BENCHMARKS OF GLOBAL CLEAN ENERGY MANUFACTURING, 2014–2016

CEMAC Clean Energy Manufacturing Analysis Center

Operated by the Joint Institute for Strategic Energy Analysis

Acknowledgments

The principal investigators—Debra Sandor and David Keyser—would like to acknowledge the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), led by the Strategic Analysis Team, for its support in development of this report, including Brian Walker, Ben King, and Paul Spitsen. We also acknowledge the members of the Clean Energy Manufacturing Analysis Center (CEMAC) Advisory Committee for their advice throughout the development process. Key expert input was provided by John Reilly (Massachusetts Institute of Technology), Rebecca Hill (Colorado State University), and Ben Mandler (American Geosciences Institute). Many analysts within CEMAC made major contributions, including Ashwin Ramdas, Samantha Reese, Ahmad Mayyas, Scott Caron, Eric Lantz, Jon Weers, Robert Spencer, James McCall, Tian Tian, Tsisilile Igogo, and Billy Roberts. We also appreciate the editorial support of Beth Clark and Mike Meshek, and the design services of Liz Craig. Operational support by the Joint Institute for Strategic Energy Analysis (JISEA)'s Jill Engel-Cox and the National Renewable Energy Laboratory (NREL)'s Doug Arent and Gian Porro have been instrumental to CEMAC in producing this benchmark report.

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About this Data Book

The *Benchmarks of Global Clean Energy Manufacturing* report provides an assessment of the global state of clean energy manufacturing between 2014 and 2016.[1] Researchers examined four technologies—wind turbine components (blade, tower, nacelle), crystalline silicon (c-Si) solar photovoltaic (PV) modules, light-duty vehicle (LDV) lithium-ion battery (LIB) cells, and light-emitting diode (LED) packages for lighting and other consumer products—across manufacturing supply chains that include processing raw materials, making required subcomponents, and assembling final products.[2]

The impacts of the manufacturing supply chain for these four technologies are assessed in terms of three common benchmarks: market size (including manufacturing capacity and production), global trade flows, and manufacturing value added, and across 13 economies that comprise the primary manufacturing hubs for the technologies: Brazil, Canada, China, Denmark, Germany, India, Japan, Malaysia, Mexico, South Korea, Republic of China (referred to throughout this report as Taiwan), the United Kingdom, and the United States.[3] New methodologies were developed to generate the data sets for each benchmark, while accommodating the variations in clean energy technology manufacturing[4] supply chains and data availability. Throughout this report, general drivers for benchmark trends in the context of an ever-changing clean energy manufacturing landscape have been identified, but specific analysis of trends over the study period were not included in the scope of effort. Nonetheless, the data and insights provided by these benchmarks can help guide research agendas, inform trade decisions, and identify manufacturing opportunities by location and technology.

Focus and Framework

The Clean Energy Manufacturing Analysis Center (CEMAC)[5] developed and uses a common framework and standardized methods for assessing and comparing clean energy technology supply chains.[6] The analysis presented in this benchmark report focuses exclusively on the manufacturing aspects of the larger clean energy value chain and examines each technology in terms of four manufacturing supply chain links: raw material, processed material, subcomponents, and end products.

Just one piece of the larger clean energy economy, manufacturing is the linchpin between technology development and its deployment in the marketplace (see *Benchmarks of Global Clean Energy Manufacturing report framework* on p. 2). Upstream, innovation in the development stage has economic value in the form of intellectual property, research, and corporate management. Downstream, installation, systems integration, and operations bring economic value through employment, services, property taxes, improved efficiency, decreased energy consumption, and reduced negative environmental impacts. While development and deployment of technologies[7] make tremendous contributions to the economy, this report focuses on the value added by and opportunities found in the manufacturing supply chain.

While there is a wide array of clean energy in the global marketplace today, this report uses four technologies as proxies for broader market trends. Wind turbine components, c-Si PV modules, lithium-ion battery cells, and LED packages were selected for this report because they all experienced significant cost reductions, demand growth, and had adequate data to analyze during the report period. The specific materials and subcomponents in the analysis were selected based on standard criteria including data availability; uniqueness, or role as an enabling process/product; involvement in global trade; impact on overall cost, and contribution to quality (see the methodologies report[8] for details on selection criteria).

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[1] For more information, previous versions of the benchmark report, related reports, and key figures, see the CEMAC "Benchmarks of Global Clean Energy Manufacturing" website at https://www.jisea.org/benchmark.html.

[2] Throughout this report, *clean energy manufacturing* refers to aggregated metric values for the four end products, unless stated otherwise.

[3] Where data are available, a *rest of world* designation is used to present data from other economies beyond the thirteen. Throughout this report, *global* refers to aggregated metric values across the 13 economies examined and the rest of the world, unless stated otherwise.

[4] Throughout this report, *clean energy manufacturing technologies* refers to the four end products examined in this report (wind turbine components, crystalline silicon solar photovoltaic modules, light-duty vehicle lithium-ion battery cells, and light-emitting diode packages for lighting and other consumer products), unless stated otherwise.

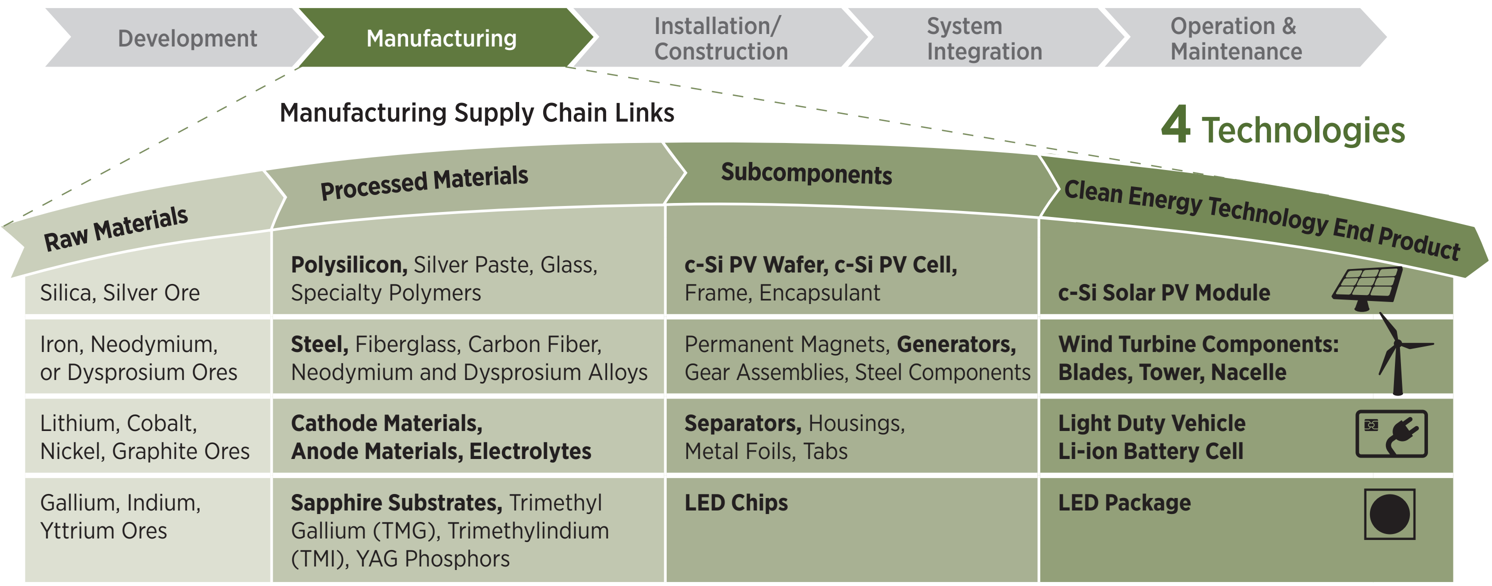
[5] CEMAC is a program under the Joint Institute for Strategic Energy Analysis (JISEA). More information about CEMAC can be found at https://www.jisea.org/manufacturing.html.

[6] For details about the benchmark methodology, see CEMAC's *Benchmarks of Global Clean Energy Manufacturing, 2014-2016: Framework and Methodologies* (Sandor et al. 2021).

[7] Data related to the deployment of some of the technology end products examined in this report can be found in the International Renewable Energy Agency's *Statistics Time Series* (IRENA n.d.)

[8] Benchmark methodologies are detailed in CEMAC's *Benchmarks of Global Clean Energy Manufacturing, 2014-2016: Framework and Methodologies* (Sandor et al. 2021).

Benchmarks of Global Clean Energy Manufacturing report framework



Value chain for clean energy technologies

Development → **Manufacturing** → Installation/ Construction → System Integration → Operation & Maintenance

Manufacturing Supply Chain Links

4 Technologies

Raw Materials	Processed Materials	Subcomponents	Clean Energy Technology End Product
Silica, Silver Ore	**Polysilicon,** Silver Paste, Glass, Specialty Polymers	**c-Si PV Wafer, c-Si PV Cell,** Frame, Encapsulant	**c-Si Solar PV Module**
Iron, Neodymium, or Dysprosium Ores	**Steel,** Fiberglass, Carbon Fiber, Neodymium and Dysprosium Alloys	Permanent Magnets, **Generators,** Gear Assemblies, Steel Components	**Wind Turbine Components: Blades, Tower, Nacelle**
Lithium, Cobalt, Nickel, Graphite Ores	**Cathode Materials, Anode Materials, Electrolytes**	**Separators,** Housings, Metal Foils, Tabs	**Light Duty Vehicle Li-ion Battery Cell**
Gallium, Indium, Yttrium Ores	**Sapphire Substrates,** Trimethyl Gallium (TMG), Trimethylindium (TMI), YAG Phosphors	**LED Chips**	**LED Package**

13 Economies Brazil • Canada • China • Denmark • Germany • India • Japan • Malaysia • Mexico • South Korea • Taiwan • United Kingdom • United States

3 Benchmarks Market Trends Trade Trends $ Value Added Trends

3 Years 2014 • 2015 • 2016

The 13 economies were benchmarked based on market size, manufacturing capacity across the supply chain, and data availability. Three common points of reference, or benchmarks—market size (including manufacturing capacity and production), global trade flows and manufacturing value added—provide a standardized basis for:

- Comparing key economic aspects of clean energy technology manufacturing on national and global levels
- Tracking changes as markets and manufacturing process evolve.

What's New

This is CEMAC's second benchmark report, expanded to summarize trends between 2014 and 2016. To address stakeholder feedback and incorporate additional years of data, this benchmark report presents some new features and formats:

- A more concise summary of the key insights from the benchmark analysis with the format modified from a full-length technical publication to a comprehensive yet easy-to-digest report
- New visualizations to present the key benchmark trends, with select visualizations published in the report, and additional visualizations available online
- The addition of Denmark to the group of manufacturing hubs examined, in recognition of its contribution to wind turbine component manufacturing and trade
- A new methodology to calculate the indirect value added metric that now includes value streams from both non-direct domestic and international intermediary components, processes, and services. A more detailed description can be found in the next section.
- Throughout the report all costs have been normalized to 2014 dollars [US$(2014)] to allow comparison over the period.
- Having secure access to raw materials is increasingly important to manufacturers who use global supply chains. For the first time, the benchmark report is able to track raw materials for light-duty vehicle lithium-ion battery cells. However, while important, in this report raw material flows were not tracked for the other three benchmark technologies because of insufficient data.

Understanding Benchmark Reporting

Market Benchmarks

Clean Energy Market Size: This benchmark provides insight into the relative concentration of demand for clean energy technologies across the globe. Market size (or market demand) data were collected from existing secondary sources to estimate the market size for each technology across the manufacturing supply chain and in each economy. When they were available actual production data for each subsequent downstream intermediate[9] formed the basis of demand estimates for key supply chain intermediates. When data were not available, typically for smaller industries (LED packages and LDV Li-ion battery cells), the demand for intermediates was approximated by assuming the production volume of the end product is equivalent to the demand for each upstream intermediate product. The monetary value of demand was determined by applying estimates of average global unit prices to allow comparison across technologies and economies.

Clean Energy Manufacturing Capacity and Production: This benchmark provides insight into the clean energy manufacturing capacity and production around the world and highlights opportunities for expansion to meet demand. Manufacturing capacity and production were estimated to highlight the economies that make the largest contributions in each category and to understand where excess capacity is located around the world for each technology. Like market size data, data were collected from existing secondary sources, and monetary values were determined by applying estimates of average global unit prices to (1) allow comparison across technologies and economies and (2) provide input for the value added benchmark based on the production value of each technology and intermediate.

Market data are presented in three visualizations in this report:

1. Stacked bar charts display the global distribution of production and demand across the supply chain, highlighting the contribution (in %) of each economy. (See *Clean energy technology end product global demand and production shares by economy, 2014–2016* on p. 6 for example.)
2. Combination line and bar charts show magnitude and trends of production and demand in end product units (e.g., megawatts for PV modules) across the supply chain. (See *Clean energy technology end product demand and production trends by economy, 2014–2016* on p. 7 for example.)
3. Stacked bar charts show excess manufacturing capacity, production, and capacity utilization for each link in the supply chain. (See *Clean energy technology end product manufacturing capacity utilization, 2016* on p. 8 for example.)

Trade Benchmark

This benchmark provides insight into global clean energy trade activity and interconnectedness across the manufacturing supply chain. Balance of trade (exports minus imports) is a key component of national GDP. The value of trade flows is derived from imports and exports data tracked by international harmonized trade codes used by the U.S. International Trade Commission (U.S. ITC) and International Trade Centre (ITC)[10]. While official trade data for the final products are often available, the upstream data are often intertwined with much larger industry sectors and difficult to extract for the specific technology of interest. With the exception of PV cells and polysilicon (two of the intermediates for PV modules), global trade data are only available for the end products included in this report.

Trade data are displayed in two visualizations:

1. Bar charts—which show imports (negative values), exports (positive values), and balance of trade (BOT) numerically—allow readers to quickly identify import and export trends among benchmarked economies. (See *National gross domestic product and clean energy manufacturing contribution to economy-wide manufacturing, 2014–2016* on p. 13 for example.)
2. Interactive chord charts that highlight the trade flows among benchmarked economies (for one year and, one technology link in each view) are available online.[11]

Value Added Benchmarks

This benchmark provides insight into the contribution and importance of clean energy manufacturing to national economies. Value added (VA) from clean energy manufacturing contributes to an economy's GDP and consists of wages, returns to capital (e.g., income to property owners), and taxes. Manufacturing VA from clean energy technologies is estimated using the estimated production value for each intermediate across the supply chain in combination with social accounting data from the Organization for Economic

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[9] Throughout this report, *intermediates* refer to the specific materials and components included in each supply chain link of the four end products.

[10] For more information about USITC, see the USITC website at https://www.usitc.gov/ and the International Trade Centre's market analysis tools at https://www.intracen.org/itc/market-info-tools/market-analysis-tools/.

[11] "Clean Energy Trade Benchmark," JISEA, https://www.jisea.org/benchmark.

Cooperation and Development (OECD) Structural Analysis (STAN) Input-Output (I-O) database.[12]

Total value added (tVA) from clean energy manufacturing is generally highest in economies with the highest levels of production and is composed of two components:

- **Direct value added (dVA)** comes solely from domestic clean energy manufacturing. This contribution to national GDP includes payments to manufacturing workers, property-type income such as profits earned by owners and investors, and taxes paid on production less government subsidies within a single economy. For example, if solar module manufacturing generated $100 million in revenue in a specific economy, and 70% of that went to intermediate inputs (payments for both domestic and non-domestic goods and services used in production), the remaining 30% would be the direct value added.
- **Indirect value added (iVA)** has two subcomponents:
  1. Domestic iVA comes from the broader supply chain that provides domestic inputs[13] used by manufacturers.
  2. Non-domestic iVA comes from goods and services exported to support manufacturing that takes place in other economies. The GDP of the economy that exports these goods and services benefits from the wages, profits, and taxes that support manufacturing in that exporting economy.

For example, a module manufacturer may purchase polysilicon from a polysilicon producer. This producer and its contribution to GDP would be included in the indirect effect, either as domestic iVA, if the polysilicon was manufactured domestically and as non-domestic iVA if the polysilicon was manufactured in another country. The non-domestic (inter-country) iVA indicates the globalization and interconnectedness of benchmarked economies with respect to clean energy manufacturing supply chains, and the domestic iVA indicates the strength of domestic supply chains.

Value added retained (VA retained) estimates the fraction of revenue an economy retains from in-economy production of clean energy technologies. VA retained varies across economies as a result of different wage rates, tax rates, government subsidies to industries, and company profitability. It can also be influenced by how much is spent on inputs, either imported or sourced domestically. When inputs such as polysilicon in solar module production are sourced domestically, both the dVA and iVA accrues to domestic industries or businesses that supply those inputs. If inputs are imported, the iVA accrues to businesses in the economy of origin and is not included in the dVA calculation. VA retained is calculated by dividing the domestic total value added (tVA) by the revenues from domestic manufacturing (aka direct output). For example, if solar module manufacturing generated $100 million in revenue in a specific economy, and domestic dVA is $30 million and domestic iVA is $20 million, VA retained is 50%: (30 +20)/100.

Value added data are presented in two different visualizations:

1. Bar charts represent dVA, iVA, and tVA for benchmarked economies by technology supply chain links for each of the three years. (See *Clean energy manufacturing total value added (tVA) by value added component, 2014–2016* on p. 11 for example.)
2. Bar charts show the share of tVA accrued from domestic and non-domestic production of clean energy technologies for each benchmarked economy. (See *Clean energy manufacturing total value added (tVA) domestic and non-domestic contribution, 2014–2016* on p. 12 for example.)

Data Confidence

This report provides a unique perspective of the clean energy manufacturing value proposition. The data needed to estimate the benchmarks at the desired level of disaggregation are not available for all technologies included in the benchmark report. By applying technology-specific engineering assumptions and analysis best practices, along with consultation and review by experts from industry and academia, we estimated benchmark metrics across the manufacturing supply chain. However, our level of confidence in data reported here varies. Details of the data confidence and specific assumptions used for each technology are provided in CEMAC's benchmark methodology report.[14]

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[12] Further information about the OECD STAN I-O database, including the data used in the benchmark report, can be found at http://www.oecd.org/sti/ind/stanstructuralanalysisdatabase.htm.

[13] Domestic inputs are payments by a domestic business or industry to other domestic businesses and industries for goods or services used in production.

[14] Benchmark methodologies are detailed in CEMAC's *Benchmarks of Global Clean Energy Manufacturing, 2014-2016: Framework and Methodologies* (Sandor et al. 2021).

Crosscutting Findings

Looking across the manufacturing supply chains of the four technologies—wind turbine components, crystalline silicon (c-Si) photovoltaic (PV) modules, light-emitting diode (LED) packages, and light-duty electric vehicle (EV) lithium-ion battery (LIB) cells—provides perspective on the collective/aggregate impacts and trends of clean energy manufacturing between 2014 and 2016.

Notable Trends

Manufacturing Capacity and Utilization

Manufacturing capacity expansion to meet anticipated demand growth was driven in part by domestic policies that set targets for renewable energy production and provide incentives to offset costs. Overall capacity utilization relative to global production for clean energy benchmark technology end products except LED chips declined from 2014 to 2016. While all economies added manufacturing capacity, China added the largest amount of new clean energy manufacturing capacity during the analysis period. Low manufacturing capacity utilization rates may imply that these industries could boost production in current manufacturing facilities to meet future demand growth or that new investment is required to modernize manufacturing processes to accommodate new technologies. Production increases that are not accompanied by increased demand, however, can place downward pressure on prices. For example, oversupply in PV module and LED chip supply chains contributed to falling prices for these components over the period.

Global Supply Chains

Across the benchmarked economies, indirect value added (iVA) from clean energy manufacturing was greater than direct value added (dVA), indicating that clean energy manufacturing supply chains added more value, both domestically and globally, than the manufacture of the end products. All benchmarked economies received iVA from the production of the four technologies in other economies as a result of global supply chains that link these economies. In general, most individual economies did not have the manufacturing capacity to meet their own demand for intermediates and services across the entire supply chain and relied on trade networks to fill the gaps.

Price and Volume

For some clean energy technologies in some economies, total value added (tVA) and market demand decreased over the period, while actual unit sales (physical units) increased due to rapidly dropping prices for end products. For example, while production of the four clean energy technologies increased significantly from 2014 to 2016 in physical units, the associated tVA decreased as a result of rapidly declining prices over the period. This situation is also reflected in the decline in global end product imports and exports in aggregate dollar terms over the period.

Wind

At $50.6 billion in 2016, tVA from wind component production across the 13 economies analyzed was the highest among the four benchmarked clean energy technologies. In addition, because tVA generally follows production trends, of the clean energy technologies studied, manufacturing of wind turbine components contributed the most value added to the benchmarked economies. A reduction in wind turbine production over the period drove the small overall decline in tVA from the four clean energy technologies (in aggregate) across the benchmarked economies.

China

China accounted for the largest demand for and production of each of the four clean energy technology end products, with tVA three to four times higher than that for each of the next three economies (the United States, Japan, and Germany). China also contributed the highest levels of non-domestic iVA to other economies. Policies focused on building manufacturing capacity and domestic supply chains and concerted efforts to increase production beyond domestic demand contributed to increased exports over the period and also helped China secure its position as the only benchmarked economy able to meet domestic demand for the four end products with domestic production alone.[15]

United States

The United States moved from third- to second-highest tVA from clean energy manufacturing of the four technologies over the period. The United States generally retained the highest shares of revenue from in-economy production of the clean energy technologies as dVA (VA retained), as a result of a combination of factors that varied across the four technologies relative to the other benchmarked economies, including robust domestic supply higher wages, greater profits to domestic shareholders, and fewer subsidies.

More detailed information can be found on the following pages.

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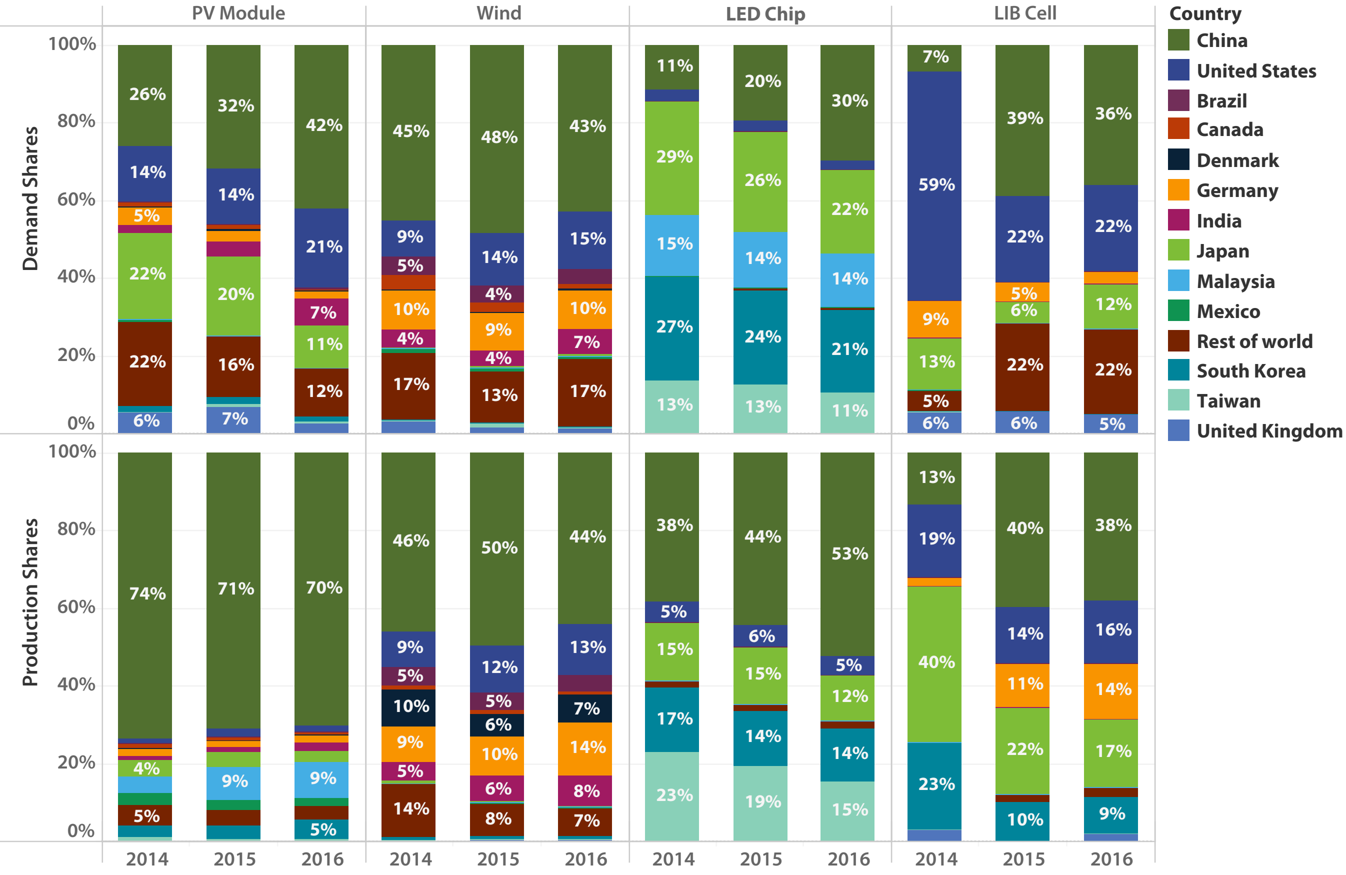
[15] See, for example, Usha C.V. Haley, George T. Haley, "How Chinese Subsidies Changed the World", Harvard Business Review, April 25, 2013, https://hbr.org/2013/04/how-chinese-subsidies-changed.

Benchmark Data: Market Trends

Clean energy technology end product global demand and production shares by economy, 2014–2016



Breakdown (in %) of global demand (top) and production (bottom) by economy for benchmarked clean energy technology end products. Note that LED chip data are presented in place of LED package data. (Due to a lack of availability of economy-specific demand data for LED packages, the benchmark analysis assumes that demand for LED packages is equal to production throughout the report).

Of the benchmarked economies in 2016, China had the largest shares of demand for and production of the four clean energy technologies. China increased its share of global demand for PV modules, LED chips, and LIB cells, while its wind turbine component share held steady.

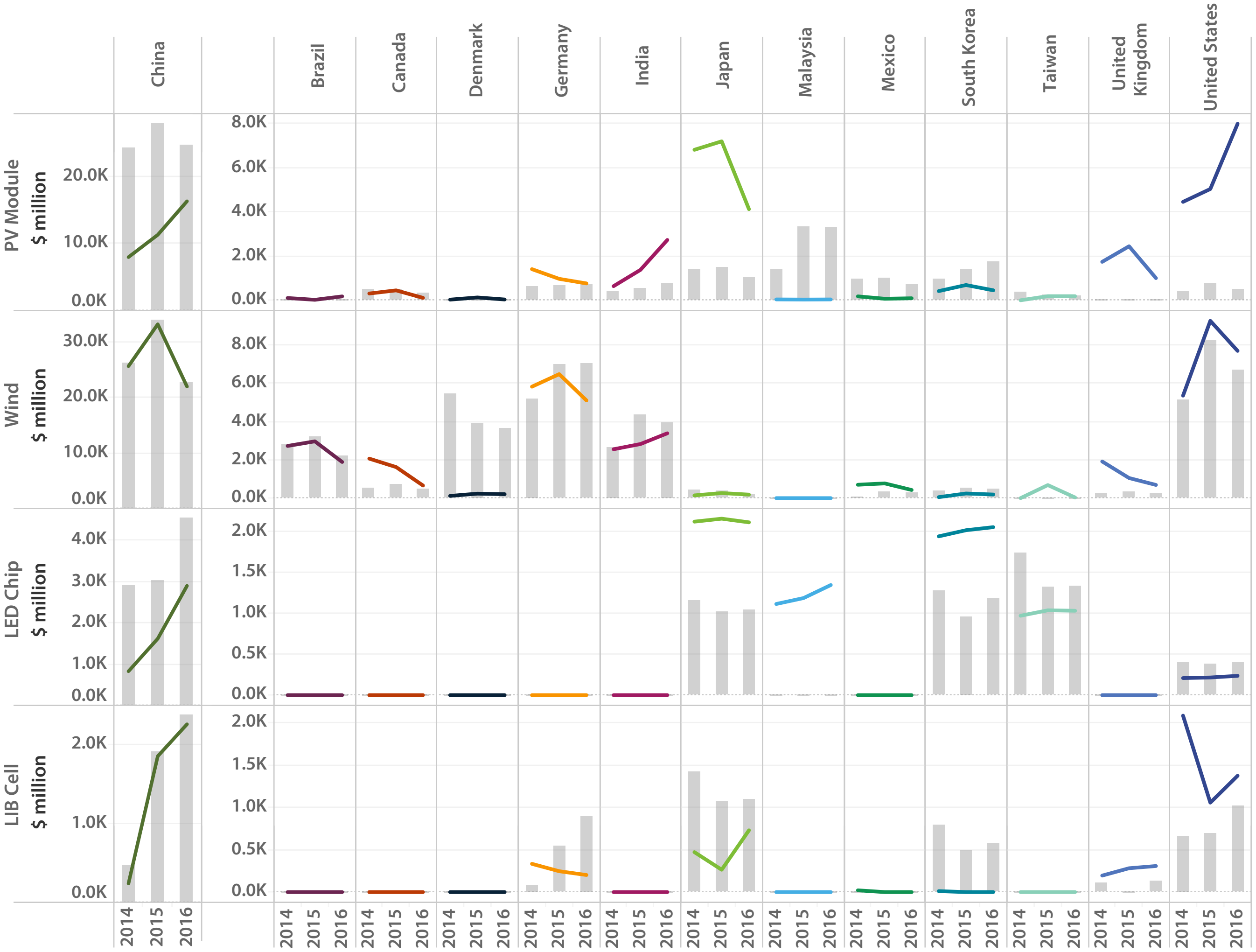
In 2016, 58% of PV demand was found outside China, while 70% of production occurred in China. C-Si PV module production outside China was dispersed across all but three of the economies included here, with Malaysia and Japan being the next largest producers.

Wind turbine component demand and manufacturing were generally colocated on a regional basis due to transportation challenges associated with their size and weight. Outside China, wind turbine production was led by the United States, Germany, India, Denmark, and Brazil.

Demand for LED packages (used in manufacturing a wide variety of products from lighting to televisions) was particularly concentrated, with nearly 100% of aggregate demand coming from only five economies—Japan, South Korea, Malaysia, Taiwan, and China—where many of the final consumer products that contain LEDs are assembled.

Lithium-ion battery cell demand was also fairly concentrated, with about 75% of aggregate demand located in four economies—China, the United States, Japan, and Germany—the top four automotive manufacturers globally. Over the period, the distribution of demand and production shares shifted significantly for LDV LIB cells. The demand shares from non-benchmarked countries increased from 5% to 22%, as U.S. demand shares declined from 59% to 22% over the period. On the production side, LIB production shares dropped to 17% in Japan (from 40%) and 9% in Korea (from 23%).

Clean energy technology end product demand and production trends by economy, 2014–2016



Demand (color-coded lines) and production (gray bars), both in US$(2014), for four clean energy technology end products by economy. Note the variable scale, which is used to help visualize data trends across the widely varying market size for the four technologies; China data are on different scales than those of the other benchmarked countries. Note that LED chip data are presented in place of LED package data, due to a lack of availability of economy-specific demand data for LED packages.

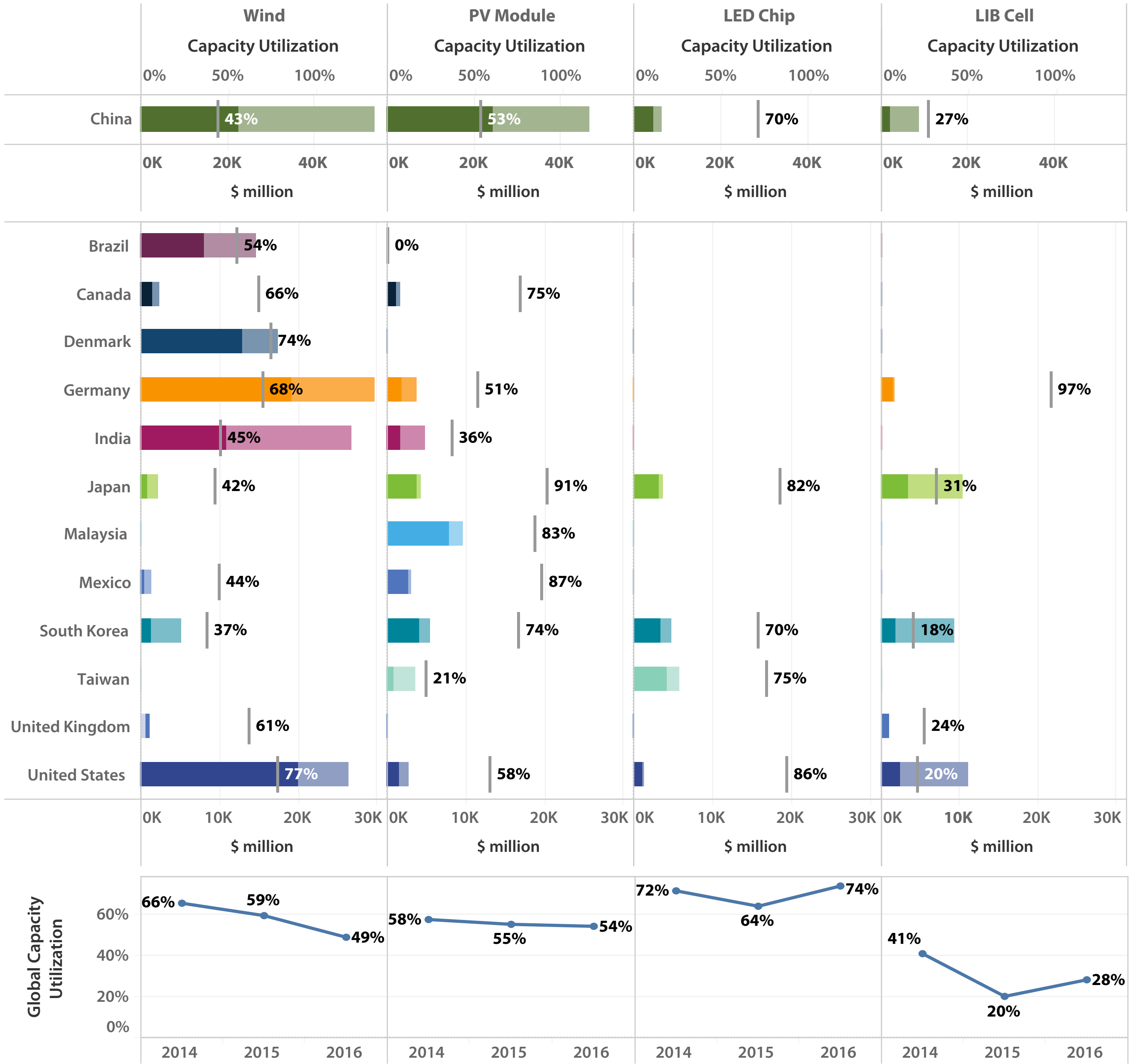
The manufacturing of the four clean energy technology end products contributed to global markets of widely varying sizes in 2016, ranging from the $42 billion wind industry to the $6 billion automotive lithium ion battery cell industry.

Between 2014 and 2016, China had the highest demand for and production of the four benchmarked clean energy technologies. Over the period, global demand (on a dollar basis) for the four clean technology end products in total decreased slightly—from $98.2 billion to $97.1 billion, with a peak of $116.8 billion in 2015. Total demand (on a dollar basis) grew only in the United States and India. Wind and c-Si PV end products constituted the largest contribution to demand for clean technologies across the 13 economies.

Of the benchmarked countries, only China had sufficient production to meet domestic demand for the four clean technology end products over the period. In 2016, Germany and India had sufficient production to meet domestic demand for PV modules and wind turbine components. Germany was also able meet its demand for LIB cells.

The smallest shortfalls between domestic production and demand appeared for wind turbine components, as these large components tend to be manufactured relatively close to where demand is located. The largest production-demand gaps were observed for PV modules in the United States, Japan, and India; LED chips in Japan, Malaysia, and South Korea; and LIB cells in the United States.

Clean energy technology end product manufacturing capacity utilization, 2016



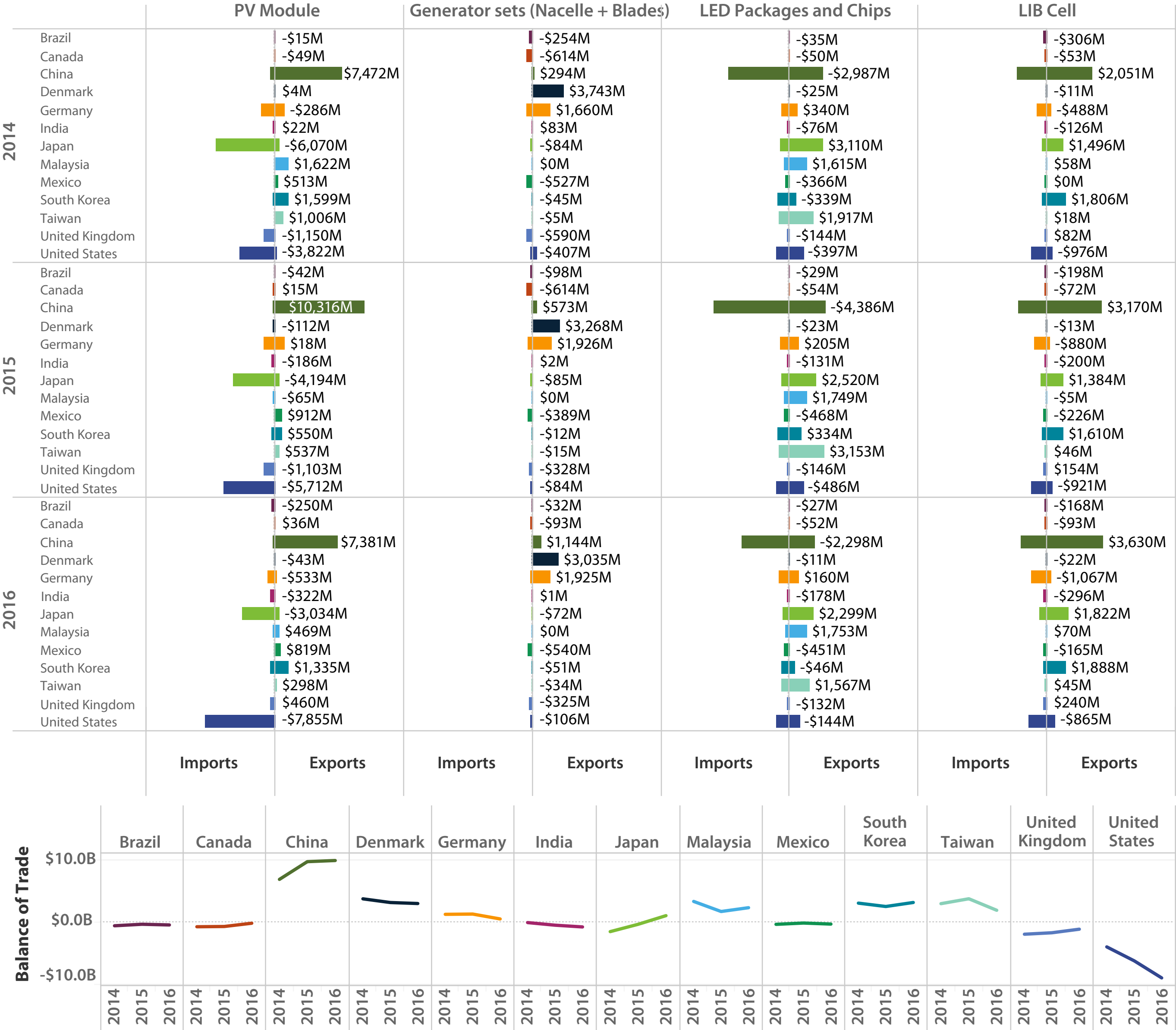
Bars show manufacturing capacity (lighter shading) and utilized manufacturing capacity (i.e., production, darker shading) in US$2014 for the benchmarked economies in 2016. Vertical lines and associated numerical values show capacity utilization (production as a % of manufacturing capacity). Trend lines show global capacity utilization percentage for 2014–2016 (bottom). Note that China is displayed on a different scale.

Global manufacturing capacity increased for all four technologies over the period. There was excess manufacturing capacity for nearly all of the four clean energy technologies, in virtually all of the 13 economies. Capacity utilization was highest for LED packages and lowest for LIB cells but was still lower than the typical economy-wide manufacturing facility capacity utilization rate of around 80% (Federal Reserve Bank of St. Louis 2018).

Increasing manufacturing capacity over the period indicates that manufacturers were anticipating continuing increased demand for the clean energy end products. Low capacity utilization implies that these industries boosted production in current manufacturing facilities to meet potential demand growth from increased technology adoption. However, without increased demand, persistent low capacity utilization rates can place downward pressure on pricing.

