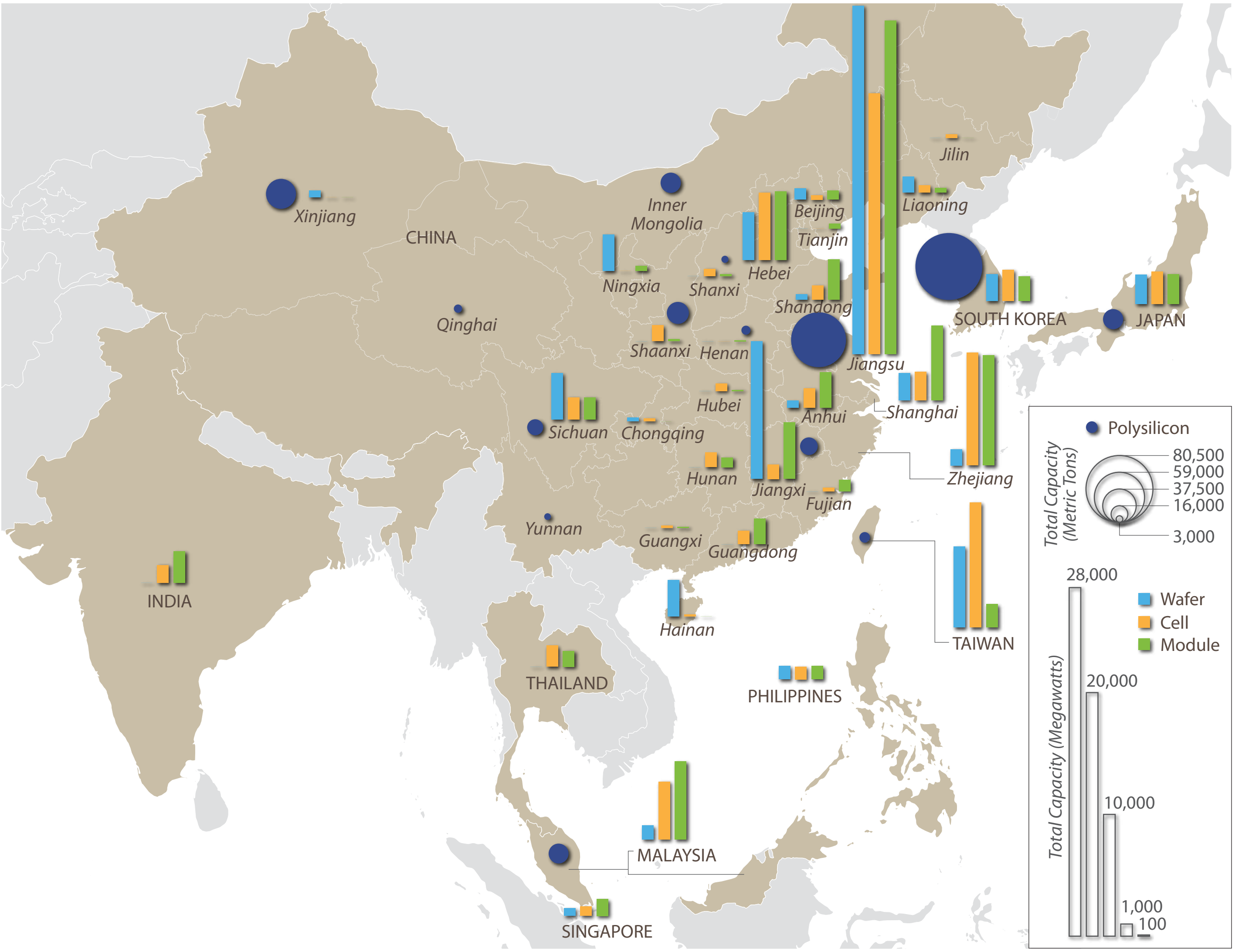


Figure 8. Distribution of photovoltaic component manufacturing in Asia. Data source: CEMAC analysis of data from Bloomberg New Energy Finance, Greentech Media, and ENF Ltd.

and facilities through a sizeable second-hand market (for example, by acquiring such assets after the bankruptcy of other photovoltaics firms). Many firms have been able to achieve complete vertical integration—from polysilicon through fully installed systems—and today the margins at the downstream systems end are generally more lucrative (Figures 7 and 10). Collectively, these supply chain and labor cost benefits offset U.S. advantages in electricity prices (Figure 9).

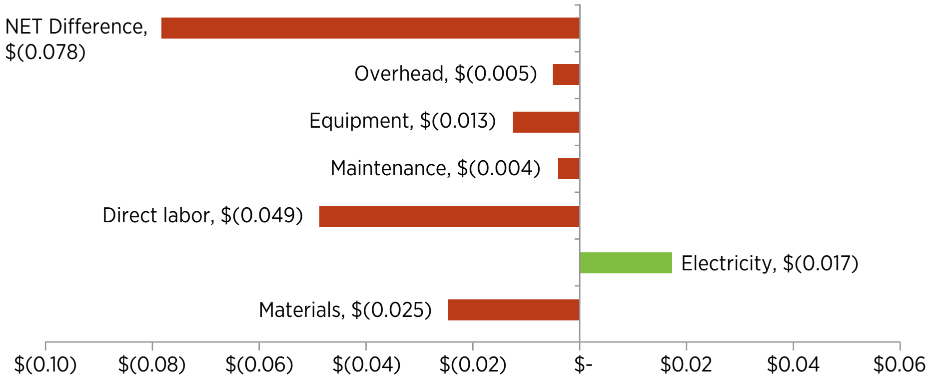


Figure 9. Cumulative cost differential—U.S. vs. urban China mono c-Si poly, wafer, cell, and module production. Insight: Low electricity prices provide a cost advantage to U.S. manufacturers of c-Si modules compared to China-based competitors, although that advantage appears to be offset by labor cost and supply chain benefits for manufacturers in China. Data source: Ongoing NREL cost analysis

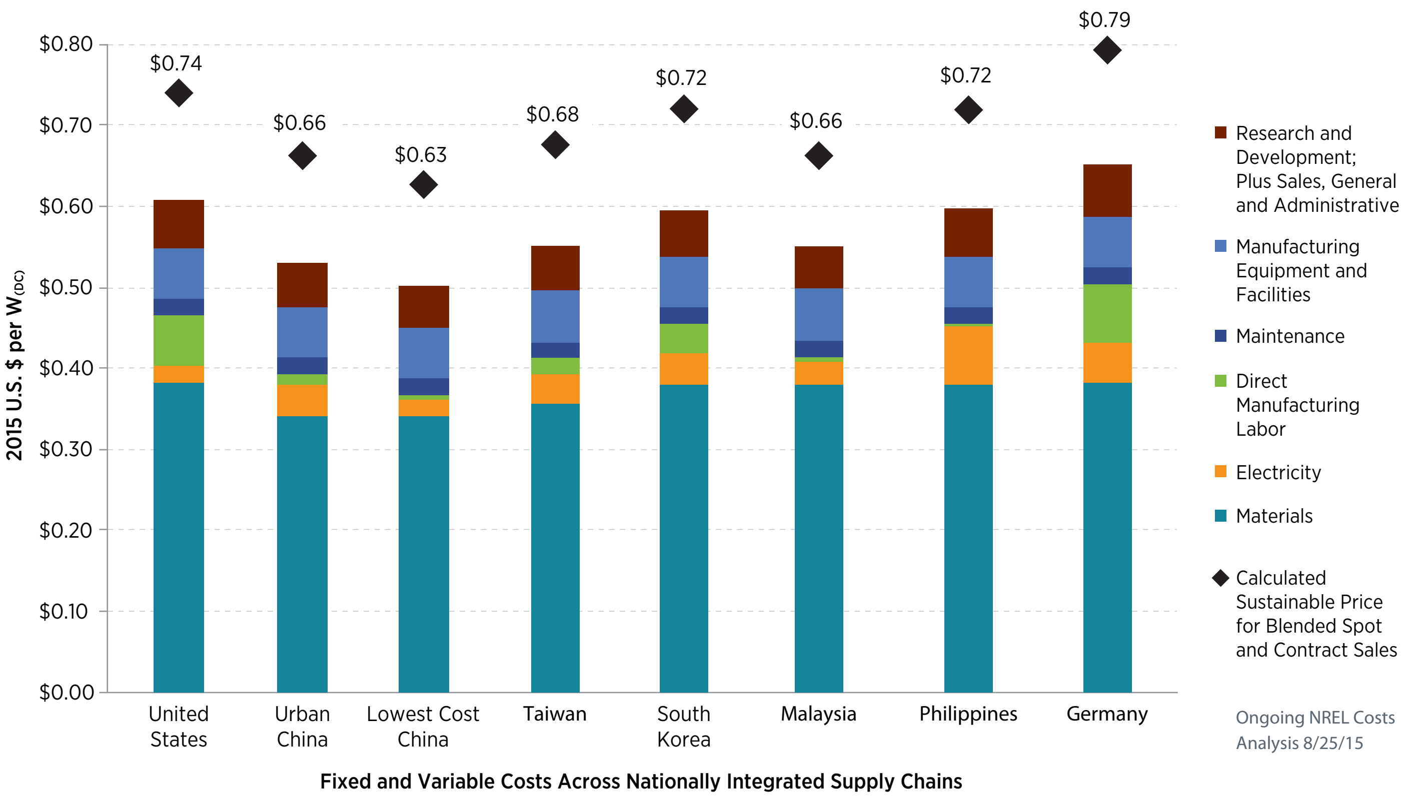
Opportunity Space

Improved levels of cost and performance, such as those outlined by the DOE SunShot Initiative, could spur demand, encourage industry growth, and drive dramatic scale-up if regions facilitate supply-chain development and access to capital (SunShot Vision Study 2012).

If it remains constant, existing global PV manufacturing capacity is capable of producing PV supply sufficient to generate 5% of the world's electricity.

Expanding manufacturing capacity is a function of investment level (capital invest rate) and cost of capital (capital demand rate). Increasing capital investment rate by $0.10/W could accelerate manufacturing cost reductions, accelerate improvements in module efficiency, reduce balance of system (soft) costs, and increase the perceived value of PV systems. Reducing the capital demand rate by half could spur similar manufacturing advances (Basore, Chung, and Buonassisi 2015).

Of the discrete steps in the PV module value chain, module assembly may be the first to show regional minimum sustainable price parity. Manufacturing of cells and wafers may also demonstrate minimum sustainable price parity over time. As the industry matures and module pricing is reduced even further, shipping and logistics costs will come to play a larger role, and so the connections between domestic demand and domestic manufacturing may grow stronger.