Benchmark Data: Trade Trends

Clean energy technology end product trade, 2014–2016

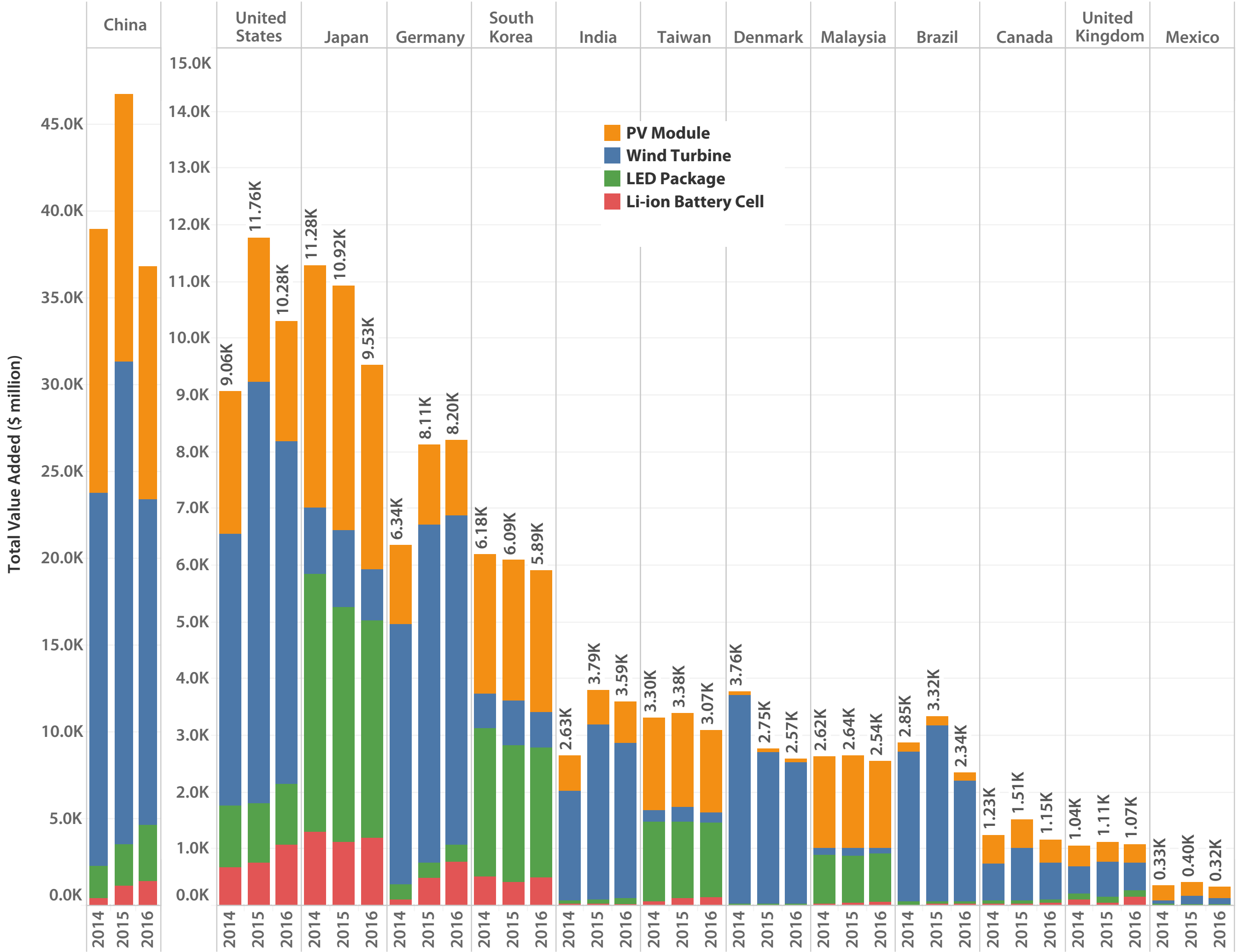


Bar chart (top) shows imports (negative values), exports (positive values), and balance of trade (exports less imports) in US dollars US$(2014) by economy for four clean energy end products: wind turbine nacelles and blades PV modules, LED chips and packages, and lithium-ion cells. Line chart (bottom) shows balance of trade trends for the four end products. Note that unlike other figures, imports and exports for PV modules are not broken out by chemistry (e.g., c-Si) and lithium-ion batteries are not broken out by end-use (e.g., light duty vehicles).

From 2014 to 2016 aggregate exports for the 13 economies declined 7.3% from $ 39.5 billion to $36.6 billion while imports declined 9.2% from $51 billion in 2014 to $46.3 billion in 2016. China was the largest exporter of benchmark technologies while the United States was the largest net importer. Exports of PV modules, LED packages, and wind turbine nacelles and blades declined (20.2%, 18.5% and 9.2%, respectively), while exports of LIB cells expanded (19.4%) over the period. From 2014 to 2016, wind turbine component imports experienced the largest decline at 48.5%; imports of LED packages declined by 16.4%; and imports of PV modules remained relatively flat, declining by just 0.7%. Imports of lithium-ion battery cells increased by 13.3%. Some net importers of end products, such as the United States, were major exporters of upstream processed materials and/or subcomponents for the same technologies, illustrating the complexity of clean technology manufacturing and trade.

Benchmark Data: Value Added Trends

Clean energy manufacturing total value added (tVA) by clean energy technology, 2014–2016



Total value added (tVA) trends in US$(2014) million from manufacturing of four clean energy technology end products in 13 key economies. Economies are ordered by tVA. Note that tVA for China is displayed on a different scale. Data are listed in order of 2016 tVA.

Total value added (tVA) from production of the four benchmark technologies increased by $89.6 billion from 2014 to $102.4 billion in 2015, and then dropped to $87.3 billion in 2016. While tVA decreased on a dollar basis, physical unit sales for the benchmark technologies actually increased because of significant technology price declines (see discussion on global average selling prices at end of Crosscutting section).

From 2014 to 2016, China accrued the largest tVA from manufacturing the four clean energy end products[16] in all three years. China's tVA grew from $39.0 billion in 2014 to $46.7 billion in 2015, and then dropped to $36.8 billion in 2016, driven by decreases in revenues from wind turbine component manufacturing.

The United States moved from third to second highest tVA among the economies, jumping from $9.1 billion in 2014 to $10.3 billion in 2016, due largely to increasing wind turbine and lithium-ion battery pack manufacturing. Japan moved from second to third due to a drop in tVA from $11.3 billion in 2014 to $9.5 billion in 2016, mainly from decreased tVA from PV module and LED package production. The greatest amount of tVA growth from 2014 to 2016 was experienced by Germany and the United States, with increases of $1.9 billion and $1.2 billion, respectively.

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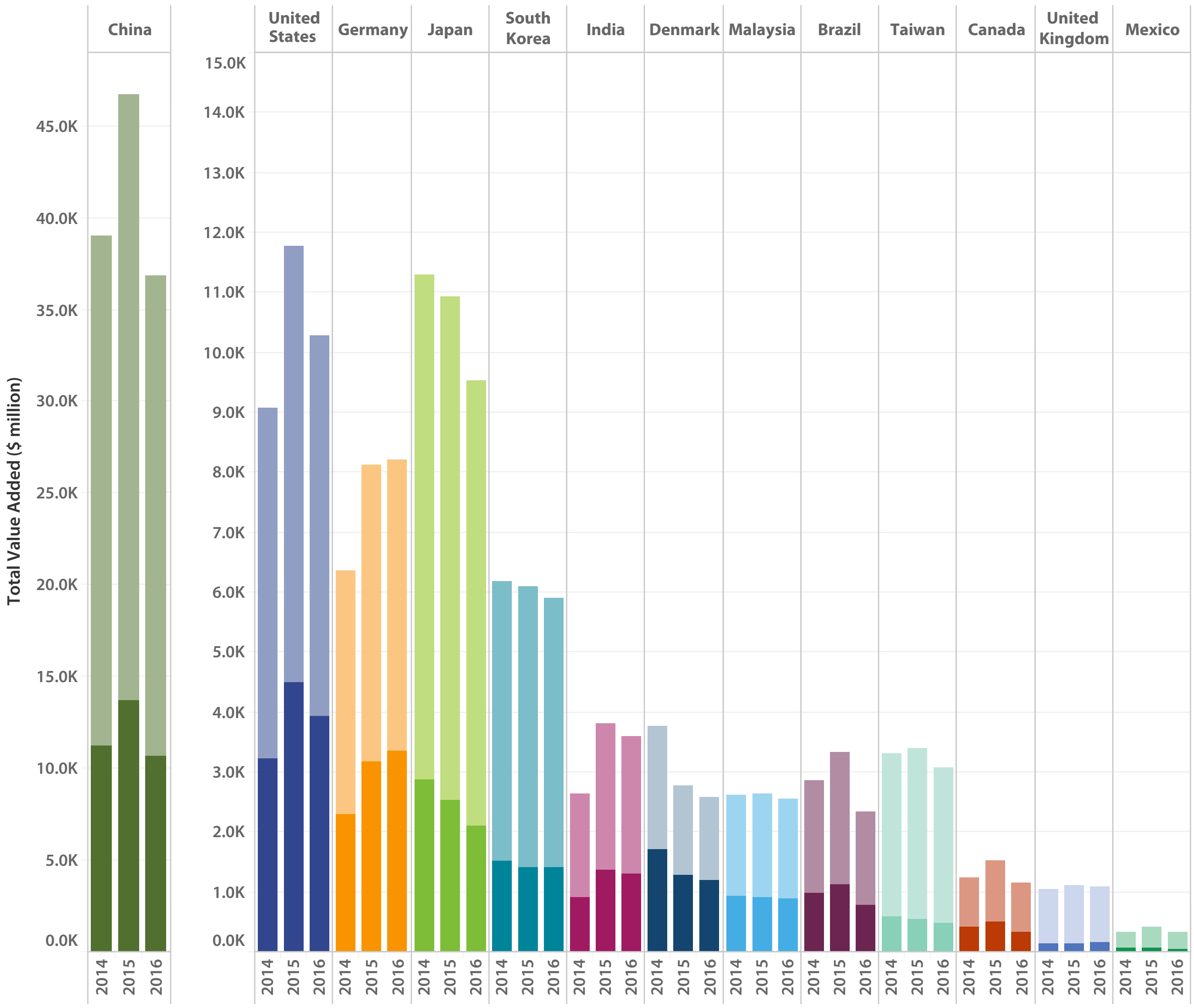
[16] Only final products are included to avoid double-counting of indirect VA numbers. For example, solar cells are used to make modules, so cells are part of indirect VA for modules. Adding tVA for cells and modules would double-count cells. Final products are defined as solar PV modules; LED cells; LIB cells for vehicles; and nacelles, generators, and towers for wind turbines.

Clean energy manufacturing total value added (tVA) by value added component, 2014–2016



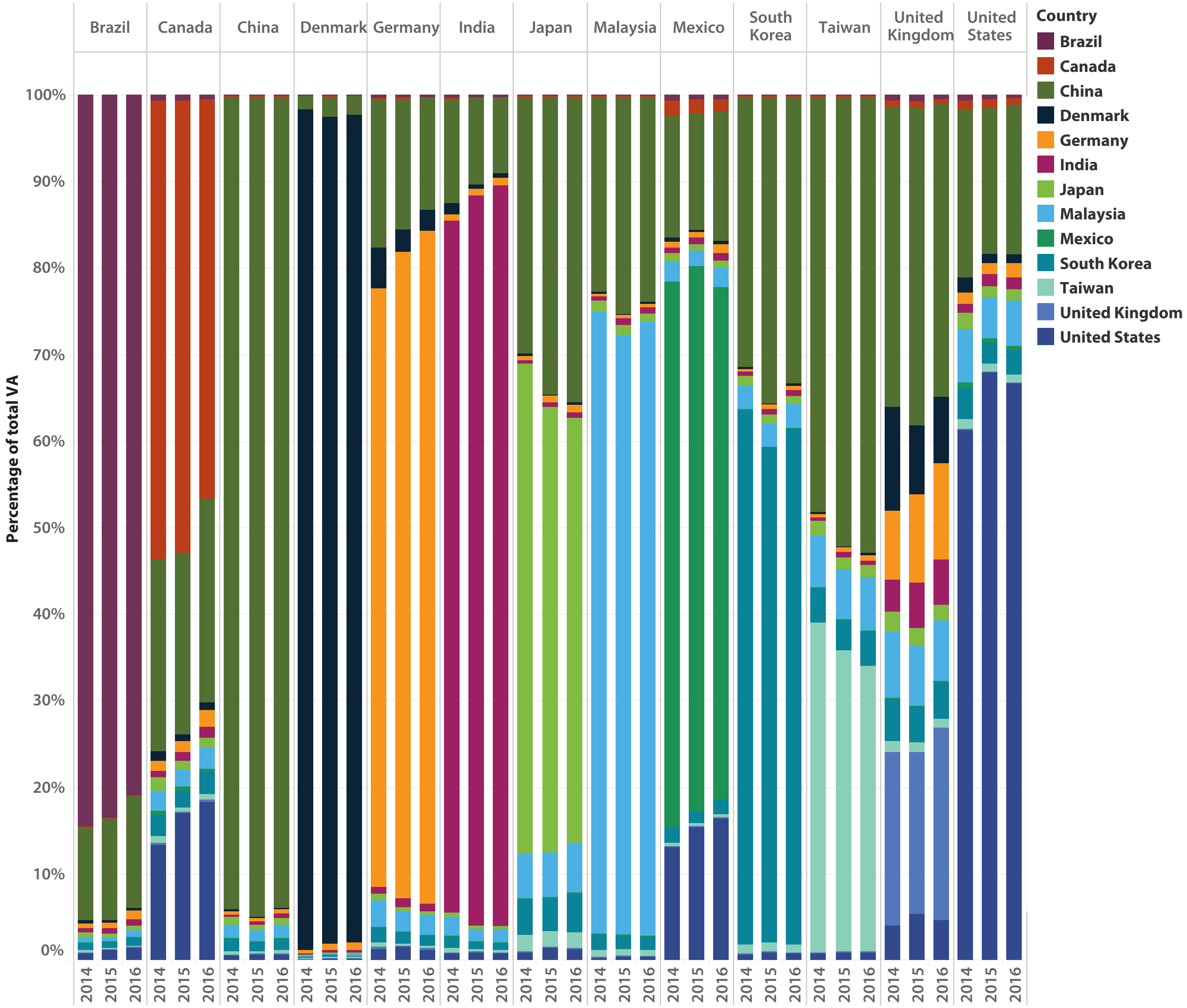
Total value added (tVA) for the period in US dollars (2014$) from manufacturing of four clean energy technology end products in the 13 economies. Darker shading indicates direct value added (dVA), and lighter shading indicates indirect value added (iVA). Economies are listed in order of dVA in 2016. Note that tVA for China is displayed on a different scale than the other economies.

Across the economies analyzed, indirect value added (iVA) from the four benchmark technologies was greater than direct value added (dVA), demonstrating the larger amount of indirect value added through processing materials, manufacturing intermediary components, and providing services throughout the supply chain instead of from directly manufacturing the clean energy technologies themselves. China's dVA and iVA from manufacturing the benchmark technologies was significantly greater other than all other economies.

Note that this benchmark report does not include a detailed decomposition of sources of indirect value added.

The United States, the United Kingdom, Canada, and Germany retained the greatest shares of tVA as a portion of manufacturing revenue. This metric reflects the extent of domestic supply chains as well as prevailing wages, domestic profits, and taxes less subsidies.

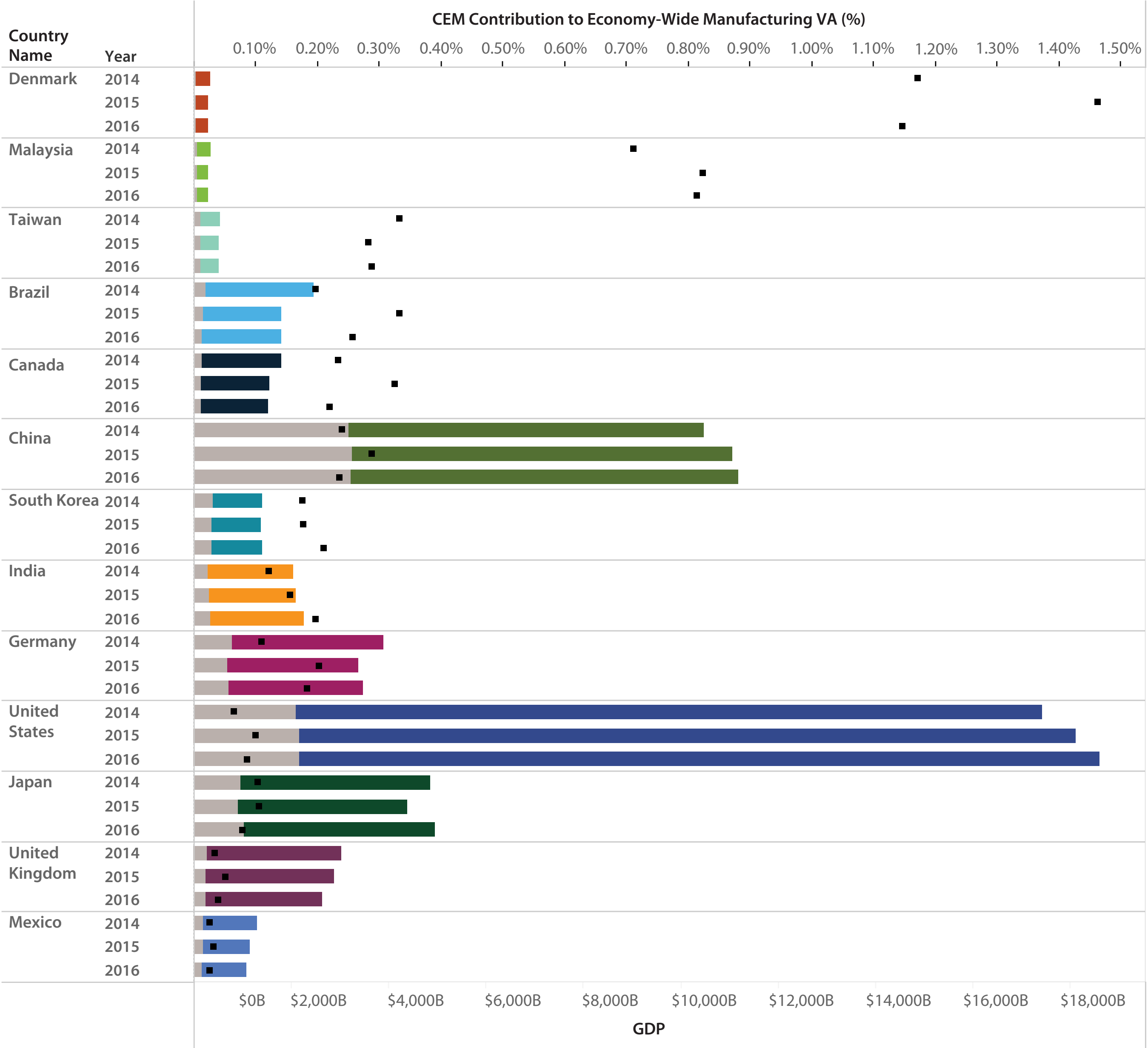
Clean energy manufacturing total value added (tVA) domestic and non-domestic contribution, 2014–2016



For each economy (listed across the top), color-coded bars show the share of tVA accrued from domestic and non-domestic production of clean energy technologies for 2014 to 2016. Domestic bars (generally, the largest in each column) represent the share of tVA (iVA plus dVA) from domestic production. Non-domestic bars represent the share of tVA (iVA only) from production in other economies (dVA only occurs in the economy where production occurs).

As a consequence of global supply chains associated with the production of the four benchmark technologies, all analyzed economies received indirect value added from the production of intermediate material, subcomponents, or services related to end product manufacturing of PV modules, wind turbine components, LED packages, and lithium-ion battery cells in other economies. For example, in 2016, the United States received $3.4 billion in iVA from manufacturing in the other economies, comprising 33.3% of the $10.3 billion U.S. tVA. China was the largest supplier of materials and components to all the other countries allowing it to contribute the most iVA to the other benchmarked economies. In the benchmarked economies, the greatest share of tVA is generally accrued from domestic production of clean energy technologies. Exceptions were the United Kingdom and Taiwan, where iVA accrued from clean energy manufacturing in China was greater than tVA accrued from domestic production.

National gross domestic product and clean energy manufacturing contribution to economy-wide manufacturing, 2014–2016

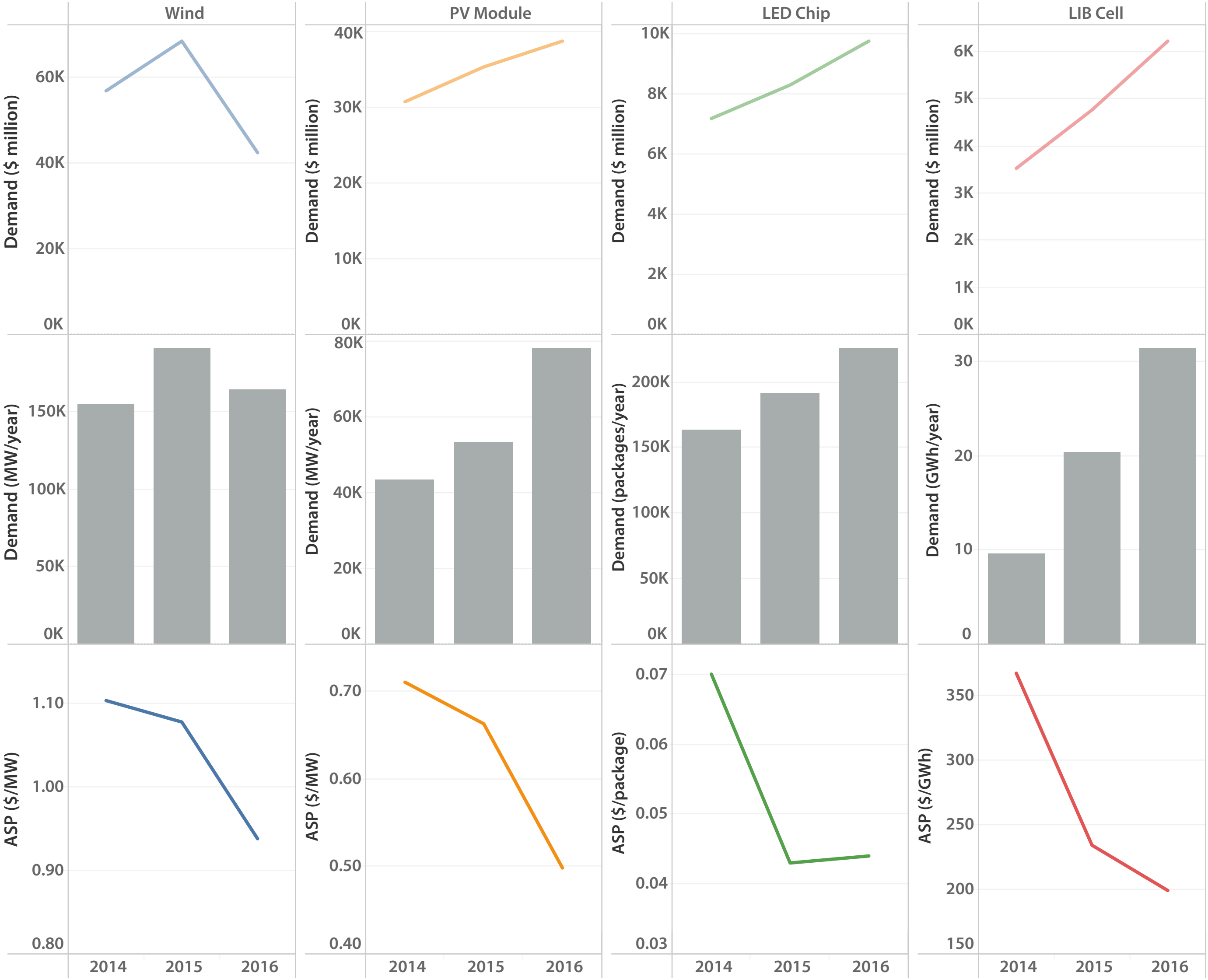


Total bar length shows national gross domestic product (GDP) in US(2014$), gray shading indicates portion of GDP contributed by all manufacturing in a given economy (bottom axis). Squares indicate the percentage of tVA from domestic clean energy manufacturing (does not include iVA from non-domestic manufacturing) as a fraction of GDP from economy-wide manufacturing (top axis). Data are presented in the order of each economy's domestic clean energy manufacturing share of national GDP.

Domestic clean energy manufacturing is a small contributor (0.03% to 1.2%) to national gross domestic product in all economies analyzed. The four benchmark technologies contributed the most to manufacturing sectors in Denmark, Malaysia, and Taiwan (the three smallest economies analyzed in this report).

Challenges: Comparing Clean Energy Manufacturing Trends Over Time

Impact of global average selling price (ASP) on global demand trends, 2014–2016



Lines (top) show global demand for the end products in US$(2014) million/year. Gray bars (middle) show demand in physical units/ year (i.e., MW for Wind and PV, number of packages for LEDs, and GWh for LIB). Lines (bottom) show estimated global average selling price for each benchmarked technology over the period. Note that each technology is presented on a different scale.

Because demand, production, and manufacturing capacity are measured in different physical units for each of the four technologies (e.g., gigawatt-hours for LIB cells and megawatts for PV modules), the market benchmarks reported here are normalized to a dollar-per-year basis to enable comparison and aggregation across technologies. However, this approach may not fully discern trends for physical units when the global average selling price (ASP) changes significantly during the period.

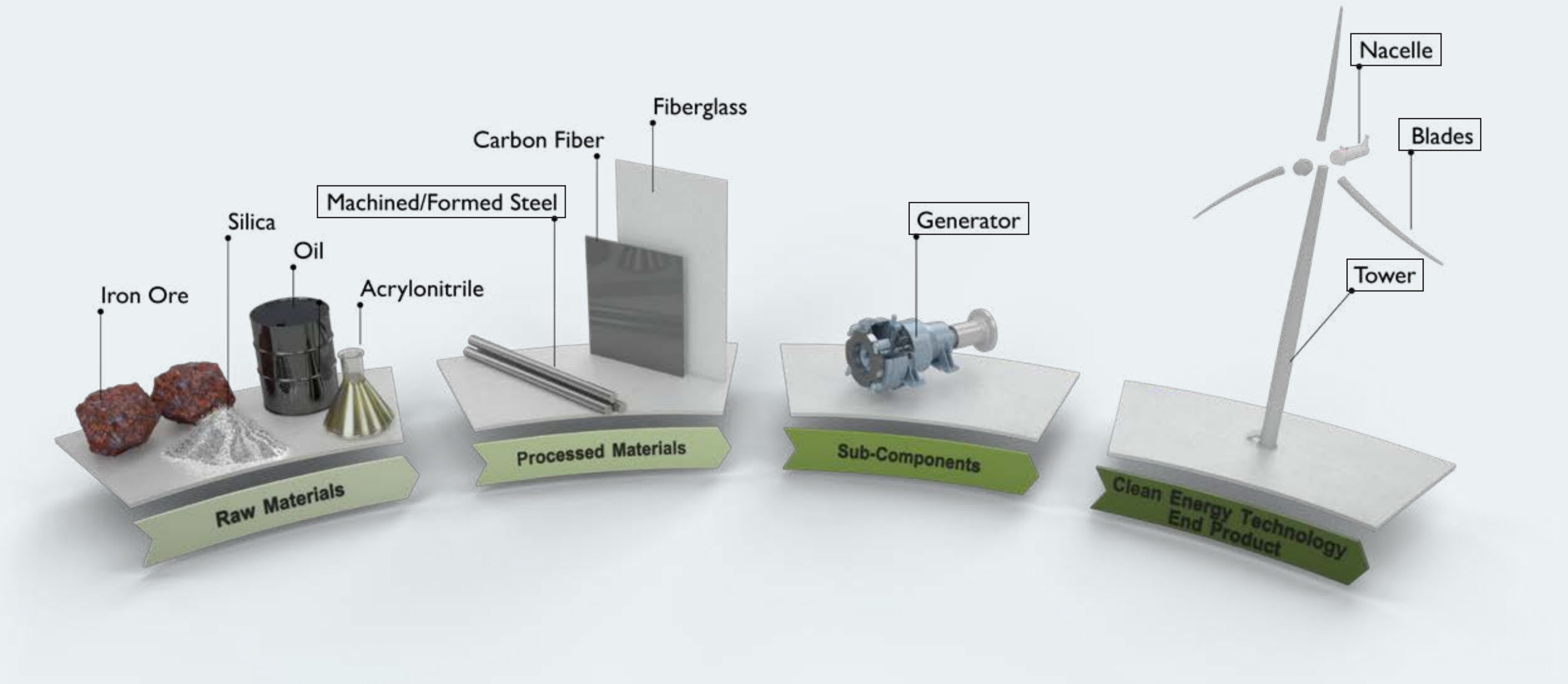
For example, global demand for wind turbines increased by 6.2% on a megawatt-per-year basis from 2014 to 2016 but declined by 26% on a dollar-per-year basis over the same period. For the other technologies, while the general unit-per-year and dollar-per-year trends were the same, the magnitude of the rates of change were different. The decline in wind demand on a dollar-per-year basis was great enough to impact the aggregate demand trend for the four clean energy technology end products.

Consideration of ASP trends can provide additional context when interpreting aggregated market and VA benchmark results and trends in this report.

Wind Turbines

Wind is the second largest source of renewable electricity generation behind hydropower, with approximately 563 GW deployed globally at the end of 2018 (IRENA n.d.). From the beginning of 2014 to the end of 2016, roughly 167 GW of new capacity was added globally, growing the cumulative capacity from 300 GW to 467 GW (an increase of 56%) (IRENA n.d.). This growth represents approximately $350 billion of new wind investment for the same period (IRENA n.d.).

Wind turbine components and supply chain



Wind turbine supply chain alignment with Clean Energy Manufacturing Analysis Center (CEMAC) benchmark framework. Boxes highlight components included in the benchmark analysis. No raw materials were included in the analysis because of a lack of data that could link specific materials to end product manufacturing. Illustration by Josh Bauer, NREL

The modern wind turbine is composed of more than 8,000 individual subcomponents (EWEA 2009). The majority of these subcomponents (especially smaller ones) are produced and transported globally. However, once assembled into intermediates or end products, they often remain “in-country” because challenges caused by their size and weight. Approximately 90% of the value of these subcomponents is reflected in estimated prices for three main components nacelles, blades, and towers (Moné et al. 2015). This analysis tracks these three high value components in addition to steel.

Continued development of offshore wind and more moderate wind-speed resource areas have created opportunities for innovation, including taller towers, longer blades, and lower-weight nacelles and rotors. These advances generally expand the accessible wind resource. Significant evolution of the global supply chain is anticipated as manufacturers evaluate further cost-cutting measures, such as consolidation and lower cost centers, and as they begin to deploy smart factories and advanced manufacturing methods.

Notable Trends

Key drivers of wind turbine supply chain trends include:

- Declining wind turbine component prices resulting from maturing supply chains
- Expiration and reduction of subsidies to promote wind turbine manufacturing and deployment
- Preference for domestic production due to cost and logistic challenges associated with transporting large wind turbine components.

Wind Turbine Component Prices and Competitiveness

Global average capacity-weighted installed wind costs (in US$(2014)) decreased from $1,655/kW in 2014 to $1,518/kW in 2016 (8% decrease) (IRENA 2020). In the United States, the average capacity-weighted project cost from 2014 to 2016 fell from $1,743/kW to $1,620/kW (7% decrease) (Wiser and Bolinger 2019). In 2016, the average generation-weighted levelized power purchase agreement price in the United States was $24.34/MWh, while today prices are estimated to be below $18.46/MWh in some parts of the country (Wiser and Bolinger 2019). Despite the price declines through 2016, wind turbines remained the most capital intensive of the technology end products evaluated over the period. As a result of higher production revenues from wind component manufacturing, economies derived greater value added from manufacturing wind components than from other clean energy technology intermediates.

Expiration of Subsidies

Uncertainty surrounding renewal of the U.S. renewable electricity production tax credit (PTC) contributed to 2015 peaks in wind energy technology demand, production, trade flows, and value added. Drops were seen in 2016 in all these metrics across the economies studied, due in part to the PTC expiration and reduction of similar subsidies in China and Germany. Declining subsidies and market maturation can also put increased pressure on the supply chain to lower prices.

Preference for Domestic Manufacturing

For wind energy technologies, domestic market demand drives domestic manufacturing of the end products and, to a lesser extent, the upstream supply chain. This domestic production alleviates cost and logistic challenges associated with transporting large wind turbine component imports. As a result, most of the tVA from wind turbine component production was accrued from domestic manufacturing, with less inter-economy trade than typically seen with other technologies. With the exception of the United States, key wind turbine manufacturing economies' domestic production was able to meet domestic demand across the supply chain. tVA from manufacturing wind turbine components was greatest for China, followed by the United States, Denmark, and Germany, the four largest wind turbine component producers.

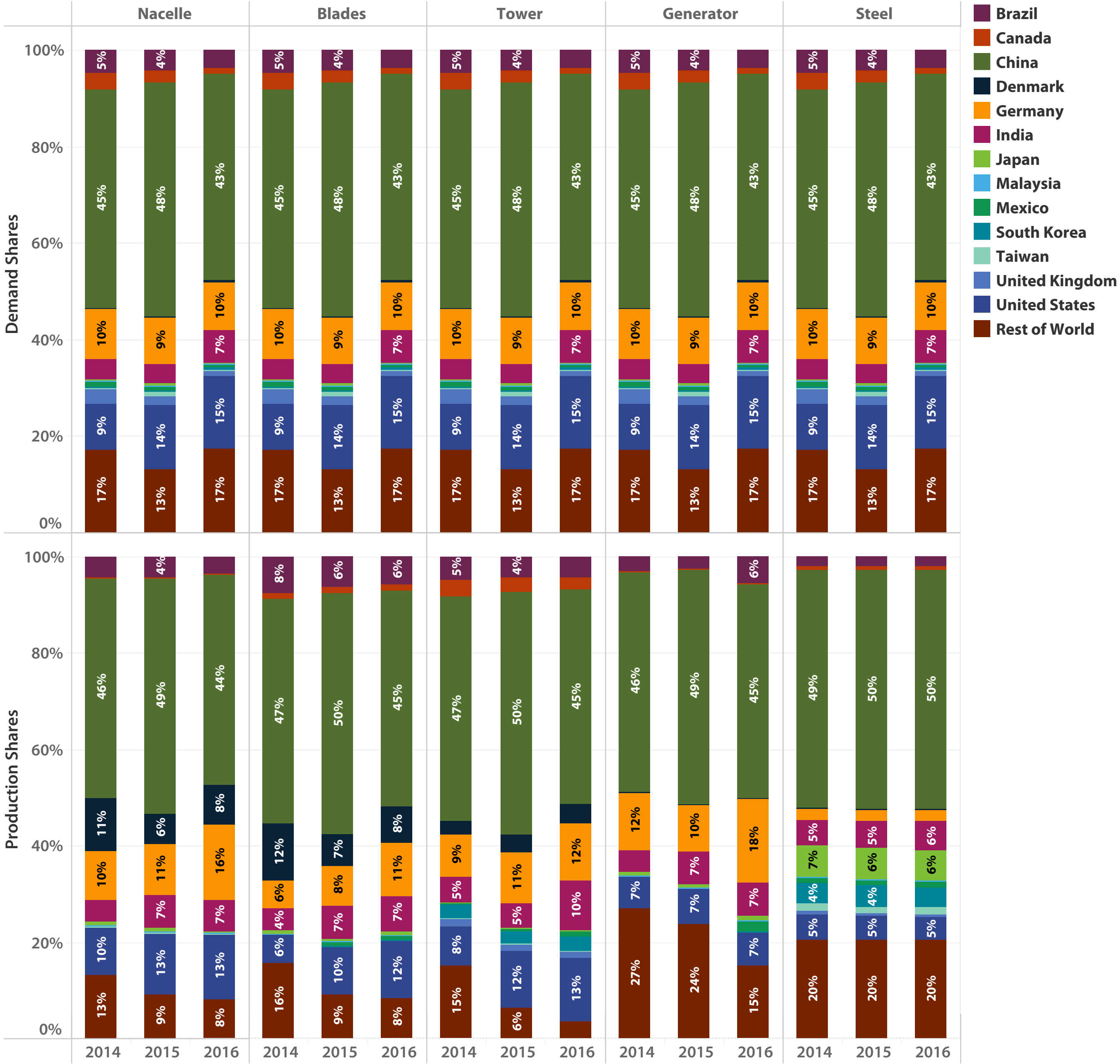
Cost Competitiveness and Advanced Manufacturing

Continuing advances in wind turbine technology (larger rotors, taller towers, deployment in lower-quality wind areas), combined with advanced manufacturing approaches (including on-site additive manufacturing and 3D printing, automation, robotics, advanced sensing, and smart/adaptable floorplans), have the potential to circumvent issues related to component transportation.

More detailed information can be found on the following pages.

Benchmark Data: Market Trends

Wind turbine supply chain demand and production shares by economy, 2014–2016

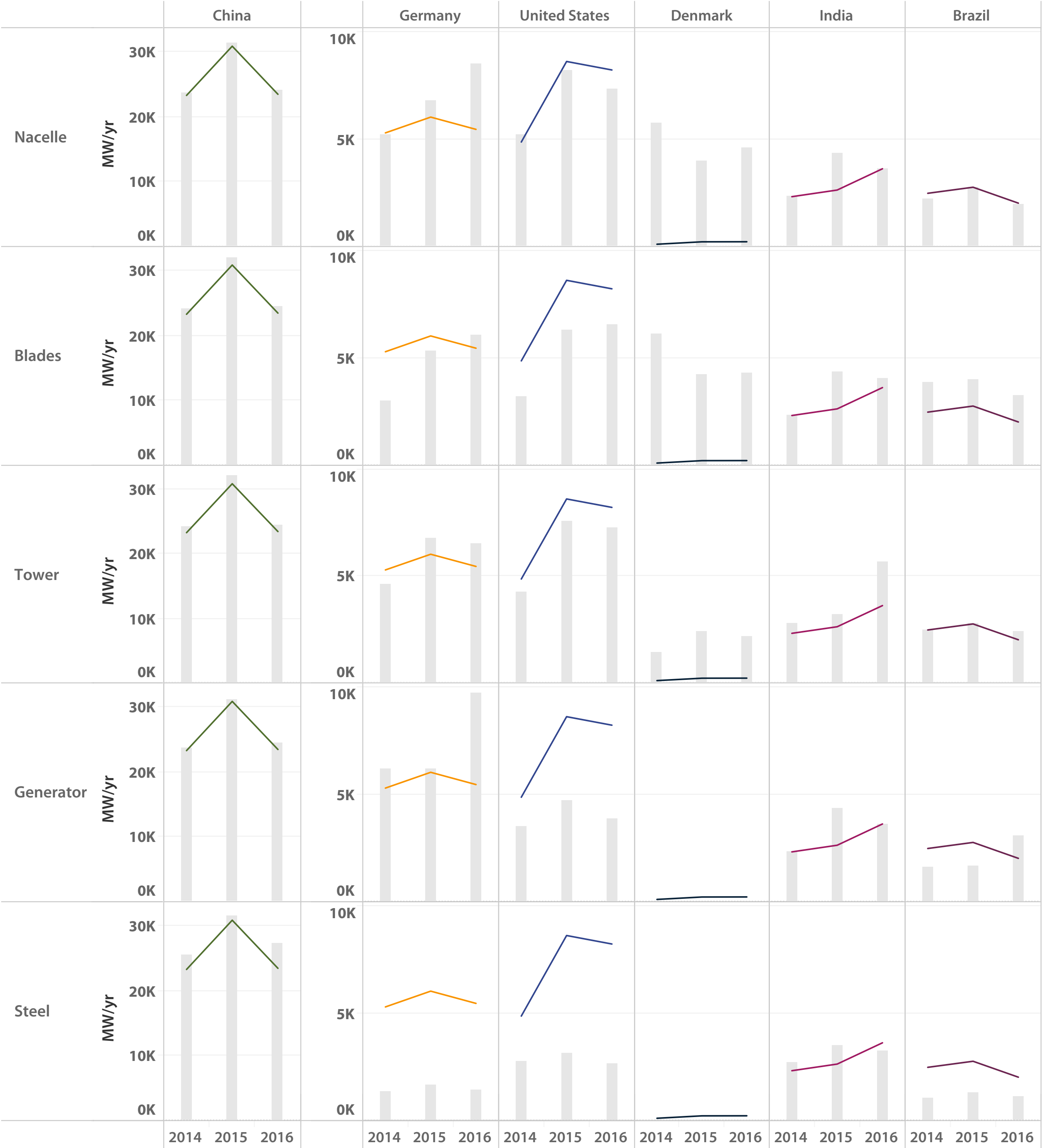


Breakdown (in %) of global demand (top) and global production (bottom) by economy for benchmarked wind turbine supply chain intermediates.

China accounted for the largest share of demand and production across the wind turbine supply chain over the period. Germany and the United States showed moderate increases in shares of global demand and production for nacelles, blades, and towers.

Wind turbine component demand and production were generally colocated on a regional basis due to transportation logistic challenges associated with their size and weight. Outside China, wind turbine production was led by the United States, Germany, India, Denmark, and Brazil.

Wind turbine supply chain production and demand trends, 2014–2016



Demand (color-coded lines) and production (gray bars) trends (in MW) by economy for wind turbine supply chain intermediates. Economies are listed in order of 2016 production levels Economies are color-coded throughout this benchmark report. China data are displayed on a different scale than those of the other countries. Because of a lack of Chinese demand data for wind turbine components and intermediates, demand and production were assumed to be equal. Because China made little inroads into the broader western market during 2014–2016, this can be considered a fairly robust assumption.

Global demand (in MW) for wind turbines increased in 2015, followed by a modest downturn in 2016 (with the expiration of renewable energy policies in China, the United States, and Germany), for a net increase of 6% from 2014 to 2016.[17] Global production (in MW) of wind turbine supply chain intermediates followed a similar global trend. With the exception of the United States, key wind turbine manufacturing economies generally had sufficient domestic production to meet domestic demand across the supply chain.

Global demand for wind turbine components (nacelles, blades, and towers) increased by 23% from 51.5 GW in 2014 to 63.5 GW in 2015, and then decreased 14% to 54.6 GW in 2016. China had the highest demand for and production of wind turbine and supply chain intermediates among the 13 economies.

The three economies with the highest levels of demand—China, the United States, and Germany—all followed a trend of demand increasing in 2015, followed by a drop in demand in 2016. The 2015 uptick in China may have been driven by a race to build, as many provinces had renewable energy targets tied to the end of that year. The follow up to a year of unusually high demand, combined with a reduction in national feed-in tariffs, likely contributed to the downturn in 2016 (BNEF 2017a).

The United States saw an uptick in demand from approximately 4.8 GW in 2014 to approximately 8.6 GW in 2015, most likely associated with an anticipated expiration of the federal production tax credit. When the credit was extended, the United States saw a slight decrease, but 2016 levels were still higher than 2014 levels (BNEF 2018a). In Germany, with the announcement that onshore wind feed-in tariffs were being replaced by market premiums for new wind projects, demand for wind in 2016 dropped to 2014 levels (BNEF 2017b). Germany also reduced its target for offshore wind capacity by 2020 from 10 GW to 6.5 GW during the period (BNEF 2018b).

India's demand for wind increased in both in 2015 and 2016, supported by the implementation of several favorable policies, including state-level feed-in tariffs beginning in 2014.

Following demand, global production for the wind turbine supply chain increased from 51.5 GW in 2014, and to 63.5 GW in 2015, followed by a decline to 54.6 GW in 2016. Germany and the United States saw the highest growth in production for nacelles, blades, and towers over the three-year period. Germany remained the second-largest exporter of nacelles and blades, behind Denmark, which saw a dip in blade and nacelle production. Denmark's nacelle, blade, and generator production rose in 2015, before dipping in 2016.

Domestic market demand tended to drive domestic production of the end products and, to a lesser extent, the upstream supply chain, over the period. Of the key wind economies considered, only the United States did not have sufficient domestic manufacturing capacity to meet domestic demand for all intermediates, other than nacelles, in 2016.