Note: Input Data Assumes No Tax Exemptions or Tariffs, Module Power= 255 W(DC)

Figure 10. Regional manufacturing costs and sustainable price requirements for a standard c-Si supply chain. Insight: The calculated regional manufacturing costs and sustainable price requirements, by country, for the standard multicrystalline silicon PV module supply chain shows that price differences are largely attributable to differences in variable costs for manufacturing modules, wafers, and cells, like labor and electricity. Data source: Ongoing NREL cost analysis

Wind Turbines

Christopher Mone, lead analyst for chapter

Since 2008, the U.S. wind industry has increased its domestic manufacturing capacity and driven down wind power costs by more than one-third. As noted in the Snapshot textbox, wind power is now a mainstream power source in the United States, supplying approximately 4.4% of electricity demand in 2014. United States investments in wind plants averaged $13 billion/year between 2008 and 2013, and total investments (which include manufacturing, development, construction, and financial costs) tallied $8.3 billion in 2014, according to the U.S. Department of Energy's *2014 Wind Technologies Market Report* (Wiser and Bolinger 2015). Additionally, 2014 ushered in some of the lowest wind energy prices ever, with Power Purchase Agreements (PPAs) falling to a national levelized average of 2.35 cents per kilowatt hour (kWhr), which accounts for a 66% decline since 2009.

This summary of the global landscape for wind turbine manufacturing is compiled from published reports and not based on new CEMAC analysis. Our focus will be primarily on the market and value chain associated with land-based turbines. Future CEMAC analysis may explore additional segments of the wind power manufacturing sector, such as nacelles, and may explore additional market segments such as off-shore wind.

Manufacturing Today

Wind turbines are composed of more than 8,000 individual components, and about 90% of the value is captured in three main component groups: blades and hubs, towers, and nacelles (Mone et al. 2015). In 2012, the United States was home to more than 60 manufacturers devoted exclusively to the wind sector. And in

SNAPSHOT: Wind Power Market*

- Wind power is a mainstream power source in the U.S. electricity portfolio, supplying approximately 4.4% of U.S. electricity demand in 2014
- General Electric (GE), Siemens, and Vestas captured 98% of the United States market in 2014.
- More than half of the content used to build turbines domestically is built in the United States to support 7 GW of domestic manufacturing.
- Exports of wind-powered generating sets from the United States rose from $16 million in 2007 to $488 million in 2014. Tower exports equated to $116 million in 2014.
- Wind sector employment increased from 50,500 at end of 2013 to 73,000 at end of 2014, a 30% increase.

*Data from Mone et al., 2015

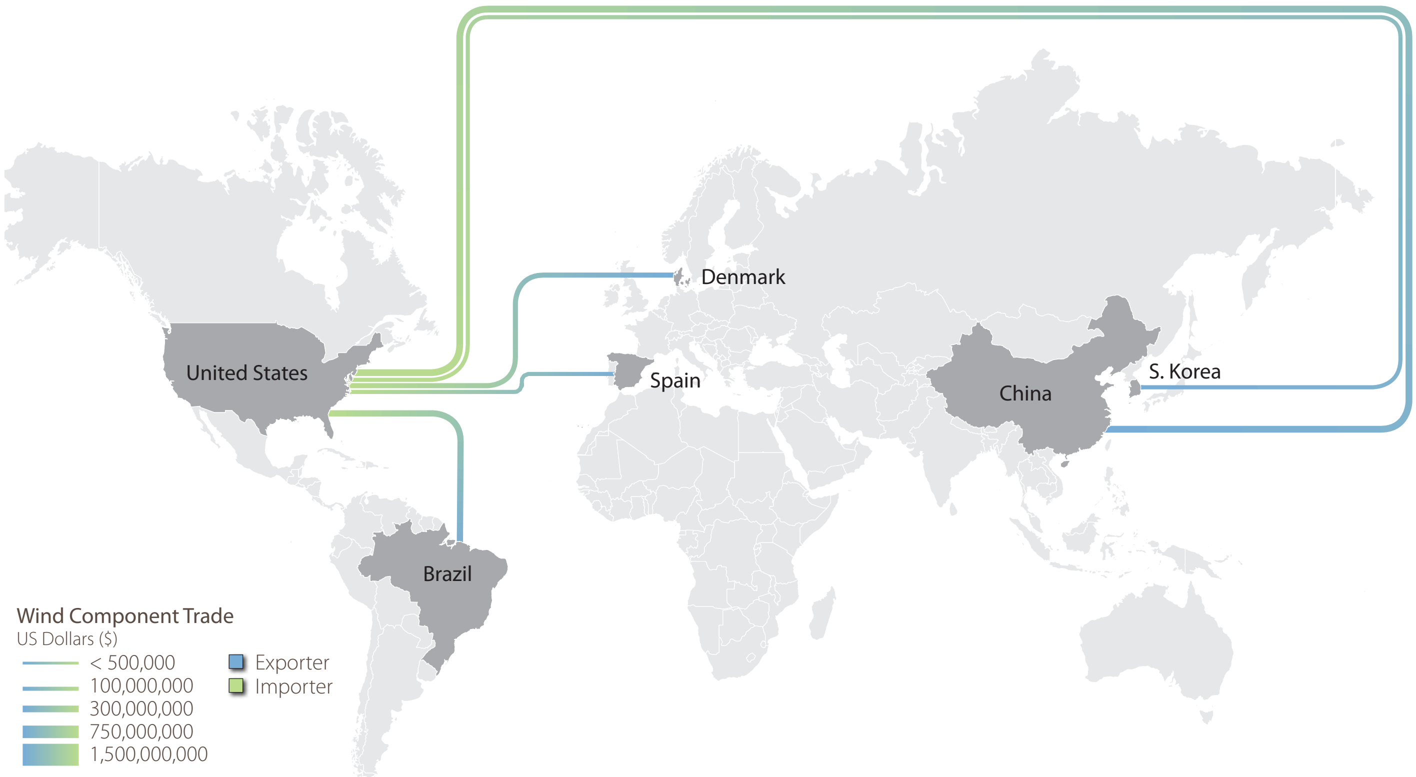


Figure 11. Value of trade in wind components between the United States and top five import markets, 3-year average (2012–2014)

2013, more than 500 facilities across 43 states supplied the wind industry with materials like sensors, bolts, lubricants, paints, bearings, composite parts, plastics, adhesives, and wiring (AWEA 2015). The global trade in wind components is illustrated in Figure 11. Even though U.S. production capacity is approximately 9 GW annually, many of the large subcomponents such as hubs, casted steel, gearboxes, and generators are imported for final assembly and manufacturing stateside. The domestic manufacturing has been a major reason for the 20% decrease in the cost of wind energy in the U.S. since 2009 (Mone et al., 2015).

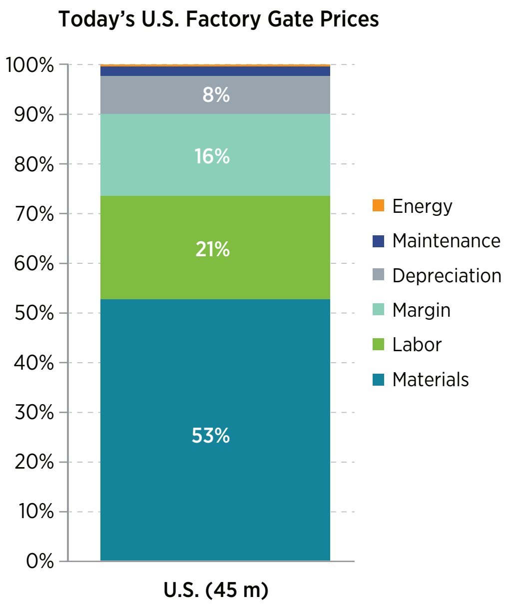
Manufacturers of large components of wind turbines, particularly the blades and towers, are more likely to locate near areas of demand due to transportation costs and logistics issues. A vast majority of components imported to the United States is used to build the three main components of a wind turbine generator (nacelle, blades/hub, and towers). For example, China produces generators that are imported into the U.S. and installed into a nacelle.

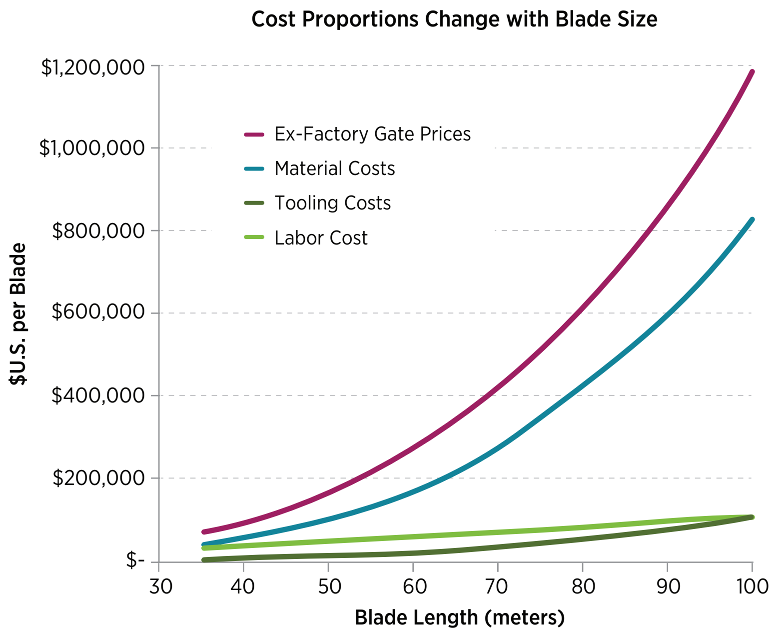
Still, trade in these large components remains vibrant. Figure 11 shows imports to the United States to top 5 source markets. Exports of wind-powered generating sets from the United States rose from $16 million in 2007 to $488 million in 2014; tower exports equaled $116 million in 2014. Brazil, China, and Denmark were major suppliers to the U.S. market.

Opportunity Space

The industry is moving toward longer blades and taller towers that capture more energy from the wind as part of efforts to improve performance and reliability and reduce the cost of individual wind turbines and wind systems. Larger turbines enable access to stronger winds at higher elevations above the ground, providing the opportunity for all 50 states to have access to additional wind resources. A study funded by DOE determined that increasing height to 140m could dramatically increase deployment in the United States, and the larger turbines and blades would most likely be manufactured in the United States due to logistical advantages (Zayas et al. 2015). To do so requires innovation in large component design and manufacturing, which may afford the United States opportunity to maintain and grow manufacturing in utility-scale wind energy (Wind Vision Report 2015).

The growth in turbine size has been impressive. In 2008, no U.S. turbines





Note: The NREL analysis was completed using 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 products.

Figure 12. Larger blades increase U.S. manufacturing opportunities as labor becomes a proportionally smaller share of factory gate prices.
Source: James and Goodrich 2013

employed rotors that were 100 meters in diameter or larger and by 2014, 80% of rotors were 100 meters or larger. For newly installed wind turbines in the United States, the average hub height in 2014 was 82.7 meters and average rotor diameter was 99.4 meters, up 48% and 108%, respectively, since 1998–1999 (Zayas et al. 2015).

As components like blades and towers increase in size, transportation and logistics cost increase on a per turbine basis. This generally makes imports less competitive, although the U.S. does import some wind turbines blades annually from Brazil, China, or Denmark this is more a function of supply chain bottlenecks and the availability of particular blade lengths. However, Mexico, with its low labor rates and proximity, could be a potential competitor to U.S. manufacturing for both the domestic as well as Central and South American markets.

As blade size increases, labor cost declines as a share of total price, and relative share of material costs climb (Figure 12). The average rotor diameter has increased 108% since 1999 and the U.S. has 7 GW of blade manufacturing for domestic and international projects. Even though the longer blades cost more to produce, the U.S. based manufacturing has assisted in lowering wind power levelized cost of energy by increasing swept area and thus capacity factors in addition to decreasing transportation and logistics concerns.

Automotive Lithium-ion Batteries

Donald Chung and Emma Elgqvist, lead analysts for chapter

Lithium-ion (Li-ion) batteries are a broad category of batteries whose electrical and chemical properties depend on lithium. Conceived in the 1970s, Li-ion batteries gained commercial prominence in the 1990s. Thanks to their high energy density and long life relative to other storage technologies, Li-ion batteries have become a favored power source for portable electronic devices. Manufacturers are now applying the Li-ion technology in new applications (see Snapshot textbox). The high power density of Li-ion batteries also makes them well-suited to certain automotive applications.

Manufacturing Today

Today, manufacturing capacity for Li-ion battery cells is heavily concentrated in East Asia (Figure 13). Currently, China, Japan, and Korea collectively produce 78% of all Li-ion batteries and 74% of automotive Li-ion batteries.

Like other technologies described in this report, production lines are operating far below their maximum capacity (Figure 14 and Table 1). Initial overly optimistic assumptions regarding plug-in electric vehicle demand contributed to over-building of large format Li-ion battery cell production capacity for automotive markets. Manufacturing investment incentives have also been made available for capacity expansions in recent years. In the United States, the American Reinvestment and Recovery Act of 2009 provided $1.5B to support the expansion of U.S.-based advanced battery manufacturing. Beginning in the 1990s, the governments of China, Japan, and Korea set aggressive goals for domestic Li-ion battery production through tax and other investment incentives, and have more recently supported consumer electric vehicle adoption (Patil 2008; Pike Research 2013).

SNAPSHOT:
Automotive Li-ion Battery Cell market

- Automotive Li-ion battery demand, estimated at 17 GWh in 2015, is expected to more than double by 2020, to 39 GWh and $14.3 billion.*
- Competitive locations and opportunities for automotive Li-ion battery cell manufacturing are not indigenous to specific regions and can be created elsewhere.
- Automotive Li-ion battery pack production may remain proximal to end-product manufacturing, but materials and cell production could locate globally.
- Li-ion battery components are not commoditized; technical and quality differentiation is possible.

* Sources: Roland Berger 2012; AAB 2014; CEMAC analysis

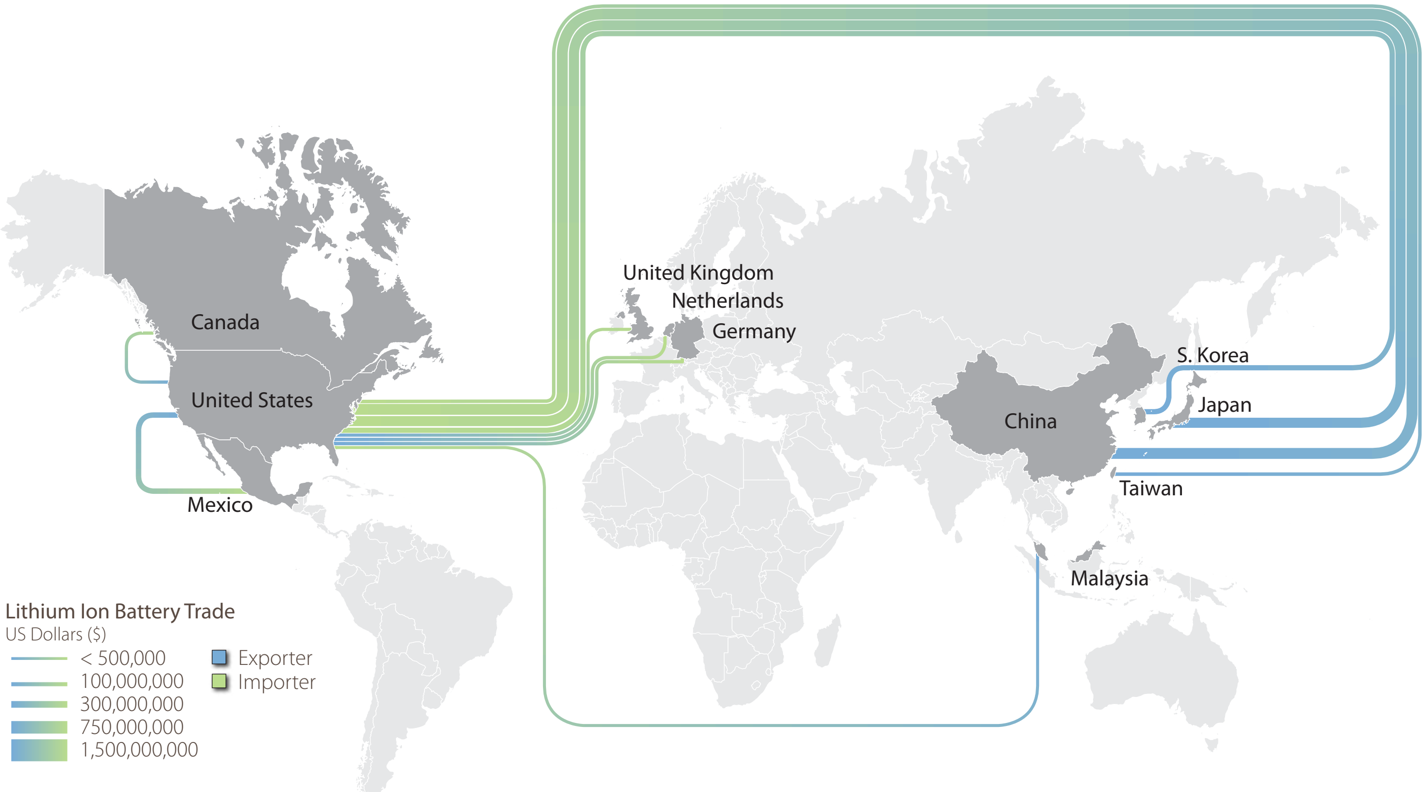


Figure 13. Value of trade in lithium-ion battery components between the United States and top five export markets and top five import sources, 3-year average (2012–2014)

Most Li-ion battery production knowledge and experience was developed by firms serving consumer electronics markets. These incumbent firms have created robust supply chains and accumulated significant production experience, much of which is transferrable to the production of large format Li-ion battery cells for automotive end-markets. Compared to Li-ion battery startups and newer competitors focused solely on automotive markets, incumbent Li-ion battery producers generally enjoy many advantages:

- Processing expertise gained through much higher cumulative production, especially with respect to small format batteries (manifested by higher yields)
- Lower total overhead and fixed costs because costs can be amortized across sales to multiple end application markets
- Stronger purchasing power
- More established regional supply chain clusters and relationships
- Potentially increased utilization as facilities may produce more diversified products for larger end-markets.

Some degree of vertical integration exists across Asian electrode materials and cell production, which may also contribute to lower input costs for certain manufacturers.

Pack production for Li-ion battery cells is now and will likely remain concentrated near electric vehicle

Table 1. Manufacturing Capacity for Lithium-ion Batteries Cells by Country/Region (2014)

	Total LiB Manufacturing Capacity (MWh)	Share of Total Capacity	Automotive LiB Manufacturing Capacity (MWh)	Share of Automotive Capacity
China	39,010	51%	11,240	41%
Japan	11,978	16%	5,750	21%
Korea	16,059	21%	4,600	17%
U.S.	4,970	7%	4,600	17%
EU	1,798	2%	1,300	5%
Rest of World	2,440	3%	0	0%
Total	**76,255**	**100%**	**27,490**	**100%**

Data source: Bloomberg New Energy Finance (2014)

Note: Includes factories that are fully commissioned, partially commissioned, and under construction.

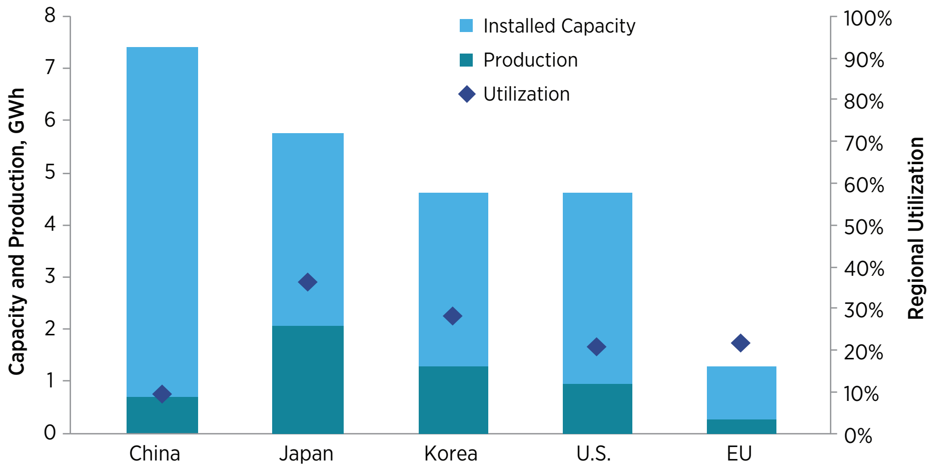


Figure 14. Automotive Li-ion battery cell manufacturing capacity and utilization (2014).
Data sources: Bloomberg New Energy Finance (2014); Pike Research (2013); Advanced Automotive Batteries (2013); Roland Berger (2012); IEA (2011); CEMAC estimates.

production. This is because complete packs are not cost-effective to ship, are specific to the electric vehicles in which they are employed, and are typically designed and built by the automakers themselves (AAB 2014). In contrast, Li-ion battery electrode materials, other processed materials, and complete sealed cells can be shipped without significant cost penalty relative to current market prices.

The United States represents a small percentage of current manufacturing supply but a large portion of global market demand. As markets evolve, the United States or other countries could become competitive in parts of the value chain with high potential manufacturing value add, including processed materials, electrodes, and final assembly of battery packs. Together these comprise nearly 75% of the value for electric vehicle applications, not including control software and system integration value-add. Cells represent 26% of the value-add in complete automotive Li-ion battery packs (see Figure 17), but 34% of the value-added comes from electrodes and other processed materials, an area where the United States could potentially be competitive. The United States already assembles cells into battery packs for electric vehicles manufactured domestically, which comprises 39% of total Li-ion battery pack value. With its Gigafactory, Tesla aims to create a more integrated supply chain to overcome the hurdles of breaking into the existing supply chains developed around manufacturing of batteries for consumer electronics. When completed, the Gigafactory will have a significant affect the global manufacturing balance of trade for Li-ion batteries for automotive and stationary energy applications (Figure 15, Table 2).