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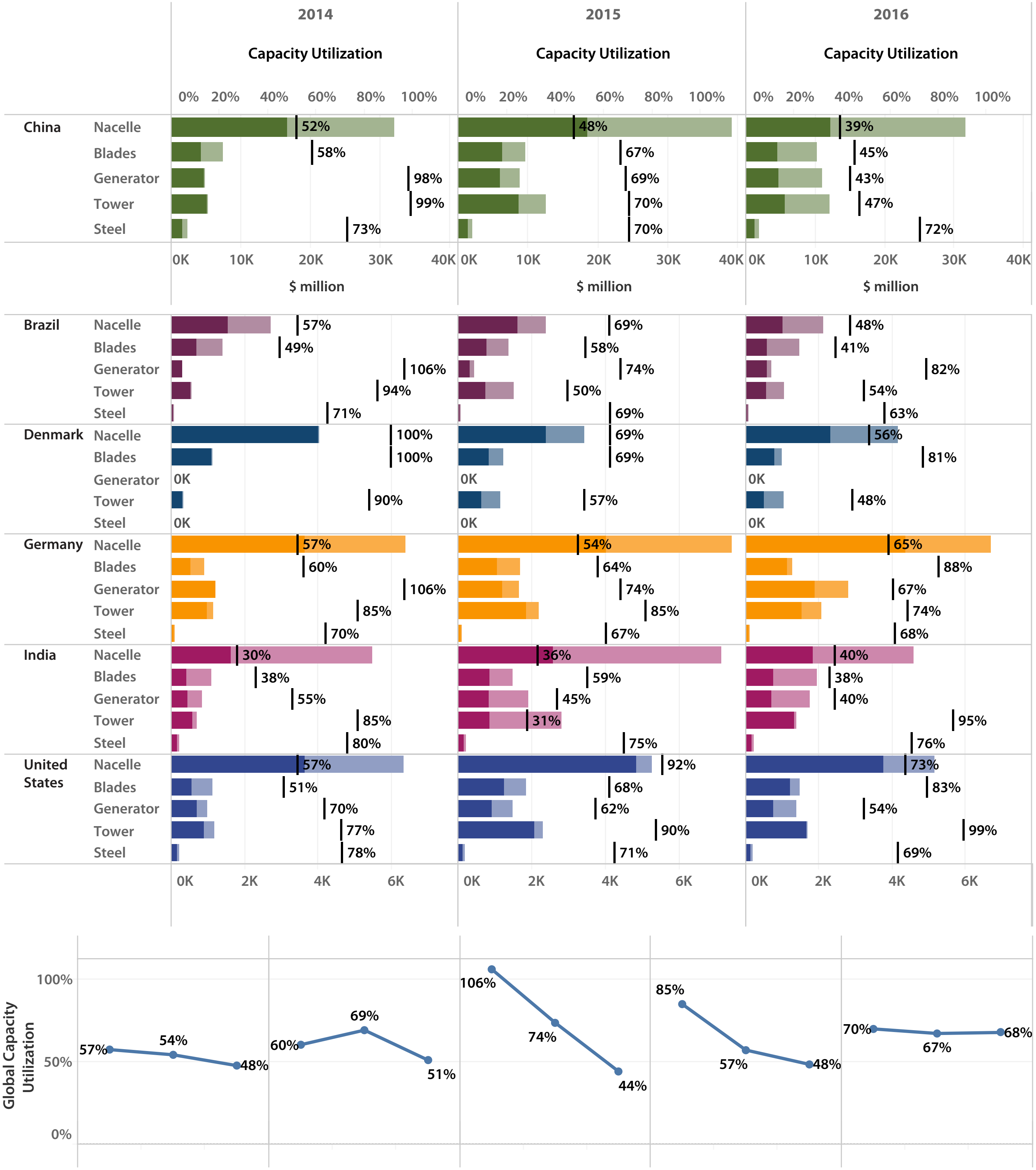
[17] Due to the steep drop in the global ASP of wind turbine components, on a megawatt-per-year basis, global demand for wind turbines increased by 6.2%, but on a dollar-per-year basis, demand declined by 26% over the period. See *Challenges: Comparing Clean Energy Manufacturing Trends Over Time* on p. 14 for details.

Wind turbine supply chain manufacturing capacity utilization, 2014–2016



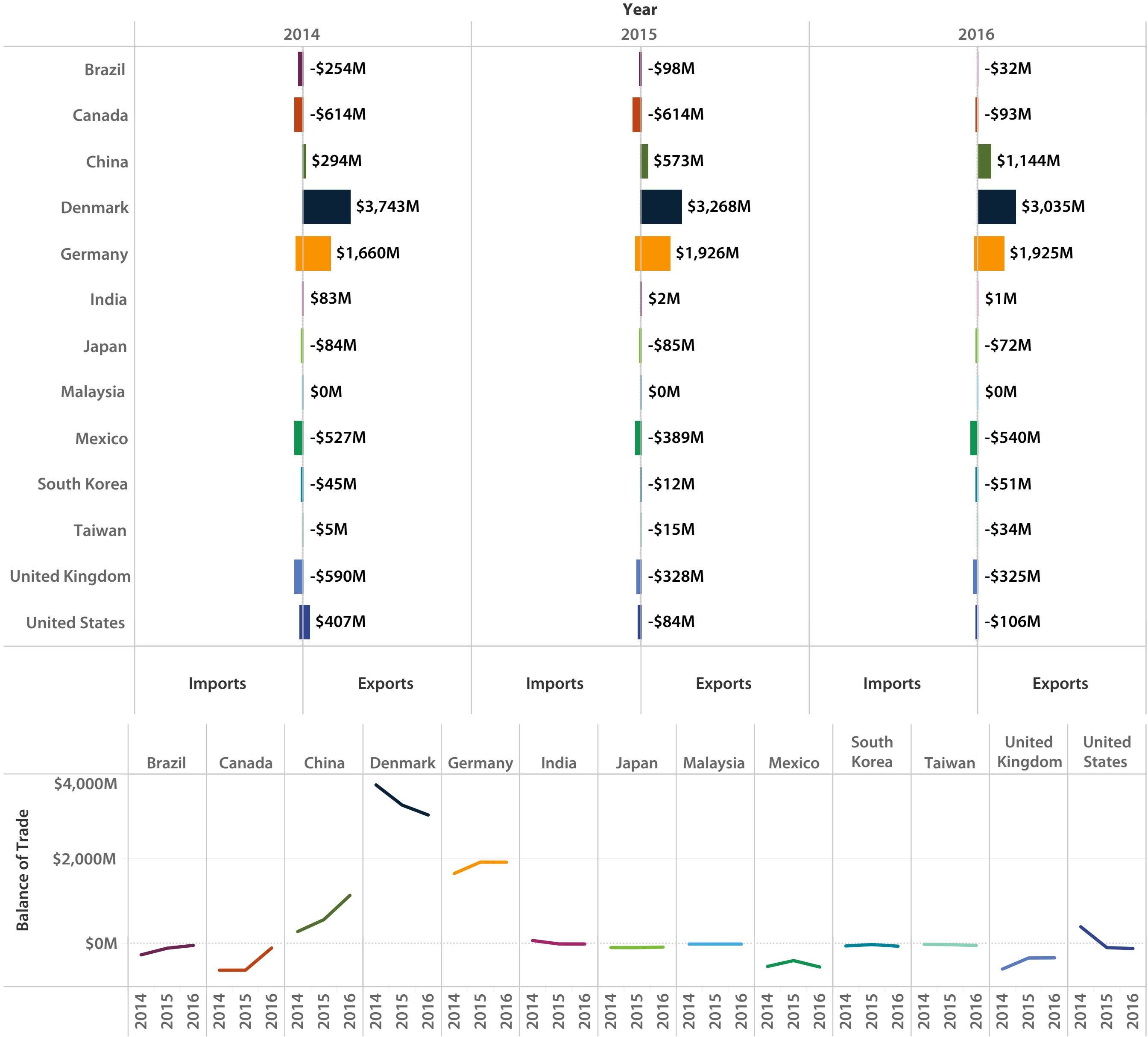
Bars show manufacturing capacity (lighter shading) and utilized manufacturing capacity (i.e., production, darker shading) in US$(2014) for key wind turbine economies. Vertical lines and associated numerical values show capacity utilization (production as a % of manufacturing capacity). Trend lines show global capacity utilization percentage for 2014–2016 (bottom). Note that China is displayed on a different scale.

In aggregate, global manufacturing capacity increased and capacity utilization declined for all wind supply chain intermediates, reflecting expanded manufacturing capacity built up in anticipation of increased demand. Capacity utilization rates in the individual benchmarked economies generally indicate an ability to expand production to meet wind demand growth.

Global manufacturing capacity for nacelles was estimated at 89.7 GW in 2014, 117 GW in 2015, and 115 GW in 2016. Corresponding production was estimated at 51.5 GW in 2014, 63.5 GW in 2015, and 54.6 GW in 2016, reflecting a global excess of manufacturing capacity that had been built up in anticipation of increasing demand. Globally, blade, generator, and tower capacity grew over the period while capacity utilization grew for these intermediates. China and India increased manufacturing capacity for nacelles, blades, towers, and generators in 2015, before curtailing nacelle capacity in 2016. Denmark's capacity utilization declined each year for nacelles and towers, while capacity utilization for blade production increased in 2016.

Benchmark Data: Trade Trends

Wind turbine generator sets (nacelles and blades) trade, 2014–2016



Bar chart (top) shows imports (negative values), exports (positive values), and balance of trade (exports positive and imports negative) in US$(2014) by economy for wind turbine generator sets. Line chart (bottom) shows balance of trade trends for wind generator sets.

Denmark, Germany, and, increasingly, China were the top exporters of wind turbine generator sets (nacelle and blades) over the period. Net exports from Denmark declined, while China's net exports increased. Mexico, the United Kingdom and Canada were the largest importers.

In 2016, the 13 benchmarked economies exported a total of almost $6.4 billion of wind generator sets, down 9.3% from $7.0 billion in 2014. Imports were also down 48.5%, from $2.9 billion in 2014 to $1.5 billion in 2016. The declining cost of wind turbine technologies over the period contributed to this contraction in trade.

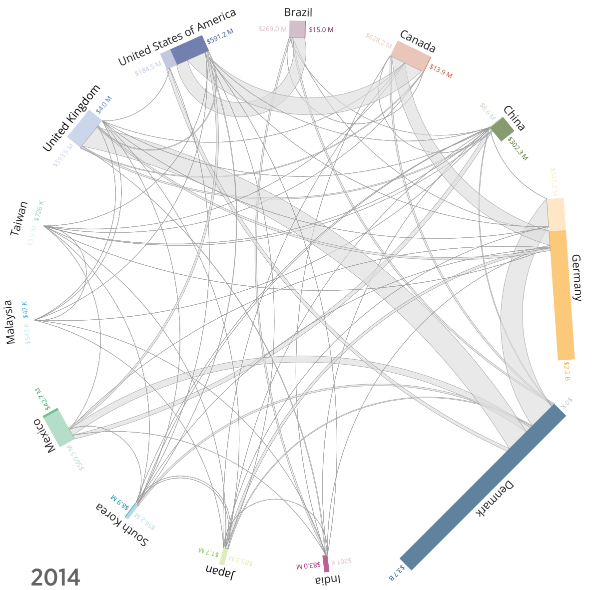
Wind turbine generator set (nacelles and blades) trade flows, 2014–2016

While global exports and imports of wind generator sets (nacelles and blades) declined over the period, the trade network among the benchmarked economies remained intact and generally followed expected flows, given the distribution of manufacturing capacity across economies.

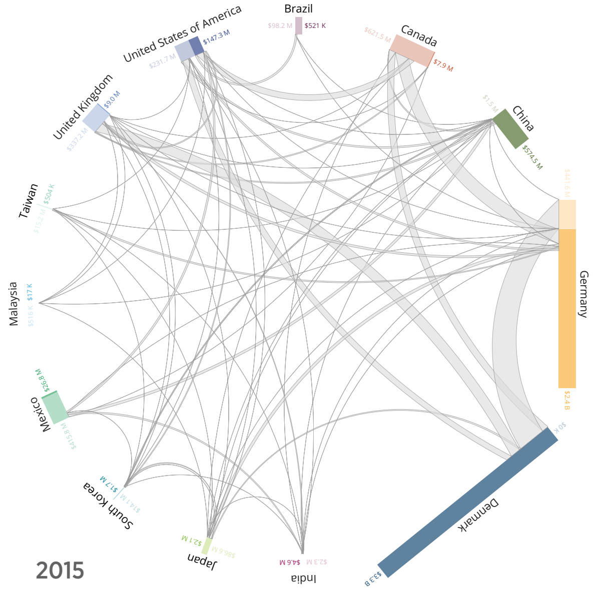
Between 2014 and 2016, the largest changes in wind turbine genset trade flow were observed in Denmark, China, Canada, and the United States. Denmark showed the largest change in net exports, declining from $3.7 billion in 2014 to $3.0 billion in 2016. Exports from Denmark to Germany and the United Kingdom dropped by $270 million and $240 million, respectively, in part due to feed-in tariff cuts implemented in early 2016. China showed the largest increase in net exports—from $300 million to $1.1 billion. With decreased domestic demand, due in part to feed-in tariff reductions, China's imports from Denmark declined, while its exports to Mexico and the rest of the world increased. Canada's wind capacity addition dropped from 1.9 GW to 0.7 GW, leading to reduced imports from the United States, Germany, and Denmark over the period. The United States moved from a net exporter to net importer as exports to Brazil and Canada declined and imports from Germany increased. Mexico's growing market primarily imported from China and Denmark in 2016.

Large wind turbine components are generally installed in the country or region where they are manufactured, because of either country-specific local content policies or high transportation and logistics costs associated with moving oversized components (e.g., assembled nacelles, large blades) to project sites, so trade for these is limited compared to the other technologies. By contrast, raw materials, processed materials, and many of the thousands of smaller wind turbine parts tend to be produced and shipped globally.

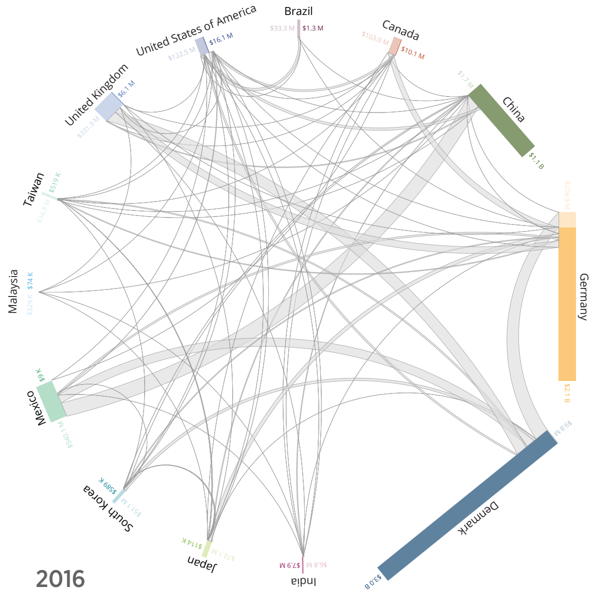
Gray chords show wind generator set trade flows in US$(2014) among benchmarked economies. Width of bars are scaled to total flows, with lighter shading showing imports and darker shading showing exports. Note that gray chords only capture the trade among the 13 benchmarked economies; trade flows with the rest of the world are not shown.



2014



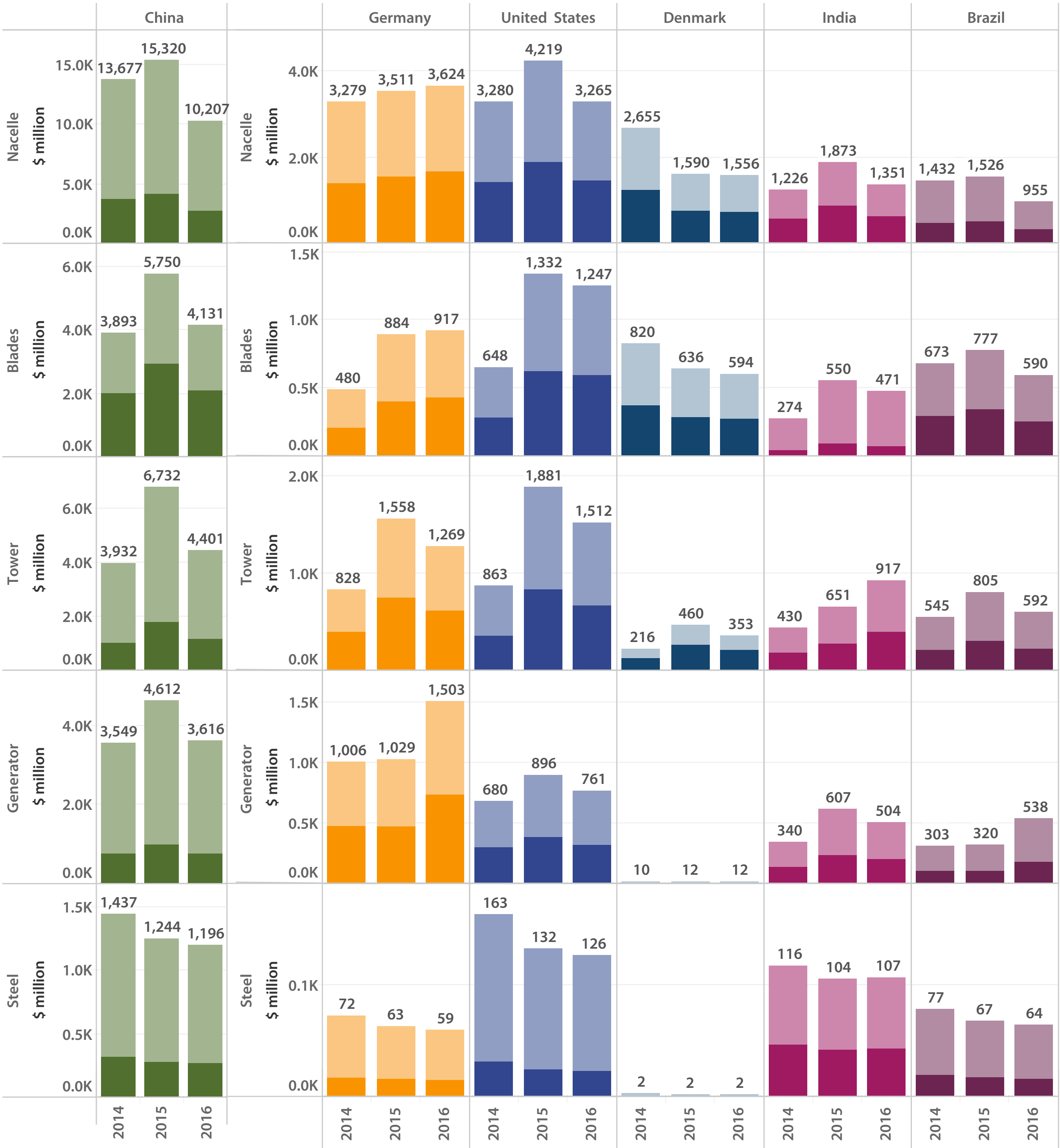
2015



2016

Benchmark Data: Value Added Trends

Wind turbine supply chain total value added (tVA) by value added component, 2014–2016



Total value added (tVA) for the period in in US$(2014) across the supply chain for key wind turbine economies. Darker shading indicates direct value added (dVA), lighter shading indicates indirect value added (iVA), and numerical values show total value added (tVA). Economies are listed in order of tVA from nacelle production in 2016. Note that tVA data for China are displayed on a different scale.

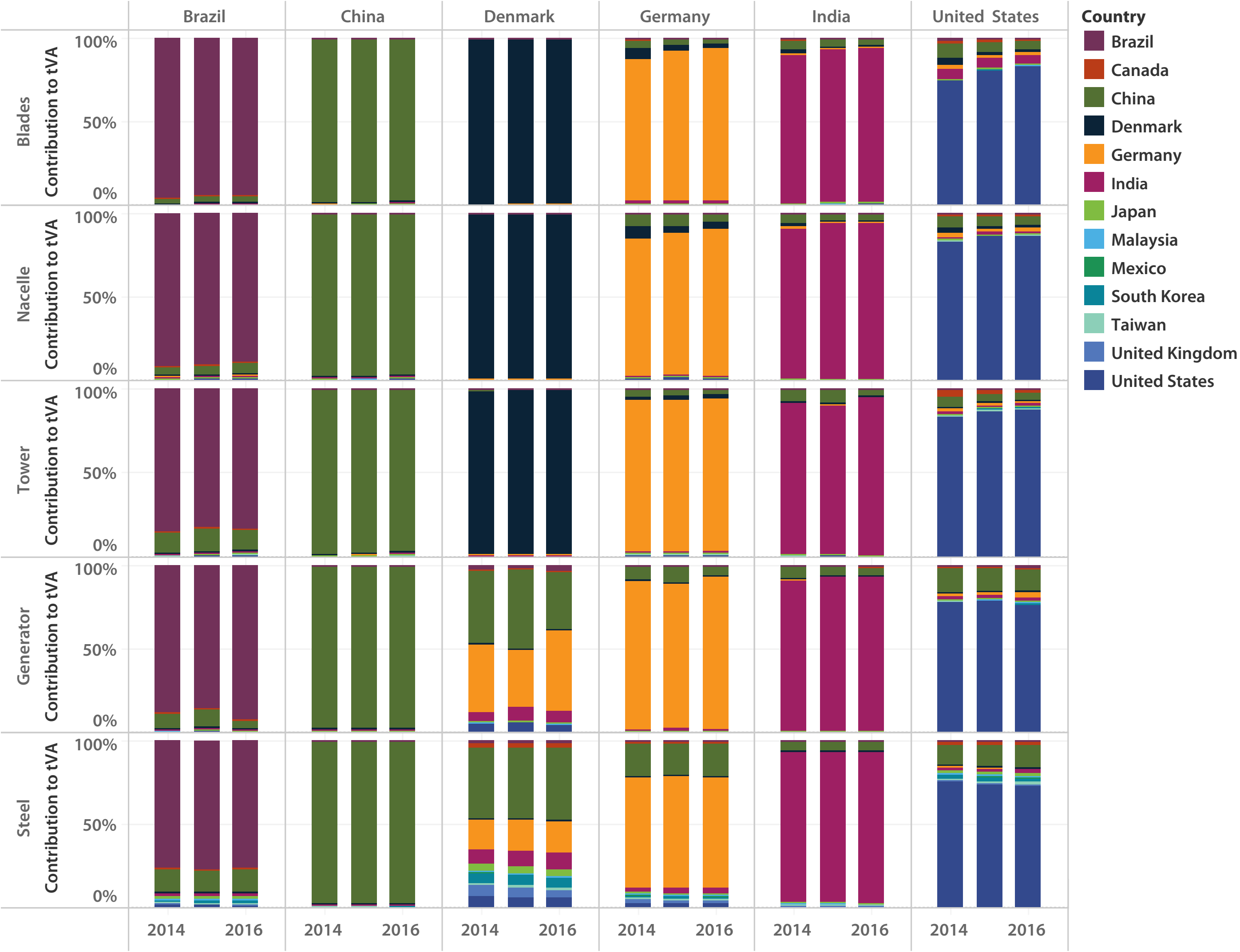
China, Germany, and the United States accrued more total value added (tVA) from manufacturing wind turbine components than the other benchmarked economies over the period. Indirect value added (iVA) was higher than direct value added (dVA) across the wind turbine supply chain, with the exception of towers in Denmark and blades in China.

tVA (iVA plus dVA) is generally greatest in the economies with the highest levels of production revenue. In 2016, China, the United States, and Germany, respectively, accrued $18.7 billion, $6.0 billion, and $5.8 billion in tVA , in aggregate from manufacturing nacelles, blades, and towers for wind turbines. Across the supply chain, China's tVA was about equal to the sum of the tVA of all other benchmarked economies combined, with the exception of steel. China, the United States, and India generally experienced peaks in tVA for wind intermediates in 2015, with the exception of generators in India and steel in all economies.

iVA and dVA generally showed similar trends over the period. iVA was higher than dVA for all benchmarked economies across the wind turbine supply chain, with the exception of tower manufacturing in Denmark and blade manufacturing in China, demonstrating that, in general, the supply chains that support wind turbine component manufacturing domestically and internationally were more important to the benchmarked economies than domestic manufacturing of these components and end product.

Between 2014 and 2016, both dVA and iVA from domestic production of steel (primarily for towers) declined slightly in the economies considered. Presumably, this reflects steel's classification as a global commodity and wind turbines' fractional value relative to other steel applications (e.g., construction, vehicles).

Wind turbine supply chain total value added (tVA) domestic and non-domestic contribution, 2014–2016



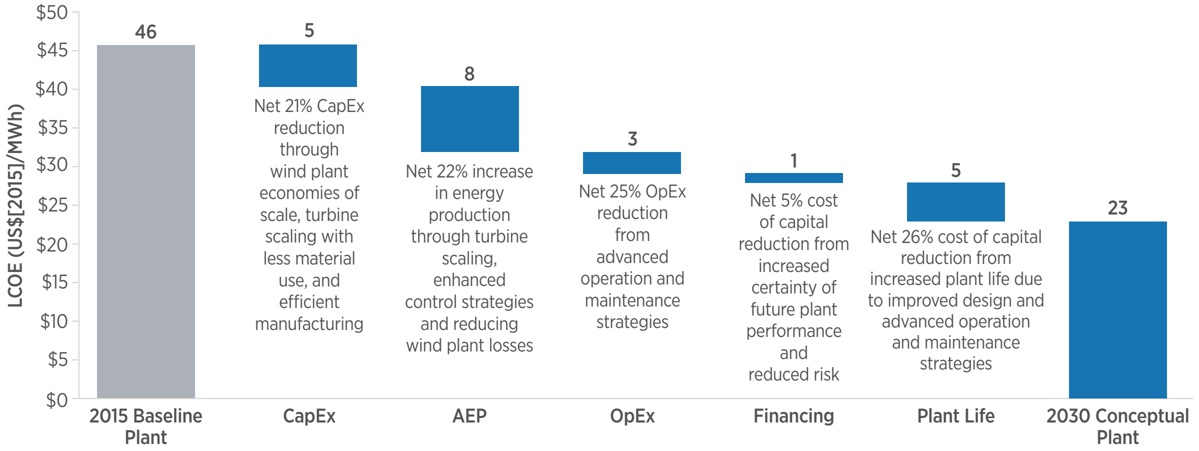
For each economy (listed across the top) color-coded bars show the share of tVA accrued from domestic and non-domestic production of wind turbine supply chain intermediates for 2014 to 2016. Domestic bars (generally the largest in each bar) represent the share of tVA (dVA + iVA) from domestic production. Non-domestic bars represent the share of tVA (iVA only) from production in other economies (dVA only occurs in the economy where production occurs).

Most of the tVA received from the production of wind turbine nacelles, blades, towers, generators, and steel in 2016 came from domestic manufacturing of those components. With its rapidly growing wind turbine component manufacturing capacity, production in China generally contributed the most to non-domestic iVA in the benchmarked economies across the supply chain.

Benchmarked economies retained varying shares of tVA as a portion of manufacturing revenue (i.e., VA retained) from manufacturing wind turbine components—ranging from 16% to 48% across the supply chain. The highest levels of VA retained occurred in the United States from manufacturing blades (48%), generators (42%) and nacelles (38%); by Denmark for towers; and by Brazil for steel production. VA retained reflects the extent of domestic supply chains as well as prevailing wages, domestic profits, and taxes less subsidies.

Wind Challenges and Opportunities: Cost Competitiveness and Advanced Manufacturing

Potential pathways to 50% LCOE reduction in 2030 by LCOE parameter



Source: Dykes et al. 2017

CapEx: capital expenditure, OpEx=operating expenses, AEP=annual energy production

Competitive pressure and the potential development of offshore wind and more moderate wind-speed resource areas continue to create opportunities for wind technology innovation, including taller towers, longer blades, and lower-weight nacelles and rotors. A 50% reduction in wind's levelized cost of electricity (LCOE) by 2030, as shown above, is expected to require both larger rotor diameters and taller towers. Some of the impacts of these advancements include:

- Assembled Turbines: Further price reductions are predicated on less costly and more efficient subcomponents, improved manufacturing processes, and economies of scale. For example, BNEF found that between 2014 and 2016, nominal turbine prices decreased from $1,200/kW to $1,070/kW (11% decrease), and fell to roughly $700/kW in 2019.[18]
- Blades: The average rotor diameter of wind turbines installed in 2016 was 108.0 meters, 127% larger than those of 1998–1999 and 13% larger than the average blade size of the previous five years (2011–2015) (Wiser and Bolinger 2017). This trend of growth in rotor sizes and growth in the size and scale of wind turbines in general as a means of system level cost reduction is expected to continue and may become an even more significant opportunity in the offshore market segment.
- Towers: The average hub height of turbines in 2016 was 83 meters, 48% taller than turbines built two decades earlier. The increased turbine height enables the machines to tap into a higher quality and more consistent wind resource which improves their total energy production (Wiser and Bolinger 2017).
- Generators: Alongside blade length and tower height, generator size has also increased while decreasing in weight, enabling turbines to consistently produce more energy.

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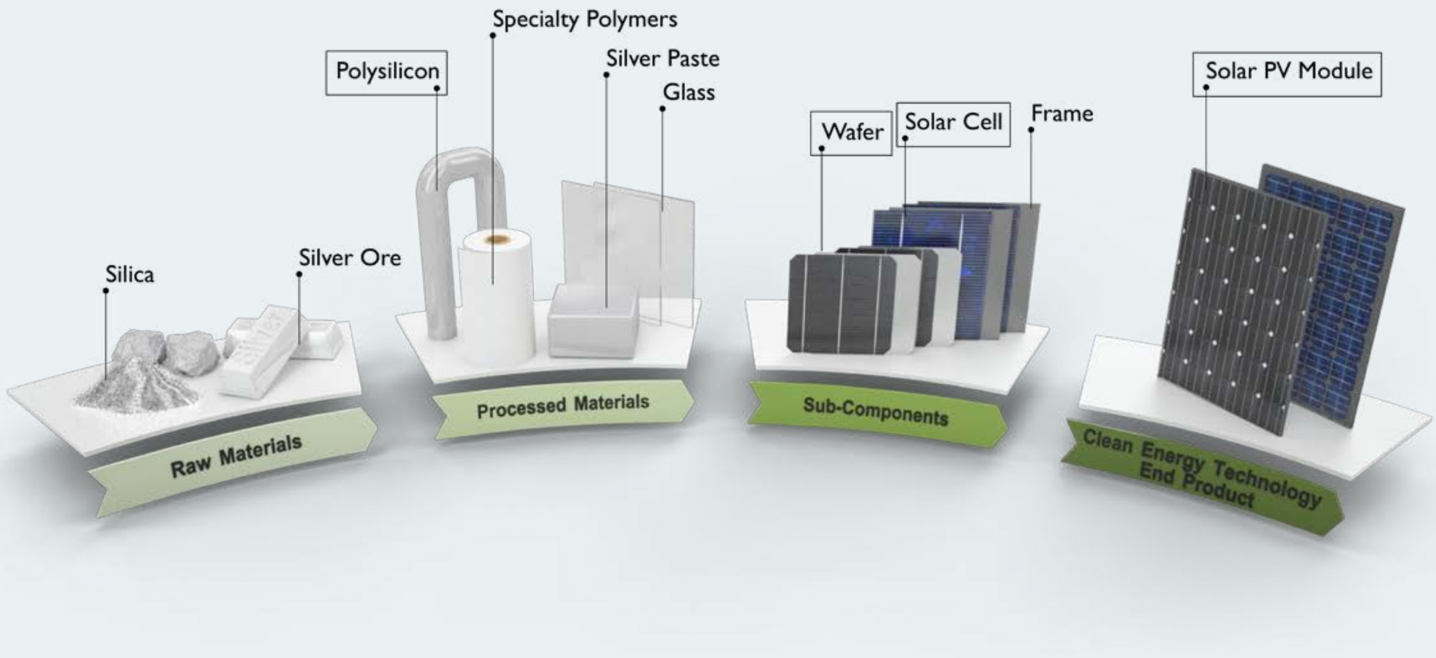
[18] Bloomberg New Energy Finance. 2019. 2H 2019 Turbine Price Index.

Accompanying these cost reduction opportunities is the potential for increased deployment in both lower and higher wind speed areas. Expansion into lower-quality wind resource regions, in particular, is expected to require more detailed site-specific and terrain-optimized solutions that present further manufacturing and logistics challenges. In some cases, the increase in component size can limit transport options and cause intermediary subcomponents to be manufactured domestically in order to reduce transport costs. This trend is expected to continue as components increase in size. Original equipment manufacturers will need to consider innovative solutions such as segmentation, advanced manufacturing, and advanced logistics to overcome the escalating costs associated with transporting large components. Advanced manufacturing—which includes additive manufacturing (3D printing), automation, robotics, advanced sensing, and smart/adaptable floorplans—has the potential to enable novel solutions (onsite manufacturing, site specific designs) that are not feasible using current manufacturing processes. Significant evolution of the global supply chain is anticipated as manufacturers begin to deploy these methods and evaluate further cost-cutting measures, such as consolidation and lower cost centers.

Crystalline Silicon Photovoltaic Modules

Solar energy is the third largest source of renewable electricity generation behind hydropower and wind, with approximately 487 GW deployed globally at the end of 2018 (IRENA n.d.). From the beginning of 2014 to the end of 2016, roughly 155 GW of new photovoltaic (PV) capacity was added globally, growing the cumulative capacity from 136 GW to 291 GW (an increase of 114%). This growth represented approximately $468 billion of new PV investment for the same period (IRENA n.d.).

Crystalline silicon photovoltaic (PV) modules and supply chain



Crystalline silicon (c-Si) photovoltaic (PV) module alignment with Clean Energy Manufacturing Analysis Center (CEMAC) benchmark framework. Boxes highlight components included in the benchmark analysis. No raw materials were included in the analysis for a lack of data. Illustration by Josh Bauer, NREL

Crystalline silicon-based technologies are considered mature and account for more than 90% of the PV market (Fraunhofer ISE 2018). Other PV technologies, such as cadmium telluride and copper indium gallium selenide thin film-based modules, are commercially available via only a limited number of producers. Researchers focus on key elements of the manufacturing supply chain for the crystalline silicon (c-Si) PV module manufacturing process—polysilicon, PV wafers, and PV cells. The market for PV modules in 2016 favored polycrystalline over monocrystalline 63% to 37% (ITRPV 2018).

The global manufacturing network for PV is well established, but opportunities for innovation remain, including cost-effective production of advanced cell architectures, enhancement of polysilicon (poly-Si) purity, and other improvements to cell and module efficiencies.

Notable Trends

Key drivers of PV module supply chain trends over the period included:

- Declining cost of solar projects, driven by manufacturing capacity increases, manufacturing cost reductions, module efficiency improvements, and module and supply chain intermediate surpluses in the global market
- Global demand growth, in part driven by declining prices and improved module efficiencies
- Shifting markets that stimulate policies and equipment contracting approaches, including installation targets, tax credits, auctions, and targeted tariffs (Kavlak, McNerney, and Trancik 2018).

Manufacturing Capacity and Inventory

Increased demand for PV modules was driven in part by domestic policies that set targets for deployment of renewable technologies or provided incentives to offset costs. For example, in the United States, PV installations grew through the period, as installers anticipated the Investment Tax Credit expiration (BNEF 2015), supported by significantly increased U.S. imports of PV modules from China from 2014 to 2016. Global manufacturing capacity expansion (led by China) to meet anticipated increases in demand resulted in excess global manufacturing capacity for all benchmarked photovoltaic (PV) supply chain intermediates and contributed to significant price drops over the period. While China maintained its position as the largest PV module and cell exporter, increased Chinese demand and an international buildup of manufacturer and installer inventory levels contributed to reduced Chinese exports in 2016.

Global Supply Chains

In most economies, indirect value added (iVA) from manufacturing PV modules and intermediates was greater than direct value added (dVA) over the period, indicating that participation in the broader supply chain that supports PV module manufacturing at home and abroad was more important to the benchmarked economies than domestic production of the end product. In addition, because none of the four economies could meet its own domestic demand for all PV module components, trade of intermediates occurred. Net exporters of PV module end products in some cases were net importers of intermediates such as polysilicon.

China

With the highest demand, production, and manufacturing capacity of the economies considered, China drove global PV module supply chain market trends and also received the highest tVA from PV manufacturing. The economic benefit of PV manufacturing in China also contributed iVA to all the benchmarked economies. China's policies focused on building manufacturing capacity and domestic supply chains, along with import tariffs levied by other economies on specific PV supply chain components and intermediates, helped shape the global market and trade landscape.

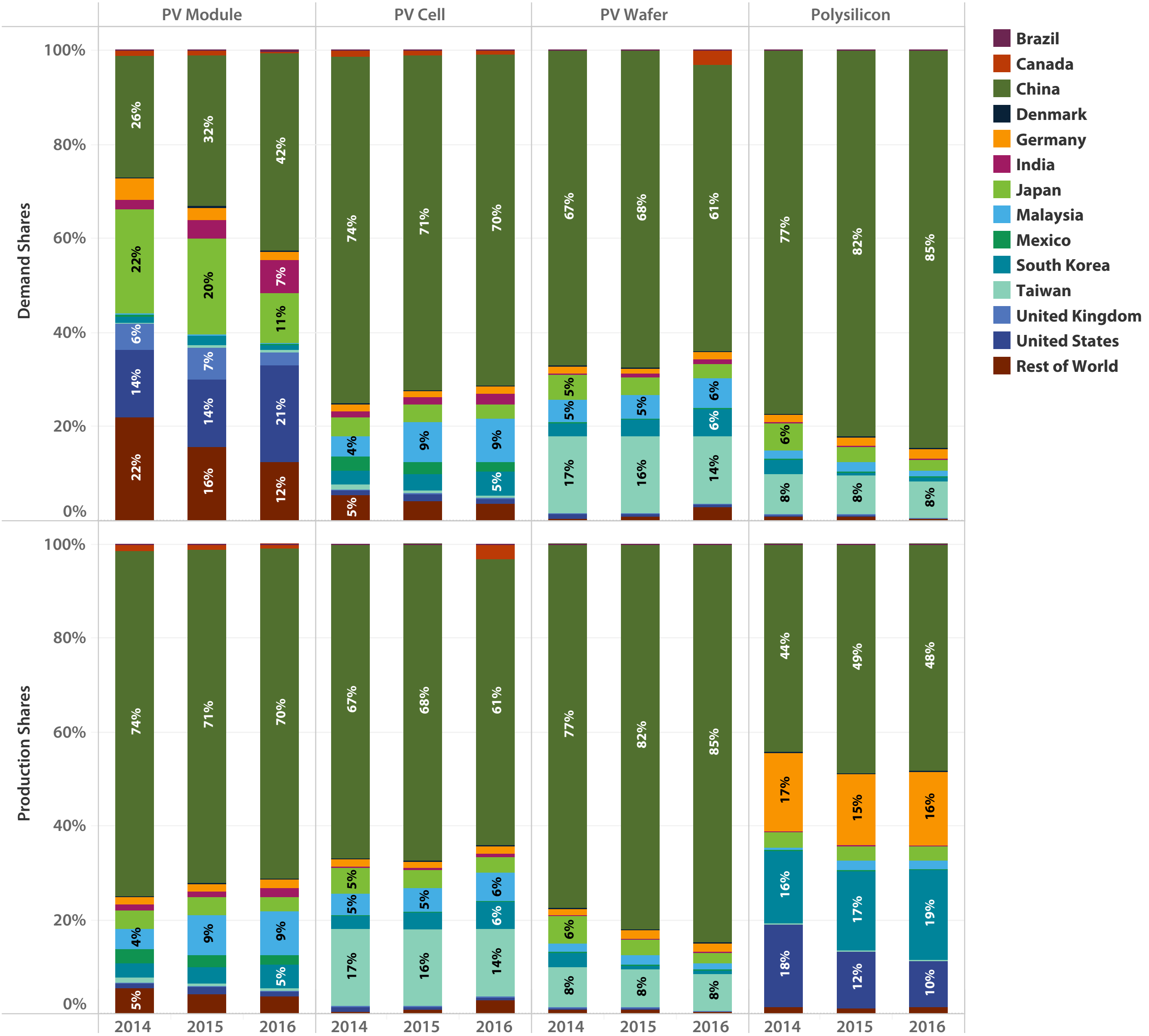
Balance of System Components

A range of balance of system (BOS) components—inverters, structural hardware, and electrical hardware—are required for PV module system installation and operation. Markets for these components tend to be highly fragmented, with U.S. PV installations sourcing BOS equipment from domestic and foreign suppliers. The price of these components, for both residential and utility-scale applications, dropped significantly over the period.

More detailed information can be found on the following pages.

Benchmark Data: Market Trends

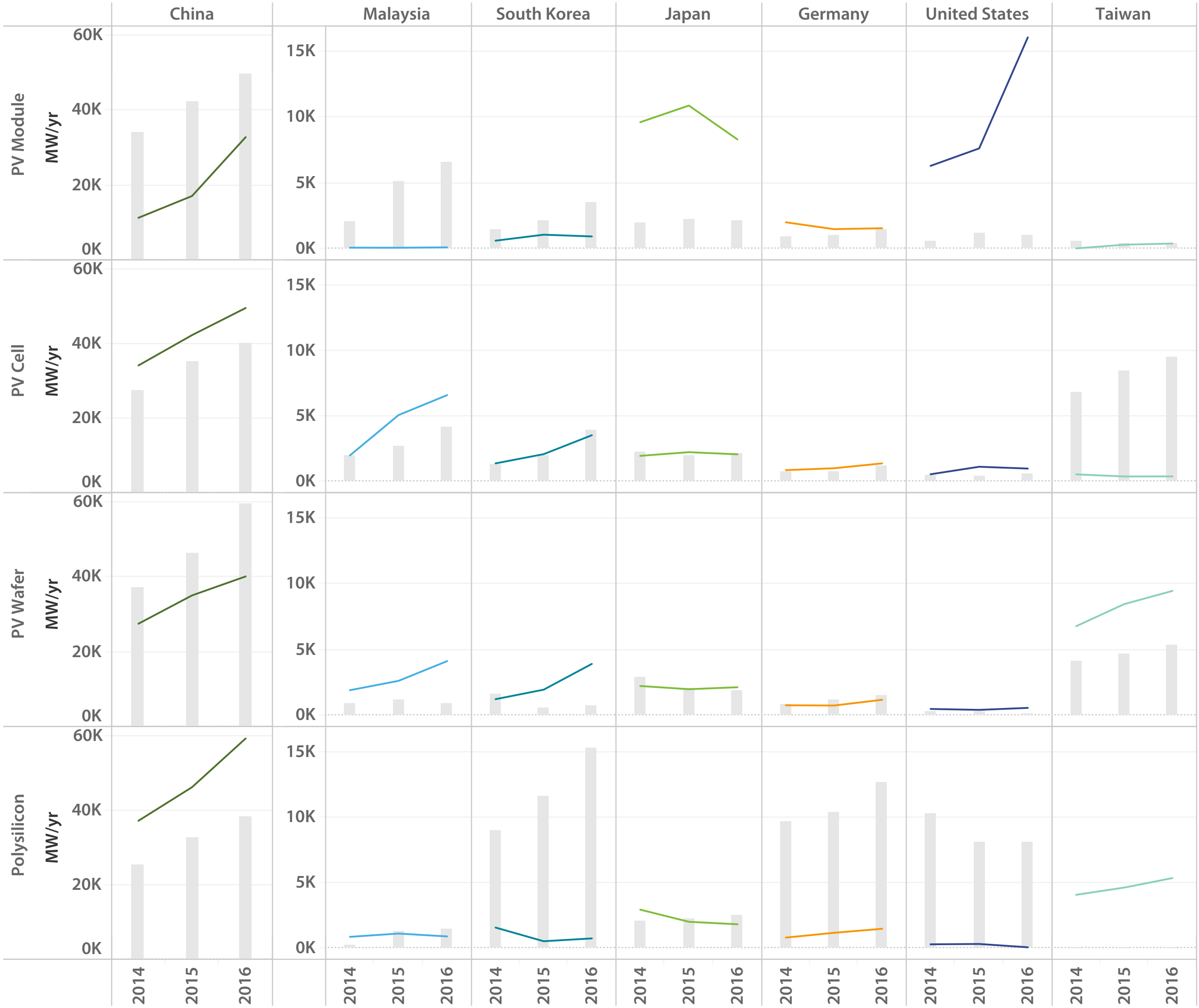
PV module supply chain demand and production shares by economy, 2014–2016



Breakdown (in %) of global demand (top) and global production (bottom) by economy for benchmarked PV module supply chain intermediates. Note that, due to lack of disaggregated data, demand for the upstream intermediate is estimated to equal the production of the preceding intermediate (e.g., demand for polysilicon equals production of PV wafers).

China accounted for the highest shares of global demand and production of PV modules and supply chain intermediates. PV module demand and polysilicon production were broadly distributed across the benchmarked economies, reflecting China's gap in production relative to demand for these two intermediates. Demand shares for PV modules showed the greatest change over the period, with Japan's demand declining while China and U.S. demand increased. The United States lost polysilicon production shares to China and South Korea over the period.

Global PV module supply chain demand and production for key PV module economies, 2014–2016



Demand (color-coded lines) and production (gray bars) trends (in MW) by PV module supply chain intermediates for top PV module economies. Economies are listed in order of 2016 production levels. China data are displayed on a different scale than the other benchmarked countries.

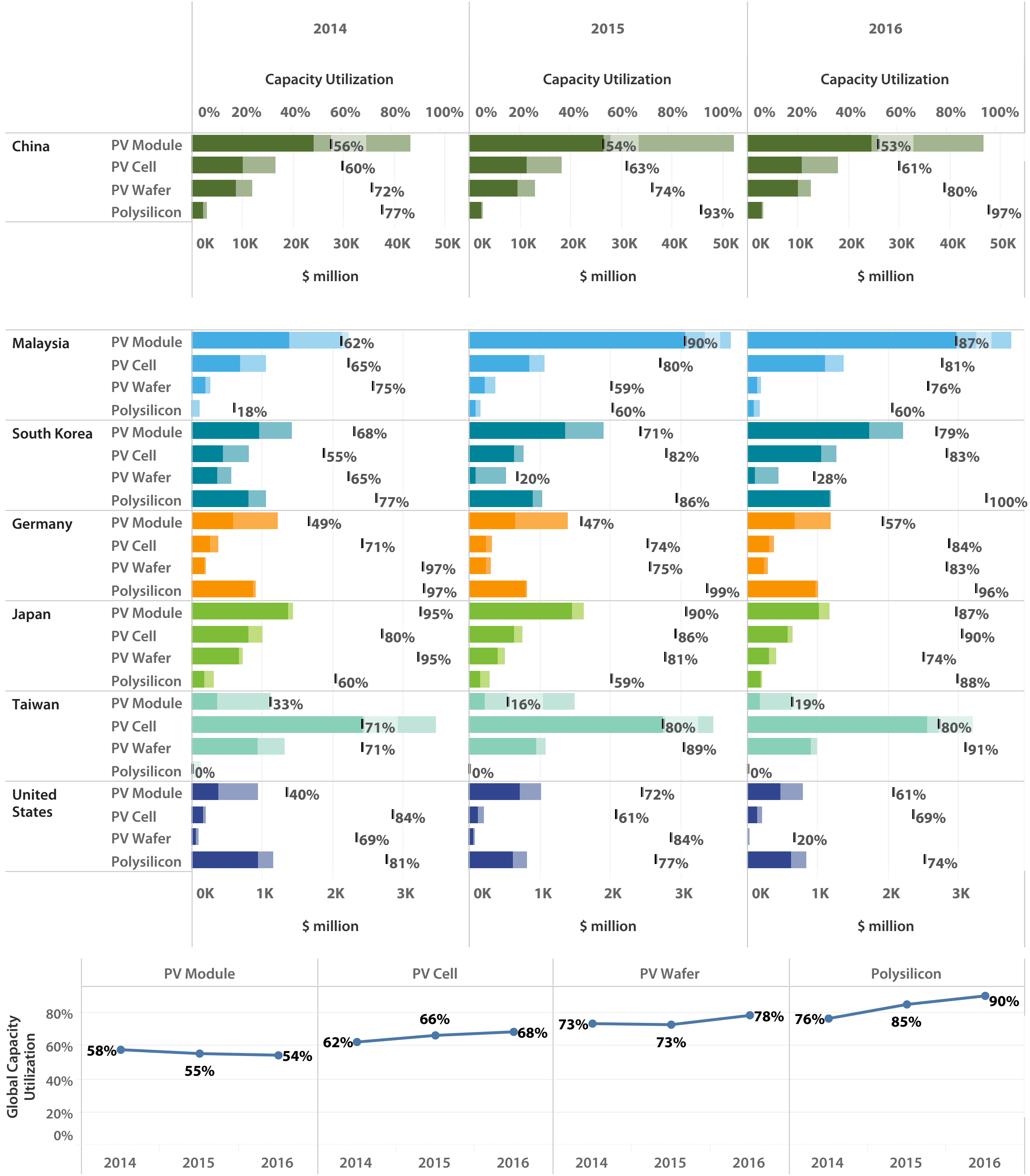
Global demand and production (in MW) for PV modules and supply chain intermediates grew from 2014 to 2016. China had the highest demand for and production of PV modules, cells, and wafers, more than offsetting shifting demand and production in the other benchmarked economies. With the exception of Germany, none of the 13 economies was able to meet domestic demand for all supply chain intermediates in 2016 with domestic production alone.

Between 2014 and 2016, global demand for PV modules increased by 80% from 43.3 GW to 77.9 GW. After China, the United States, Japan, and India had the highest demand for PV modules over the period. The biggest increases were observed in China, with demand almost tripling from 11.2 GW to 32.7 GW, and in the United States with demand increasing two-and-a-half times, from 6.3 GW to 16.0 GW. U.S. demand increased in part due to the anticipated 2015 expiration of the federal investment tax credit (ITC) and its subsequent extension in 2016. Japan's annual demand for PV modules decreased from 9.6 GW to 8.3 GW, due in part to mid-2016 revisions to feed-in tariff laws, along with new curtailment rules in early 2015. Further upstream in the supply chain, global demand increased by 51.6% for PV cells (to 70.3 GW), 60.6% for wafers (to 65.7 GW), and 45.8% for polysilicon (to 69.7 GW), reflecting increased PV module demand. Malaysia, Taiwan, and South Korea had the highest demand for these supply chain intermediates over the period.

To meet increased demand, annual global production of PV modules grew by 51.6% from 46.3 GW to 70.3 GW between 2014 and 2016. For PV modules, the biggest increases in production were observed in China (up 45.2%), Malaysia (more than tripling), and South Korea (increasing two-and-a-half times). Between 2014 and 2016, global production of PV cells, wafers, and polysilicon increased by 60.8%, 45.7%, and 38.2%, respectively. Production increases in PV cells and wafers were driven by China, Malaysia, Taiwan, and South Korea. These gains offset decreases in Japan's and South Korea's PV wafer production. Growth in polysilicon production over the period was driven by increases in China, Germany, and South Korea, which offset decreases in U.S. polysilicon production, driven by reduced exports to China (due to tariffs) and price drops (due to oversupply).

Production of PV modules in China, Malaysia, South Korea, and Taiwan was greater than domestic demand over the period; PV modules from the economies were exported to economies where demand exceeded domestic production, including Japan, Germany, and the United States. The United States had the largest gap between production and demand for PV modules, increasing from $4.3 billion in 2014 to $7.5 billion in 2016. Japan showed the second largest gap, decreasing from $5.4 billion to $3.1 billion over the period.

PV module supply chain manufacturing capacity utilization, 2014–2016



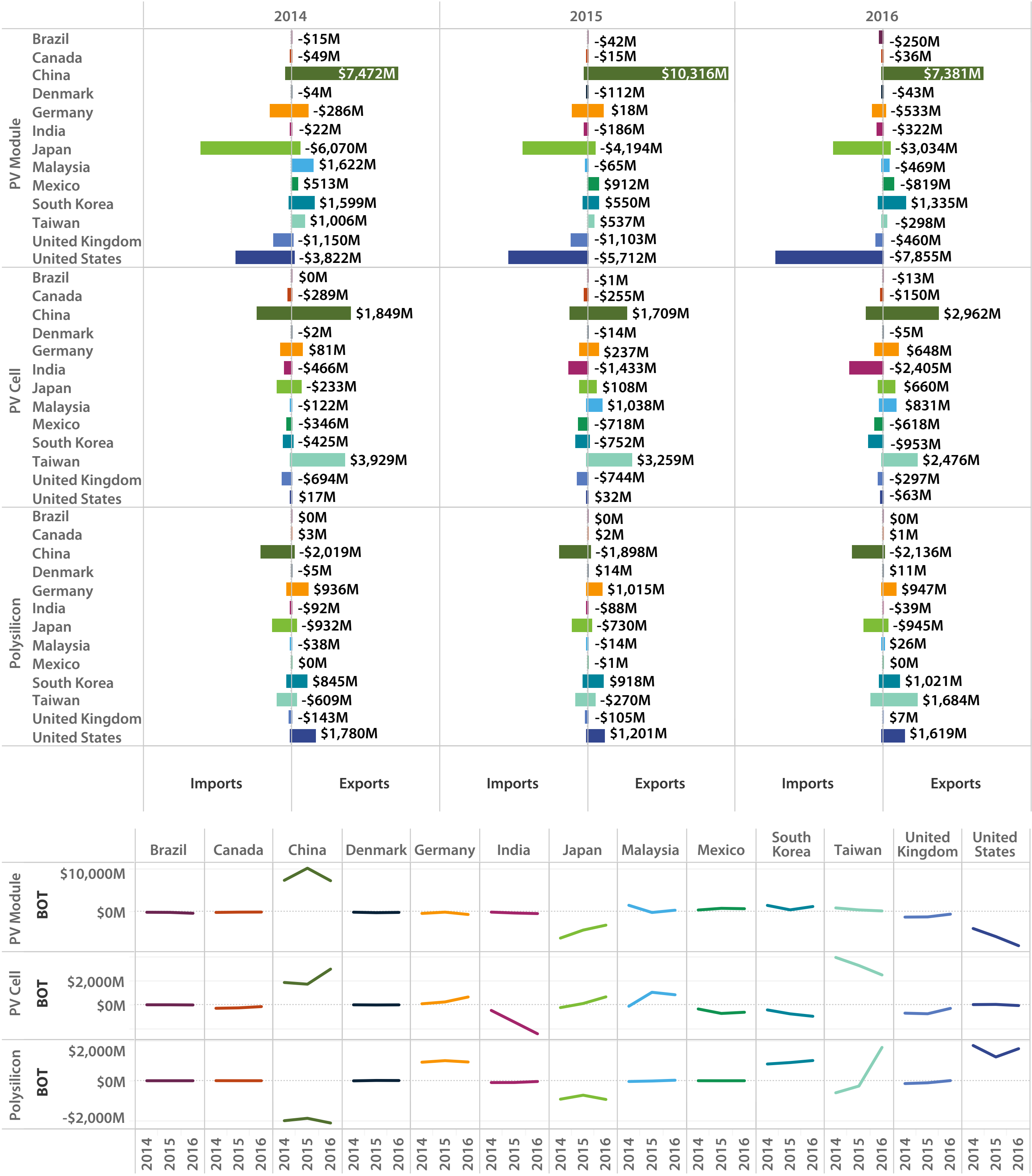
Bars show manufacturing capacity (lighter shading) and utilized manufacturing capacity (i.e., production, darker shading) in US$2014 for key PV module economies. Vertical lines and associated numerical values show capacity utilization (production as a % of manufacturing capacity). Trend lines show global capacity utilization percentage for 2014–2016 (bottom). Note that China is displayed on a different scale.

The benchmarked economies generally exhibited excess manufacturing capacity relative to global demand across the supply chain, indicating some potential to expand production in existing facilities to meet future demand growth or that new investment is required to modernize manufacturing processes to accommodate new technologies. In aggregate, global manufacturing capacity increased for all PV module supply chain intermediates in anticipation of increased demand. Globally, capacity utilization increased for all PV module supply chain intermediates (cells, wafers and polysilicon), and declined for PV modules over the period.

Global manufacturing capacity for PV modules was estimated at 80.3 GW in 2014, 107 GW in 2015 and 129 GW in 2016. Corresponding production was estimated at 46.3 GW in 2014, 59.3 GW in 2015, and 70.3 GW in 2016, reflecting a global excess of manufacturing capacity. All benchmarked PV supply chain intermediates had excess manufacturing capacity and reduced manufacturing costs over the period, which contributed to reduced prices in all four intermediates (e.g., PV module prices dropped 20%–25% over the period). China grew its manufacturing capacity and production for all PV module supply chain intermediates over the period, maintaining the highest capacity for each across the 13 economies. In 2016, both Malaysia and South Korea increased manufacturing capacity and production of PV modules and cells. Globally, capacity utilization was generally higher for the intermediates than the PV module end product.

Benchmark Data: Trade Trends

PV module supply chain trade, 2014–2016



Bar chart (top) shows imports (negative values), exports (positive values) and balance of trade (exports less imports) in US$(2014) for PV module supply chain intermediates. Line chart (bottom) shows balance of trade trends for PV module supply chain intermediates. Note that trend lines are shown on different scales for PV modules, PV cells, and polysilicon.

In the benchmarked economies, the balance of trade (exports minus imports) remained relatively stable across the PV module supply chain, with a few exceptions including PV modules in Japan and the United States, PV cells in China and Taiwan, and polysilicon in Taiwan. Some net importers of end products, such as the United States, were also major exporters of upstream processed materials and/or subcomponents for the same technologies, illustrating the complexity of clean technology manufacturing and trade.

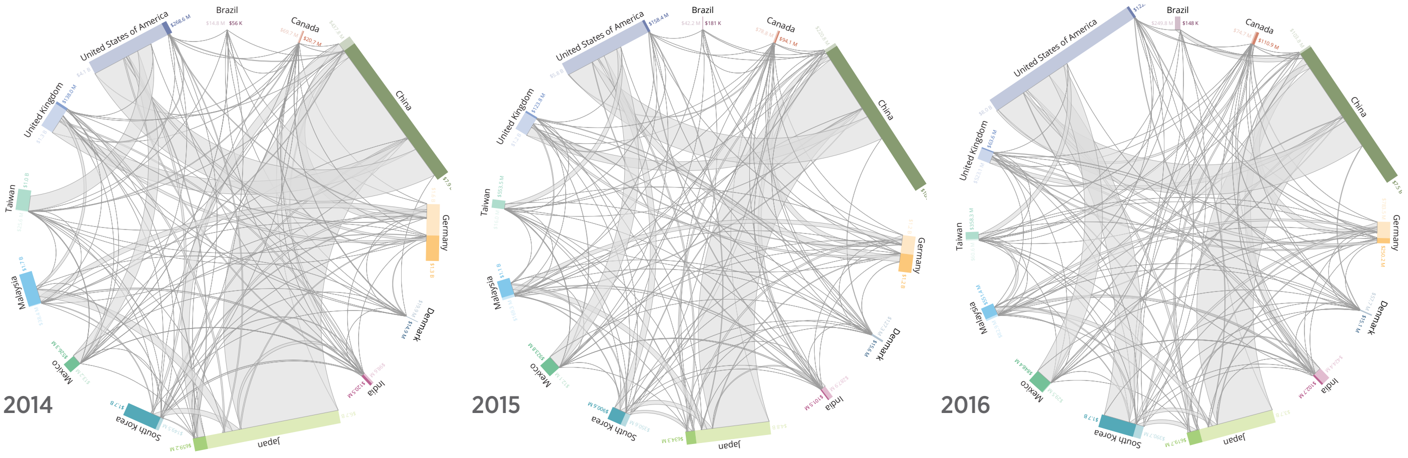
In 2016, the 13 economies exported $29.8 billion in PV modules, cells, and polysilicon, down from $31.5 billion in 2014. Imports of these products also dropped from $27.6 billion in 2014 to $26.7 billion in 2016. The rapidly declining cost of PV supply chain components over the period contributed to this contraction in trade.

China maintained its position as the largest PV module and cell exporter—primarily to the United States, Japan, and India—with 2016 decreases in exports driven in part by a buildup of manufacturer and installer inventory levels. South Korea and Malaysia emerged as growing exporters of PV modules and cells, possibly as a result of Chinese manufacturers exporting out of these countries to avoid import tariffs levied by the European Union and the United States (BNEF 2017c).

The United States and Japan were the two largest net importers of PV modules over the period. U.S. PV module net imports doubled, while Japan's net imports decreased by 50%. In 2016, the United States was the second largest exporter of poly-Si (after Taiwan), maintaining a relatively steady value of polysilicon exports despite a dip in 2015. China continued to be the largest net importer of polysilicon.

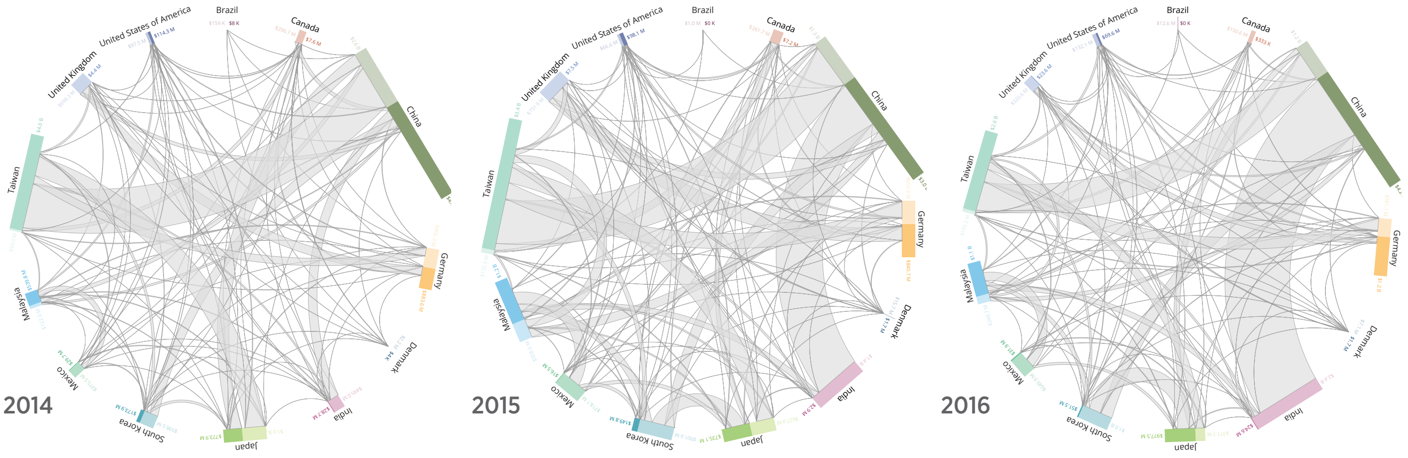
PV module supply chain trade flows, 2014–2016

PV modules



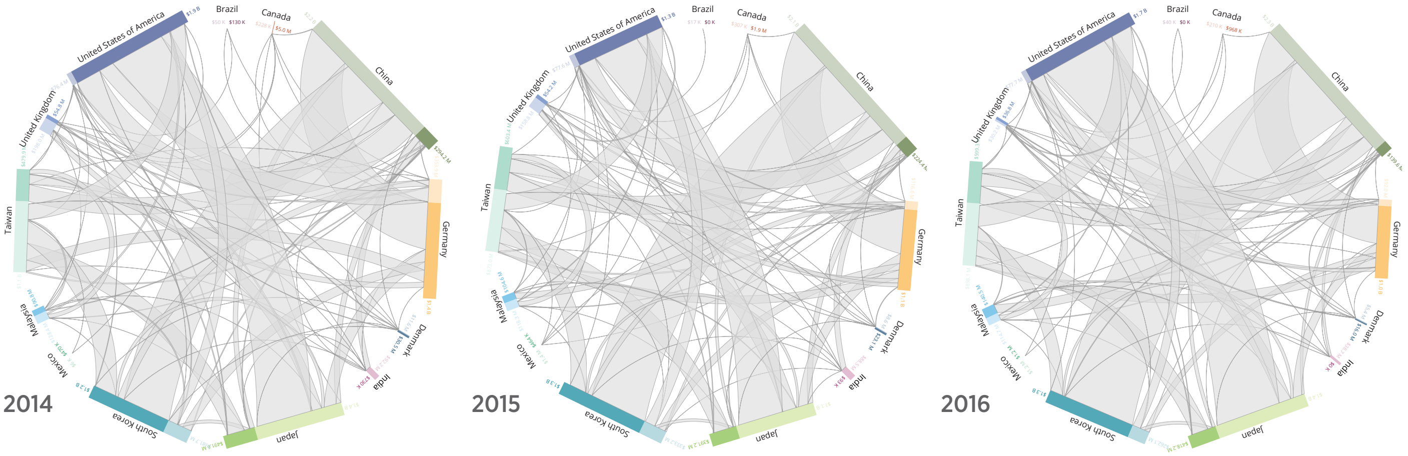
2014 2015 2016

PV cells



2014 2015 2016

Polysilicon



2014 2015 2016

Gray chords show trade flows for PV module supply chain intermediates in US$(2014) among benchmarked economies. Width of bars are scaled to total flows, with lighter shading showing imports and darker shading showing exports. Note that gray chords only capture the trade among the 13 benchmarked economies; trade flows with the rest of the world are not shown.

A dynamic trade network connects the economies that manufacture PV modules, cells, and polysilicon. Trade flow data suggest robust global trade among the economies that generally followed expected patterns given the distribution of manufacturing capacity across economies. Trade flow for PV modules, wafers, and polysilicon was impacted by changes to policies regarding subsidies, tax credits, tariffs, and grid integration of renewables.

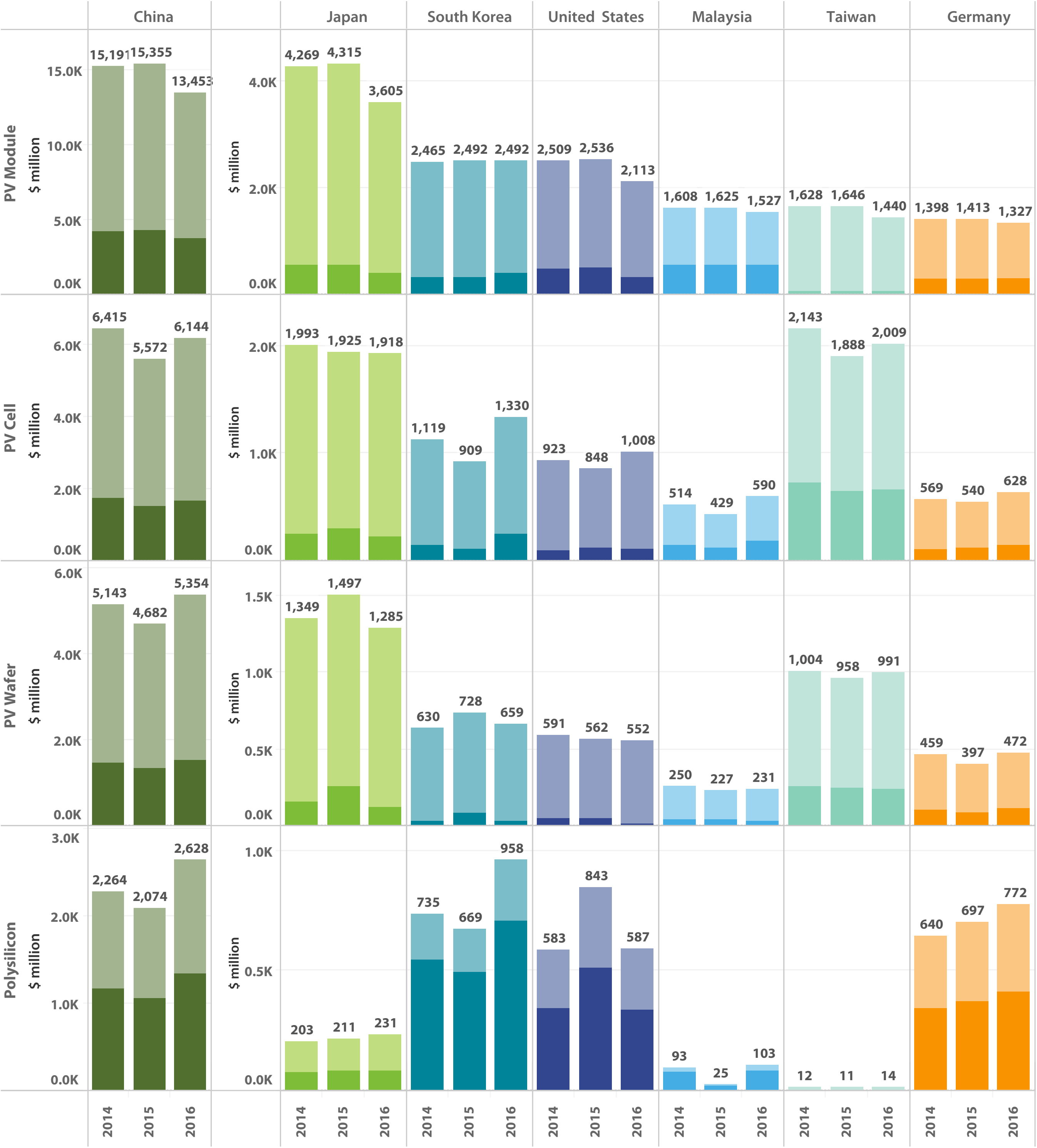
Between 2014 and 2016, the largest changes in PV module trade flow were observed in China, Japan, and the United States. China's balance of trade (BOT) 2015 peak was driven by an increase in exports from $7.9 million in 2014 to $10.5 million in 2015. Potential drivers of the 2015–2016 drop in exports to $7.5 million include buildup of inventory in 2015 and expiration of a PV subsidy in 2016. Japan's 2014–2016 BOT increase was driven by decreases in imports from $6.7 billion to $3.7 billion, triggered by reduction in demand from $6.8 billion to $4.1 billion. Potential reasons for the drop include a decline in solar project commissioning after mid-2016 revisions to feed-in tariff laws, along with the early-2015 introduction of new curtailment rules that dampened demand. The U.S. BOT decrease was driven by increases in imports to meet growing demand, as well as a rush to beat solar investment tax credit (ITC) expiration.

The biggest changes in BOT for PV cells were observed in China, India, and Taiwan. In 2016, China's PV cell exports rebounded from a 2015 drop, due to decreases in imports from $2.6 billion to $1.2 billion and triggered in part by the 2016 expiration of its PV subsidy. Taiwan's BOT decrease was driven by decreases in exports from $4.0 billion to $2.6 billion, potentially due to manufacturers' pausing production based on oversupply and low cell prices.

Between 2014 and 2016, the largest changes in polysilicon trade flow were observed in Taiwan, Japan, and the United States. Potential drivers include the higher quality of polysilicon imported from other countries and the failure of Chinese polysilicon production to keep up with increasing domestic demand. Taiwan's BOT increase was driven by increases in exports of polysilicon from $470 million to $2.6 billion. During the period, the United States, South Korea, and Germany began exporting polysilicon to Taiwan to avoid Chinese tariffs. Despite its lack of any production capacity, Taiwan then exported poly-Si produced by other economies to China. The U.S. BOT 2015 dip was driven by decreases in exports from $1.9 billion to $1.3 billion, as a result of reductions in polysilicon production from $940 million to $620 million, possibly due to oversupply and a related 32% drop in prices.

Benchmark Data: Value Added Trends

PV module supply chain total value added (tVA) by value added component, 2014–2016



Total value added (tVA) for the period in US$(2014) across PV module supply chain for key PV economies. Darker shading indicates direct value added (dVA), lighter shading indicates indirect value added (iVA), and numerical values show the total value added (tVA). Note that tVA data for China are displayed on a different scale.

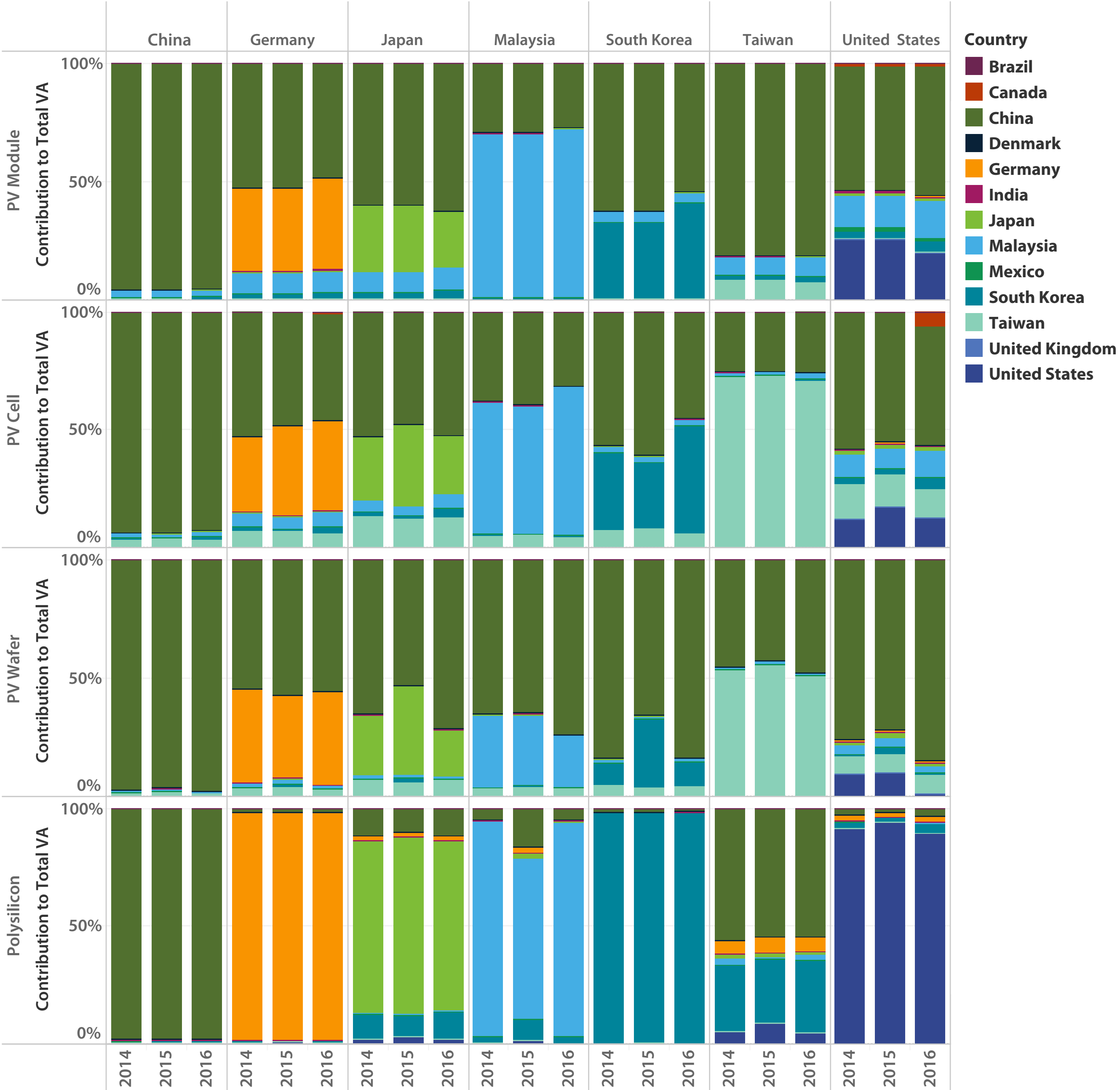
Total value added (tVA) to China's economy from production of PV modules, cells, and polysilicon was much greater over the period than that of any other benchmarked economy. Japan's tVA was second highest tVA, but 10% to 30% that of China's tVA across the supply chain. tVA from global production of PV modules generally declined over the period, while tVA increased slightly or remained flat for PV cells, PV wafers, and polysilicon. Indirect value added (iVA) was generally greater than direct value added (dVA) for the key PV module economies.

Over the period, tVA from global production of PV modules generally decreased—in part due to sharply declining prices that reduced production revenues—while tVA increased slightly or remained flat for PV cells, wafers, and polysilicon. Between 2014 and 2016, tVA from PV modules declined or remained flat for all benchmarked economies. Between 2014 and 2016, tVA from polysilicon generally increased, with the exception of the United States, where a downward production trend was triggered by declining prices and Chinese tariffs on U.S. polysilicon imports.

tVA is generally highest in economies with the highest levels of production revenue. In 2016, the 13 benchmarked economies produced $57.6 billion in tVA from the production of c-Si PV modules, cells, wafers, and polysilicon, down 3.4% from $59.6 billion in 2014. $14.5 billion of the 2016 aggregate tVA was dVA from domestic manufacturers. iVA was higher than dVA for all benchmarked economies across the supply chain, with the exception of polysilicon production in South Korea, Malaysia, and the United States, demonstrating, in general, that the supply chains that support PV module manufacturing domestically and internationally were more important to the benchmarked economies than the domestic manufacturing of the intermediates (PV wafers, PV cells and polysilicon) and end product (PV modules).

Benchmarked economies retained varying shares of tVA as a portion of manufacturing revenue (i.e., VA retained) over the period from manufacturing PV modules and intermediates. While the value added to China's economy from manufacturing across the PV module supply chain was much greater than that of any other benchmarked economy, the other economies generally had higher VA retained, led by the United States, Germany and Japan (37% - 65% across the supply chain). VA retained reflects the extent of domestic supply chains as well as prevailing wages, domestic profits, and taxes less subsidies.

PV module supply chain total value added (tVA), domestic and non-domestic contribution, 2014–2016

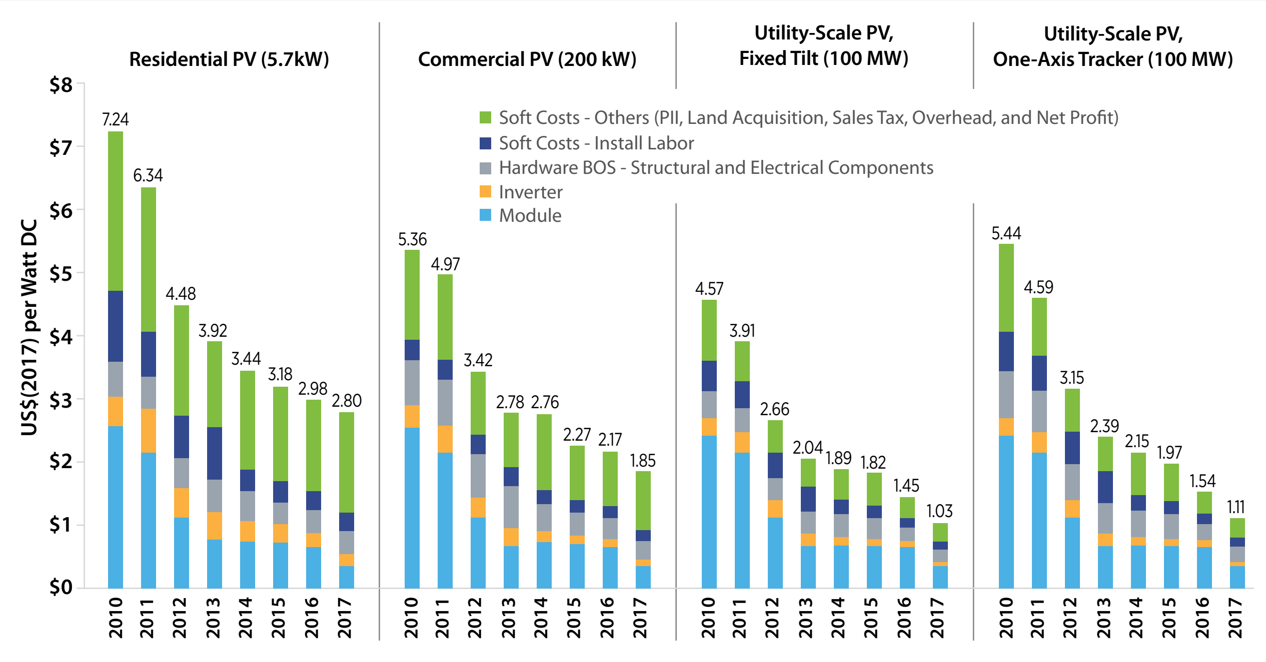


For each economy (listed across the top) color-coded bars show the share of tVA accrued from domestic and non-domestic production of PV module intermediates for 2014 to 2016. Domestic bars (generally the largest in each bar) represent the share of tVA (iVA plus dVA) from domestic production. Non-domestic bars represent the share of tVA (iVA only) from production in other economies (dVA only occurs in the economy where production occurs).

While all benchmarked economies received iVA from production of PV modules, cells, wafers, and polysilicon in other economies over the period, most of the tVA came from domestic manufacturing of those intermediates. Production in China, driven in part by growth in manufacturing capacity, impacted all benchmarked economies over the period and generally contributed more iVA than the other economies.

PV Challenges and Opportunities: Balance of System Components

Modeled cost breakdown trends for PV systems installed in the United States (inflation adjusted), 2010–2017



Source: Fu et al. 2017

This benchmark report focuses on the impacts of the manufacturing supply chains of selected clean energy technologies but does not currently address the manufacture and trade of the other equipment required to actually use the technology. For example, the report does not consider the impacts of the supply chains of balance of system (BOS) components—inverters, and structural (e.g., racking and frames) and electrical hardware—required for PV module system installation and operation.

PV installations in the United States have relied on BOS equipment from both domestic and foreign sources. U.S. inverter manufacturing capacity was at a five-year low in 2017, with companies consolidating their global supply chains to reduce costs and China and Europe supplying most PV inverters for the U.S. market. Still, approximately 30% of all inverter capacity installed in the United States in 2017 was domestically sourced.

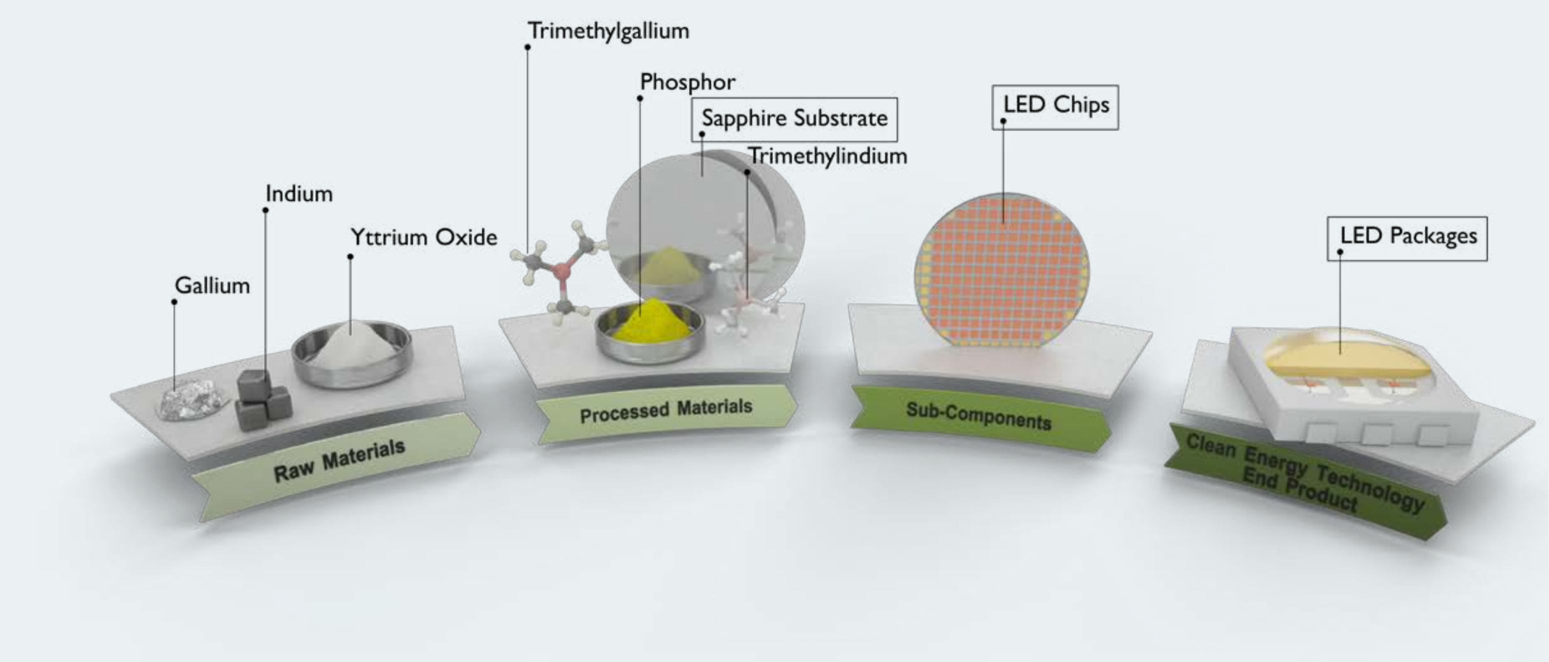
The U.S. PV racking market has been extremely fragmented by market segment. While the top five suppliers in each segment collectively provided more than 80% of the market in 2017, there were a large number of small racking suppliers. Foreign and domestic racking companies supplied to the U.S. market, with some foreign parent companies operating U.S. subsidiaries with local manufacturing. As shown in the figure, 2017 hardware BOS structural and electrical component costs ranged from $0.20/W for utility-scale (fixed-axis) to $0.36/W for residential PV systems, a large reduction from 2010 values of $0.43/W for utility-scale (fixed-axis) and $0.56/W for residential.