Opportunity Space

To identify the factors that drive regional competitiveness in automotive Li-ion battery production, CEMAC modeled the costs of labor, materials, facilities, and other factors, and compared the cost of production of automotive Li-ion battery cells in six different manufacturing scenarios, described in Table 3 (Chung, Elgqvist, and Santhanagopalan 2015). From this analysis, CEMAC determined the cost drivers and minimum sustainable prices (MSP) required in each region for automotive Li-ion battery cell production to be globally competitive. The analysis suggests that under certain circumstances, the United States could be competitive in automotive Li-ion battery cell production.

Reported costs from Tesla for battery packs are on the order of $350/kWh, excluding inverters, software, and control systems. However, Tesla uses 18650-type cells rather than the large-format cells commonly used by other manufacturers in the automotive industry. The technological development and cost reductions for 18650 cells are more mature than the large-format cells. Other automakers expect long-term prices for large-format cells to dip below those of the 18650. Future analysis will evaluate the drivers. Cost modeling indicates that the United States and especially Mexico may be competitive in automotive Li-ion battery manufacturing under certain conditions (Figure 16). Mexico's low cost of labor, combined with a low cost of capital, could sustain the most competitive prices on the global market.

- The market for automotive Li-ion batteries is relatively immature, and characterized today by low factory utilizations, relatively low yields, and a diversity of participants with varying levels of experience. Yet, in terms of market share the industry is moderately concentrated, with 93% of share divided among 11 competitors (AAB 2014). As demand increases through 2020 and beyond, competitors will likely consolidate capacity, improve yields, and incrementally advance currently commercialized technologies to improve costs going forward (Roland Berger 2012).

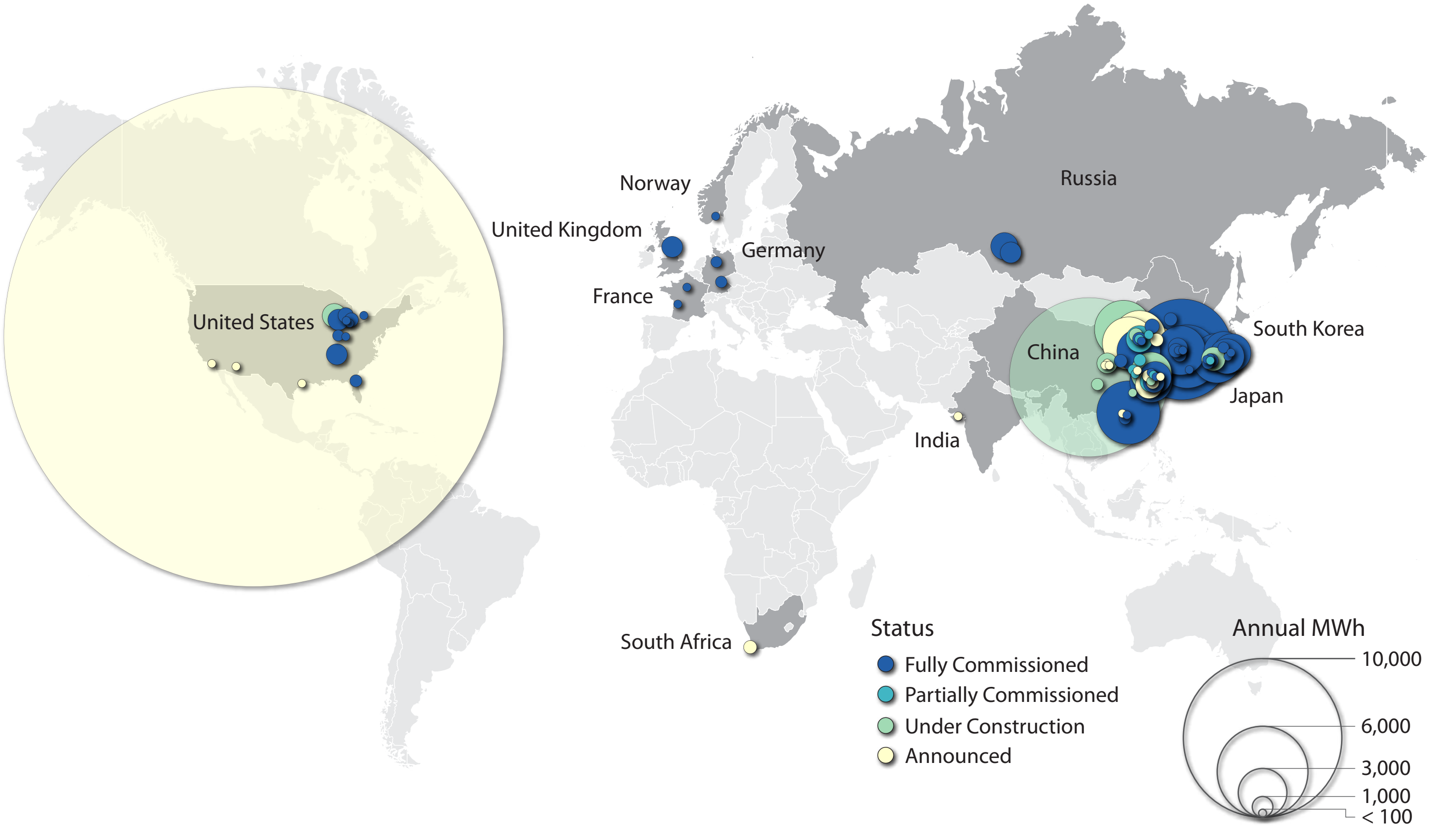


Figure 15. Manufacturing capacity for lithium-ion batteries is heavily concentrated in Asia, though Tesla's planned "Gigafactory" in Nevada (reflected in yellow) could alter the status quo. Data source: Corporate reporting

- Li-ion battery components are not commoditized: each is particularly important to overall battery performance, and technical/quality differentiation is possible, although future manufacturers may face the type of commoditization seen in the PV industry as significant manufacturing capacity is supported and built. Value chain elements noted in Figure 17 as "critical to quality" are of particular interest as they represent areas where intellectual property and trade secrets may confer competitive advantage and the basis for competition beyond price. Further, advantages gained in these critical-to-quality elements are generally transferrable across end-applications. For example, intellectual property developed for electrodes used in consumer electronics Li-ion batteries could also be applied to electrodes used in automotive Li-ion batteries.
- Qualitative factors contribute to competitiveness and manufacturing location decisions and can offset regional cost advantages in the current state of the market. In the automotive Li-ion battery market, those qualitative factors include policy and regulatory contexts, access to raw materials, ease of doing business, logistical risks, and proximity to end markets. These are reflected in the success factors as shown in Figure 17.

Table 2. Manufacturing Capacity for Lithium-ion Cells, Operational, Under Construction, and Planned, by Country/Region

	Fully Commissioned (MWh)	Partially Commissioned (MWh)	Under Construction (MWh)	Announced (MWh)
China	16,704	3,576	18,730	12,847
Japan	10,778	0	1,200	0
Korea	16,059	0	0	0
U.S.	3,770	0	1,200	35,000
EU	1,798	0	0	0
Rest of World	2,440	0	0	564
Total	**51,549**	**3,576**	**21,130**	**48,412**

Data source: Corporate reporting

- Further, the relative immaturity and imbalance in the automotive market suggests that firm-specific strategies may have a disproportionate effect on location decisions currently. Firms may prioritize strategic factors such as proximity to auto engineering centers or to battery research centers in order to have better integration with cell development and design. As the market matures, location decisions may turn more on low-cost production.
- Even though prices under the Mexico scenario remain difficult to match, future U.S. pricing could possibly be competitive with current minimum sustainable pricing from low-cost producer nations such as Korea and China. While the assumptions required to create the competitive U.S. Future case (with MSPs at or below Japan and China Tier 2 scenarios) are aggressive, it is possible that these conditions could be met. Regarding cost of capital assumptions, for example, a comparison of two established U.S.-based battery manufacturers (JCI and Energizer) suggests a weighted average cost of capital (WACC) of 8.3% appears possible for U.S. companies engaged in the battery sector. Further, modeling suggests that low WACC together with assumed input costs equal to incumbents could create competitive opportunity in the U.S. case. Indeed, some U.S. firms are competitive in various parts of the automotive Li-ion battery value chain. Future analysis could provide more in depth examination of areas of current and potential competitiveness.

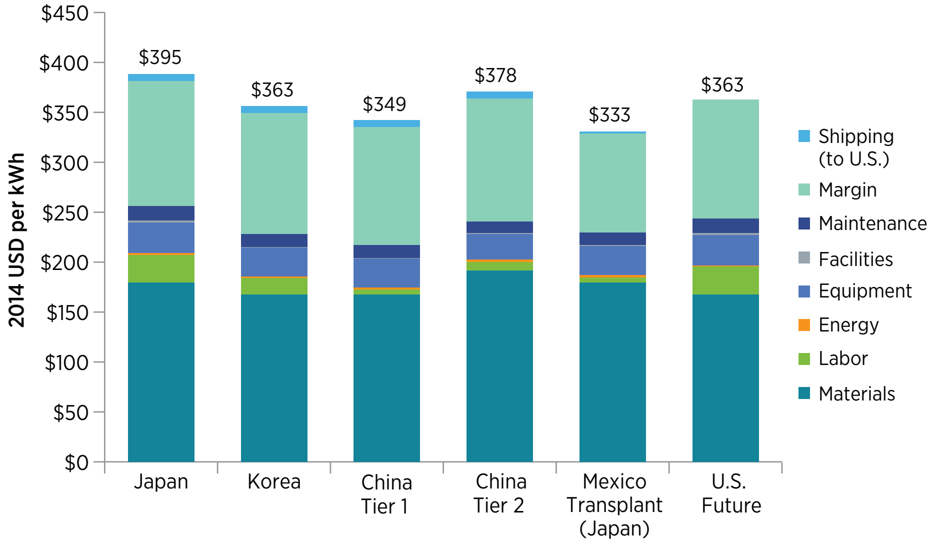


Figure reflects costs modeled using 2014 data. Costs and prices have changed since the original analysis was performed, and the changes will be reflected in forthcoming CEMAC analysis. Figure reflects costs modeled using 2014 data. Costs and prices have changed since the original analysis was performed, and the changes will be reflected in forthcoming CEMAC analysis.