Steel makes up the largest amount of raw material used in PV racking. Due to concerns about tariffs with some Asian countries, many providers used North American steel (GTM Research 2017). The supply of other BOS equipment, such as wiring and combiner boxes, was also highly fragmented, with U.S. manufacturing companies sourcing material (e.g., aluminum and steel) from a global marketplace.

LED Packages

The light-emitting diode (LED)—a solid-state semiconductor device that emits light when an electric current is passed through it—is one of today's most energy-efficient and rapidly-developing lighting technologies, according to the U.S. Department of Energy.[19] Between 2014 and 2016, global production of LED packages and chips increased by 37.8% from 162.0 billion to 223.4 billion packages annually. Between 2015 and 2016, the market entered a period of oversupply, with price pressure driving average selling prices down by 30%–40%. The global market for LED packages used in luminaires, one specific application, expanded from $7.9 billion in 2014 to $9.1 billion in 2016. Global revenue from LED lighting systems for all applications is expected to total $216 billion by 2024 (Navigant Research 2015).

Light-emitting diode (LED) packages and supply chain



Light-emitting diode package alignment with the Clean Energy Manufacturing Analysis Center (CEMAC) benchmark framework. Boxes highlight components included in the benchmark analysis. No raw materials were included in the analysis because of a lack of data. Illustration by Josh Bauer, NREL

Researchers focus on the LED package as the end product of the supply chain framework, even though these act as components in a variety of other products, including automobiles, personal electronics, displays, and lighting. This simplified version of the manufacturing supply chain includes the sapphire substrate, LED chips, and LED packages.

Multiple opportunities exist for innovations that could lead to improvements in LED product efficacy, quality, and/or price. These include new chip and package designs; improvements in package substrate, encapsulant, optic, and phosphor materials; as well as novel processing techniques such as wafer bonding, substrate removal, and wafer-level processing (Navigant Consulting 2014).

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[19] For more information, see the DOE "LED Lighting" web page at https://www.energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/led-lighting.

Notable Trends

Key drivers of LED package supply chain trends include:

- Demand growth related to regulated phaseouts of incandescent lighting
- Declining prices resulting from oversupply and industry consolidation.

Industry Consolidation

Historically, regulated phaseouts of incandescent lighting to meet domestic energy efficiency targets in the benchmarked economies, as well as and declining LED costs, have driven demand growth for LEDs used in lighting. Global demand for light-emitting diode (LED) packages, chips, and sapphire substrate grew rapidly between 2014 and 2016, led by China. Demand in other individual benchmarked economies was relatively flat. Even with increased demand, oversupply (due in part due to China's large and increasing manufacturing capacity) combined with industry consolidation drove down the price of LEDs.

Global Supply Chains

Across the LED supply chain for all benchmarked economies, indirect value added (iVA) from manufacturing was greater than direct value added (dVA), indicating that participation in the broader supply chain that supports LED manufacturing at home and abroad was more important to the benchmarked economies than domestic production of the intermediates end product. Production of LED packages and chips in Japan and China contributed the largest share of non-domestic iVA to the benchmarked economies. Only Taiwan had sufficient domestic production to meet domestic demand across the supply chain. Other economies relied on trade to fill the supply chain gaps.

China and Japan

China's concerted efforts to expand production of LED packages and chips contributed to its displacement of Japan as the top global producer over the period. As new Chinese foundries came online, Chinese imports from Taiwan dropped, and a global excess of manufacturing capacity was established. China was also the largest net importer of LED chips and packages.

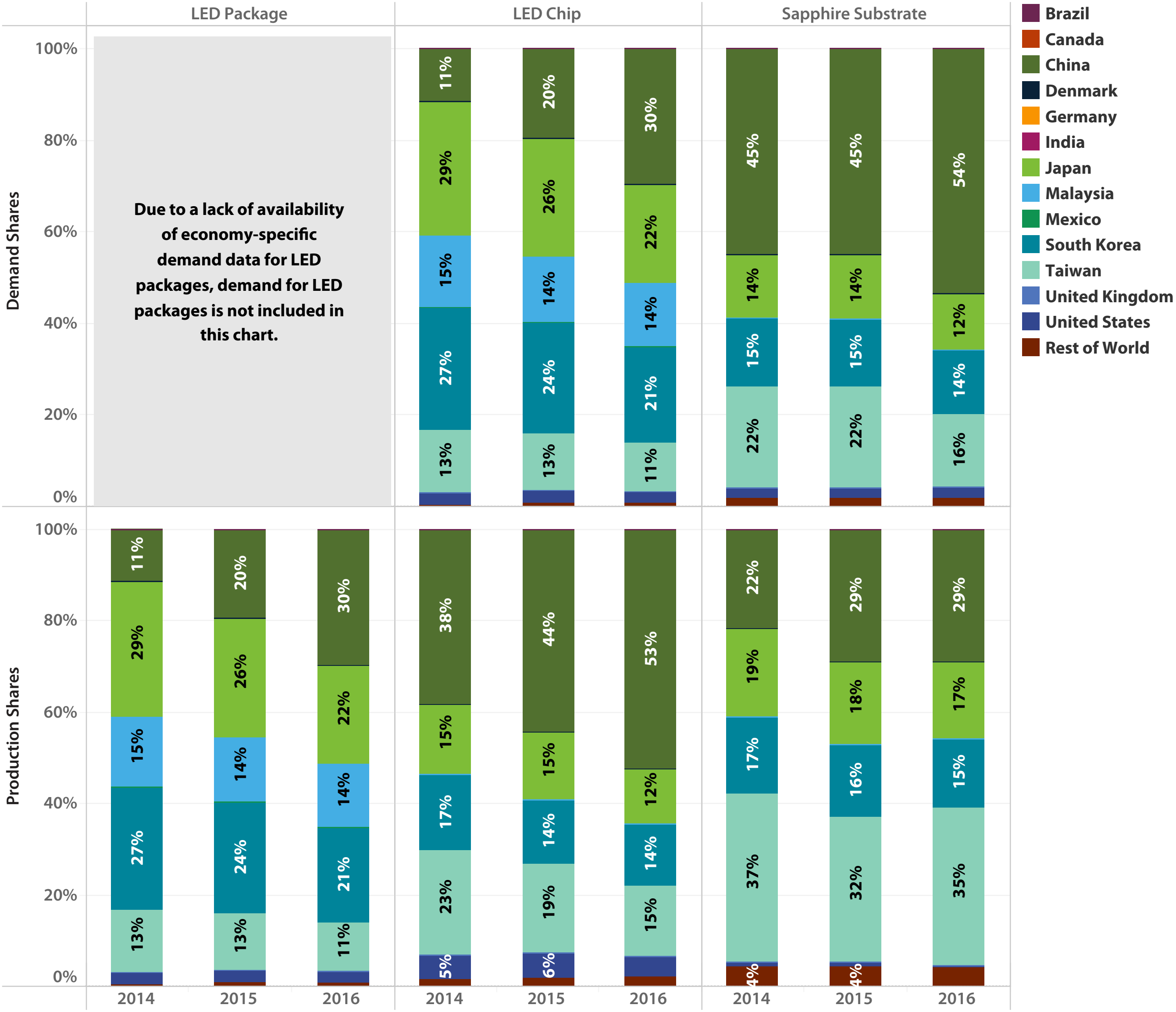
Quality and Cost

LEDs are used in a wide range of products. Each application has a unique set of specifications defining color temperature, lumens (brightness), and voltage requirements. Due to differences in LED specifications for various applications, LED quality and performance varies. In 2016, Chinese manufacturers commanded the greatest share of the lower-cost, low-lumens LEDs used for television and personal lighting, while U.S. and European companies retained market share for brighter, higher-lumen equipment that yielded larger profit margins (Bradsher 2014).

More detailed information can be found on the following pages.

Benchmark Data: Market Trends

LED package supply chain demand and production shares, 2014–2016

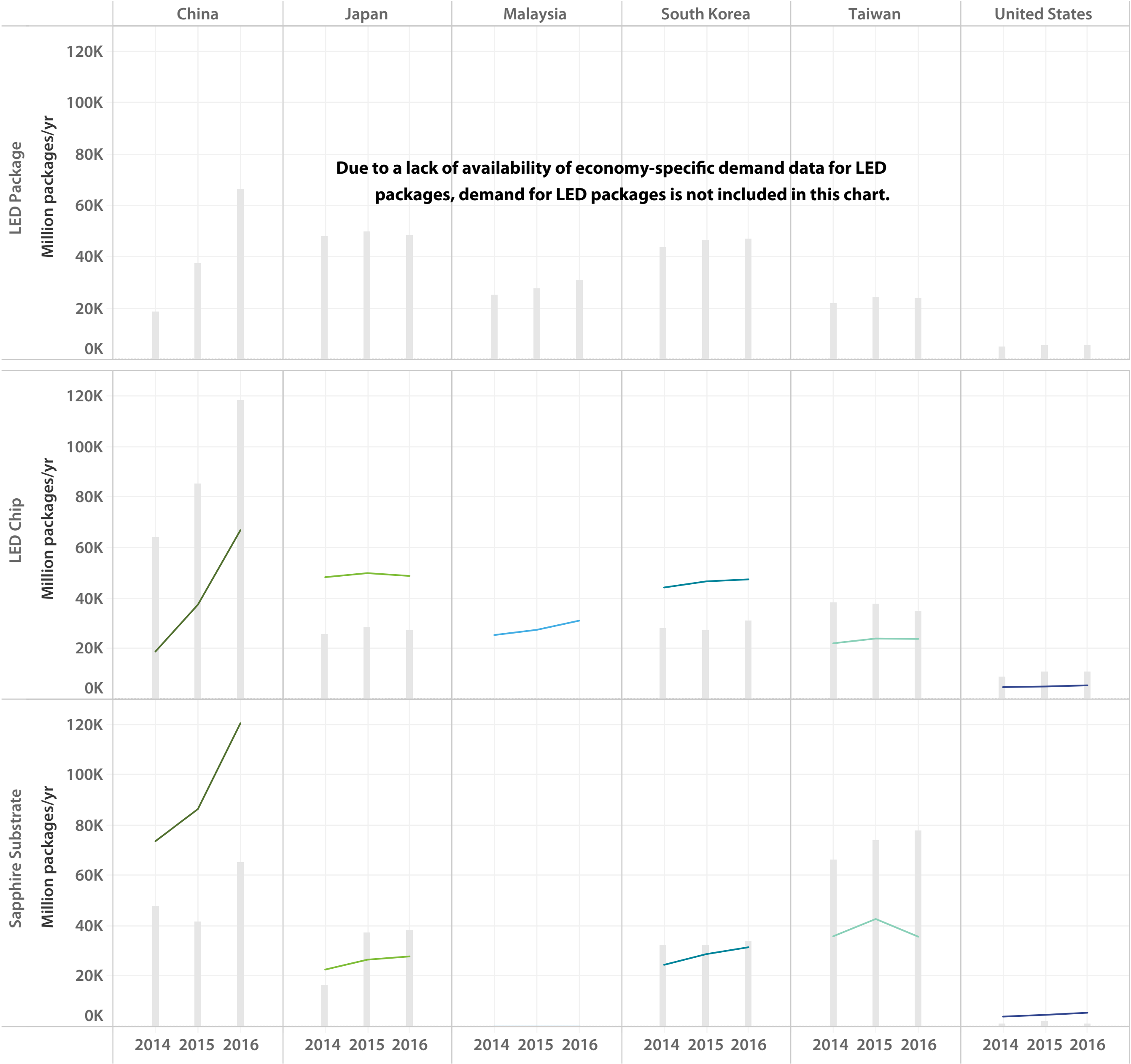


Breakdown (in %) of global demand (top) and global production (bottom) by economy for benchmarked LED package supply chain intermediates. Due to a lack of availability of economy-specific demand data for LED packages, demand for LED packages is not included in this chart.

China grew its shares of global demand and production of LED packages and chips over the period, accounting for the highest share of each among the economies in 2016. Taiwan accounted for the highest shares of global production of sapphire substrate. Shifts in shares over the period were driven by China's concerted efforts to expand production of LED packages and chips.

LED package production in Japan and South Korea constituted more than 55% of total global package output in 2014, with China and Taiwan together contributing another 24%. By 2016, China was the highest-volume package producer with a 30% share, with Japan, South Korea, and Taiwan together contributing 54%.

LED package supply chain demand and production for key LED package economies, 2014–2016



Demand (color-coded lines) and production (gray bars) trends (in millions of packages) for LED package supply chain intermediates by economy. Economies are listed in order of 2016 production levels. Due to a lack of availability of economy-specific demand data for LED packages, demand for LED packages is not included in this chart.

Global demand for and production of LED packages, chips, and sapphire substrate grew significantly over the period, led by China. Production and demand in other individual benchmarked economies was relatively flat. Only Taiwan had sufficient domestic production to meet domestic demand across the supply chain.

Between 2014 and 2016, annual global production and demand for LED packages increased by 37.8% from 162.0 billion to 223.4 billion packages. Over the period, the most significant increases in LED package and chip production were observed in China, with many new foundries coming online in that country in 2015.

LED package supply chain manufacturing capacity utilization, 2014–2016

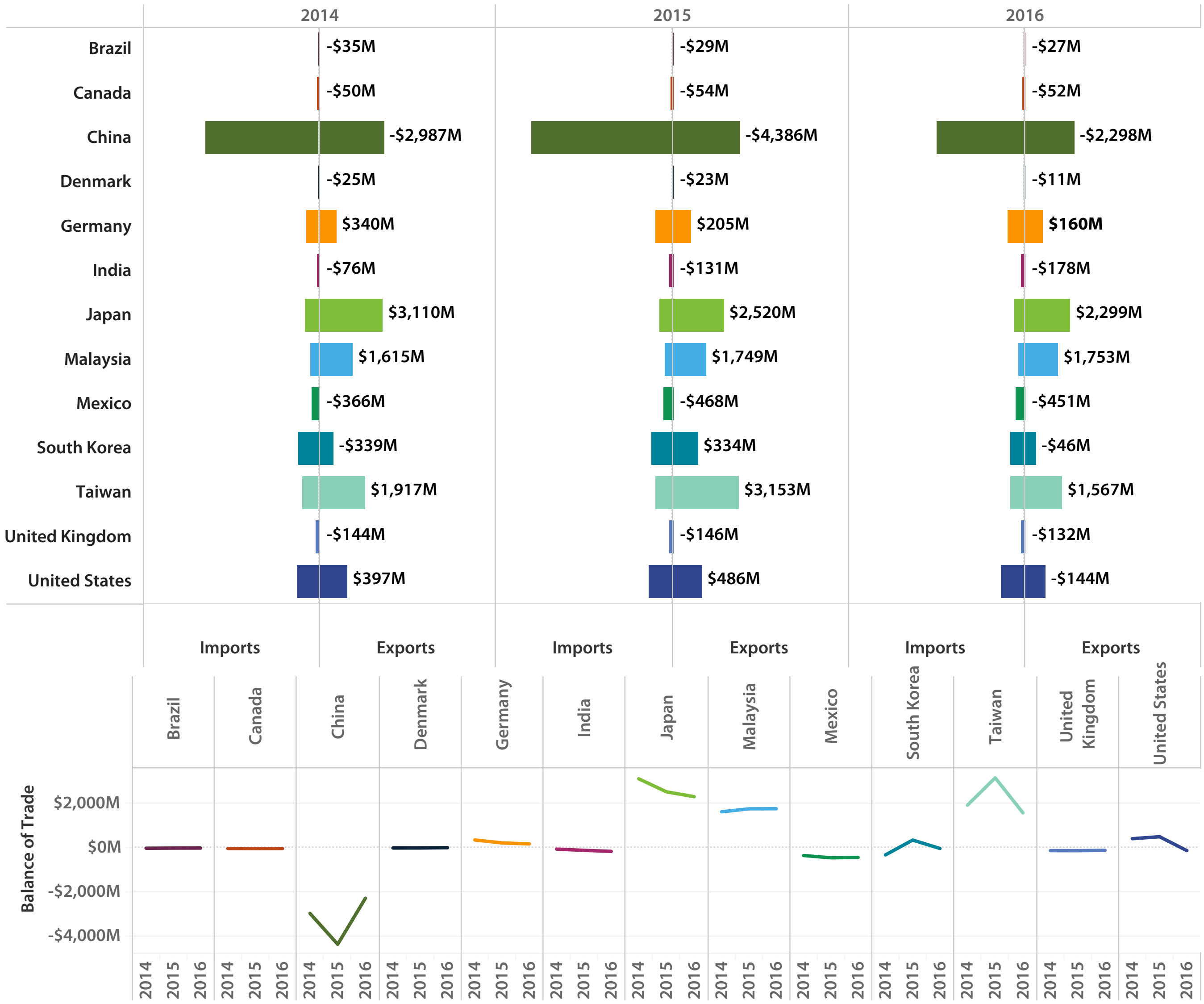
Bars show manufacturing capacity (lighter shading) and utilized manufacturing capacity (i.e., production, darker shading) in US$2014 for LED package economies. Vertical lines and associated numerical values show capacity utilization (production as a % of manufacturing capacity). Trend lines show global capacity utilization percentage for 2014–2016 (bottom); because of a lack of economy-specific manufacturing capacity data for LED packages, manufacturing capacity of LED packages is assumed equal to production.

China's large and increasing manufacturing capacity contributed to an excess of manufacturing capacity for LED chips and sapphire substrate relative to global demand, indicating some potential to meet future demand growth by expanding production. Globally, capacity utilization for LED chips was relatively flat (64% to 74%) while capacity utilization for sapphire substrate dropped from 74% to 17% over the period.

Global manufacturing capacity for LED chips was estimated at $10.4 billion in 2014, $10.4 billion in 2015 and $11.5 billion in 2016. Corresponding production was estimated at $7.4 billion in 2014, $6.7 billion in 2015, and $8.5 billion in 2016, reflecting a global excess of manufacturing capacity. Globally, capacity utilization was much higher for LED chips than for sapphire substrate, as sapphire substrate manufacturing capacity grew much faster than production over the period.

Benchmark Data: Trade Trends

LED package trade, 2014–2016



Bar chart (top) shows imports (negative values), exports (positive values) and balance of trade (exports less imports) in US$(2014) by economy for LED packages. Line chart (bottom) shows balance of trade trends for LED packages.

Between 2014 and 2016, China was the largest net importer of LED packages, while Japan, Malaysia, and Taiwan were the largest net exporters. In the benchmarked economies, the balance of trade (exports minus imports) remained relatively stable, with a few exceptions including China, Taiwan, the United States, and South Korea.

Over the period, the value of global exports of LED packages among the benchmarked economies decreased by 18.5% (from $17.1 billion to $14.0 billion) and the value of global imports decreased 16.4% (from $13.8 billion to $11.5 billion), reflecting lower prices and oversupply in the LED market.

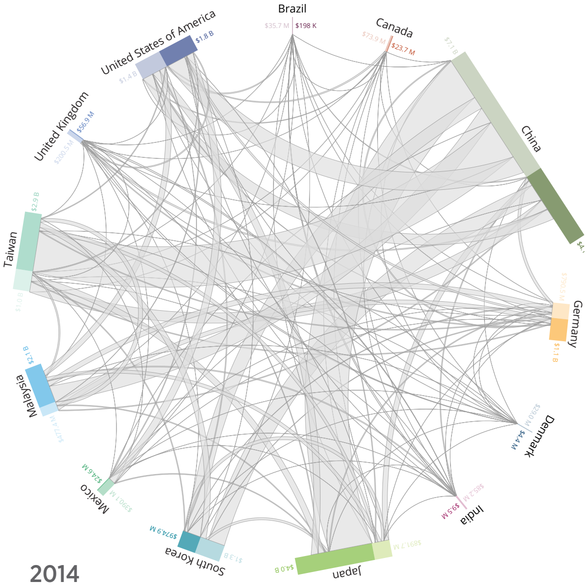
Japan, Malaysia, and Taiwan had trade balances (BOT) of $2.3 billion, $1.8 billion, and $1.6 billion, respectively for LED chips and packages in 2016, while China's BOT was negative $2.3 billion in 2016.

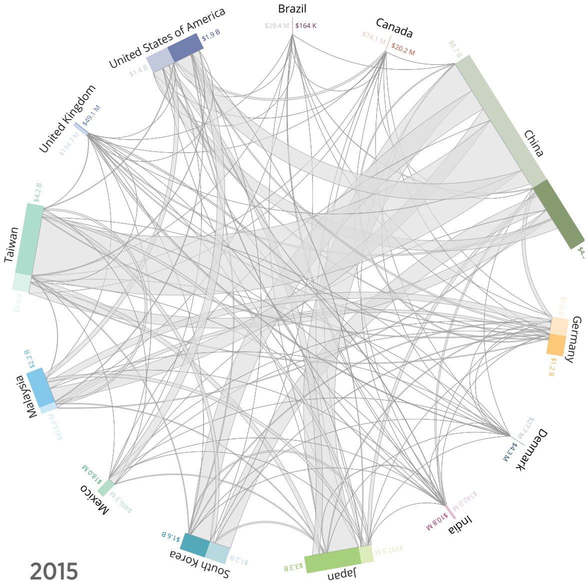
LED package trade flows, 2014–2016

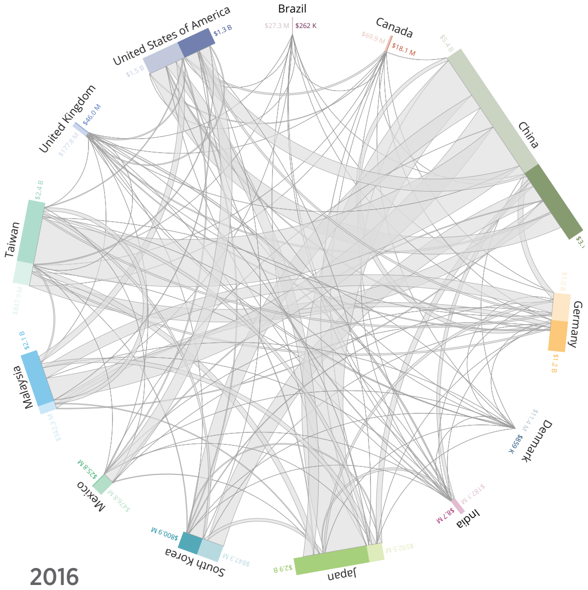
While global exports and imports of LED packages declined over the period, the trade network among the benchmarked economies remained intact and generally followed expected flows, given the distribution of manufacturing capacity across economies. China's expanding LED package and chip manufacturing capacity contributed to trade shifts in benchmarked economies.

Between 2014 and 2016, the largest changes in trade flow of LED chips and packages were observed in China, Japan, and Taiwan. Many new Chinese foundries came online in 2015, abruptly reducing imports from Taiwan and contributing to the sharp reduction in China's net imports (from -$4.4 billion to -$2.3 billion) and Taiwan's net exports (from $3.2 billion to $1.6 billion) from 2015 to 2016. New capacity in China also contributed to net exports reductions in Japan from $3.1 billion in 2014 to $2.3 billion in 2016.

Gray chords show LED package trade flows in US$(2014) among benchmarked economies. Width of bars are scaled to total flows, with lighter shading showing imports and darker shading showing exports. Note that gray chords only capture the trade among the 13 benchmarked economies; trade flows with the rest of the world are not shown.

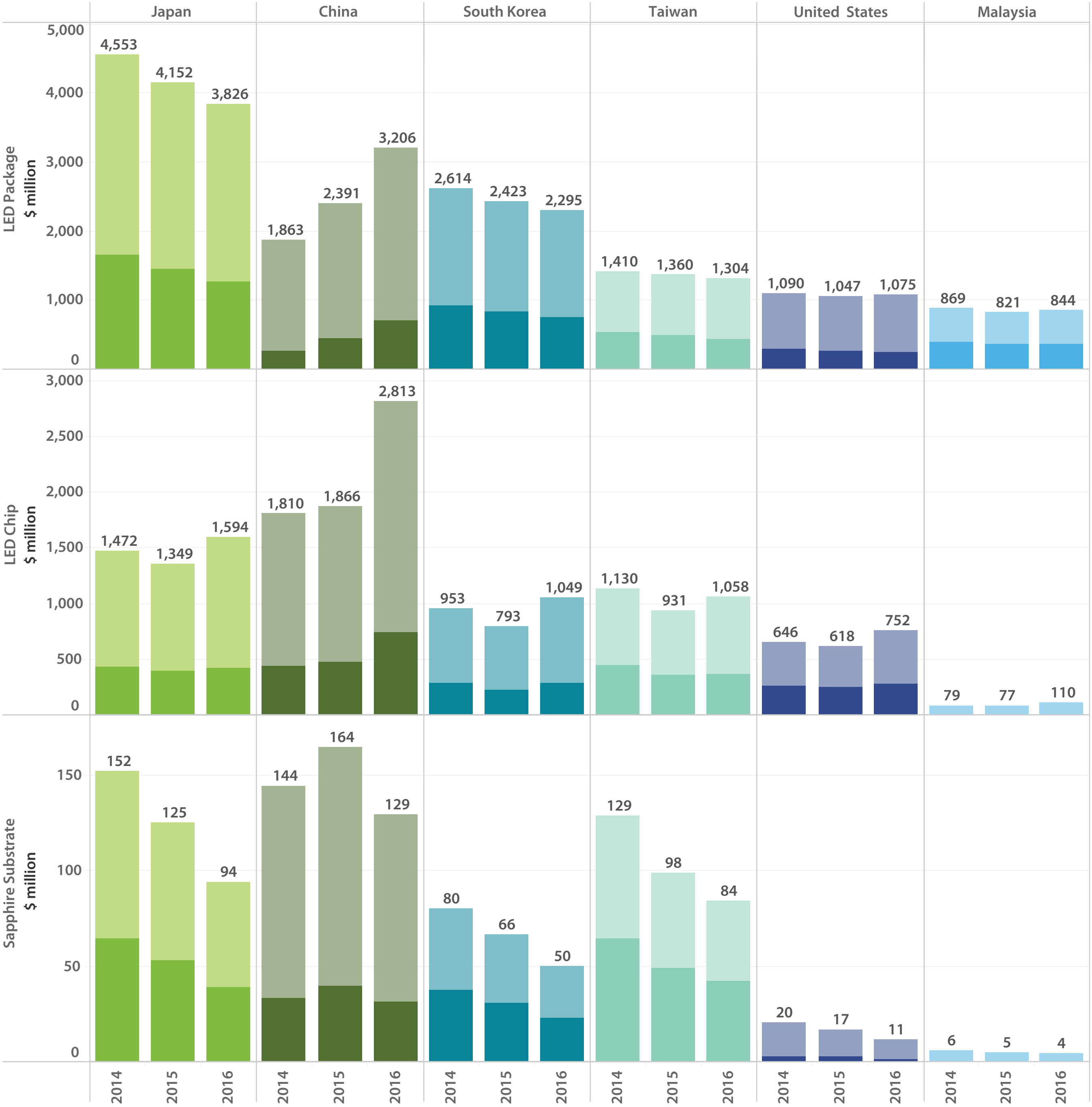






Benchmark Data: Value Added Trends

LED package supply chain total value added (tVA) by value added component, 2014–2016



Total value added (tVA) for the period in US$(2014) from manufacturing LED supply chain intermediates in key LED package economies. Darker shading indicates direct value added (dVA), lighter shading indicates indirect value added (iVA), and numerical values show total value added (tVA). Economies are listed in order of tVA from LED package production in 2016. Note that each intermediate is displayed on a different scale.

Of the benchmarked economies, total value added (tVA) from global production of LED packages, chips, and sapphire substrate was greatest for Japan, China, South Korea, and Taiwan. Indirect value added (iVA) was higher than direct value added (dVA) for all LED supply chain intermediates considered, indicating that participation in the broader supply chain that supports global LED package manufacturing domestically and internationally was more important to the benchmarked economies than domestic production of these intermediates and end products.

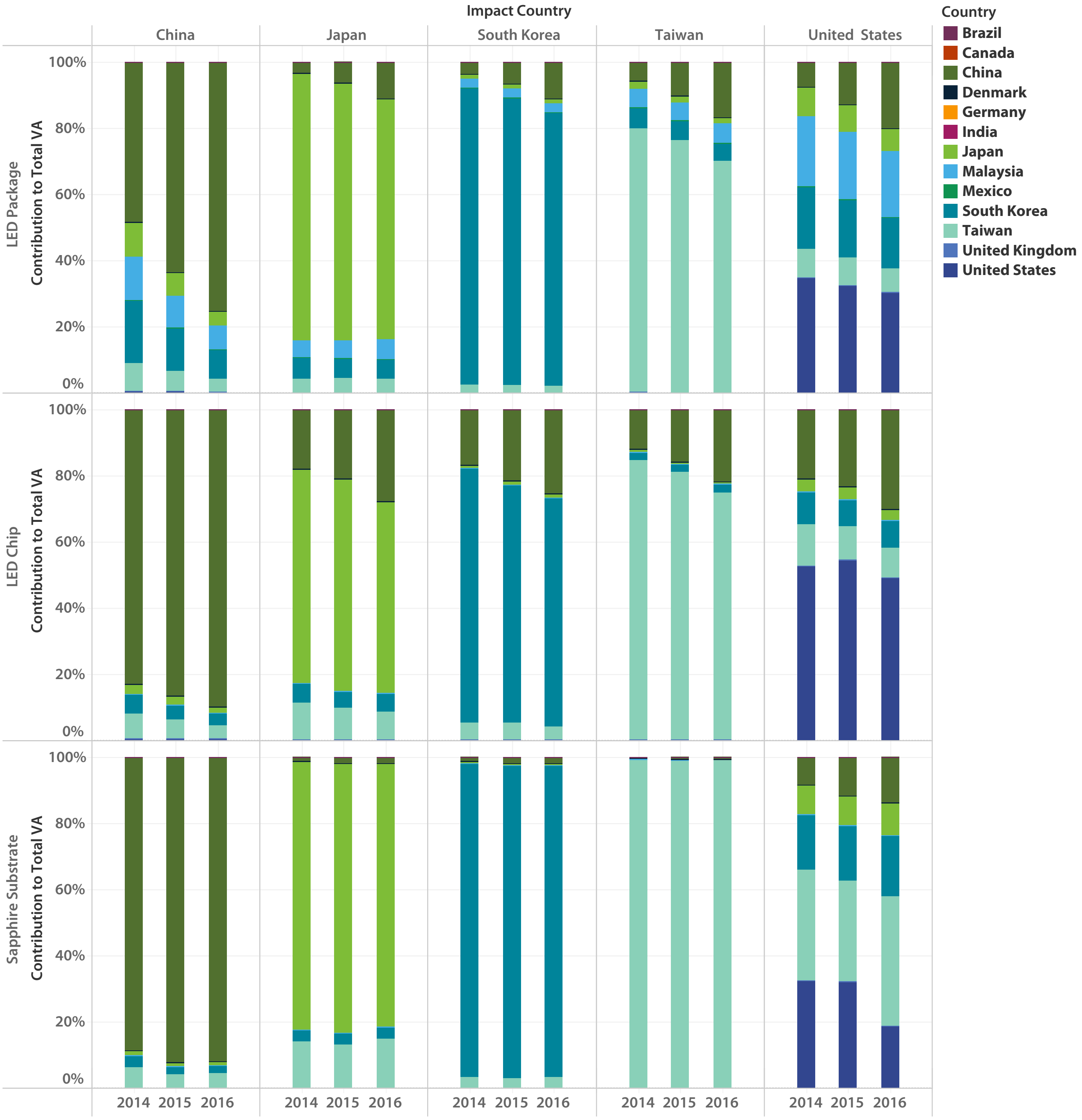
tVA from the production of LED packages in benchmarked economies was up slightly, from $13 billion in 2014 to $13.2 billion in 2016. In 2016, manufacturing LED packages delivered tVA of $3.8 billion for Japan, $3.2 billion for China, and $2.3 billion for South Korea. China's tVA from LED package and chip manufacturing increased over the period, while tVA in the other economies for all supply chain intermediates remained relatively flat or declined. China's tVA from LED chip manufacturing increased significantly over the period, resulting from a concerted effort to expand domestic manufacturing. tVA accrued to China, Japan, South Korea, and Taiwan from production of LED packages and chips over the period was each greater than that accrued to the United States.

dVA from domestic production of LED packages declined or remained flat over the period for all economies except China, where dVA increased by 167% as a result of increases in domestic production revenues over the period. The greatest declines were observed in Japan (24.0%) and South Korea (19.3%). iVA from global LED package production generally followed the same trends over the period.

Both dVA and iVA for LED chip production increased in the five key LED chip manufacturing economies—with tVA up by 55.4% in China, 16.3% in the United States, 10.1% in South Korea, and 8.3% in Japan. tVA for Taiwan decreased by 6.4% over the period. From 2014 to 2016, both dVA and iVA from domestic production of sapphire substrate declined for all economies, reflecting production trends due to oversupply.

Benchmarked economies retained varying shares of tVA as a portion of manufacturing revenue (i.e., VA retained) over the period from manufacturing LED packages and intermediates. China netted the lowest VA retained across the LED package supply chain (15% - 21%).The United States netted the highest VA retained for LED package and chip production (65%), despite relatively low production. For sapphire substrate production, only Japan had a higher VA retained (45%) than the United States (36%). VA retained reflects the extent of domestic supply chains as well as prevailing wages, domestic profits, and taxes less subsidies.

LED package supply chain total value added (tVA), domestic and non-domestic contribution, 2014–2016



For each economy (listed across the top) color-coded bars show the share of tVA accrued from domestic and non-domestic production of LED package intermediates for the top LED economies between 2014 and 2016. Domestic bars (generally the largest in each bar) represent the share of tVA (iVA plus dVA) from domestic production. Non-domestic bars represent the share of tVA (iVA) only from production in other economies (dVA only occurs in the economy where production occurs).

In general, the benchmarked economies received the greatest portion of tVA from domestic production of LED packages, chips, and sapphire substrate. However, production of LED packages and chips in China, Japan, Malaysia and South Korea impacted all economies considered through iVA.

LED Challenges and Opportunities: Quality and Cost

LED Applications, 2014–2016

Application	2014	2015	2016
General Lighting	51%	58%	63%
LCD TVs and Monitors	15%	12%	10%
Cell Phones	11%	10%	9%
Notebooks and Tablets	9%	7%	6%
Signs and Large Displays	6%	5%	5%
Automotive Lighting	4%	4%	4%
Other Displays	3%	3%	2%
Personal Lighting	1%	1%	1%

Percentage indicates the portion of LEDs used globally for each application (Mukish and Virey 2017).

The high-level view of clean energy manufacturing supply chains provided in this benchmark report is based on available market and trade data, which are typically highly aggregated. Disaggregating these data to gain insight into the differences in quality of the products tracked is difficult due to data reporting limitations. The challenges of assessing the impacts of different types of LEDs manufactured around the world in terms of the benchmark metrics provides one example. LEDs are not all created equal. LEDs are used in an impressive array of products, from stadium scoreboards to televisions, household lightbulbs, and car headlamps. In 2016, more than 60% of LEDs were used for general lighting, as shown above. Within the lighting category, there is also variation in LEDs due to optimization of different parameters—saturation, preference, efficiency—for different uses.

In the highly segmented LED industry, Chinese manufacturers command the greatest share of the lower lumen LEDs used for lighting. Western manufacturers retain market share for brighter, higher-lumen devices that yield larger profit margins (Bradsher 2014).

Even within an application like general illumination, the specifications for each type of LED product varies significantly depending on the customer's needs and budget; for example, color quality requires balancing spectral fidelity and gamut with well-documented preference. Beyond color quality, customers also frequently have requirements for lighting output, reliability, and efficacy. Products frequently need to withstand temperature, humidity, ultraviolet radiation exposure, and voltage variation varies depending on the application. The specifications that an LED need to meet are critical factors in determining its cost. A single LED in a commercial light has a much lower cost and much lower specification than a single smaller LED in a smart phone that doubles as a high-lumen flashlight.

Application-driven differences are combined with quality differences among LED manufacturers. Although no analytical data are available on product quality across manufacturing regions, some conclusions can be drawn from anecdotal information. For example, consumer and media reviews might mention that one brand of LEDs is considered notably more long-lasting and of higher quality, or that other LED brands are known for early burnout. Where they can be verified at all, such claims can require careful laboratory tests.

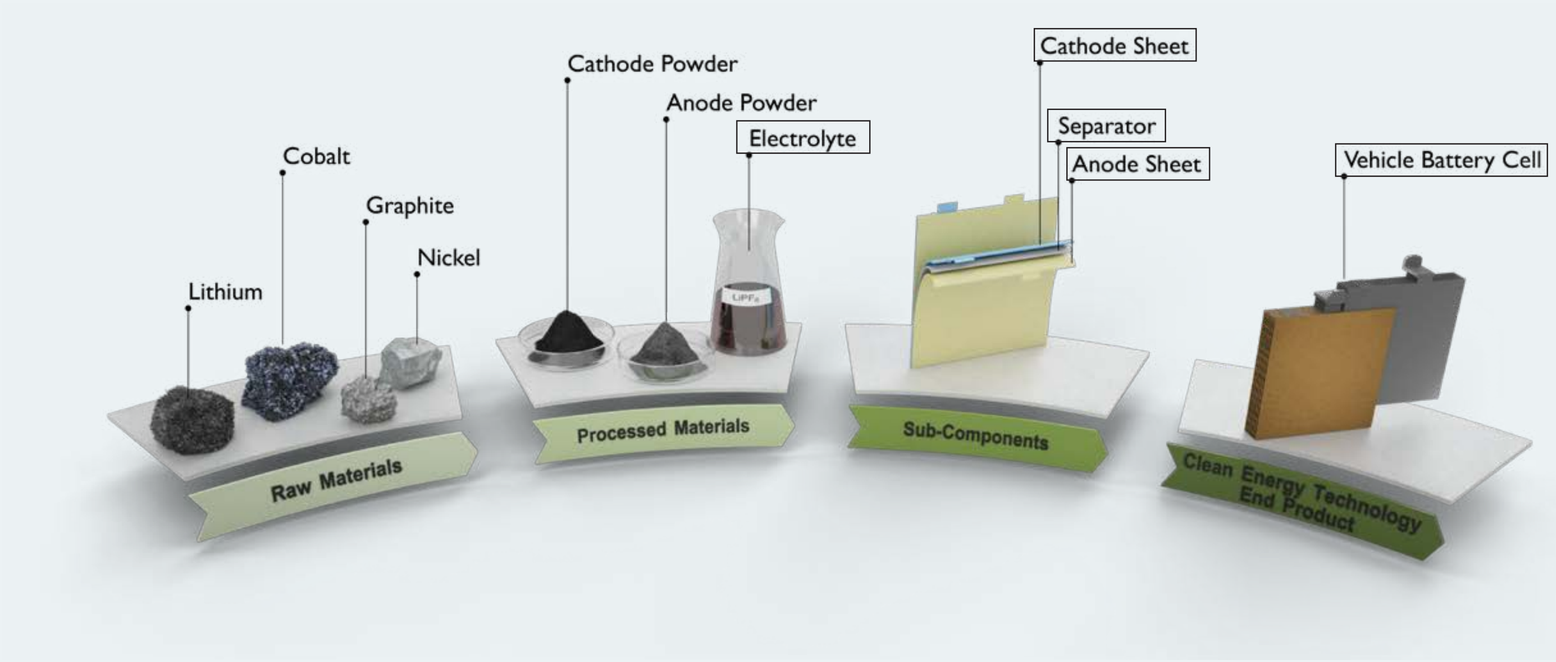
The trade-off between quality and cost can take time to manifest itself in the field. For example, the ceramic packaging used for high-power LEDs and polyphthalamide packaging (Tuttle and McClear 2014) used in low power LEDs behave significantly differently with time and heat exposure. The polyphthalamide will also cause color shifting and other issues as the LED ages.

Reporting on LEDs using the CEMAC benchmark methodology makes highlighting differences in LED quality and cost challenging. Benchmark results may show, for instance, that an economy has only 5% of the market by physical volume, but this amount could represent 15% of revenue. The discrepancy between the price of the various types of LEDs means it is difficult to ascertain quantitatively the physical volume of production and its impact on any specific regional economy might be.

Lithium-Ion Battery Cells for Light-Duty Electric Vehicles

The global market for automotive lithium-ion battery (LIB) cells grew rapidly as a direct result of the increasing demand for plug-in, hybrid and fully electric vehicles (EVs). Global annual demand for EV LIB cells increased threefold over the period, from 9.6 GWh in 2014 to 31.1 GWh in 2016.[20] This demand was mainly driven by sales of EVs (plug-in, hybrid and fully electric vehicles), which constituted 2.6% of global light-duty vehicle (LDV) sales in 2016.[21]

Light-duty vehicle lithium-ion battery (LIB) cells and supply chain



Lithium-ion battery cell alignment with the Clean Energy Manufacturing Analysis Center (CEMAC) benchmark framework. Boxes highlight components included in the benchmark analysis. No raw materials were included in the analysis for lack of data. Illustration by Josh Bauer, NREL

LIB cells constitute a large portion of the cost structure for complete battery packs, and cell cost and performance drive overall pack cost and performance. This report focuses on cells, rather than packs, because car manufacturers typically design and assemble their own packs using purchased LIB cells.

Opportunities for innovation include advances in cell chemistries, formats, and manufacturing processes. Researchers focus on LIB cells used for LDVs and the intermediate materials required to make these cells, namely the cathode, anode, electrolyte, and separator.

Concerns about availability of some elements critical to LIB manufacturing (e.g., lithium and cobalt) that are largely sourced outside the major economies analyzed here, along with environmental concerns about disposal at the end of battery life, are spurring new research, policies, and regulations.

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[20] NREL estimate based on Curry (2017), BNEF (2017b), Zamorano (2017), Yano (2017), and Pillot (2017)

[21] NREL estimate based on Richter (2017), EIA (2017;), and BNEF (2016)

Notable Trends

LIBs represent a strong growth industry for participating economies. Key drivers of LIB cell supply chain trends include:

- Growing global demand for LIB cells in the manufacture of battery packs used in EVs
- Development and expansion of domestic LIB cell manufacturing supply chains to meet all or part of domestic demand growth
- China's strong backing of its domestic LIB industry through policy and investment to support deployment of EVs (Chung, Elgqvist, and Santhanagopalan 2016).

Manufacturing Capacity

Led by China, growth in demand for lithium-ion battery (LIB) cells was driven by the benchmarked economies' investment in electric vehicles (EVs), including hybrid electric and fully electric vehicles, often supported by subsidies. In anticipation of continued increasing demand, global LIB cell manufacturing capacity soared in 2016, creating excess capacity across supply chain intermediates. If the manufacturing facilities remain underutilized, this surplus capacity could continue to place downward pressure on LIB prices.

Global Supply Chains

Across the LIB cell supply chain, indirect value added (iVA) was greater than direct value added (dVA), except for U.S. production of LIB cells, indicating that participation in the broader supply chain that supports LIB cell manufacturing at home and abroad was more important to the benchmarked economies than domestic production of the intermediated and end product. All benchmarked economies received iVA from production in China, Japan, South Korea, and Germany. In addition, none of the benchmarked economies could meet its own domestic demand for all supply chain components, relying instead on trade to fill gaps.

China, Japan, South Korea, United States, and Germany

China, Japan, and the United States accrued more tVA from manufacturing LIB cells than the other benchmarked economies over the period, resulting from production to meet LIB demand for EVs. Leveraging mature domestic supply chains originally developed to serve consumer electronics markets, China, Japan, and South Korea were the top-three producers of LIB cell intermediates, as well as the top net exporters of LIB cells. While both the United States and Germany remained leaders in EV deployment, their domestic LIB supply chains could not meet domestic EV demand, resulting in the two countries becoming the largest net importers of LIB cells.

Raw Materials in the Manufacturing Supply Chain

Some of the key raw materials used in manufacturing LIBs include lithium, graphite, cobalt, and manganese. These materials are used to manufacture a range of products, from LIBs for consumer electronics and vehicles to superalloys, hard metals, ceramics, and polymers. As more EVs with LIBs are deployed, these vehicles are driving demand for materials used in LIB cells. Understanding these materials' markets is critical to comprehending the impact of continued EV deployment on mineral production and vice versa.

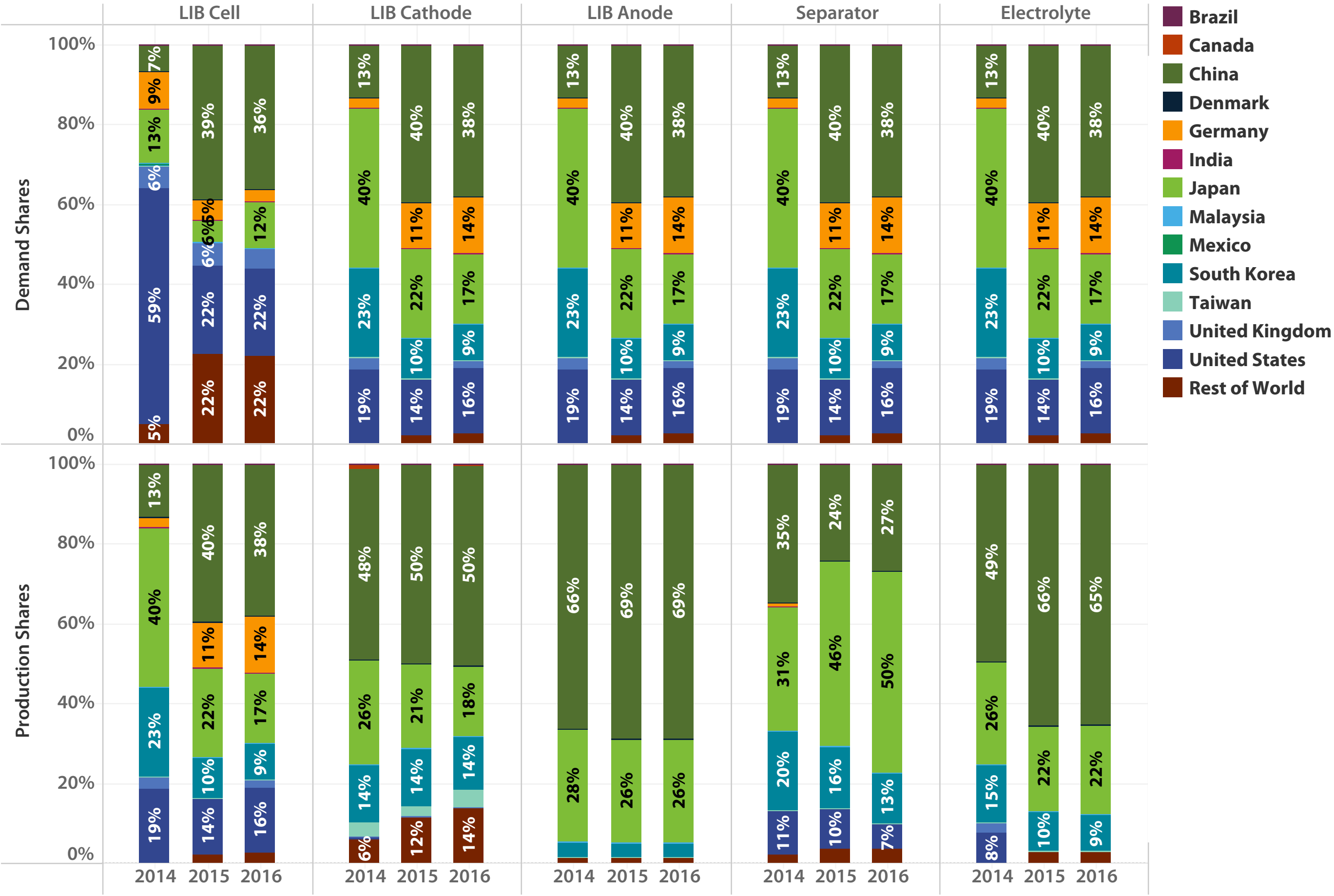
Recycling Critical Materials

As production of LIB cells for EVs continues to expand to meet increasing demand, and the early generations of these batteries begin to reach the end of their lifespans, the opportunities to reuse and recycle components and raw materials used in these technologies have grown in scale and importance. The development of closed-loop systems with end-of-life recycling can diminish environmental impacts from disposed batteries and provide secure sources of high-value materials that can be recovered and reused to produce new batteries at lower costs.

More detailed information can be found on the following pages.

Benchmark Data: Market Trends

Automotive LIB cell supply chain demand and production shares, 2014–2016



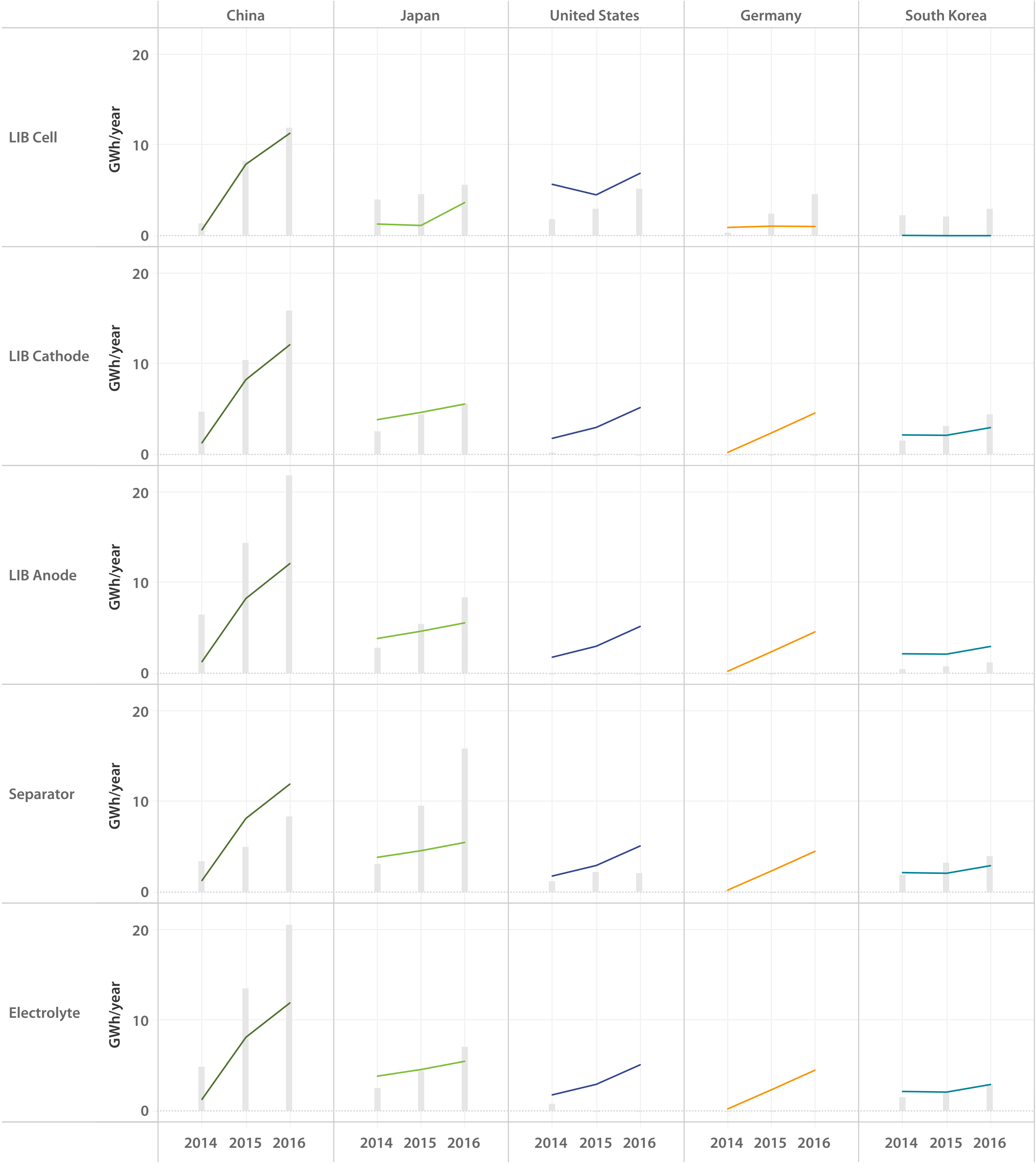
Breakdown (in %) of global demand (top) and global production (bottom) by economy for benchmarked LIB cell supply chain intermediates. Note that due to lack of country-specific demand data for the LIB intermediates, the demand shares for intermediates was assumed to equal production shares of LIB cells.

Over the period, China's demand and production shares for LIB cells increased sharply, reflecting its investment in and promotion of electric vehicles (EVs). U.S. demand and production shares decreased, and Japan and South Korea production shares also declined. Across the other supply chain intermediates, China and Germany demand shares increased, while distribution of production shares remained relatively unchanged.

By 2016 China had the highest share of global demand (36%) for LIB cells, while the U.S. share dropped to 22% (down from 59% in 2014). While absolute demand for LIB cells grew over the period in the United States, its decrease in global demand share could indicate a reduction in market share for EV production.

Production shares among the top five LIB economies shifted over the period as China and Germany increased production more rapidly than the other economies in efforts to build vertically integrated domestic and regional supply chains. In 2014, 40% of global LIB production occurred in Japan, and about 23% of automotive LIBs were made in South Korea. China contributed 13% and the United States contributed 19% to global automotive LIB production in 2014. In 2016, China's share of global automotive LIB production increased to 38%, with Japan contributing 17%, South Korea contributing 9%, and the United States contributing 16%.

Automotive LIB cell supply chain demand and production for key LIB cell economies, 2014–2016



Demand (color-coded lines) and production (gray bars) trends (in GWh) for LIB supply chain intermediates in key LIB cell economies. Economies are listed in order of 2016 production levels. Note that because of lack of data, global production of automotive LIB cells was assumed to equal global demand; the remaining benchmarked economies (not shown here) and the rest of the world make up the production-demand gaps indicated in the data presented.

China had the highest global demand and production of LIB cells and supply chain intermediates over the period. Global demand for and production of LIB cells and supply chain intermediates grew rapidly, largely driven by China's increasing production of EVs for domestic use. Japan, the United States, and South Korea were the next three largest markets for LIB cells and intermediates. None of the economies considered could meet domestic demand for all supply chain intermediates.

Between 2014 and 2016, annual global demand for and production of automotive LIB cells increased by 224% from 9.6 GWh to 31.3 GWh.[22] Demand for LIB cells was concentrated in China, the United States, Japan, South Korea, Germany, and the United Kingdom, with the biggest increases observed in China and the United States, driven by increases in the domestic demand for EVs.

To meet increasing demand, global production of LIB cells and supply chain intermediates (cathodes, anodes, electrolytes, and separators) more than tripled between 2014 and 2016. Production of LIB cells was concentrated in Japan, South Korea, the United States, and China. China's LIB cell production in 2016 was more than two times that of any other benchmarked economy. For LIB cathodes, the biggest production increases were observed in China (increasing 3.4 times, from 4.6 GWh to 15.8 GWh), Japan (increasing 2.2 times, from 2.5 GWh to 5.6 GWh), and South Korea (increasing 3 times, from 1.4 GWh to 4.3 GWh). For LIB cell separators, the biggest production increases were observed in Japan (increasing 4.3 times, from 3.0 GWh to 15.8 GWh) and China (increasing 1.5 times, from 3.3 GWh to 8.4 GWh). For LIB cell anodes and electrolytes, the biggest production increases were observed in China and Japan. With limited amounts of raw materials (e.g., cobalt and lithium), many LIB manufacturers have tried to secure their material supply chains for cathode, anode, and electrolyte materials.

Between 2014 and 2016, the United States, Japan, and South Korea did not produce enough separators, anodes, cathodes, and electrolytes to meet their respective domestic demands. In contrast, China expanded production over the period to surpass domestic demand for three of the four intermediates. While major producers of cells, the United States and Germany lagged in domestic production of intermediates, with the exception of some U.S. production of separators, and instead depended on imports from Asia for upstream links in the supply chain.

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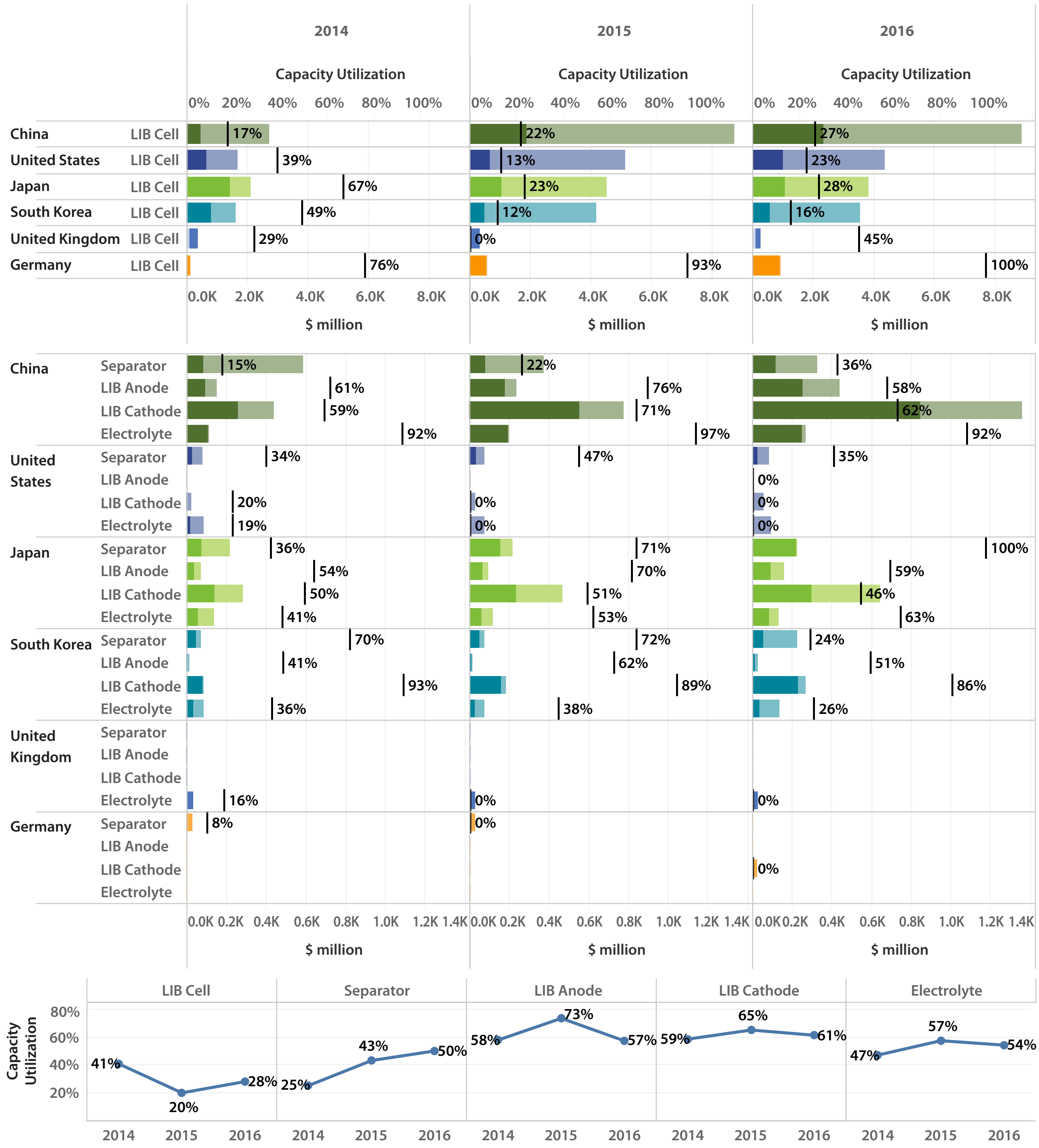
[22] Because of lack of data, global production of automotive LIB cells was assumed to equal global demand. See CEMAC's *Benchmarks of Global Clean Energy Manufacturing, 2014-2016: Framework and Methodologies* (Sandor et al. 2021) for details.

Automotive LIB cell supply chain manufacturing capacity utilization, 2014–2016



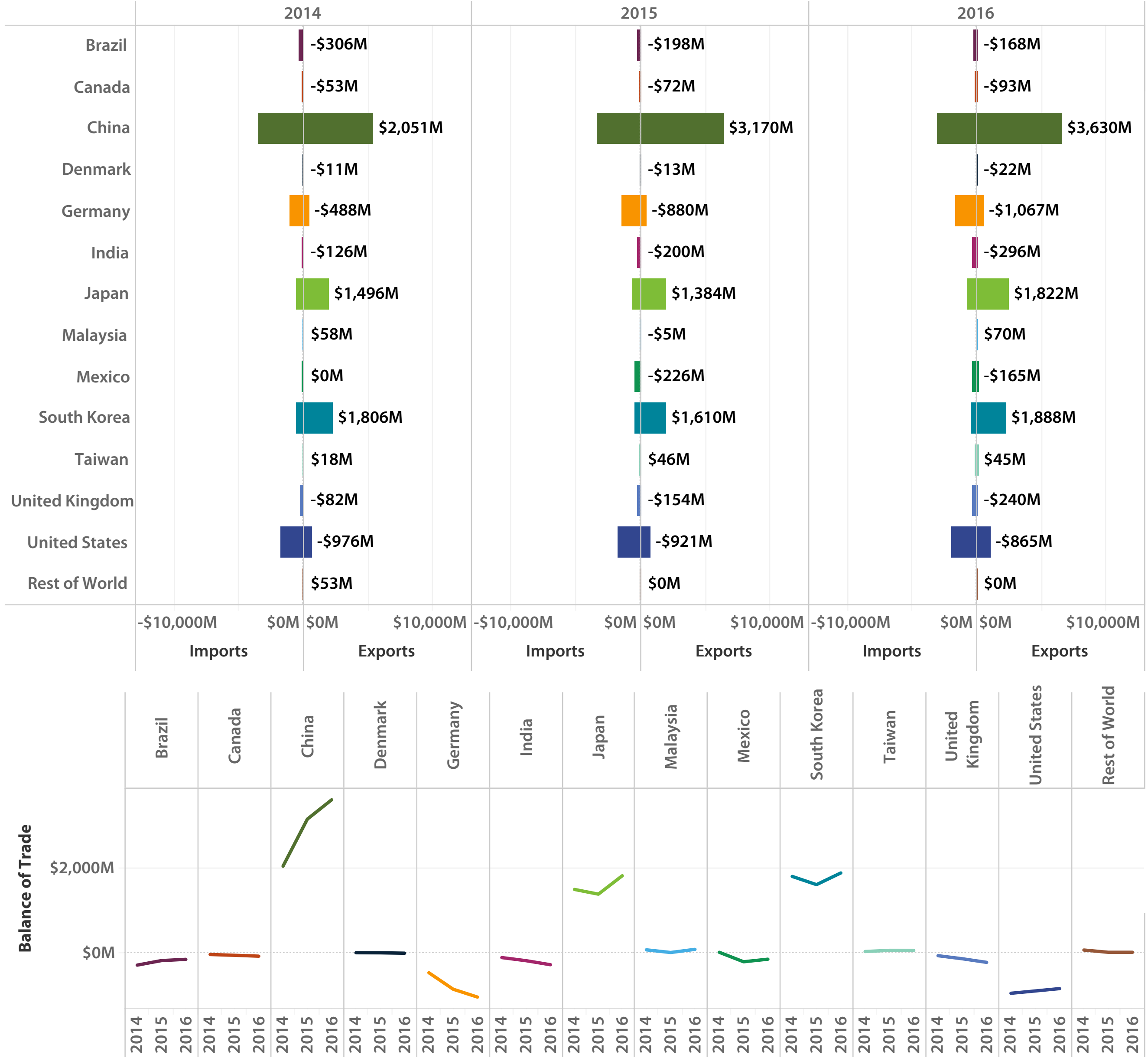
Bars show manufacturing capacity (lighter shading) and utilized manufacturing capacity (i.e., production, darker shading) in US$2014 for key LIB cell economies. Vertical lines and associated numerical values show capacity utilization (production as a % of manufacturing capacity). Trend lines show global capacity utilization percentage for 2014–2016 (bottom). Note that LIB cells are displayed on a different scale than the LIB intermediates. Where “0%” is noted next to a vertical line, manufacturing capacity was available but no production occurred; where no percentage is noted, no manufacturing capacity was available.

Global manufacturing capacity increased for all LIB cell intermediates over the period. In addition, there was generally an excess of manufacturing capacity relative to global demand for all LIB intermediates in 2016, indicating the potential to expand future production as demand increases. Globally, capacity utilization generally increased for LIB cell intermediates and declined for LIB cells over the period.

Global manufacturing capacity for LIB cells was estimated at 23.5 GWh in 2014, 101.5 GWh in 2015 and 110.9 GWh in 2016. Corresponding production was estimated at 9.6 GWh in 2014, 20.4 GWh in 2015, and 31.2 GWh in 2016, reflecting a global excess of manufacturing capacity. Between 2014 and 2016, China, Japan, and South Korea were home to the majority of global manufacturing capacity for LIB cells and intermediates (cathodes, anodes, electrolytes, and separators). In 2016, the United States hosted 10% of global LIB cell manufacturing capacity but was not a significant manufacturer of intermediates. While capacity utilization generally increased for the LIB cell intermediates, capacity utilization for LIB cells dipped significantly (dropping from 41% in 2014 to 20% in 2015, and then increasing to 28% in 2016) over the period, driven by rapid expansion of manufacturing capacity in anticipation of future increased demand.

Benchmark Data: Trade Trends

LIB cell (for all applications) trade, 2014–2016



Bar chart (top) shows imports (negative values) and exports (positive values) and balance of trade (exports less imports) in US$(2014) by economy. Line chart (bottom) shows balance of trade trends for LIB cells over the period.

Trade of LIB cells among the benchmarked economies remained relatively stable over the period, with China, Japan, and South Korea the top exporters, leveraging their mature domestic supply chains originally developed to serve consumer electronics markets. Between 2014 and 2016, the United States and Germany remained the largest importers of LIB cells, despite increased domestic production, driven by their increased production of EVs.

In 2016, the 13 benchmarked economies exported almost $13.7 billion in LIB cells and packs, up from $11.6 billion in 2014. Imports also increased from $8.2 billion in 2014 to $9.2 billion in 2016.

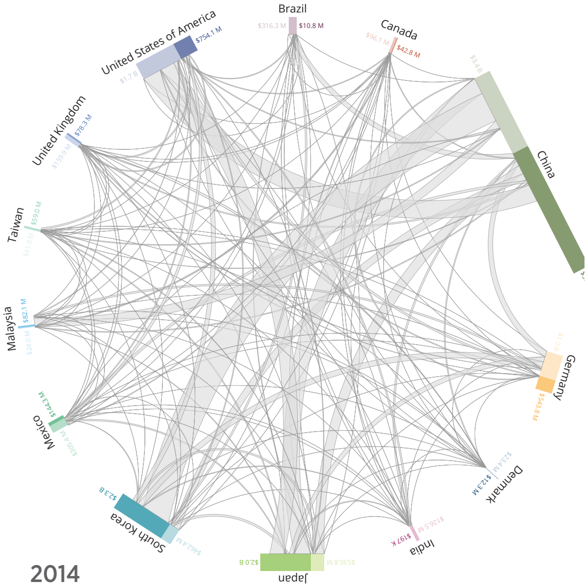
LIB cell (for all applications) trade flow, 2014-2016

Trade flow data suggest growing global trade of LIB cells among the economies over the period, generally following expected flows given the distribution of manufacturing capacity across economies.

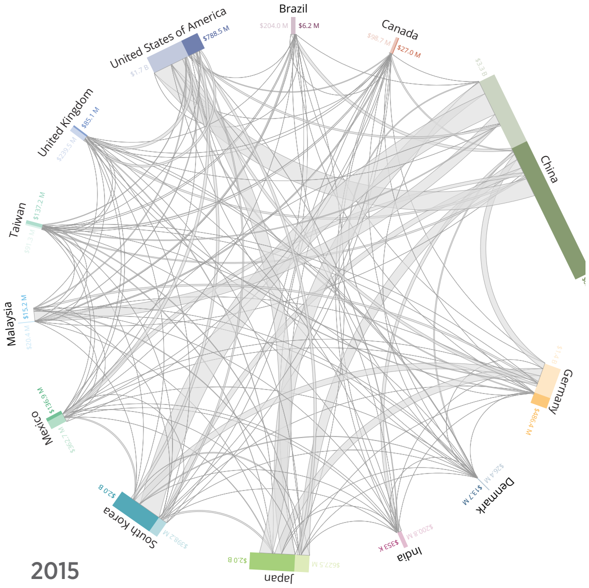
China's well-established vertical supply chains, along with increased production and manufacturing capacity to meet increasing domestic demand, helped lower the price of LIBs (in $/kWh), making China's LIB exports less expensive than those from other countries.

Japan produced more LIB cells than its domestic market demand and exported them to other countries in North America and Europe. Germany was a net importer of LIB cells, due in part to increasing demand from German automakers, in combination with relatively immature European LIB supply chains. The United States' supply chain was similarly immature, with most U.S. cell and battery plant operators relatively new to the industry.

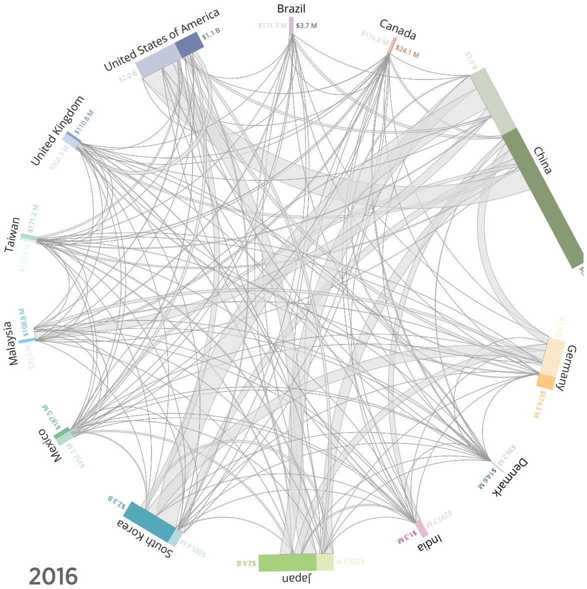
Gray chords show LIB cell trade flows in US$(2014) among benchmarked economies. Width of bars are scaled to total flows, with lighter shading showing imports and darker shading showing exports. Note that gray chords only capture the trade among the 13 benchmarked economies; trade flows with the rest of the world are not shown.



2014



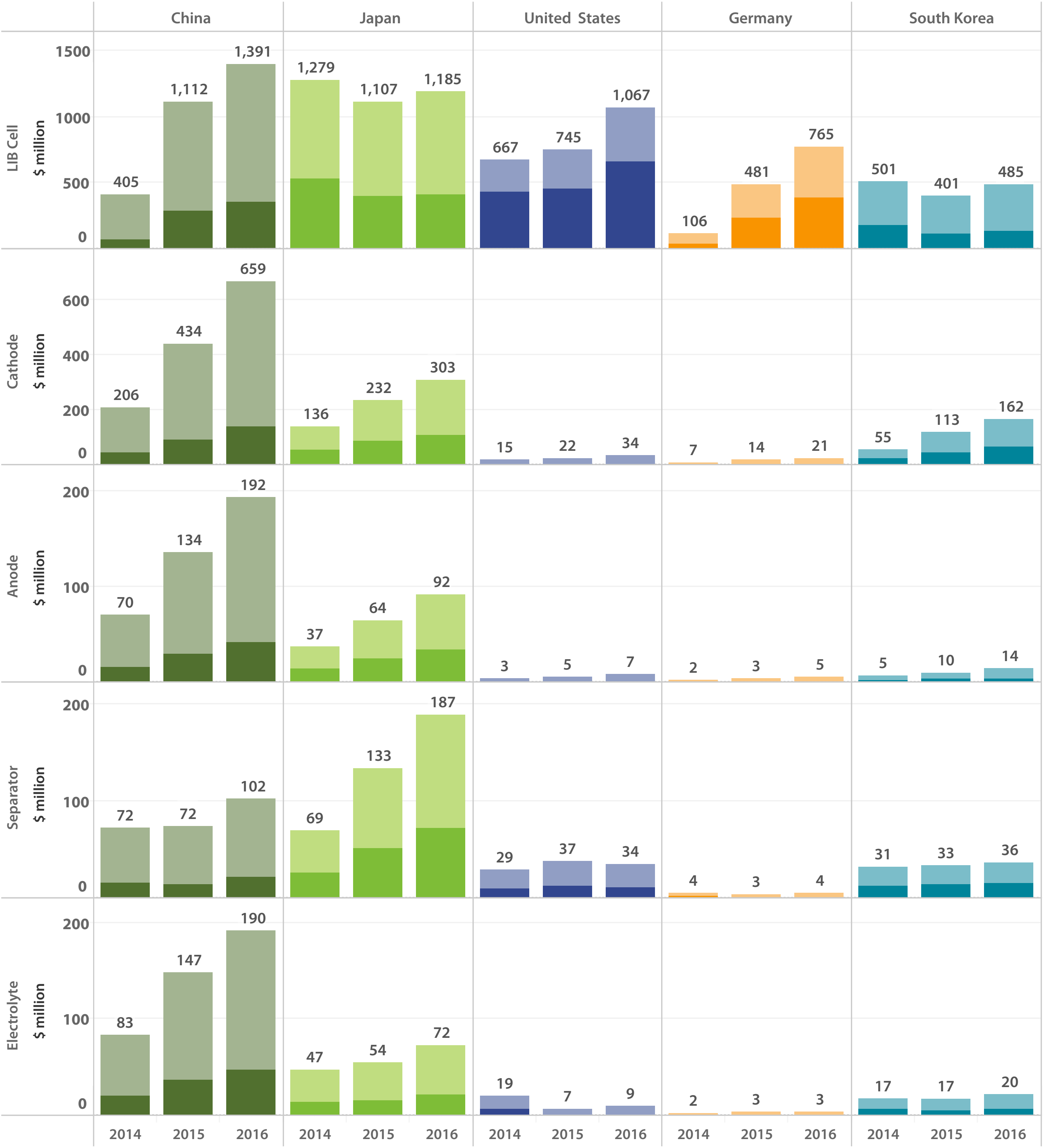
2015



2016

Benchmark Data: Value Added Trends

Automotive LIB cell supply chain total value added (tVA) by value added component, 2014–2016



Total value added (tVA) for the period in US$(2014) from manufacturing LIB cell intermediates in key LIB cell economies. Darker shading indicates direct VA (dVA), lighter shading indicates indirect VA (iVA), and numerical values show the total VA (tVA). Note that intermediates are shown on different scales. Economies are listed in order of tVA from LIB cell manufacturing in 2016.

China, Japan, and the United States accrued more total value added (tVA) from manufacturing LIB cells than the other benchmarked economies from 2014 to 2016. Supported by mature domestic supply chains, China, Japan, and South Korea accrued the highest levels of tVA from manufacturing LIB intermediates. Indirect value added (iVA) was generally greater than direct value added (dVA) for the benchmarked economies across the LIB supply chain, with the exception of U.S. production of LIB cells.

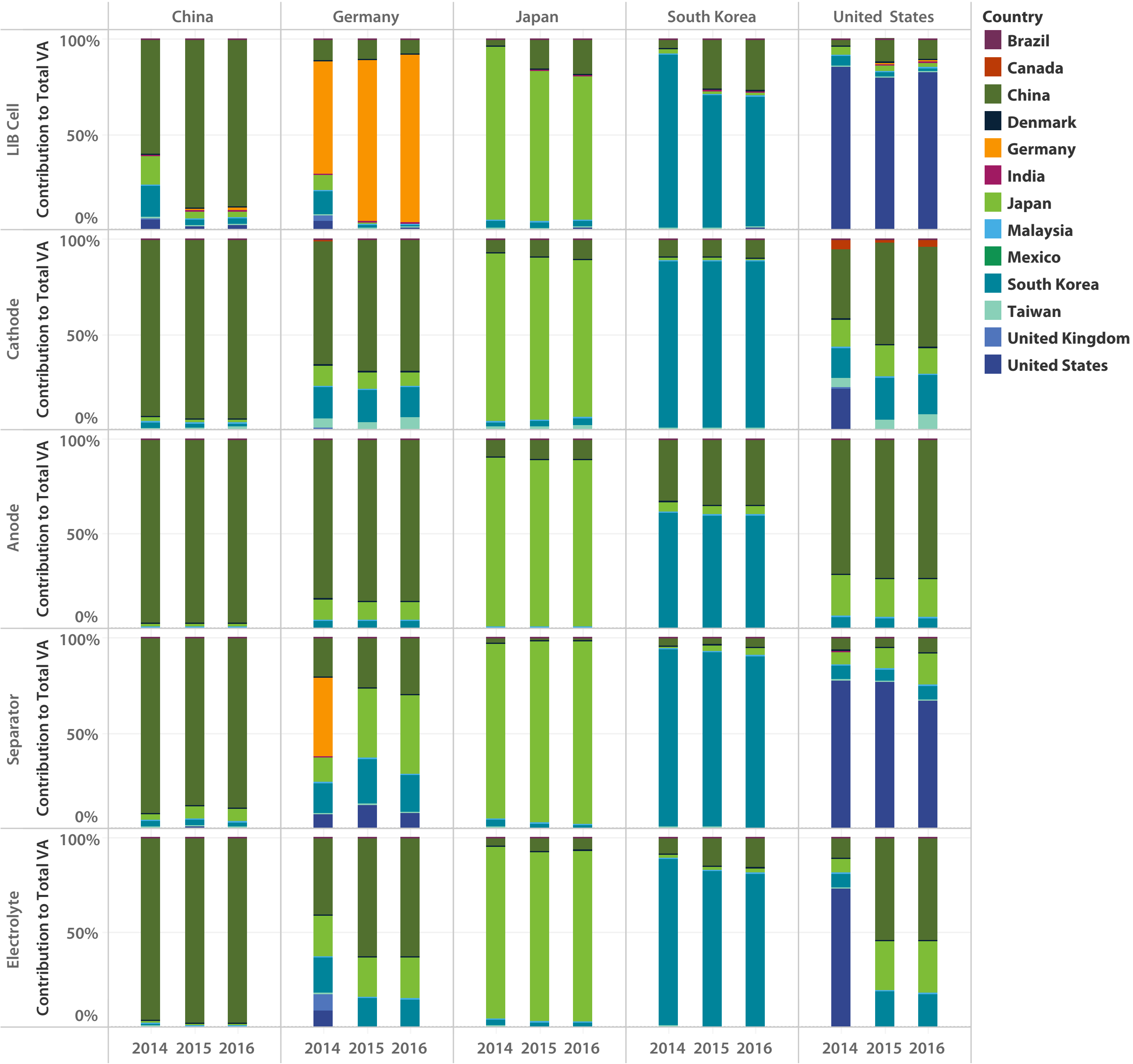
tVA is generally highest in economies with the highest levels of production revenue. In 2014, Japan showed the highest tVA from LIB cell production, but by 2016 China significantly increased LIB cell production and overtook Japan ($1.4 billion to $1.2 billion). As the third-largest LIB cell producer, the United States accrued $1.1 billion in tVA, up from $670 million in tVA in 2014, due to increased production and iVA from production in other economies.

tVA from LIB cells showed the greatest increases in Germany, China, and the United States over the period, as production ramped up to meet growing EV demand in those economies. tVA from global cathode production also increased in China, Japan, and South Korea.

iVA was higher than dVA for all LIB supply chain intermediates considered, with the exception of LIB cells for the United States, indicating that participation in the broader supply chain that supports global LIB manufacturing domestically and internationally was more important to the benchmarked economies than domestic production of the intermediates (anodes, cathodes, separators, electrolyte) and end products (LIB cells).

Benchmarked economies retained varying shares of tVA as a portion of manufacturing revenue (i.e., VA retained) over the period from manufacturing LIB cells and intermediates. VA retained was highest in economies the United States, Germany and Japan. The United States' VA retained for LIB cell production (65%) was higher than the other economies, while China's was the least (15%). VA retained reflects the extent of domestic supply chains as well as prevailing wages, domestic profits, and taxes less subsidies.

Automotive LIB cell supply chain total value added (tVA) domestic and non-domestic contribution, 2014–2016



For each economy (listed across the top) color-coded bars show the share of tVA accrued from domestic and non-domestic production of LiB cell supply chain intermediates for 2014 to 2016. Domestic bars (generally the largest in each bar) represent the share of tVA (dVA + iVA) from domestic production. Non-domestic bars represent the share of tVA (iVA only) from production in other economies (dVA only occurs in the economy where production occurs).

In general, the benchmarked economies received the greatest portion of tVA from domestic production of LIB cells over the period. Production in China, followed by Japan and South Korea, had the most impact on the other benchmarked economies through iVA across the LIB cell supply chain.

The United States and Germany accrued iVA over the period from the manufacturing of LIB cells in China, Japan, and South benefitting from the global supply chains that connect the economies.

Raw Materials in the Manufacturing Supply Chain

The CEMAC benchmark framework presents raw materials as the first link in the clean energy manufacturing supply chain. This link is intended to capture the value added from mining and processing to refining stages in manufacturing clean energy technologies.

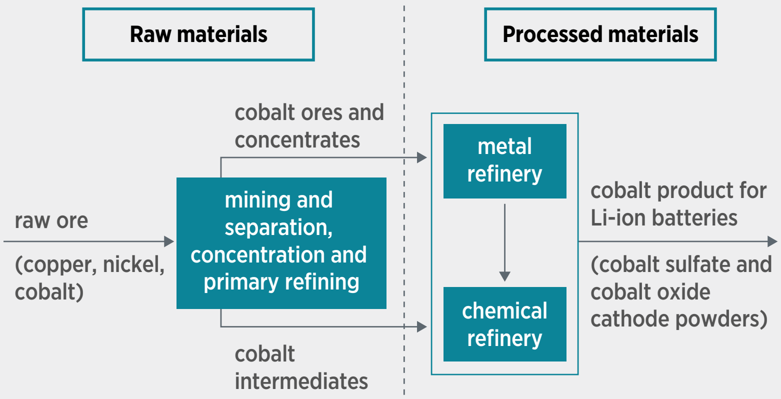
While information about final manufactured products is generally available, upstream data for raw materials are often difficult to gather, track, and analyze. Finding data at the level of detail required for robust analysis remains a challenge. Disaggregating trade and market data to estimate the contribution to a specific technology can be difficult for any industry. The challenge is even greater with clean energy technologies that account for a very small, albeit growing, fraction of the market. At the same time, benchmarking raw materials data has the potential to provide a broader view of economies' accrual of value added from clean energy technology manufacturing, along with additional insight into potential supply chain risks and opportunities.

To more effectively explore this important supply chain link, the following analysis examines raw materials used to manufacture cathode sheets for EV LIB cells (Igogo et al. 2019).

Some of the key raw materials used in manufacturing LIBs include lithium, graphite, cobalt, and manganese. These materials are used to manufacture a range of products, from LIBs for consumer electronics and vehicles to superalloys, hard metals, ceramics, and polymers.

As more EVs with LIBs are deployed, these vehicles are driving demand for materials used in LIB cells. Understanding these materials' markets is critical to comprehending the impact of continued EV deployment on mineral production and vice versa. The following case study applies CEMAC benchmark methodologies to assess cobalt as a raw material for LIB cells between 2014 and 2016.

Cobalt supply chain supporting lib manufacturing



The cobalt supply chain encompasses mining, ore processing to produce concentrates and intermediates, and metal and chemical refining to extract precursor materials.

At a high level, the cobalt supply chain encompasses mining (which includes both large-scale and small-scale (artisanal) mining operations), ore processing to produce concentrates and intermediates, and metal and chemical refining to extract precursor materials.[23] Battery-grade precursors are then used by cathode active material manufacturers to produce cathode sheets for LIB cells.