Figure 16. Modeled cost of automotive Li-ion battery packs (2014 USD per kWh).
Source: NREL cost analysis (January 2015)

Table 3. Modeling Scenarios for CEMAC Automotive Lithium-ion Battery Manufacturing Analysis as shown in Figure 16

Scenario	Description	Company Domicile/ Manufacturing Location
Japan[1]	Japanese firm with experience in automotive and consumer electronics Li-ion battery.	Japan / Japan
Korea[1]	Korean firm with experience in automotive and consumer electronics Li-ion battery.	Korea / Korea
China Tier 1[1]	Chinese firm with experience in automotive and consumer electronics Li-ion battery.	China / China
China Tier 2[1]	Chinese firm with experience in automotive and consumer electronics Li-ion battery. Firm employs less automated processes and slightly lower quality materials.	China / China
Mexico Transplant (Japan)[2]	Mexican manufacturing facility owned by a Japanese corporate parent with experience in automotive and consumer electronics Li-ion battery. Combines Mexico region advantages with incumbent firm advantages.	Japan / Mexico
U.S. Future[2]	U.S. firm partnering with more experienced firms to produce Li-ion batteries in the U.S. Combines U.S. region advantages with incumbent firm advantages.	U.S. / U.S.

[1] Representative scenario [2] Future scenario

	Raw Materials	Processed Materials	Electrodes	Cells	Battery Pack	Total
Value		$168	$28	$146* (cum. $342*)	$229	$571
Share		29%	5%	26%	40%	100%
Currently Shipped	Globally	Globally	Regionally	Globally	Locally	
Success Factors	• Indigenous resources • Low export restrictions or limitations	• Critical to quality • Demand assurance • Cost of capital • Production cost inputs: e.g. regulatory, energy.	• Critical to quality • Processing know-how: e.g. coating thickness uniformity, solvent & moisture content.	• Critical to quality • Processing know-how: e.g. stack uniformity, drying, formation, electrolyte additive	• End-product knowledge and integration know-how • Proximity to customers: shipping costs, exchange of technical specifications	

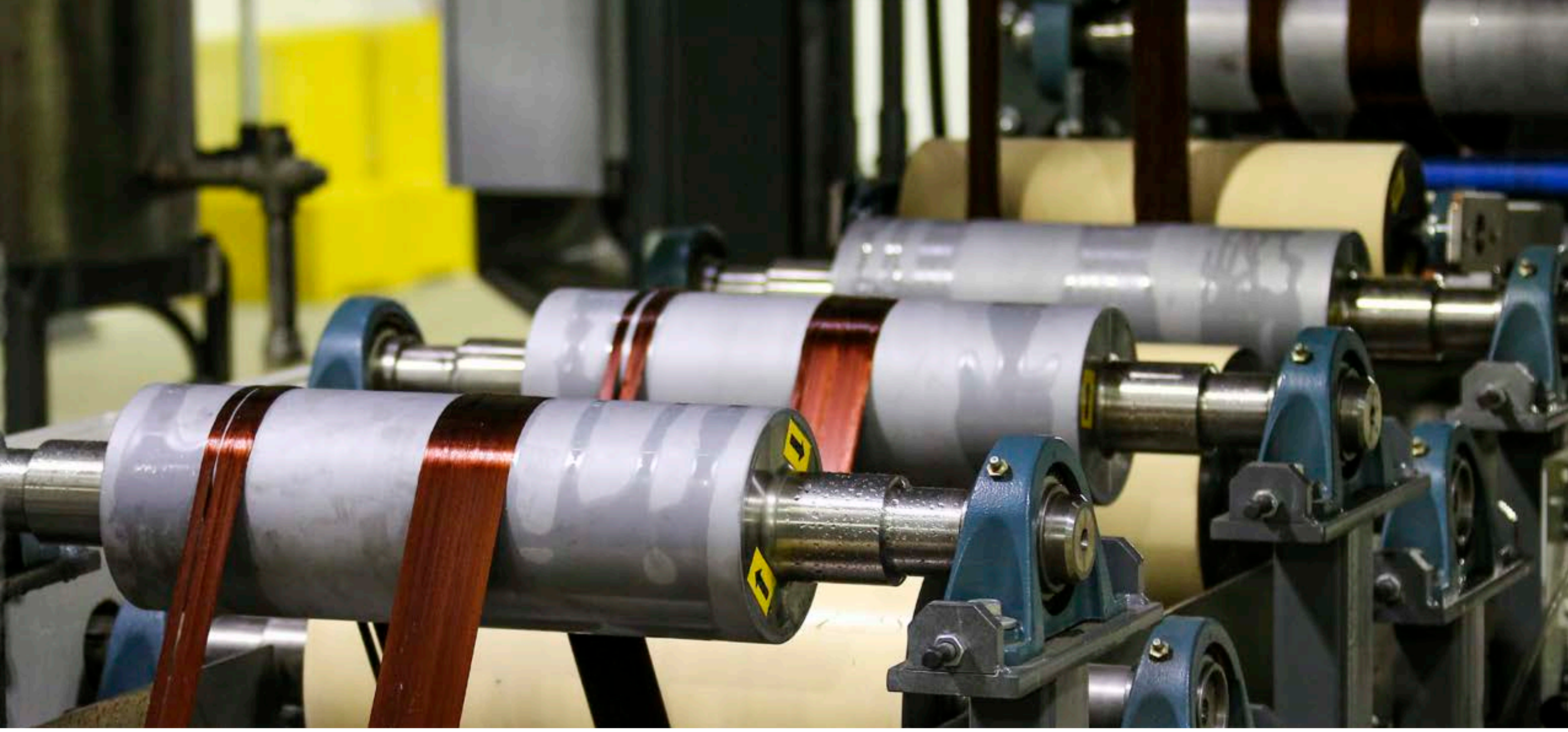
* Ex factory gate – shipping from Asia to the west coast of the United States adds approximately $7/kWh

Note: $571 represents the lowest minimum sustainable price in actual scenarios at the time of the analysis.

Figure reflects costs modeled using 2014 data. Costs and prices have changed since the original analysis was performed, and the changes will be reflected in forthcoming CEMAC analysis.

Data sources: CEMAC estimates, BNEF (2014), Pike Research (2013)

Figure 17. Value chain for best-in-class plug-in electric hybrid vehicle lithium-ion batteries 2014 (modeled costs, $US/kWh), with success factors highlighted.



Carbon Fiber

Sujit Das, lead analyst for chapter

Carbon fiber and carbon fiber reinforced polymer (CFRP) composites[1] are materials consisting of fibers that are 92% or greater carbon. This structure leads to advantageous materials properties including light weight, high strength and stiffness, and corrosion resistance—properties that make carbon fiber attractive for use in a number of clean energy technologies. For instance, vehicles made with lightweight carbon fiber can increase fuel economy by up to 35% versus conventional steel vehicles. In addition to saving fuel as a part of the vehicle body lightweighting, carbon fiber enables additional technologies, including pressurized tanks for on-board natural gas, that can further improve fuel economy and reduce carbon dioxide emissions. Moreover, carbon fiber and CFRP are important new materials in the wind industry's ongoing efforts to expand resources via larger turbines and longer blades for land-based wind power generation, as well as to enable offshore wind.

Transportation lightweighting has been the key potential carbon fiber application area to enable significant fuel savings in automotive, marine, rail, and air transport. Air transportation has particularly high energy intensity, and the aerospace industry has been an early adopter of CFRP technology to improve fuel economy. For instance, new aircraft, such as the Boeing 787/777 and the Airbus A350XWP, have CFRP content above 50% by weight. The breadth of carbon fiber- and CFRP-containing products reflects their strong impact on energy efficiency. This chapter will provide a general overview (including value chain) of the CFRP industry in four major clean energy application areas—wind energy, aerospace, automotive, and pressure vessels—with a focus on the competitiveness analysis of CFRP wind turbine blade manufacturing. Future CEMAC analysis will focus on the competitiveness analysis of the remaining three clean energy application areas.

Manufacturing Today

In the generalized CEMAC value chain, carbon fiber is considered one of the major advanced lightweight materials, and CFRP enables the design of critical subcomponents of the finished clean energy product. In the initial steps of carbon fiber production (illustrated in Figure 18), raw materials like oil and natural gas are converted into

[1] Numerous parallel filaments are typically grouped together into what is referred to as a carbon fiber tow. The term tow count refers to the number of filaments per tow and is often expressed with nomenclature such as 24K where the letter K designates the number 1000. Thus, a 24K tow describes a carbon fiber tow having 24,000 filaments. Carbon fiber having 24,000 or fewer filaments is referred to as small tow. The most common small tow product forms are 1K, 3K, 6K, 12K, and 24K tows. Tows having more than 24K filaments are referred to as large tow, with 48K and 50K tows being common large tow product forms. However, heavy tows with multiple hundreds of thousands filaments are also available.

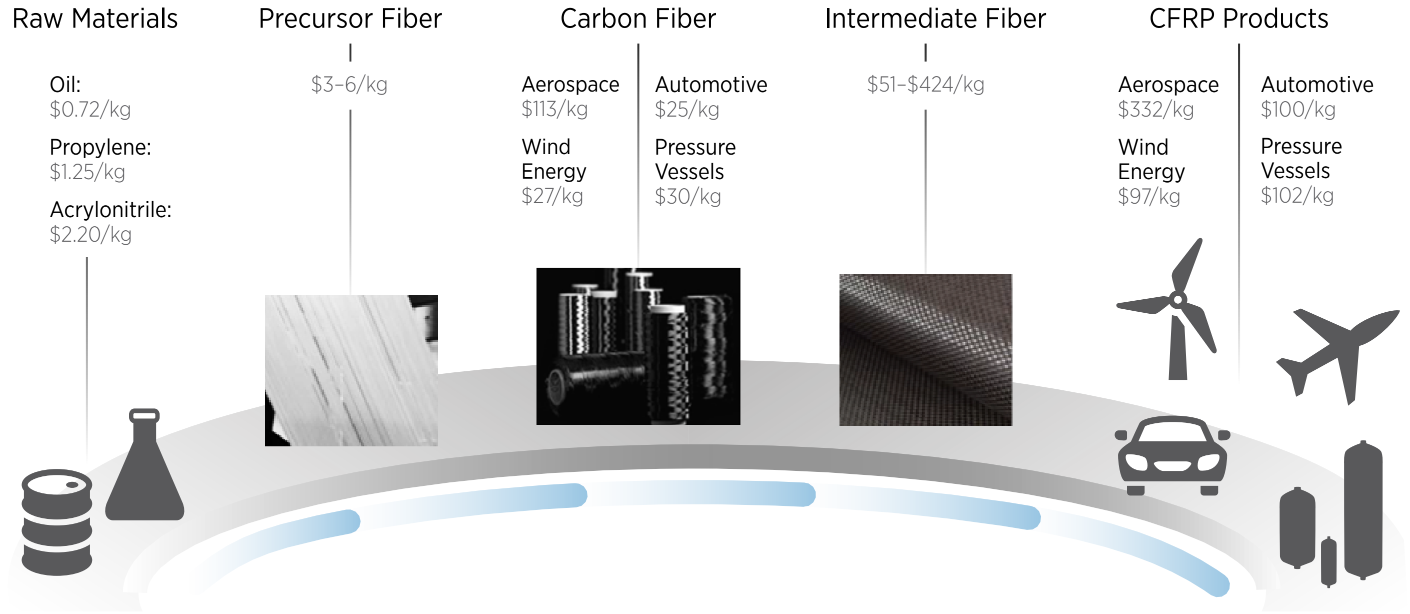


Figure 18. Value chain for carbon fiber. Data source: Oak Ridge National Laboratory

acrylonitrile, the basic raw material for precursor fiber manufacturing technology. Carbon fiber manufacturers have their own in-house polymerization and precursor spinning capabilities. The processes and recipes used to convert acrylonitrile into carbon fiber-grade polyacrylonitrile (PAN) and then precursor are closely guarded intellectual property that the manufacturers are reluctant to outsource or sell in the open market to carbon fiber manufacturers. When produced as an advanced material, each carbon fiber filament has a diameter of 5–15 microns, which are separated and/or optimized for particular products. Figure 18 also shows the estimated demand for carbon fiber-based final products by four major application industries: aerospace, automotive, wind energy, and pressure vessels.

Most manufacturers are vertically integrated to the penultimate step of final composite part manufacturing because significant value-added occurs in the conversion of fiber to its intermediate product form (Figure 18). The carbon fiber supply chain value increases toward the final composites product such as intermediate carbon fiber product form (e.g., prepreg[2], fabric) and carbon fiber composites. Lower shipping cost of carbon fiber allows the final composite product manufacturing to be located near the final demand point. The value of the final CFRP product varies widely among the four major application industries, a maximum in the case of aerospace sector due to expensive small tow, high modulus fiber use for superior property requirements, compared to the low-cost, industrial grade, standard modulus, and large tow fibers considered for the automotive industry.

Carbon fiber manufacturing capacity is heavily concentrated in North America, Japan, and Europe (Figure 19). Of the 2014 global capacity of 125,000 tonnes, North America and Europe had a share of 31% and 20%, respectively (Witten et al. 2015). Toray's recent acquisition of Zoltek makes it the major carbon fiber producer in the world today with an estimated annual capacity of 44,500 tonnes. The industry is highly concentrated with almost 88% of the global fiber capacity held by ten leading manufacturers. Chinese firms Zhongfu-Shenying and Hengshen Fibre Materials have been the new entries to the top leading manufacturers, with an estimated production capacity of 4,000 tonnes and 3,000 tonnes, respectively. Imported technology needs, stable product quality, and development of product manufacturing are the major concerns of the growing Chinese carbon fiber industry. Other countries making initial investments are South Korea (Hyosung), Russia (Compiste Holding Co., Alabuga-Fibre LLC), and India (Kemrock Industries and Exports Ltd.), with a total annual capacity of less than 3,000 tonnes.

[2] Prepreg is carbon fiber impregnated with the polymer resin matrix material of CFRP.

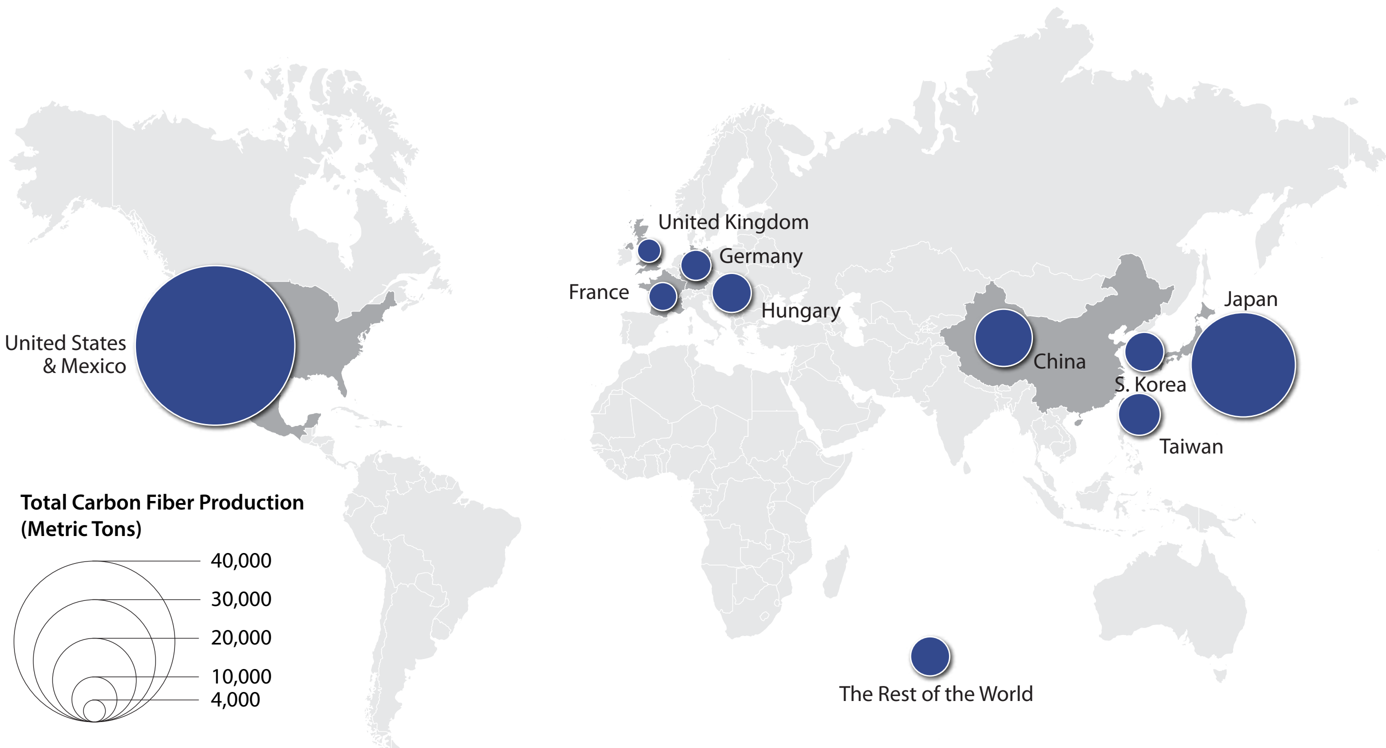


Figure 19. Carbon fiber manufacturing production capacity. Data source: Witten et al. 2015

In 2014, the carbon fiber industry showed over-capacity; estimated capacity was 125,000 tonnes while demand was 53,000 tonnes (Witten et al. 2015). This lower utilization of rated capacity is attributed to a lack of operational experience, material packing efficiency, and online availability. By 2020, worldwide carbon fiber demand is projected to increase from 82,400 tonnes to 150,200 tonnes, and nameplate capacity is expected to reach 181,300 tonnes (Red 2015). The aerospace sector leads the carbon fiber market in terms of value, but is comparable to the wind energy sector in terms of tonnage. A recent optimistic market forecast indicates the strongest growth in the industrial sector as before, and the share of four major market areas (automotive, wind energy, aerospace, and pressure vessels) will be 25%, 20%, 15%, and 13%, respectively, of total CF demand by 2020 (Red 2015). With the introduction of carbon fiber in BMW i3 starting with the model year 2014 and the lightweighting potential of CFRP, the demand for a lower cost industrial grade carbon fiber is expected to grow in the automotive sector, and may reach the same level as the aerospace sector by the end of this decade (Industry Experts 2013); see Figure 20. Lightweighting is seen as the major driving force behind the growth of carbon fiber over the next years and the total worldwide fiber and composites market are projected to reach more than $4 billion and $20B (Industry Experts 2013), respectively, by the end of this decade. Several partnerships between fiber manufacturers and automotive original equipment manufacturers developed recently, such as such as between DowAksa and Ford Motor Co. in 2015, indicate a stronger projected growth in the sector. Due to a potential large mass of carbon fiber application per blade and the growing interest of renewable wind energy, a significant carbon fiber growth (in terms of tonnage) in that sector is anticipated.

The United States had the largest share (38%) of 2014 worldwide demand of 83,000 tonnes of CFRP (corresponding to carbon fiber demand of 53,000 tonnes), driven by the aerospace and defense sectors (Witten et. al.2015). Europe's 35% share of total composites demand was driven by aerospace, wind turbine, automotive, and mechanical engineering sectors. The United States and Europe are expected to face competition from Asia in the future, particularly as major state subsidies have been recently announced or are expected for both the carbon fiber and composites sectors. The CFRP market is predicted to be an extremely vibrant market but a number of hurdles such as automation, cost cutting, and the development of manufacturing processes suitable for mass production remain to be addressed.

Carbon fiber and composites trade data are considered "nonelectrical articles of graphite or other carbon," a trade category that includes other advanced fibers, other materials, and different forms of products such as resins and CFRP honeycomb cores. Major U.S. imports came from Europe, Asia, and Japan. The United States, Japan, and Europe are the leading exporters (see Table 4). Carbon fiber including its intermediate product form (i.e., prepregs and preforms) and composites of higher specific strength and modulus and software and equipment used for production are export-controlled today. Restrictive domestic export control procedure developed originally for premium grade carbon fiber for aerospace and defense applications has caused a loss of export opportunities and a limited R&D cooperation (Larkin 2013).

2.4.2 Opportunity Space

Wind energy is projected to be one of the highest growth areas of the carbon fiber use, with estimates of demand ranging from 30,000 tonnes/year (Red 2015) to 36,000 tonnes/year (Industry Experts 2013) by 2020 (see Figure 20). Carbon fiber use of 3.8 tonnes is projected for a 4 MW generation plant by 2018. Europe will likely continue to be the largest wind energy consumer due to 20% future renewable energy requirements[3], followed by North America rising demand in Asia.

With carbon fiber, manufacturers can create blades that are longer and lighter than conventional glass fiber blades. Blade mass, cost, and deflection increase with cube of the turbine radius. It thereby allows access to the stronger and more consistent wind speeds that occur at higher elevations, which can produce more electricity per tower and reduce cost per kW and kWh of wind power. A clear trend toward longer, lighter blades, particularly within the offshore sector, is being seen in the market today as 100-meter blades are needed to make offshore wind compete with fossil fuels (Bullis 2013).