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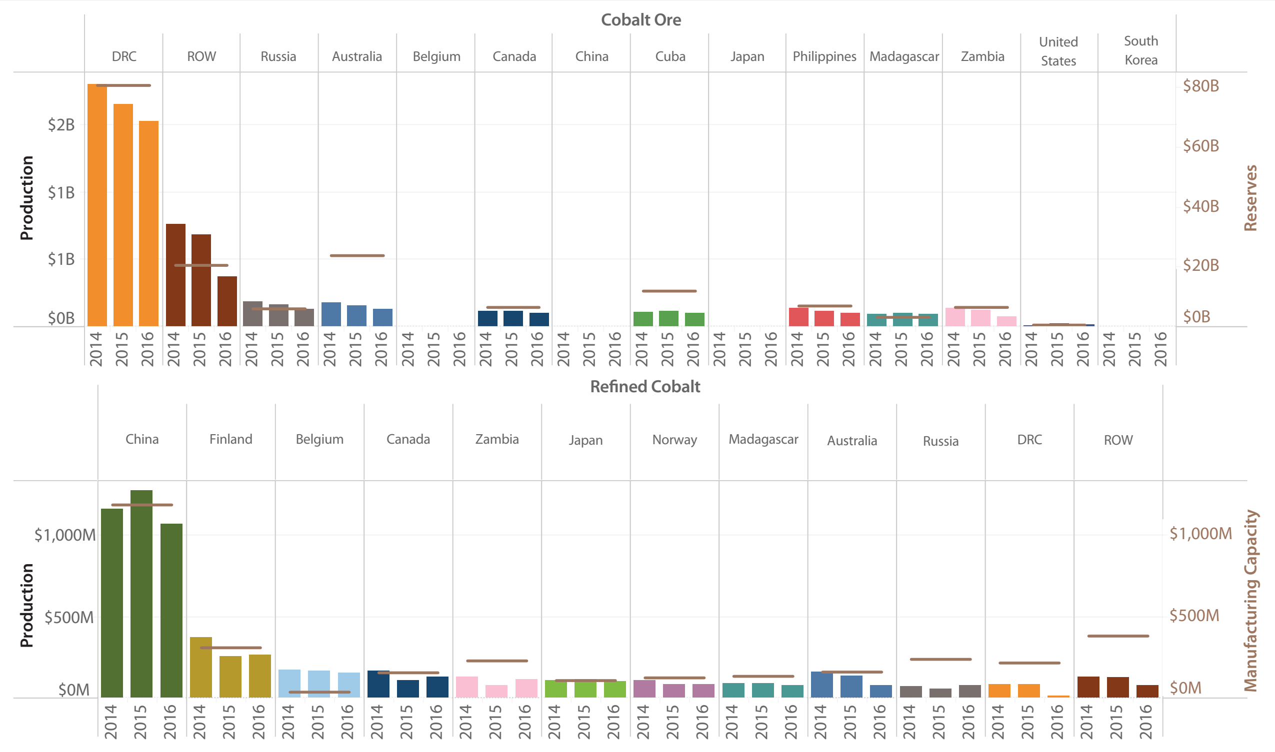
[23] With nickel-cobalt or copper-cobalt ore and concentrates, the main goal is to extract nickel or copper; thus, these concentrates are likely to end up at metal refineries rather than chemical refineries. Metal scraps are likely to be processed to produce metal first, while recycled batteries are likely to be directly converted into cobalt chemicals.

Benchmark Data: Market Trends

Cobalt reserves and mines production, 2014–2016



Cobalt ore production (colored bars) and reserves (brown lines) with data shown on different scales (top). Refined cobalt production (colored bars) and manufacturing capacity (brown lines) with data shown on different scales (bottom). All data are in US$(2014). Note that cobalt ore reserves are much greater than production amounts. Note that the data show that refined cobalt production output from Belgium was greater than manufacturing capacity due to lack of inclusion of Belgium's refinery capacity that is located in China and refined cobalt that is recovered from UMICORE's recycling operations (USGS 2018: Cobalt Institute 2018; NREL estimates).

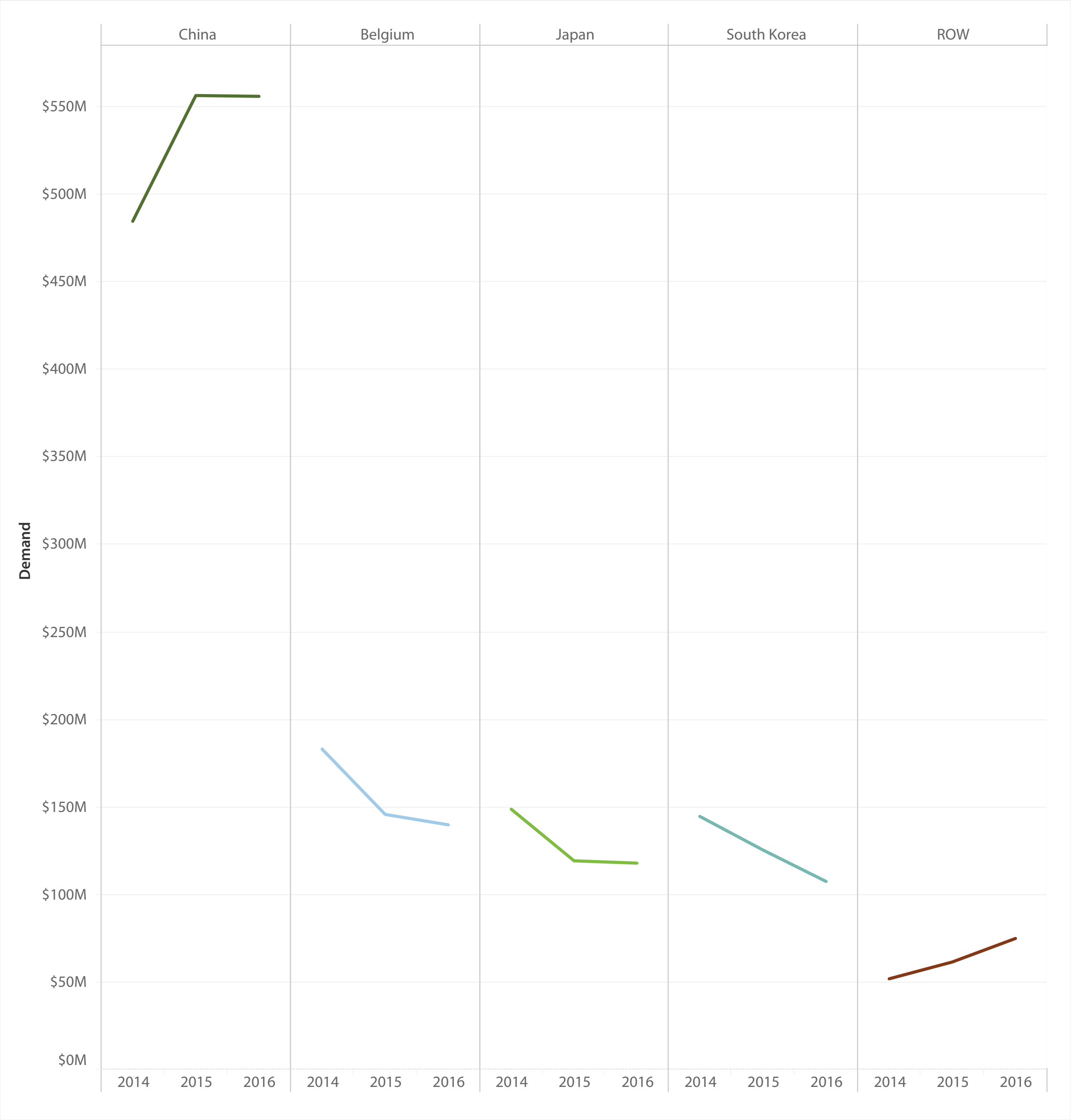
Sources: USGS 2018; NREL estimates

Cobalt is usually mined as either a by-product of copper (67%) or nickel (32%), with just 1% of production from mines that are dedicated to cobalt extraction. Most cobalt deposits are in the Central African Copperbelt, which includes the Democratic Republic of the Congo (DRC), Central African Republic, and Zambia. In 2016, the United States Geological Survey estimated global cobalt reserves at about 7 million metric tons (MT).

The DRC led all suppliers with a global production share of 53% from 2014 to 2016. Overall global cobalt production decreased by 7% from 119,000 metric tons in 2014 to 111,000 metric tons in 2016 (USGS 2018). The decrease was in part due to declining prices of copper and nickel, which were impacted by oversupply and economic slowdown in economies such as China (Shumsky 2015; Miller 2016; Burns 2016; IMF 2016; World Bank n.d.).

The majority of the DRC's active mines are owned by Chinese companies (Darton Commodities 2018) to support China's large domestic cobalt refining capacity, which accounted for about 47% of global refined cobalt production over the period. Global excess manufacturing capacity (i.e., refining capacity) was about 37,000 metric tons in 2016, indicating that production could be expanded to meet additional demand without bringing new refineries online.

Cobalt demand to support EV LIB cathode production, 2014–2016



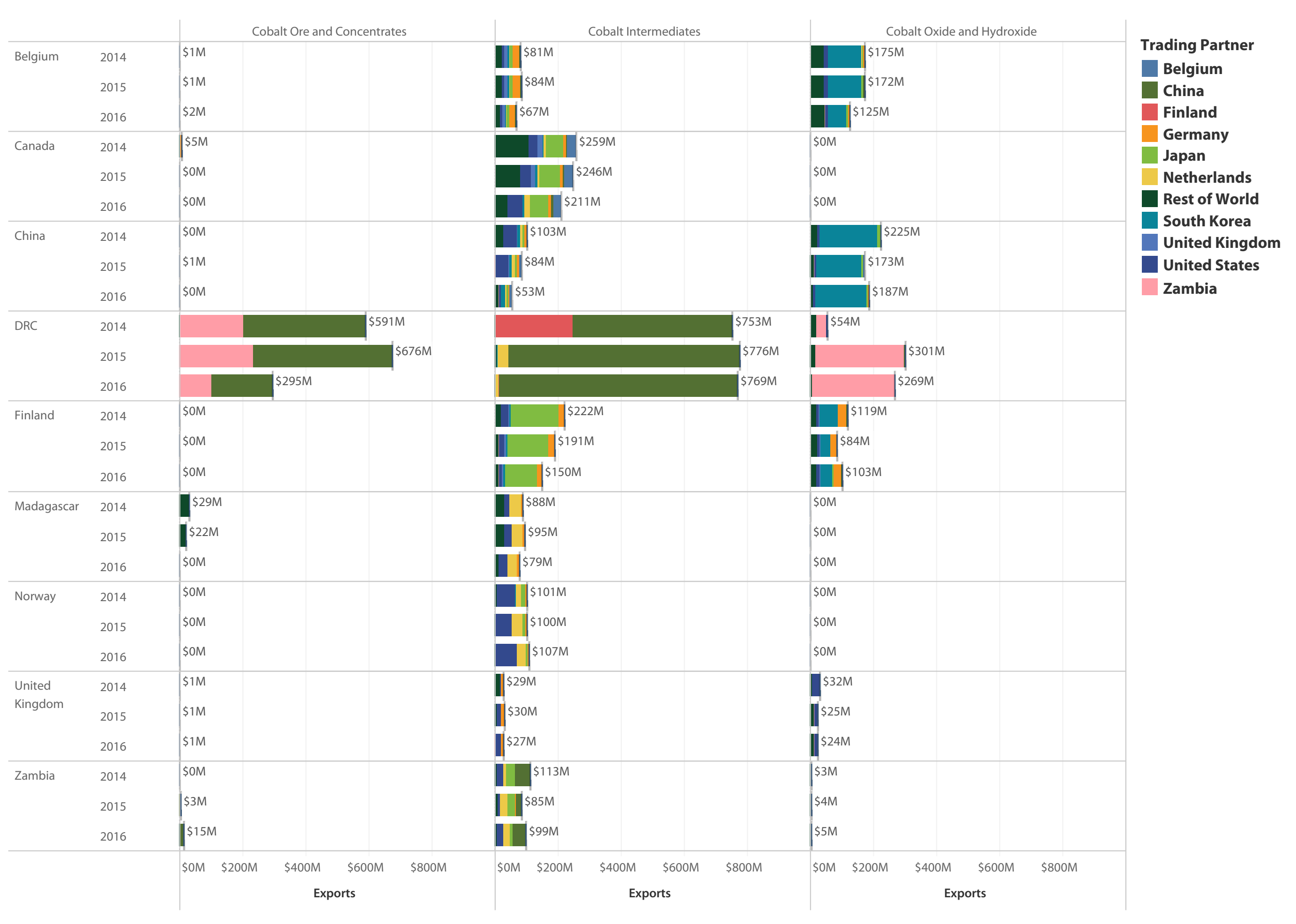
Cobalt demand for economies manufacturing cathode materials for EV LIB cells. All data are in US$(2014).

Source: NREL estimate

Global sales of EVs grew by 133% from 323,000 vehicles in 2014 to 753,000 vehicles in 2016 (IEA 2017), driving a sharp increase in demand for LIBs from 9.6 GWh to 31.1 GWh (Pillot 2017; BNEF 2017d). During the same period, the proportion of cobalt used globally in EV LIB cells surged from 1.4% to 5% of total mine production. China remained the largest consumer of cobalt used to manufacture EV LIBs.

Benchmark Data: Trade Trends

Cobalt material exports, 2014–2016



Bars show exports from country listed on left to countries as color coded for three categories of materials: cobalt ores and concentrates (HS-260500); cobalt oxides, hydroxides, commercial cobalt oxides (HS-282200), and cobalt mattes; and other intermediate products of cobalt metallurgy including unwrought cobalt and powders (HS-810520).

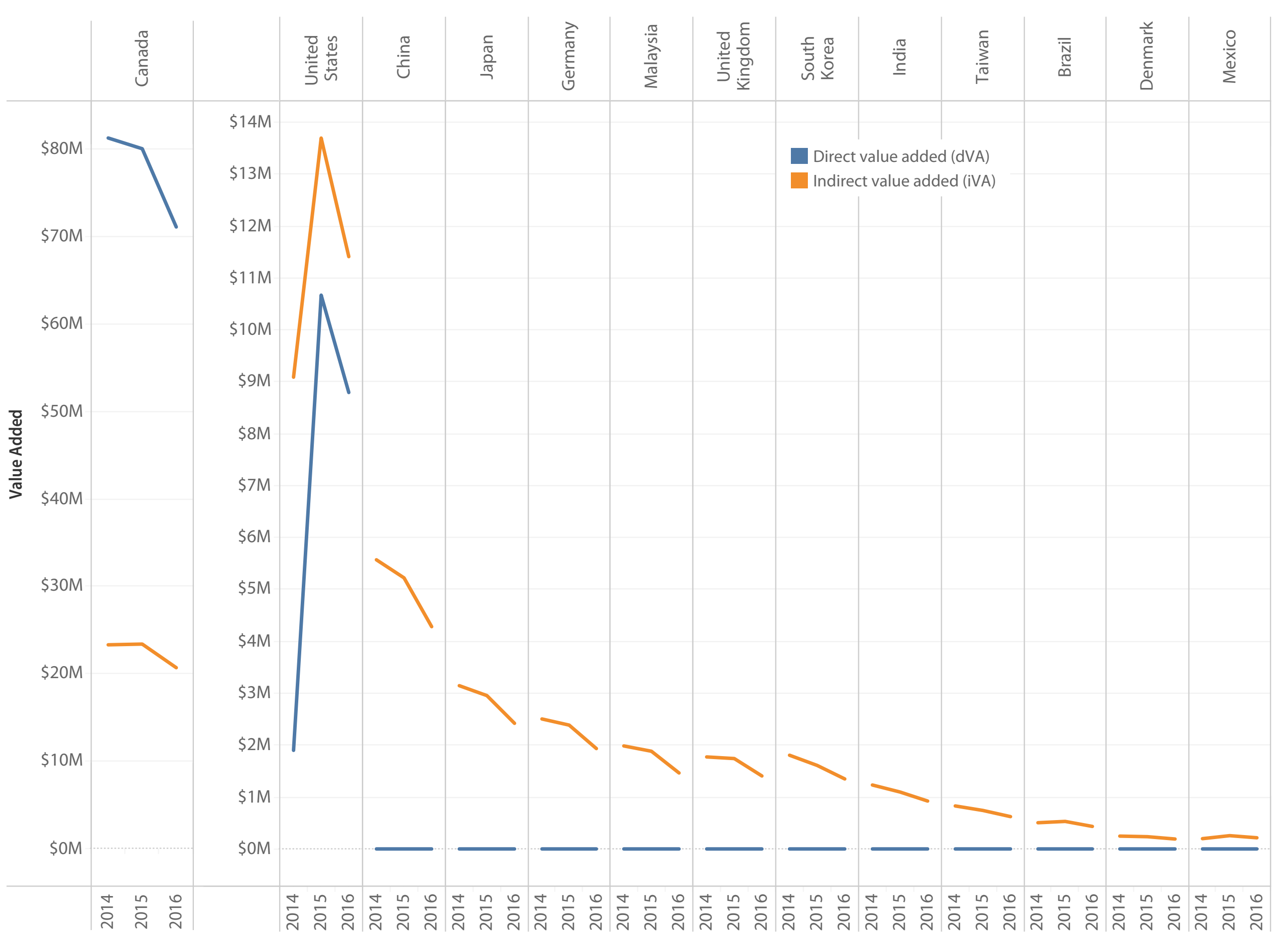
Sources: UN-Comtrade n.d.; Trademap n.d.; NREL estimates

Globally traded cobalt materials include ores and concentrates; intermediate products of cobalt metallurgy, unwrought cobalt, and powders; and oxides and hydroxides. The DRC was the leading exporter of cobalt materials, while China was the leading importer. From 2014 to 2016, the DRC exported a total of $4.5 billion worth of cobalt materials, primarily to China and Zambia. During the same period, China imported a total of $3.0 billion worth of cobalt materials, almost entirely from the DRC.

Most economies in this period experienced a slight decrease in exports and imports of cobalt, consistent with the economic slowdown in emerging markets and an associated decline in metal prices. The DRC experienced a substantial drop in exports relative to other economies, with exports decreasing by 31% from $1.8 billion in 2015 to $1.3 billion in 2016

Benchmark Data: Value Added Trends

Cobalt mining total value added (tVA), 2014–2016



Blue lines indicate dVA and orange lines indicate iVA for cobalt mining. All data are in US$(2014). Economies are listed in order of tVA from cobalt mining in 2016. Note that Canada is on a different scale.

Only two of the benchmarked economies—Canada and the United States—accrue dVA from domestic cobalt mining. However, the 13 benchmarked economies all accrue some iVA from cobalt mining in Russia, Australia, Philippines, Canada, and the United States. tVA from cobalt mining in Canada declined to $91.8 million in 2016, down from $104.6 million in 2014.

tVA in the United States increased from $11.0 million in 2014 to $20.2 million in 2016. Almost half of the tVA in the United States came from domestic cobalt mining, with $8.8 million in dVA accrued in 2016.

Based on the available data[24], tVA from cobalt mining within the benchmarked economies was significantly smaller than tVA from manufacture of LIB cells, cathodes, anodes, and electrolytes. In 2016, tVA accrued by the five economies for which there are data (Canada, the United States, Russia, Australia, and the Philippines) from cobalt mining was $127 million, while tVA from the finished product (cells) was $5.3 billion.

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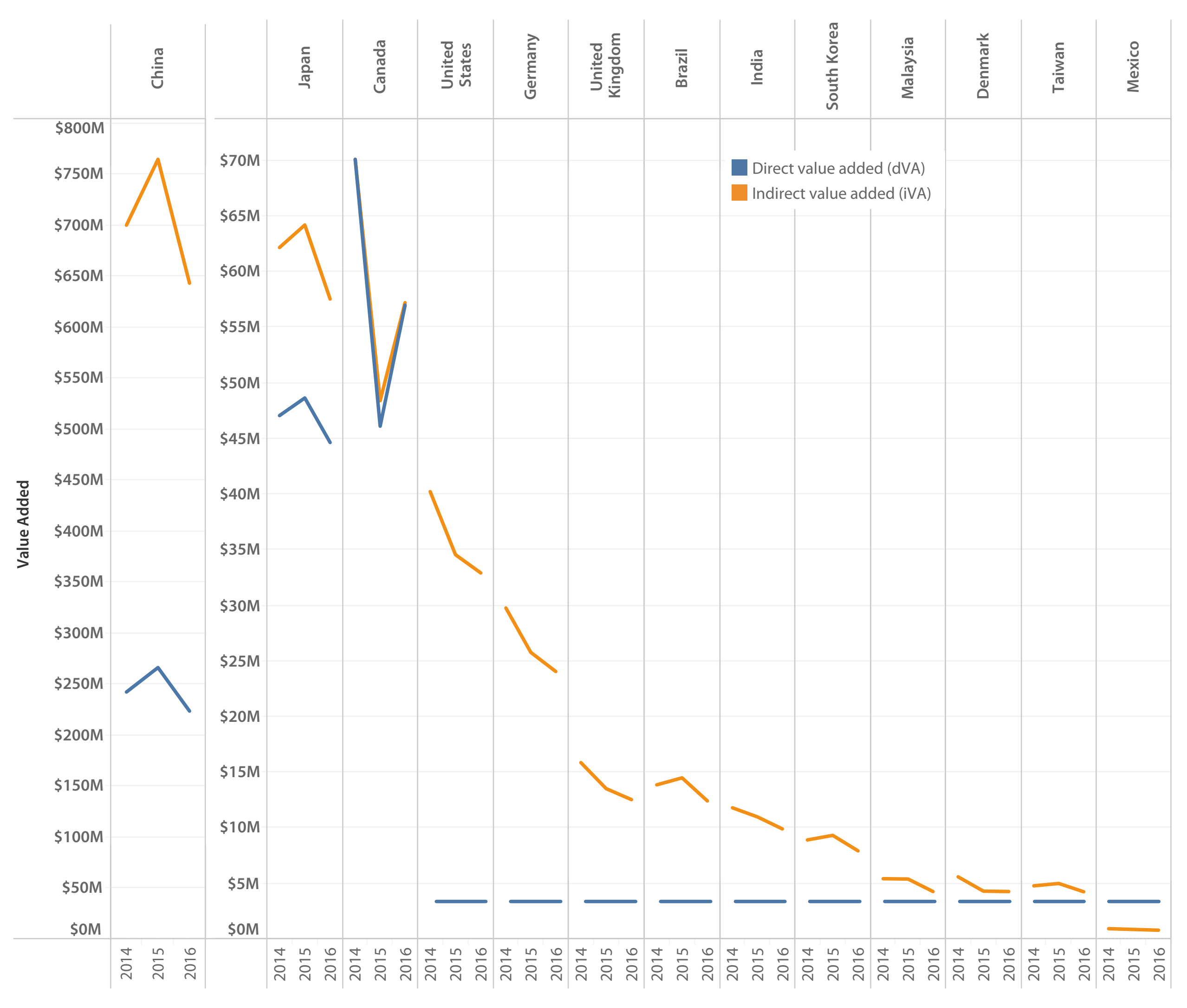
[24] This analysis is limited due to the fact that the Organization for Economic Co-operation and Development (OECD) Structural Analysis (STAN) Input-Output (I-O) database used to estimate tVA does not include the world's largest producer—the DRC—nor Cuba, Madagascar, or Zambia.

Cobalt refining total value added (tVA), 2014–2016



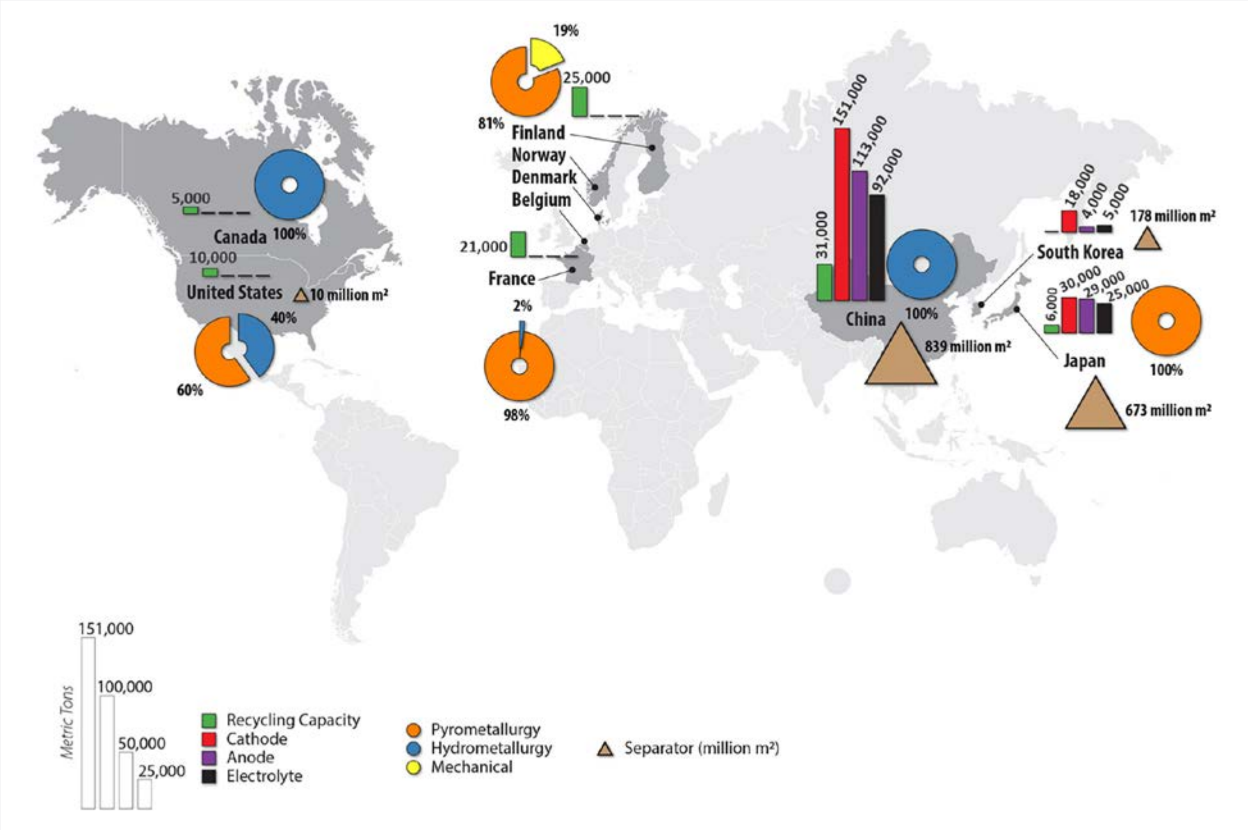
Blue lines indicate dVA and orange lines indicate iVA for cobalt refining. All data are in US$(2014). Economies are listed in order of tVA from cobalt mining in 2016. Note that China is on a different scale.

Three of the benchmarked economies—China, Japan, and Canada—accrued dVA from domestic cobalt refining. In addition, all 13 benchmarked economies accrued some iVA from cobalt refining in Australia, Belgium, Finland, Norway, Canada, China, and Japan. tVA attributed to cobalt refining was greater than from other intermediates in the LIB raw material supply chain: $1.2 billion in 2016, down from $1.3 billion in 2014.

China, as the primary cobalt refiner, accrued the highest tVA, with $940 billion in 2014, $1.0 billion in 2015, and $870 million in 2016. tVA in the United States declined from $40.2 million in 2014 to $32.9 million in 2016. As the United States did not refine cobalt during the period, this drop was entirely due to changes in other countries' production levels.

LIB Challenges and Opportunities: Recycling Critical Materials

Global li-ion battery recycling capacity, 2016



Bars show estimated global electrochemical storage batteries (except for lead acid batteries) recycling capacities (MT) and cathode, anode, and electrolyte production capacity for virgin materials (MT) in 2016. Donut charts show the percentage of recycling capacity used for each recycling method (pyrometallurgy, hydrometallurgy, or mechanical separation). Triangles show separator production capacity (sq. meters) in 2016.

Source: Mayyas, Steward, and Mann 2019

As production of clean energy technologies expands to meet increasing demand, the opportunities to reuse and recycle components and raw materials used in these technologies have grown in scale and importance. LIB cells for LDVs present one such opportunity, as the early generations of these batteries begin to reach the end of their lifespans.

Demand for LIBs continues to increase in response to the growing demand for EVs. The global demand for LIB cathode material exceeded 180,000 metric tons in 2016 (Avicenne Energy 2017). Some scarce critical elements used in LIBs, namely cobalt and lithium, are mined and/or processed in only a few countries where trade policies or geopolitics could limit availability and create instabilities in market prices, which could discourage further expansion of the market for EVs and other products that rely on LIBs.

Closed-loop systems with end-of-life recycling not only diminish environmental impacts from disposed batteries, but also provide sources of high-value materials that can be recovered and reused to produce new batteries at potentially lower costs.

In 2016, as shown above, world battery recycling capacity exceeded 98,000 metric tons (Mayyas, Steward, and Mann 2019), including all types of electrochemical storage batteries, except for lead-acid batteries (the ones most commonly used in traditional internal combustion engine vehicles). Three technologies are used alone or in combination for recycling LIBs: pyrometallurgy, hydrometallurgy, and mechanical processes such as cryomilling (Ordoñez, Gago, and Girard 2016; Ellis and Mirza n.d.). Currently these technologies focus on recycling the high-value cobalt (Co), lithium (Li), and nickel (Ni) cathode materials, ignoring anodes and other pack components.

Environmental regulations regarding LIBs differ from one region to another. China hosted 32% of the world's battery recycling capacity in 2016, and this capacity is expected to grow significantly in the near-term (Dai 2018).[25] After establishing end-of-life policies and regulations for vehicles in 2001 (Wang and Chen 2013), China more recently issued "interim" rules requiring automakers to collect and recycle the retired LIBs from electric vehicles (Wang and Chen 2013). Japan (METI 2006), Korea (ChemSafetyPro 2007), and the European Union (European Parliament 2000) also have policies for dealing with end-of-life vehicle components, including batteries.

The primary challenges for LIB recycling in the near term in many countries, including the United States, are the lack of viable collection mechanisms, low collection volumes, and insufficient economic information to inform investors on long-term costs and benefits. All these factors have resulted in a lower LIB recycling volume compared to that for recycled lead-acid and nickel-metal hydride (NiMH) batteries (Steward, Mayyas, and Mann 2018).

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[25] Tom Daly, "Chinese Carmaker BYD Close to Completing Battery Recycling Plant," *Reuters*, March 21, 2018, https://www.reuters.com/article/uschina-byd-batteries-recycling/chinese-carmaker-byd-close-to-completing-batteryrecycling-plant-idUSKBN1GX1EZ.

Glossary

Clean Energy Technologies: Technologies that produce energy with fewer environmental impacts than conventional technologies, or enable existing technologies to operate more efficiently, consuming fewer natural resources to deliver energy services. Clean energy technologies may include renewable energy, clean non-renewable energy, and energy efficiency technologies for electricity generation, fuel production, and sustainable transportation.

Clean Energy Technology End Product: The finished product of the manufacturing process, assembled from subcomponents, and ready for sale to customers as a completed item. Clean energy examples include photovoltaic (PV) modules and lithium-ion battery (LIB) cells. In this link of the supply chain, value added comes from assembling subcomponents into a marketable product that customers value.

Clean Energy Technology Manufacturing: Manufacturing of clean energy end products (renewable energy, sustainable transportation, and energy efficiency technologies) and their associated supply chains, as well as activities to improve manufacturing of all products by increasing energy productivity and using low-cost domestic fuels and feedstocks in the production process.

Direct Value Added (dVA): Value added from the output of the sector in question, accrued solely from the domestic manufacturers of a product. For example, if solar PV module manufacturing generated $100 million in production revenue with 70% of that associated with intermediate inputs, dVA would consist of the remaining $30 million.

Indirect Value Added (iVA): Value added that is supported by the intermediate expenditures made by the sector in question. The indirect VA (iVA), sometimes referred to as "the economic ripple effect," comes from the greater supply chain that provides domestic inputs used by manufacturers (domestic iVA), and from goods and services exported to support manufacturing that takes place in other economies (non-domestic iVA). This is a comprehensive figure that captures all supply chain activity (domestic and international) needed to support the output of the sector in question within the economy in question. The non-domestic (intercountry) iVA indicates the globalization and interconnectedness of benchmarked economies with respect to clean energy manufacturing supply chains, and the domestic iVA indicates the strength of domestic supply chains.

Manufacturing Capacity: Amount of product in physical units that can be produced in a given period by existing physical plant and other necessary infrastructure (e.g., megawatts of PV modules per year). Production is the physical amount of a product actually produced in a given period. Manufacturing capacity and production are measures that reflect supply. Capacity and production, in combination with market size and growth, are the basic metrics used in assessing the supply, demand, and trade flow dynamics occurring within an industry.

Manufacturing Supply Chain: A complex and dynamic supply and demand network consisting of an integrated system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities involve the procurement of transformation, and logistics of, raw materials, and components into a finished product that is delivered to the end customer.

Manufacturing Value Chain: The value created in each step of the supply chain though the key activities that companies perform to bring a product from conception to end use. Value chain activities can produce goods or services, include a single company or span multiple companies, and occur within a single geographical location or are spread across economies. While the supply chain tracks the flows of raw materials and intermediate products to customers (upstream to downstream), the value chain tracks the demand and cash flows from customers to companies (downstream to upstream).

Market Size: Estimate of the demand for a specific product or service within an economy, typically expressed in units of product volume (e.g., megawatts of PV modules) and in terms of monetary value (e.g., US$). The latter expression of market size accounts for both demand volumes and selling prices. Market size serves as a core metric of demand development and growth over time, and it is a key measure of the relative importance of an industry within an economy and globally.

Processed Materials: Materials that have been transformed or refined from basic raw materials as an intermediate step in the manufacturing process. Processed materials include steel, glass, and cement. In this link of the supply chain, value added comes from processing raw materials into precursors that can be more easily transported, stored, and used for downstream subcomponent fabrication.

Raw Materials: Basic materials mined, extracted, or harvested from the earth. Also referred to as "unprocessed material," examples include raw biomass and iron ore. In this link of the supply chain, value added comes from extracting, harvesting, and preparing raw materials for international marketing in substantial volumes.

Subcomponents: Unique constituent parts or elements that contribute to a finished product. Clean energy technology examples include generation sets for wind turbines and crystalline silicon wafers for crystalline silicon PV modules. Note that what is considered a component by the manufacturer may be considered the finished product by its supplier. In this link of the supply chain, value added comes from fabricating processed materials into subcomponents that can then be assembled (with other subcomponents) into end products.

Total Value Added (tVA): Total value added is the sum of indirect and direct value added.

Trade: The buying and selling of goods and services between economies. Trade measures include the balance of trade in terms of the amount of goods that one economy sells to other economies (exports) minus the amount of goods that same economy buys from other economies (imports).

Trade Flows: As applied in this report, identifies the trade between specific economies for specific intermediates and the end product in a supply chain.

Value Added (VA): The contribution from an industry or government sector to overall GDP. VA consists of labor payments, gross operating surplus, and taxes, and can be a measure of GDP. Labor payments include all payments to workers, including benefits. Gross operating surplus is a property-type income that includes payments for capital (including depreciation) and payments to investors and includes profits. Taxes are net payments to or from the government with subsidies potentially resulting in negative tax amounts.

Value Added Retained: A measure of an industry's contribution to GDP per unit of production revenue. Value added retained is calculated by dividing manufacturing VA by production revenue. High wages and larger economies tend to retain higher levels of VA, as more inputs can be sourced domestically, and workers are paid higher wages.

Wind Generator Sets (Gensets): Assembled nacelles shipped with blades.

List of Acronyms and Abbreviations

ANL	Argonne National Laboratory
ASP	average selling price
BNEF	Bloomberg New Energy Finance
BOS	balance of system
BOT	balance of trade
CEMAC	Clean Energy Manufacturing Analysis Center
c-Si	crystalline silicon
DOE	U.S. Department of Energy
DRC	Democratic Republic of the Congo
dVA	direct value added
GDP	gross domestic product
GW	gigawatt
GWh	gigawatt hour
I-O	input-output
iVA	indirect value added
kWh	kilowatt hour
LCOE	levelized cost of electricity
LDV	light-duty vehicle
LED	light-emitting diode
LIB	lithium-ion battery
M	million
MT	metric tons
MW	megawatts
NiMH	nickel-metal hydride
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Cooperation and Development
poly-Si	polysilicon
PV	photovoltaic
ROW	the rest of the world
tVA	total value added
USITC	U.S. International Trade Commission
VA	value added

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Appendix

Crosscutting

Additional Benchmark Data: Trade Trends—Impact of Currency Rate Fluctuations

Exchange Rates for Benchmarked Economies Relative to the U.S. Dollar, 2012–2017

Economy	Currency	2012	2013	2014	2015	2016	2017
Brazil	Brazilian real	1.95	2.16	2.35	3.34	3.48	3.19
Canada	Canadian dollar	1.00	1.03	1.10	1.28	1.32	1.30
China	Chinese yuan	6.31	6.15	6.16	6.28	6.64	6.76
Denmark	Euro	1.29	1.33	1.33	1.11	1.11	1.13
Germany	Euro	0.78	0.75	0.75	0.90	0.90	0.88
India	Indian rupee	53.37	58.51	61.00	64.11	67.16	65.07
Japan	Japanese yen	79.82	97.60	105.74	121.05	108.66	112.10
Malaysia	Malaysian ringgit	3.09	3.15	3.27	3.90	4.14	4.30
Mexico	Mexican peso	13.15	12.76	13.30	15.87	18.67	18.88
Korea	South Korean won	1126.16	1094.67	1052.29	1130.96	1159.34	1129.04
Taiwan	New Taiwan dollar	29.56	29.68	30.30	31.74	32.23	30.40
UK	British pound	0.63	0.64	0.61	0.65	0.74	0.78
US	United States dollar	1.00	1.00	1.00	1.00	1.00	1.00

Annual average exchange rates expressed in units of local currency (to the left) per US dollar (nominal).

Source: Federal Reserve Bank of St. Louis n.d.

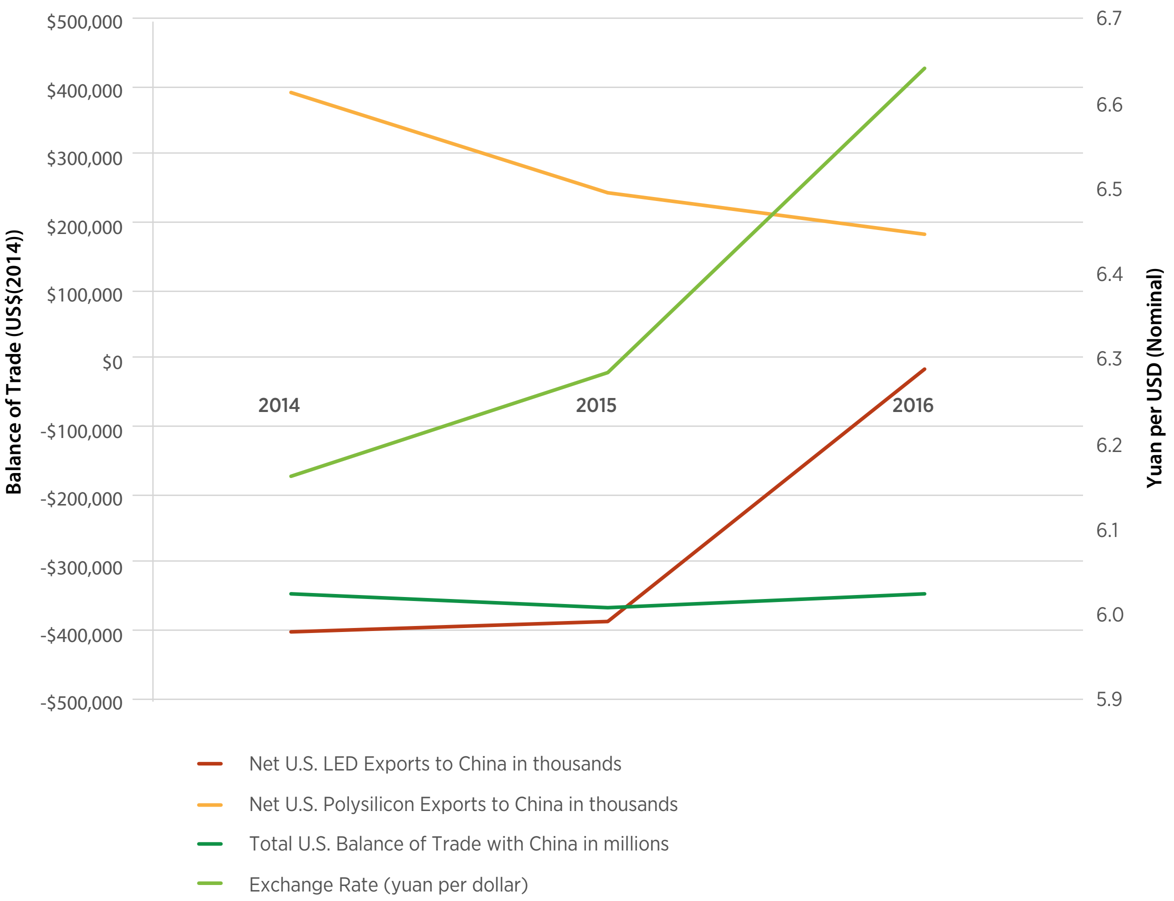
Over the period, currency rate fluctuations were relatively large, moving up and down by double digit percentage points in some cases. For example, according to a study sponsored by the International Monetary Fund, the dollar appreciated by more than 10%, while the euro and yen depreciated by more than 10% and 30%, respectively, between 2012 and 2015 (IMF 2015). Exchange rates for India, China, Taiwan, and South Korea showed the most stability over the period.

Macroeconomic theory indicates that as a currency appreciates in an economy, its exports become more expensive relative to an economy with a weaker currency and its imports become less expensive, leading to a decrease in exports and increase in imports in the economy with the stronger currency. Some studies have shown that empirical data are consistent with this theory for the economy writ large (Rose 1991). For example, Leigh et al. (2017) and Campa (2000) find that a 10% depreciation in a currency leads to a 1.5% increase in net exports; this depreciation effect on trade varies from economy to economy because the relative strength of the other currencies vary. There are economists who disagree with these findings.

While economies in aggregate reacted to currency fluctuations in these studies and several others in a statistically significant way, when disaggregated by activity (e.g., manufacturing, sales, professional services), this relationship is not necessarily maintained (Leigh et al. 2017). In addition, for products with extensive global supply chains, the cost of production can be impacted by the exchange rates of economies (i.e., those providing supply chain intermediates) that are not direct trading partners, reducing the influence of exchange rate changes on trade flows (Leigh et al. 2017). Trade agreements, tariffs, and preferences of importers (such as preferring a specific brand or economy of origin) can impact demand, product quality or availability, and government subsidies. Any number of nonmonetary factors can also impact imports and exports of specific commodities.

For these reasons, estimating the impact of currency rate variability on imports and exports of the four clean energy technologies is challenging. In addition, in total the four technologies represent just a small fraction of total trade in the benchmarked economies and each clean energy technology represents a different industry within the manufacturing sector, supported by its own global supply chain. The figure below illustrates the difficulty of attributing trade trends for a specific product to changes in currency rates.

Exchange rate and balance of trade, United States with China, 2014–2016



Annual average exchange rate (lime green line) in yuan per U.S. dollar (nominal). U.S. Total BOT with China (green line) in US$(2014) millions. U.S. LED package BOT with China (red line) in US$(2014) thousands. U.S. Polysilicon (poly-Si) BOT with China (yellow line) in US$(2014) thousands.

The figure compares the balance of trade between the United States and China for two different commodities—LED chips and packages, and polysilicon—and exchange rate trends between 2014 and 2016. As the U.S. dollar became more expensive for Chinese importers, the total U.S. balance of trade declined. Over the period, polysilicon (poly-Si) net exports from the United States declined, yet LED net exports increased, suggesting that currency rate fluctuation is not the only driver affecting trade. For example, in this period, polysilicon trade was also impacted by Chinese tariffs on polysilicon imports from the United States.