Carbon fiber is used primarily in the spar, or structural element, of wind blades longer than 45m – both for land-based and offshore systems. Its stiffness-to-weight advantage is particularly important as designers create even larger blades. A 20% mass savings can be achieved when moving from an all-glass blade to one with a carbon fiber-reinforced spar cap (Wood 2012). The higher stiffness and lower density of carbon fiber allows a thinner blade profile while producing stiffer, lighter blades. Lighter blades require less robust turbine and tower components, so the cascading cost savings could justify the additional cost of carbon fiber (Wood 2012). Increasing blade length improves turbine efficiency, and switching to longer blades with carbon fiber eliminates a blade mass weight penalty. Vestas, GE Energy, and LM Wind Power manufacturers have demonstrated the use of carbon fiber spar caps in their 54.6 m, 48.7 m,

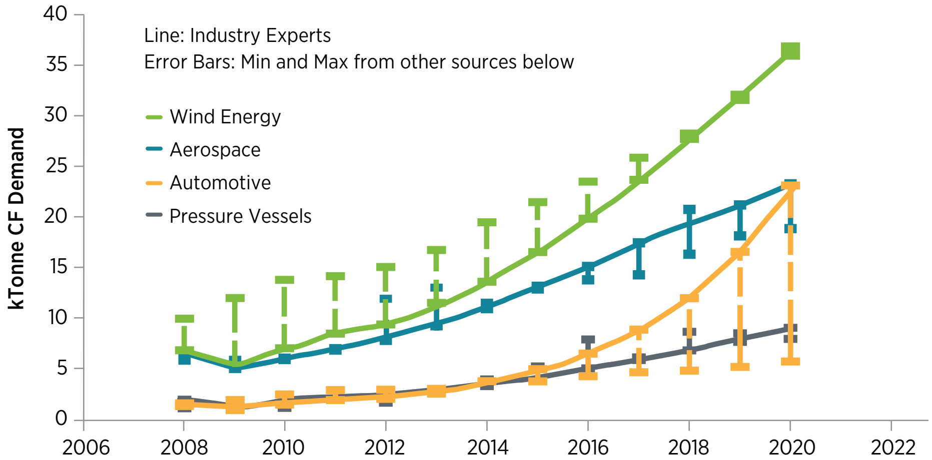


Figure 20. Estimated increase in carbon fiber demand by end-use markets.
Data sources: Industry Experts (2013), Lucintel (2013), Red and Zinn (2012), Holmes, M. (2013).

Table 4. 2014 ITC Trade Map Data for Product Code 681510: Nonelectrical Articles of Graphite or Other Carbon

Export from	Import to				
	Europe	America	Asia	Africa	Japan
Europe		312,732	224,160	25,470	29,903
America	654,906		294,565	9,252	101,264
Asia	268,404	282,817		2,586	55,027
Africa	6,333	1,165	772		71
Japan	123,109	163,011	387,567	16,232	

(Values in '000 U.S. Dollars)
Data Source: ITC Trade Map Data http://www.trademap.org/(S(ey53fnnvm2ptvwqbmmmt3j45))/Bilateral_TS.aspx

[3] 2015 U.S. production tax credit extension has not yet been factored into this analysis.

and 73.5 m blades, respectively. Other potential carbon fiber applications of wind energy include blade skins, trailing edge, drive shafts, nacelle, and tower. Today, wind turbine blades typically comprise epoxy resin systems within fiber-reinforced components that are manufactured through a vacuum impregnation process and finished with surface coatings to enhance properties like abrasion resistance. Carbon fiber spar caps mostly used in turbine blades today are made separately by the vacuum-assisted resin transfer molding process, which then is integrated into the final blade manufacturing process.

Large tow (>24K) carbon fibers required for wind energy are limited to four major carbon fiber producers who have a collective share of approximately 30% of total worldwide CF capacity of 144,300 tonnes in 2015 (Red 2015). Of that total large tow CF capacity, most (59%) is located in Europe and Russia, compared to only 15% in North America (Red 2015). Europe and Russia will continue to dominate the large tow CF supply in 2020, but their share is expected to fall to 45% as U.S. share grows from 24% to 31% even with a total higher projected supply of 67,900 tonnes (Red 2015). The supply chain of limited carbon fiber spar blades manufactured today by TPI Composites, Inc., Nordex, Vestas, and Gamesa (mostly outside the United States) are also reflected in the potential scenarios considered for the CEMAC manufacturing supply chain competitiveness analysis (Table 5 and Figure 21).

This analysis shows that material costs, primarily PAN precursor material, contribute the largest share of the carbon fiber production cost before profit margin. China and Mexico may also play an important role in the carbon fiber supply. Zoltek has acquired a textile acrylic fiber plant and thereby doubled its production capacity to 5,000 tonnes/year in Mexico. Labor costs contribute very little to the overall production cost, regardless of location, indicating that regions with high-cost labor are not necessarily disadvantaged for siting carbon fiber. Energy costs, however, are the key differentiator between carbon fiber costs in different manufacturing locations (Figure 21).

Table 5. U.S. Carbon Fiber Turbine Blade Manufacturing Supply Chain Scenarios Considered

Scenario	Carbon Fiber Manufacturing Location	Fabrics/Prepreg Manufacturing Location	Blade/Turbine Manufacturing Location
MUCP: Mexico to United States	Mexico	US	Central U.S./Port U.S. (Offshore)
JEPP: Japan to United Kingdom	Japan	Europe (UK)	Port U.S./Port U.S. (Offshore)
UUCC: United States to United States	U.S.	U.S.	Central U.S./Central U.S.
CCPP: China to China	China	China	Port U.S./Port U.S. (Offshore)

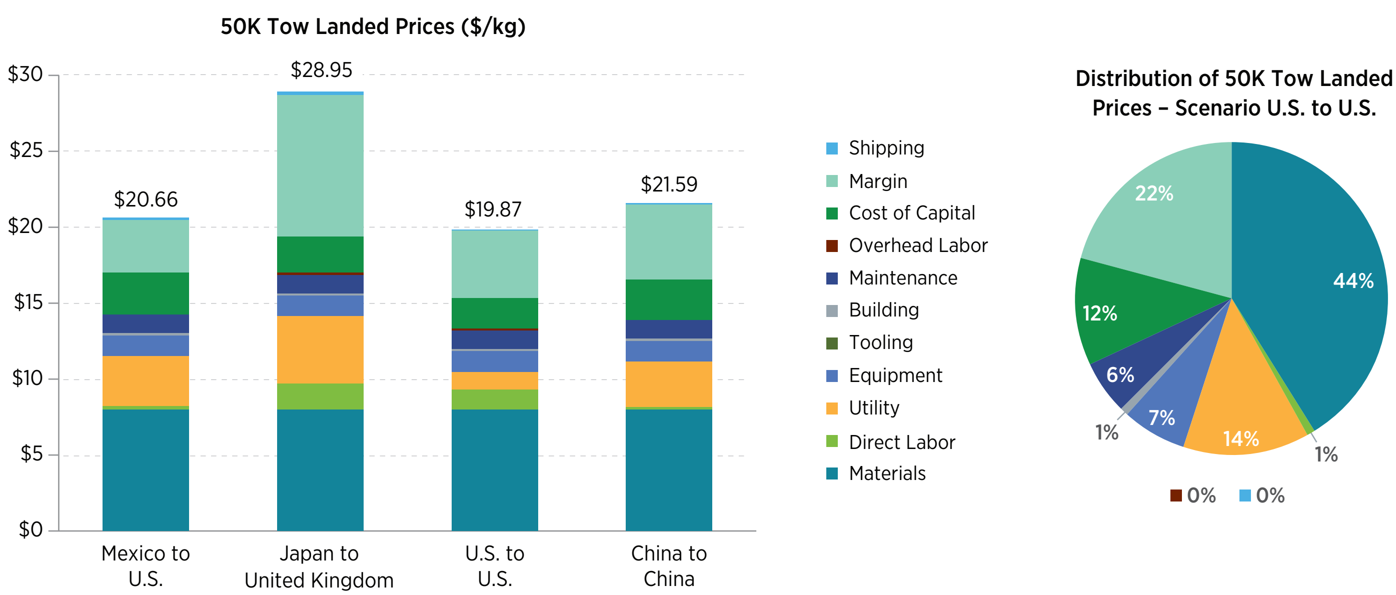


Figure 21: CEMAC modeled cost of manufacturing carbon fiber. Data source: Oak Ridge National Laboratory

Owing to low electricity and fuels costs, carbon fiber manufacture costs are lowest in the United States. Most U.S. carbon fiber manufacturing facilities are located in states with low energy costs (e.g., Washington, South Carolina, Alabama, and Tennessee), including the latest SGL Automotive Carbon Fibers plant located in Moses Lake, WA, which has low-cost hydroelectric energy available. Shipping costs, estimated to be the least detrimental factor, do not preclude the manufacture of carbon fiber in low-cost regions distant from end-use markets such as aerospace and automotive components, wind turbine blades, and pressure vessels. Conversations between Oak Ridge analysts and industry experts indicate that stable supply, low cost, and consistent carbon fiber quality is essential to meet the strong CFRP demand of clean energy manufacturing. Innovative low-cost carbon fiber manufacturing technology and cost-effective high-throughput CFRP manufacturing technologies could help the domestic industry to maintain its competitiveness.

The U.S. manufacturing cost of 61.5m spar cap carbon fiber turbine blades for onshore and offshore energy generation based on the worldwide supply of carbon fiber and intermediate fiber form estimated by CEMAC for four plausible scenarios (shown in Table 5) indicate the materials account for approximately 60% of the total blade cost, of which carbon fiber cost share is approximately 40% (Figure 22). Other insights:

- Lower-cost domestic carbon fiber producer has the cost advantage if both blade manufacturing and energy generation are located domestically, as in the UUCC scenario.
- Labor has a relatively lower share (13–16%) of total blade cost and is not detrimental to the relative domestic manufacturing competitiveness of blade manufacturing among various scenarios considered in this analysis.
- In the CCPP scenario, the domestic landed blade cost is the least due to low-cost Chinese raw material use and the avoidance of shipping cost that would be incurred if both domestic blade manufacturing and energy generation co-located offshore.
- For offshore wind energy, competitiveness can be significantly improved by transportation logistics in terms of co-locating near-shore both blade manufacturing and energy generation facilities. Unlike fiber and intermediate fiber form manufacturing, shipping costs would dictate the future siting of lightweight and longer blade manufacturing facilities. The shipping cost has a significantly larger cost share for onshore large blade manufacturing locations, i.e. approximately 20% of landed cost for shipping from central United States to offshore U.S. east coast and so resulting in the least competitive for the Mexico-based lower fiber cost blade manufacturing scenario (i.e., MUCP) considered in the analysis.

Lightweight and longer carbon fiber blade manufacturing is the most competitive in offshore energy generation consistent with the industry outlook today. Investments in maritime infrastructure and logistics necessary to support a viable offshore blade manufacturing industry could potentially increase U.S.-based carbon fiber blade manufacturing (Global Wind Network 2014). There is one such U.S.-based manufacturing facility—Blade Dynamics (acquired by General Electric Co. in 2015) in New Orleans, LA—with direct port access today.

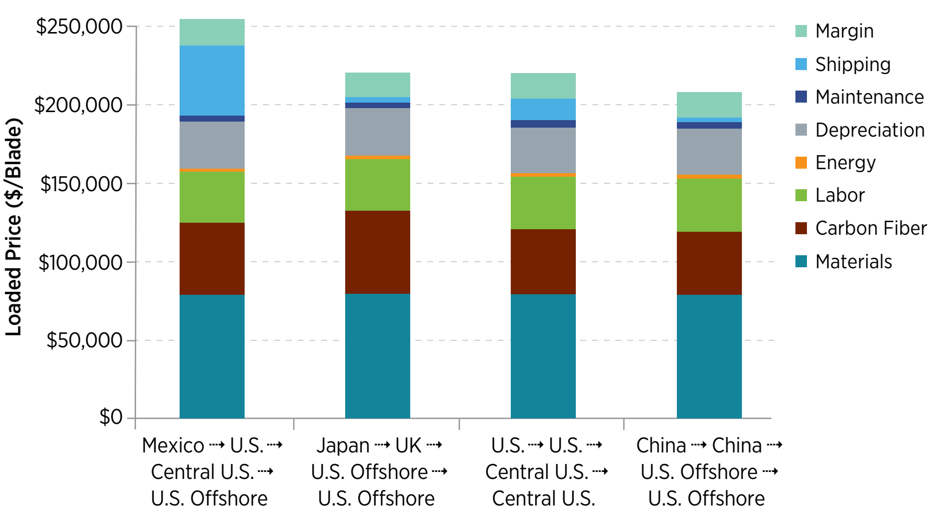


Figure 22. CEMAC modeled cost of manufacturing 61.5m carbon fiber spar cap blade

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LOOKING FORWARD

Between 2004 and 2014, investments in renewables alone, as one component of the broader clean energy landscape, jumped more than five-fold, from $60 billion to $310 billion (Bieter 2015)—driven by cost and performance improvements and supportive policy environments. Investments in renewable energy technologies, including hydropower, could grow to $400 billion by 2030 (IEA 2015), as countries commit to climate and clean energy goals outlined in the Paris Conference of Parties meeting (COP21), as consumers demand cleaner options, and as manufacturers and system providers innovate to provide increased value and affordable prices.

Over the past decades, manufacturers have responded to the market growth opportunities, principally seeking least cost options to serve both local and export markets, taking into account key factors such as labor, cost of capital and shipping costs.

While the clean energy transition in the United States and other OECD countries will continue to confront incumbent technologies in legacy sectors, the barriers to entry may be lower—and the projected market opportunities are greater—in non-OECD countries. As many clean energy technologies are poised to realize significant growth, cost reductions, and continued innovation, it is important to closely monitor market dynamics to uncover insights that decision-makers and producers can use to drive competitive advantage in the global clean energy marketplace.

The CEMAC mission is to provide robust, data-rich insights on clean energy markets and global trade flows. To support the global transition to a clean energy economy, in 2016 CEMAC and our partners plan to conduct new or additional analysis on technologies such as:

- Biomass-derived chemicals and products (NREL, Argonne National Laboratory, Pacific Northwest National Laboratory)
- Carbon fiber for lightweighting (Oak Ridge National Laboratory, NREL)
- Conventional and advanced heat pumps (NREL)
- Energy-efficient insulated windows (Lawrence Berkley National Laboratory, NREL)
- Geothermal binary power plants (NREL)
- Hydrogen filling stations (NREL, Argonne National Laboratory)
- LED commercial lighting (NREL)
- Small hydropower generation (Oak Ridge National Laboratory, NREL)
- Solar PV (NREL)
- Vehicle lithium-ion batteries (NREL, Argonne National Laboratory)
- Wide bandgap devices for clean energy technologies (NREL, Oak Ridge National Laboratory).

Several of these studies will contribute to CEMAC's forthcoming flagship publication, an annual benchmark of global clean energy manufacturing. Other studies will focus on specific parts of the larger supply chain in order to provide insights for study sponsors.

CEMAC is open to conducting studies with partners of all kinds, both government and industry, to help understand the complexities of the rapidly change clean energy market and enabling decisions related to policy and investment.

About the Clean Energy Manufacturing Analysis Center

Founded in 2015 with support from U.S. Department of Energy's Clean Energy Manufacturing Initiative, the Clean Energy Manufacturing Analysis Center (CEMAC) draws from open source and industry data to deliver insights of supply chains and manufacturing for clean energy technologies through uniquely-detailed bottom-up cost analysis. CEMAC provides objective analysis and up-to-date information on global clean energy manufacturing to inform choices for economic growth and the transition to a clean energy economy.

Going forward, CEMAC is tasked to:

- **Deliver world class analysis** on supply chains for clean energy technologies
- **Engage decision makers** to inform the transition to a clean energy economy
- **Develop innovative models and tools,** and high-impact publications
- **Increase capacity** for clean energy manufacturing analysis.

CEMAC Organization and Leadership

Housed within the Joint Institute of Strategic Energy Analysis (JISEA) at DOE's National Renewable Energy Laboratory (NREL), CEMAC harnesses the talent of the national laboratory network, in partnership with industry, universities, and research affiliates. Initial work, including this report, has benefited from research, publications, and insight from these organizations: Argonne National Laboratory, Lawrence Berkeley National Laboratory, NREL, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratory.

Advisory Committee

The CEMAC Advisory Committee composed of experts from industry, trade associations, academia, and government provides programmatic guidance to CEMAC. Advisory Committee members include:

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Methodology

CEMAC calculates the cost of manufacturing clean energy technologies through the well-accepted approach of discounted cash flow rate of return analysis. The result of this calculation is the minimum sustainable price, which is the required selling price of the product necessary for the operation to achieve a specified internal rate of return, or discount rate, on the total investment in capital and operating expenses. Included in the calculations are capital costs (i.e., the costs of purchasing equipment), fixed operating costs (labor, depreciation, property taxes, insurance, rent), variable operating costs (raw material inputs, supplies, utilities), maintenance and repairs, interest rate on debt, and general expenses (administrative, sales, and R&D costs). Total costs include balance of system costs that impact the economic viability of the technology being studied. In some cases, the boundary of the analysis is drawn to include the costs of retrofits, depending on the market opportunities for the technology. CEMAC uses the weighted-average cost of capital specific to the technology's industry, as the internal rate of return.

The tradeflow maps included in this report (Figures 6, 11, and 13) depict three-year average (2012–2014) value of trade flows in each technology between the United States and major trading partners. Values were derived from U.S. International Trade Commission (ITC) data on imports and exports, organized by harmonized tariff schedule (HTS) codes. HTS codes provide a proxy for selected technologies, but are not an exact match. For example, ITC data for solar PV cover PV modules but not related products like inverters or mounting hardware.

To the extent possible, we limit codes to commodities that are exclusive to the category. For example, the blades and hubs code (HTS 8412909081) only includes wind energy components. These numbers should be interpreted as a sample of trade activity associated with each category, not a comprehensive sum of all activity. These numbers do not include domestic sales, so they also should not be interpreted as a measure of overall economic activity by category.

Other HTS codes used in this analysis: Batteries: rechargeable lithium-ion batteries (includes all applications for rechargeable Li-ion batteries) – 8507600000; Solar PV: PV semiconductor devices including cells and modules (assembled) – 8541406020; PV semiconductor devices including cells – 8541406030; Carbon Fiber: Nonelectrical articles of graphite or carbon – 6815100000.

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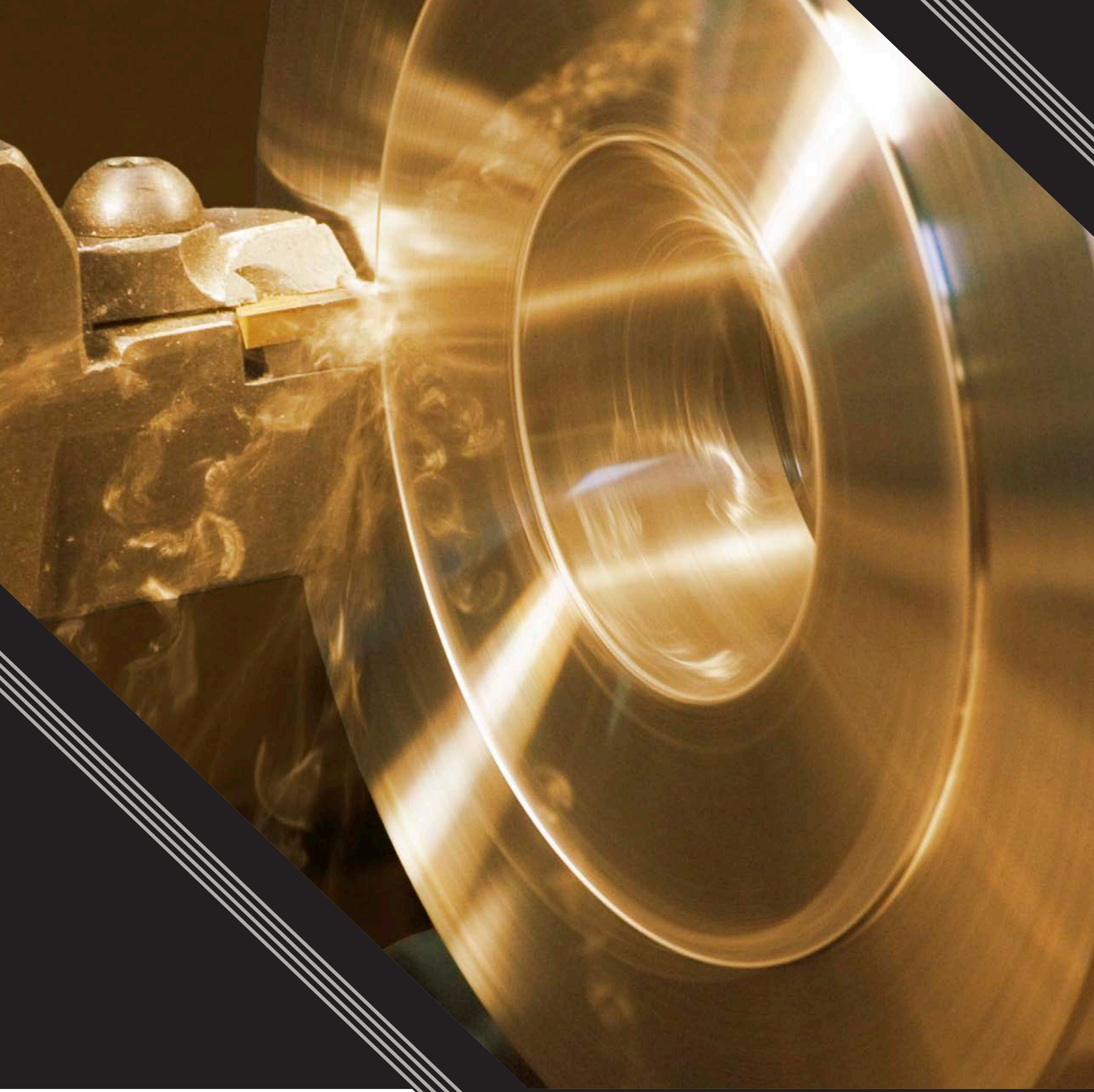

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Established in 2015 by the U.S. Department of Energy's Clean Energy Manufacturing Initiative, CEMAC engages the DOE national lab complex, DOE offices, U.S. federal agencies, universities, and industry to promote economic growth in the transition to a clean energy economy. CEMAC is operated by the Joint Institute for Strategic Energy Analysis at the DOE's National Renewable Energy Laboratory.

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