Wind Turbines

Manufacturing Capacity and Production Origins and Explanations

Key Wind Supply Chain Manufacturers by Location, 2016

Manufacturing Location	Nacelles	Blades	Towers	Generators
Brazil	Enercon, GE, Nordex Group, SGRE, Vestas, WEG	Enercon, LM	Enercon, Torrebras/Windar	ABB, Enercon, GE, WEG
Canada		LM, SGRE	CS Wind, Marmen	
China	CCWE, CSIC Haizhuang, DEC, Envision, GE, Goldwind, Mingyang, SANY, SEwind, SGRE, Sinovel, TYHI, United Power, Vestas, Windey, XEMC	Aeolon, Dawntine, Jilin Chongtong Chengfei New Material, LM, Sinoma, Sino-wind, Sunrui, TPI, ZFLZ, Zhuzhou Times New Material Technology	AVIC Hongbo Windpower Equipment, CRRC Tongli Steel, Dajin Heavy Industry Corporation, Fuchuan Yifan New Energy, Gansu Jiugang, Qingdao Tianneng Electric Power Engineering Machinery, Qingdao Wuxiao, Sinohydro Bureau 4, TITAN, TSP	ABB, CRRC Yongji Electric, CRRC Zhuzhou Electric, Dongfeng Electric, Nanjing Turbine & Electric Machinery Group, Shanghai Electric, XEMC Xiangtan Electric-DFIG, XEMC Xiangtan Electric-PMG
Denmark	MHI Vestas, SGRE, Vestas	LM, MHI Vestas, SGRE, Vestas	TITAN, Welcon	
Germany	Enercon, GE, Nordex Group, Senvion, SGRE	Carbon Rotec, Enercon, Nordex Group, Senvion, SGRE, Vestas	Ambau, Enercon, Max Bogl Wind AG	Enercon, Loher GmbH, VEM, Vensys, Vestas
India	GE, Global Wind Power, INOX, Leitwind, Nordex Group, REGEN, SGRE, Suzlon, Vestas, WWI	INOX, LM, SGRE, Suzlon, Vestas, WWI	Barakath Engineering, Fedders Lloyd, INOX, Nordex Group, Suzlon, Windar	ABB, GE, Regen Powertech, Suzlon, WWI
Japan	Hitachi			Hitachi
Mexico		TPI	Trinity, Windar Renovables	Potencia Industrial
South Korea	Doosan, Unison		Dongkuk S&C, Speco, Unison	
United Kingdom	SGRE	MHI Vestas, SGRE		
United States	GE, SGRE, Vestas	LM, SGRE, TPI, Vestas	Broadwind, Gestamp, Marmen, Trinity, Vestas	Ingeteam, SGRE, Vestas

Modern wind turbine manufacturing originated in Europe in the 1980s and 1990s, and it continued to have a strong presence in Germany and to a lesser extent in Denmark and Spain. Generally, European manufacturing capacity levels stabilized and, in some cases, eroded as demand in Western Europe slowed, and new growth has emerged elsewhere in the world, specifically North America and Asia. More recently however, the offshore sector has begun to gain market share in Europe and Asia and has grown its manufacturing footprint.

Beginning in the early to mid-2000s, the United States, China, India, and Brazil began increasing wind turbine manufacturing capabilities. In the United States, manufacturing capacity was developed or repurposed from complementary industries as an increasing number of U.S. states adopted renewable energy portfolio standards (RPS), and steady extensions of a federal production tax credit (PTC) supported robust growth, typically 5–10 gigawatts (GW) per year with a peak of 13 GW installed in 2012 (Wiser and Bolinger 2016). The first components to be manufactured in the United States were technologically simple but large and relatively costly to transport, including towers and blades. Nacelle assembly capacity was followed by production of some subcomponents within the nacelles (e.g., bearings, gearboxes, electrical components), which came online in anticipation of sustained North American wind energy growth. By the end of the period, U.S. production included 2 megawatt (MW) and 3 MW wind turbines with capabilities for blades, towers, generators, and gearboxes (Fullenkamp and Holody 2014). Accordingly, U.S. domestic content estimates included 80%–85% for towers, 50%–70% for blades and hubs, and more than 85% for nacelle assembly (Wiser and Bolinger 2016). At the same time, much of the nacelle internals were still imported and domestic content for wind turbine equipment as a whole was estimated at approximately 40% in 2012 (Wiser and Bolinger 2016). Along with imports for nacelle internals generally, a persistent gap in the U.S. supply chain was the large structural castings used in the nacelle. U.S.-based manufacturers tended to import these castings from Asia and South America (Fullenkamp and Holody 2014).

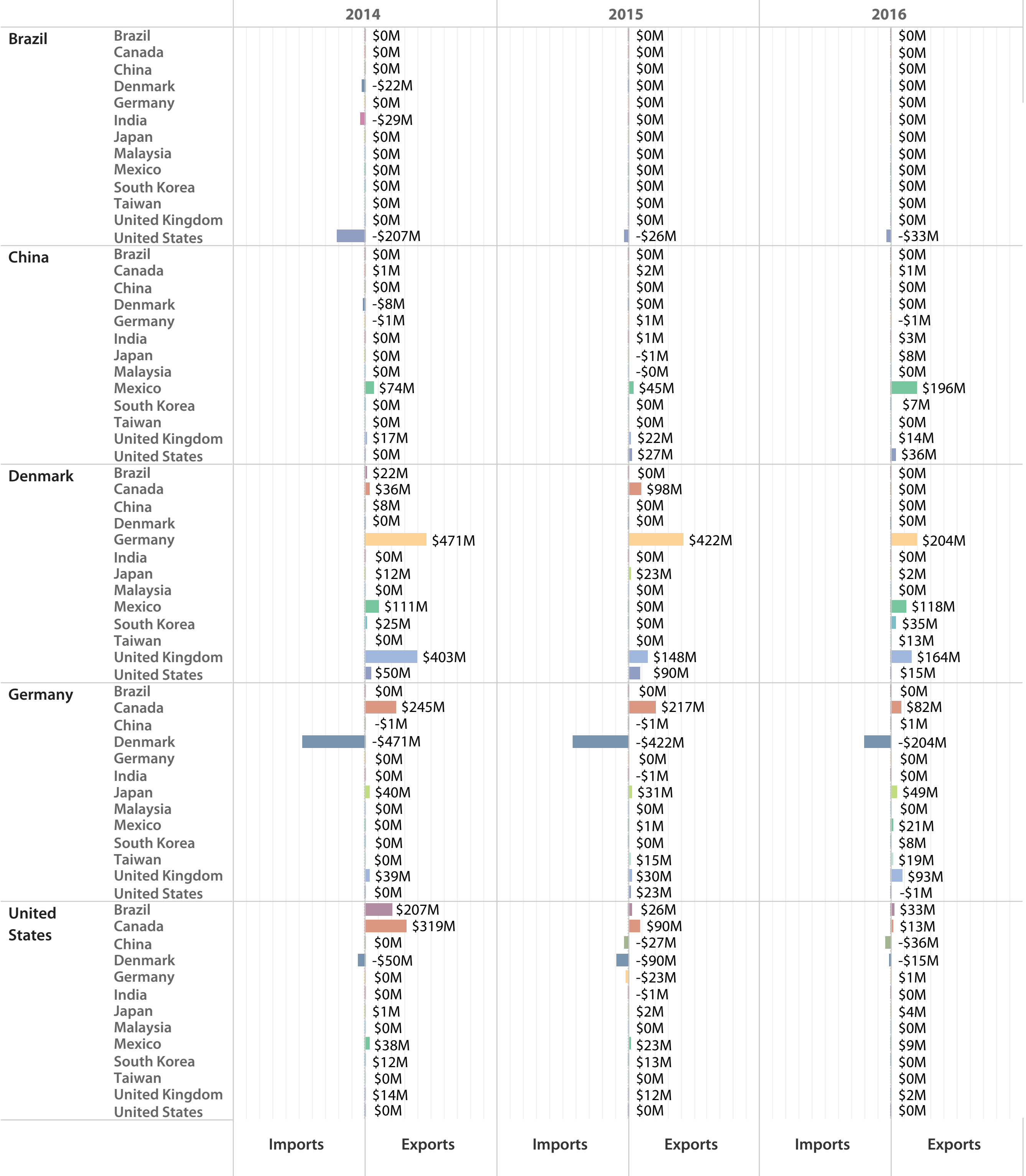
Over the period examined, China was the largest manufacturer of wind power equipment in the world in terms of production capacity and output, supported predominately by its domestic demand (MAKE 2015a). A number of policies in the mid-2000s supported the establishment of a local Chinese wind power supply chain (Wang, Qin, and Lewis 2012).

Brazil has also observed the development of a sizable wind market built upon reverse auctions. In part as a function of increased demand, as well as strict domestic content requirements for wind equipment, blade, tower, hub, and nacelle assembly facilities were developed in Brazil. India also maintained gigawatt scale manufacturing facilities serving primarily domestic demand (Make 2015b). Canada, Mexico, and an array of other European and Asian economies also maintained some degree of manufacturing capacity; however, these more isolated pockets of manufacturing tended to focus on specific components for which they had a comparative advantage. For example, Mexico had relatively lower labor costs and close proximity to U.S. markets (Make 2015b).

Through 2016, global wind power manufacturing was driven by a combination of historical demand, projected future demand, and existing complementary production and fabrication industries. Europe and Germany in particular had robust wind power demand in the past, and a sophisticated manufacturing sector that allowed Europe to be the primary source of wind turbine components through the early 2000s. Given their existing infrastructure and skill sets, some European manufactures were able to remain a continued source of supply for local European demand, to serve economies with somewhat variable demand (e.g., the United States) that might not always be met with domestic production, and to serve markets otherwise too small to justify local manufacturing capacity (e.g., Africa, the Middle East, and Central and South America). In contrast, manufacturing capacity in the United States, China, and Brazil was established primarily due to high transport costs for large wind turbine components, and the relatively large quantities of current and anticipated domestic or regional demand. Moreover, in each of these economies, there was some ability to leverage existing manufacturing synergies within existing large and diverse industrial sectors.

Additional Benchmark Data: Trade Trends—Expanded View

Wind turbine generator set (nacelles and blades) trade, 2014–2016



		2014	2015	2016
Brazil	Brazil	$0M	$0M	$0M
	Canada	$0M	$0M	$0M
	China	$0M	$0M	$0M
	Denmark	-$22M	$0M	$0M
	Germany	$0M	$0M	$0M
	India	-$29M	$0M	$0M
	Japan	$0M	$0M	$0M
	Malaysia	$0M	$0M	$0M
	Mexico	$0M	$0M	$0M
	South Korea	$0M	$0M	$0M
	Taiwan	$0M	$0M	$0M
	United Kingdom	$0M	$0M	$0M
	United States	-$207M	-$26M	-$33M
China	Brazil	$0M	$0M	$0M
	Canada	$1M	$2M	$1M
	China	$0M	$0M	$0M
	Denmark	-$8M	$0M	$0M
	Germany	-$1M	$1M	-$1M
	India	$0M	$1M	$3M
	Japan	$0M	-$1M	$8M
	Malaysia	$0M	-$0M	$0M
	Mexico	$74M	$45M	$196M
	South Korea	$0M	$0M	$7M
	Taiwan	$0M	$0M	$0M
	United Kingdom	$17M	$22M	$14M
	United States	$0M	$27M	$36M
Denmark	Brazil	$22M	$0M	$0M
	Canada	$36M	$98M	$0M
	China	$8M	$0M	$0M
	Denmark	$0M	$0M	$0M
	Germany	$471M	$422M	$204M
	India	$0M	$0M	$0M
	Japan	$12M	$23M	$2M
	Malaysia	$0M	$0M	$0M
	Mexico	$111M	$0M	$118M
	South Korea	$25M	$0M	$35M
	Taiwan	$0M	$0M	$13M
	United Kingdom	$403M	$148M	$164M
	United States	$50M	$90M	$15M
Germany	Brazil	$0M	$0M	$0M
	Canada	$245M	$217M	$82M
	China	-$1M	-$1M	$1M
	Denmark	-$471M	-$422M	-$204M
	Germany	$0M	$0M	$0M
	India	$0M	-$1M	$0M
	Japan	$40M	$31M	$49M
	Malaysia	$0M	$0M	$0M
	Mexico	$0M	$1M	$21M
	South Korea	$0M	$0M	$8M
	Taiwan	$0M	$15M	$19M
	United Kingdom	$39M	$30M	$93M
	United States	$0M	$23M	-$1M
United States	Brazil	$207M	$26M	$33M
	Canada	$319M	$90M	$13M
	China	$0M	-$27M	-$36M
	Denmark	-$50M	-$90M	-$15M
	Germany	$0M	-$23M	$1M
	India	$0M	-$1M	$0M
	Japan	$1M	$2M	$4M
	Malaysia	$0M	$0M	$0M
	Mexico	$38M	$23M	$9M
	South Korea	$12M	$13M	$0M
	Taiwan	$0M	$0M	$0M
	United Kingdom	$14M	$12M	$2M
	United States	$0M	$0M	$0M

Bars show trade (exports positive and imports negative) and numerical value indicates balance of trade (BOT, exports minus imports) for wind turbine generator sets (nacelles and blades) by economy. All data are in US$(2014).

Denmark, Germany, and, increasingly, China were the top exporters of wind turbine generator sets (nacelle and blades) over the period. The top three destinations for exports from Denmark were Germany, the United Kingdom, and Mexico. Germany exported primarily to Canada and the United Kingdom. The majority of Chinese exports went to Mexico.

Between 2014 and 2016, a few economies contributed to the trade of wind turbine generator sets. Specifically, Denmark, Germany, and China were critical exporters; Mexico, the United Kingdom, and the United States were the largest importing economies. Trading partners for the five key wind turbine economies remained relatively consistent over the period.

In 2016, the top three destinations for exports of generator sets from Denmark were Germany ($200 million), the United Kingdom ($160 million), and Mexico ($120 million). Germany exported $93 million, $82 million, and $49 million to the United Kingdom, Canada, and Japan, respectively. China exported $196 million of generator sets to Brazil in 2016.

U.S. exports to Canada and Brazil dropped dramatically over the period from $319 million to $16 million and from $207 million to $33 million, respectively. Germany's and Denmark's exports to Canada also declined over the period.

Crystalline Silicon Photovoltaic Modules

Manufacturing Capacity and Production Origins and Explanations

Key PV Supply Chain Manufacturers by Location, 2016

Manufacturing Location	PV Module	PV Cell	PV Wafer	Polysilicon
China	Trina, Jinko, Canadian Solar, JA Solar, Yingli	Trina, JA Solar, Yingli, Jinko, Canadian Solar	GCL, LDK, ReneSolar, Yingli, Jinko	GCL, REC
Germany	SolarWorld	SolarWorld	SolarWorld, PV Crystalox Solar	Wacker
United States	SolarWorld, Suniva	SolarWorld, Suniva	Panasonic	Hemlock, REC, Wacker
South Korea	LG, Hyundai	LG, Hyundai, Shinsung Solar Energy	Nexolon, Woongjin Energy	OCI, Hanwha
Malaysia	Hanwha, Panasonic	SunPower	AUO, Comtec	
Philippines	SunPower[a]	SunPower		
Taiwan	Neo Solar	Motech, Gintech, Neo Solar	Gigastorage, Green Energy Technology, Sino-American Silicon Products	

a. SunPower announced in August 2016 its intent to close its Philippines module assembly capacity and relocate a portion of it to Mexico (http://www.pv-tech.org/news/sunpower-streamlining-project-development-focus-and-closing-module-assembly)

Some vertical integration existed during the period across the PV manufacturing industry between wafer, cell, and module production, with integrated manufacturers citing lower “in-house” production costs as compared to those achieved when sourcing materials and components from third parties (Chase et al. 2016). Several companies shown owned manufacturing assets in economies other than their headquarters locations (e.g., Wacker and SolarWorld were headquartered in Germany, but owned manufacturing facilities in the United States; Panasonic is headquartered in Japan but owned manufacturing facilities in Malaysia and the United States).

The buildup of manufacturing capacity through 2011 was driven by expectations of continued strong demand growth, and especially in China by local and provincial subsidies and investment supports (Quitzow 2015).

The resulting overcapacity drove large price reductions between 2008 and 2012, exacerbated by a slowdown in global demand between 2011 and 2012. However, with robust demand returning and pricing stabilizing, PV manufacturer capital expenditures (related to capacity additions) rebounded again in 2014 and 2015.[26]

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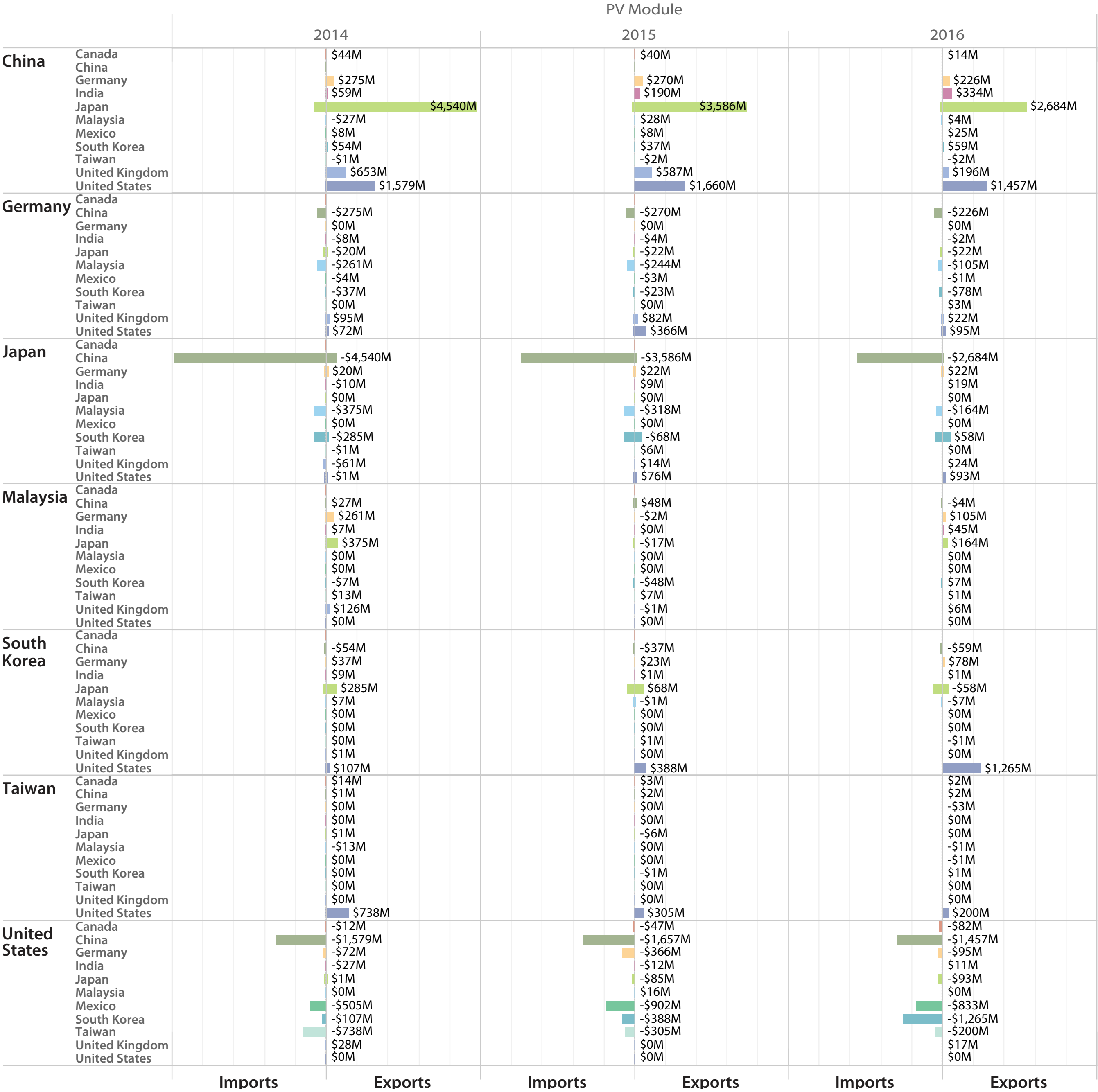
[26] Bloomberg L.P. 2016. “PV Operating Margins”. Bloomberg Terminal. Accessed Aug 1 ,2017.

Additional Benchmark Data: Trade Trends—Expanded View

PV module trade, 2014–2016



Bars show trade (exports positive and imports negative) and numerical value indicates balance of trade (BOT, exports minus imports) for PV modules by economy. All data are in US$(2014).

In the benchmarked economies, the balance of trade (exports minus imports) remained relatively stable for PV modules, with the exception of Japan (imports from China declined) and the United States (imports from South Korea increased).

China maintained its position as the largest PV module exporter over the period. The biggest changes in PV module trade were observed for Japan and the United States; China's PV module exports to the United States and Japan declined over the period. At the same time, U.S. imports from South Korea and the rest of the world increased.

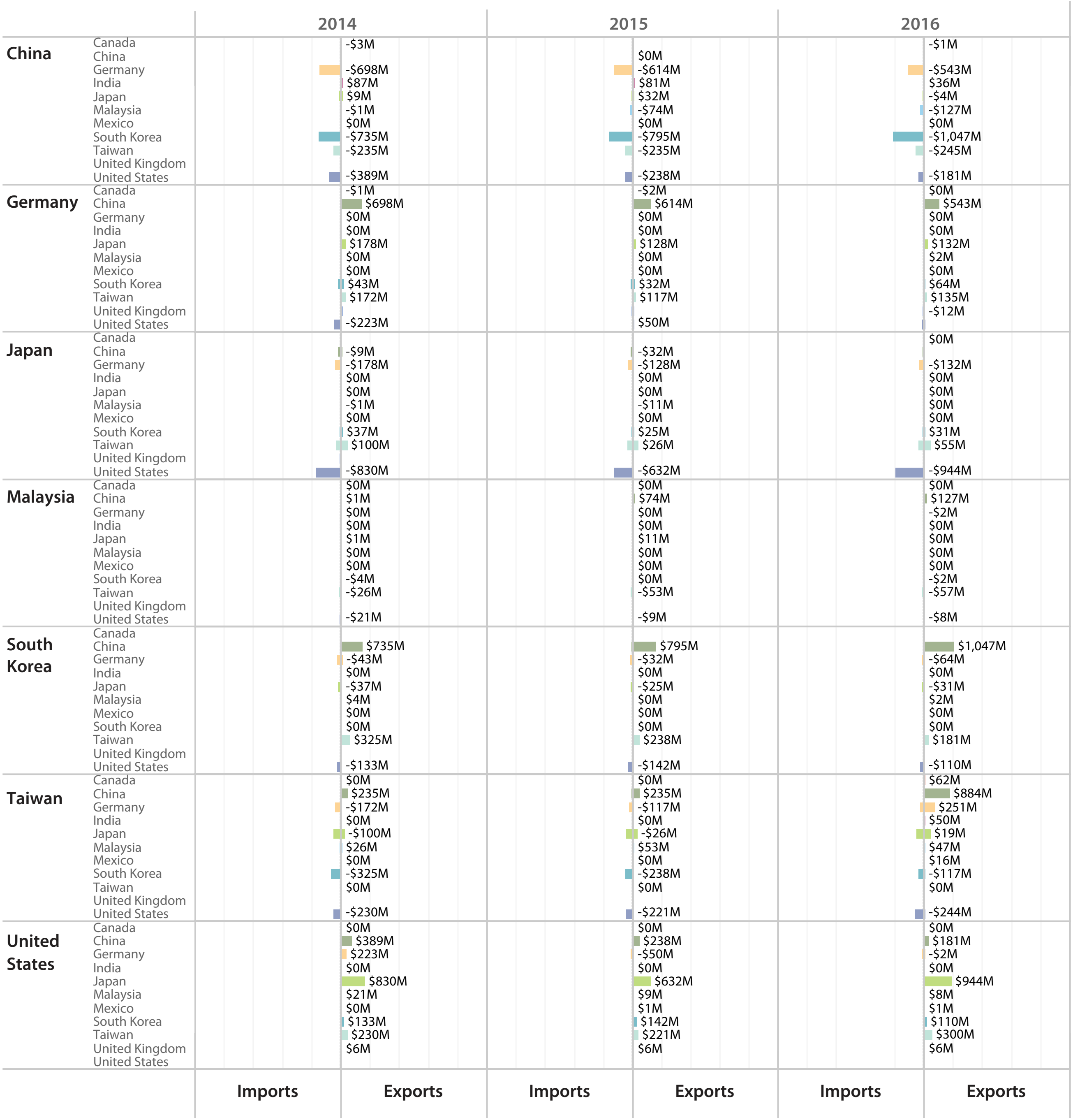
PV cell trade, 2014–2016

Bars show trade (exports positive and imports negative) and numerical value indicates balance of trade (BOT, exports minus imports) for PV cells by economy. All data are in US$(2014).

In the benchmarked economies, the balance of trade (exports minus imports) remained relatively stable for PV cells, with the exception of China (exports to India increased sharply) and Taiwan (exports to China and Japan declined).

China maintained its position as the largest PV cell exporter between 2014 and 2016. The largest changes in PV cell trade were observed for China and the Taiwan; China's PV cells exports to Taiwan decreased, while exports to India increased. Taiwan exports to China and Japan declined over the period.

Polysilicon trade, 2014–2016



Bars show trade (exports positive and imports negative) and numerical value indicates balance of trade (BOT, exports minus imports) for polysilicon by economy. All data are in US$(2014).

Over the period, the balance of trade (exports minus imports) for polysilicon shifted among the benchmarked economies, led by China, South Korea, Taiwan and the United States.

In 2016, China continued to be the largest net importer of polysilicon. The United States was the second largest exporter of polysilicon (after Taiwan), maintaining a relatively steady value of polysilicon exports despite a dip in 2015. Between 2014 and 2016, the United States, South Korea, and Germany exported polysilicon to Taiwan to avoid Chinese tariffs (although still exporting some polysilicon directly to China) and Taiwan increased exports to China. The United States increased exports to Japan to offset some of the loss of exports to China over the period.

Light-Emitting Diode Packages

Manufacturing Capacity and Production Origins and Explanations

Key LED Supply Chain Manufacturers by Location, 2016

Manufacturing Location	Package[a]	Chip[b]	Substrate[2]
China	ChangFang, HongliZhihui (Honglitronic), Jufei Opto, Mulinsen (MLS), NationStar, Refond Opto	Electech ETI, Epistar, HC Semitek, Lextar, Nantong, San'an, Tongfang	Aurora Sapphire, Crystaland, Crystal Applied Technology, Crystal Optech, ECBO, Fujian Crystal, GAPSS, J-Crystal, JeShine, Nanjing J-Crystal Photoelectric, NJC, SinoNitride, SinoNitride (Sinopat), TDG Core, Unisem New Material Technology-Youzhong
Germany	Osram OS		
Japan	Citizen, Nichia, Sharp, Stanley, Toyoda Gosei	Nichia	Kyocera, Namiki
South Korea	LG Innotek, Lumens, Samsung, Seoul Semiconductor	LG, Samsung, Seoul Vyosis	Hansol Technics, Iljin Display, LGS, Unisem, Sapphire Technology, SSLM
Taiwan	AOT, Everlight, Harvatek, Kingbright, Lextar, Lite-On, Unity Opto	Epistar, Lextar	Aceplux Optotech, AimCore, Crystal Applied Technology, Crystalwise, Lucemitek, Phecda, Procrystal, Rigidtech, Tera Xtal, TXC Quartz
United States	CREE, Lumileds	Cree	Rubicon

a. Manufacturing location indicates company headquarters, not equipment location.

b. Manufacturing location indicates equipment location. List does not include vertically integrated companies.

Light-emitting diodes (LEDs) were first used as an electronic component in 1968 (Schubert 2003). Early LEDs were used as indicators in electronic devices and in displays. As LEDs improved with longer lifetimes, smaller size, and lower energy consumption, uses expanded to include general lighting, consumer electronics, displays, signs, automotive, and other uses (Mukish and Virey 2014; Wright 2016).

The growth of the LED market was driven by increased electricity costs coupled with the worldwide adoption of standards and regulations for energy efficiency, including the phase-out of incandescent lighting (En.Lighten n.d.). Furthermore, Navigant Research (2015) reported that "LED prices have declined to a point where this type of lighting is becoming the economical choice in almost every application."

While LEDs were originally invented in the United States, Shuji Nakamura from Japan's Nichia Corporation made enormous scientific advances in LEDs in the early 1990s and catapulted Japan into a leading market position. Prior to 2010, Japan maintained this technical leadership, capturing more than 50% of market share (Su 2014). In 2010, lower-priced products helped Taiwanese, South Korean, and Chinese firms gain market share, and Japan for the first time garnered less than 50%.

South Korean advances were led by Samsung's and LG's development of LCD televisions with LED backlighting. South Korean companies further leveraged their brand advantage and, with the government support, adopted vertically integrated operations, leading to further market share gains.

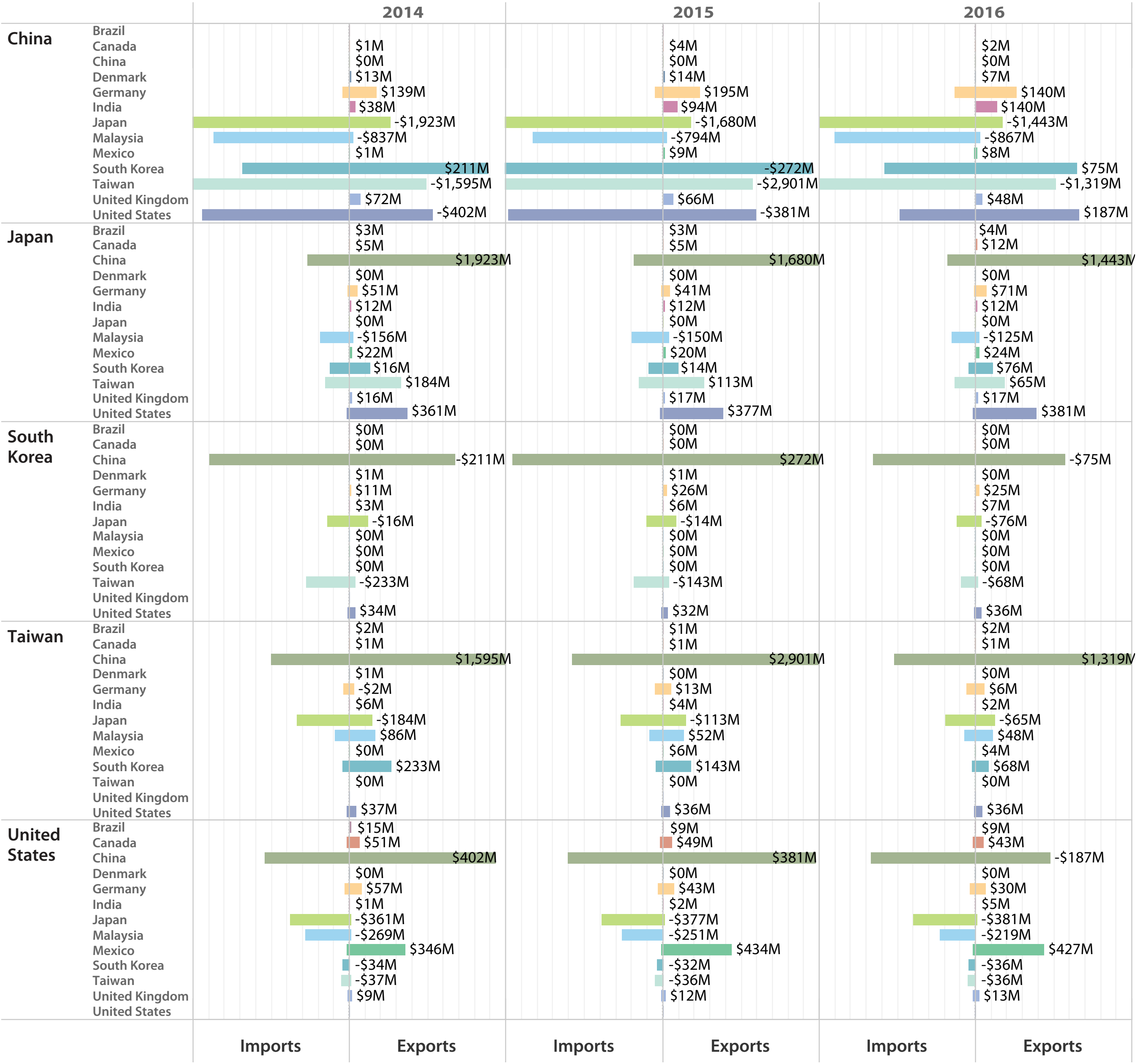
Taiwan's industry originally grew from international investment that established the first packaging plants. Taiwan formed a collaborative in the late 1990s which focused on integrating the entire LED value stream into three main industrial clusters that created a pool of expertise in the LED and opto-electronic fields. As a consequence, Taiwan companies reduced product development time and costs and slowly gained market share in both LED packages and sapphire substrate.

China's LED industry grew significantly between 2005 and 2007. LEDs Magazine identified only one Chinese firm in 2005, with the number jumping to 51 by 2007 (Sanderson and Simons 2014). By 2009, there were 100 wafer companies, but by 2016 industry consolidation reduced the total number to about 28 with meaningful levels of revenue (Mukish and Virey 2017). Government subsidies for production equipment, land, leasing, and taxation aided domestic firms (Schubert 2003; Mukish and Virey 2014).

LED package production in Japan and South Korea constituted more than 55% of total global package output in 2014, with China and Taiwan together contributing another 25%. By 2016, China was the highest-volume package producer with a 30% share, with Japan, South Korea, and Taiwan together contributing 54%. Sapphire substrate production was concentrated in Taiwan and China, accounting 35% and 29% of global production in 2016.

Additional Benchmark Data: Trade Trends—Expanded View

LED package trade, 2014–2016



Bars show trade (exports positive and imports negative) and numerical value indicates balance of trade (BOT, exports minus imports) for LED packages by economy. All data are in US$(2014).

From 2014 to 2016, China was the largest net importer of LED packages and Japan, Malaysia, and Taiwan were the largest net exporters (primarily to China). In the benchmarked economies, the balance of trade (exports minus imports) remained relatively stable, with a few exceptions including China, Taiwan, the United States, and South Korea.

From 2014 to 2016, the largest changes in trade flow of LED chips and packages were observed in China, Japan, and Taiwan. In 2014, South Korea, Japan, China, and Taiwan were key exporters of LED packages. By 2016, China had become the largest LED package trading partner with the other key LED package economies. Over the period, China primarily imported LED packages and chips from Taiwan, Japan, and Malaysia. Top destinations for China's LED packages and chips were the United States, South Korea, and Taiwan. Top U.S. import partners in 2016 included China, Japan, and Malaysia.

Lithium-Ion Battery Cells

Manufacturing Capacity and Production Origins and Explanations

Key LIB Supply Chain Manufacturers by Location, 2016

Manufacturing Location	Cell	Cathode	Anode	Separator	Electrolyte
China	BAK, BYD, CATL, Guoxuan, Op-timumNano	Jinhe, Reshine, ShanShan	ShanShan, Shenzhen	Fengfan, Jinhui	Cap-chem, Guotai-Huarong, ShanShan Zhnagjiang
Japan	AESC, Panasonic, Pri-mearth	Nichia, Nihon Kagaku Sangyo, Sumi-tomo, Toda Kogyo,	Hitachi, Mitsubishi Chemical, Nippon Carbon	AsahiKASEI, Toray, Sumito-mo, Ube Indus-tries, W-Scope	Mitsubishi Chemical, Mitsui, Tomiyama, Ube Industries,
South Korea	LG Chem, Sam-sung SDI	Ecopro, L&F Umicore	LGC, Posco, Samsung SDI	Tonen	Panax-Etec, Soulbrain
United States	LG Chem, Panasonic, Tesla			Celgard	

Lithium-ion batteries (LIBs) were developed in the 1990s to power consumer electronics. Electric vehicle (EV) original equipment manufacturers (OEMs) have since adopted LIBs as a technology of choice for the rechargeable batteries used in their vehicles.

In 2016 electrified vehicles (including pure electric, plug-in hybrid, and hybrid drive vehicles) constituted nearly 2.6% of global light-duty vehicle (LDV) sales.[27]

In 2016, LIB cell manufacturing capacity (serving all end-market applications) was primarily located in China, Japan, South Korea, and the United States. Together, these economies constituted 90% of 2016 global LIB cell production capacity for all end-use applications. Notably, clusters of key intermediate product manufacturing facilities were also well established in China, Japan, and South Korea.

Such clusters may contribute to regional supply chain advantages and cost benefits not available to cell manufacturers located outside such clusters. Some degree of vertical integration exists across Asian processed materials and cell production, which may also contribute to lower input costs for certain manufacturers. The United States, in contrast, hosted a relatively immature supply chain, and most U.S. cell and battery plant operators were relatively new to the industry. Nearly all U.S. LIB capacity was targeted at serving the automotive market.

Japan's LIB cluster grew from sustained investments in LIB technology by consumer electronics companies in the 1990s. The Japanese government bolstered private sector investments with research and development (R&D) funding and low-cost capital to establish manufacturing plants. Japan made these investments despite the long commercialization cycle of Li-ion technologies and the low returns on the LIB business because the technology enabled competitive advantages in portable consumer electronics end applications (Chung, Elgqvist, and Santhanagopalan 2016). Korea and China followed Japan's lead in investing in LIB cell and pack production for consumer electronics.

South Korea's LIB cell cluster is a result of government and industry efforts, started in the 2000s, to build up this portion of the supply chain (Chung, Elgqvist, and Santhanagopalan 2016; Cision PR Newswire 2013). China, too, has fortified its LIB cluster development through various government research and development, tax, and investment incentives (Lowe et al. 2010; Chung, Elgqvist, and Santhanagopalan 2016). While South Korean and Chinese cell manufacturers initially relied heavily on Japanese suppliers, their national efforts to build LIB clusters resulted in less dependence on Japanese suppliers and may have contributed to advantageous pricing on key materials for fully scaled and colocated cell producers (Cision PR Newswire 2013).

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[27] NREL estimate based on Richter (2017), EIA (2017), and BNEF 2016

Historically, the United States has not been a leader in LIB manufacturing. The United States hosted 16% of global LIB cell production capacity for EVs in 2016; this share is expected to increase with the expansion of Tesla's Gigafactory, a joint venture between Tesla and Panasonic with an announced production capacity upon completion of 35 GWh.[28]

China, Japan, and South Korea developed vertically integrated supply chains for LIB cells and intermediate products (cathodes, anodes, electrolytes, and separators). However, the U.S. supply chain is more focused on cell and pack manufacturing.

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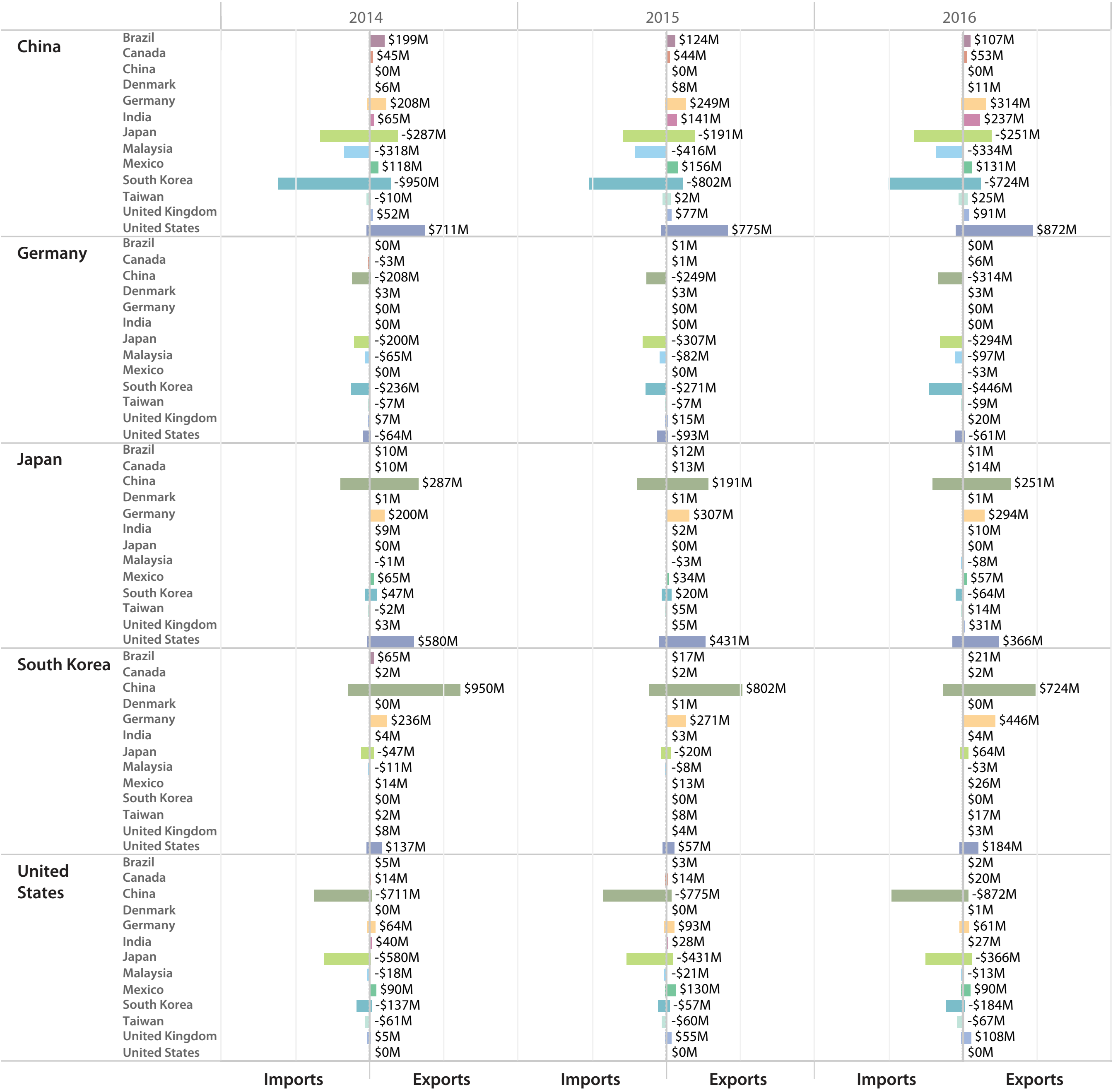
[28] Information was accessed November 2018 on the Tesla 2018 Tesla Gigafactory website (https://www.tesla.com/gigafactory).

Additional Benchmark Data: LIB Cell Trade Trends—Expanded View

LIB cell trade, 2014–2016

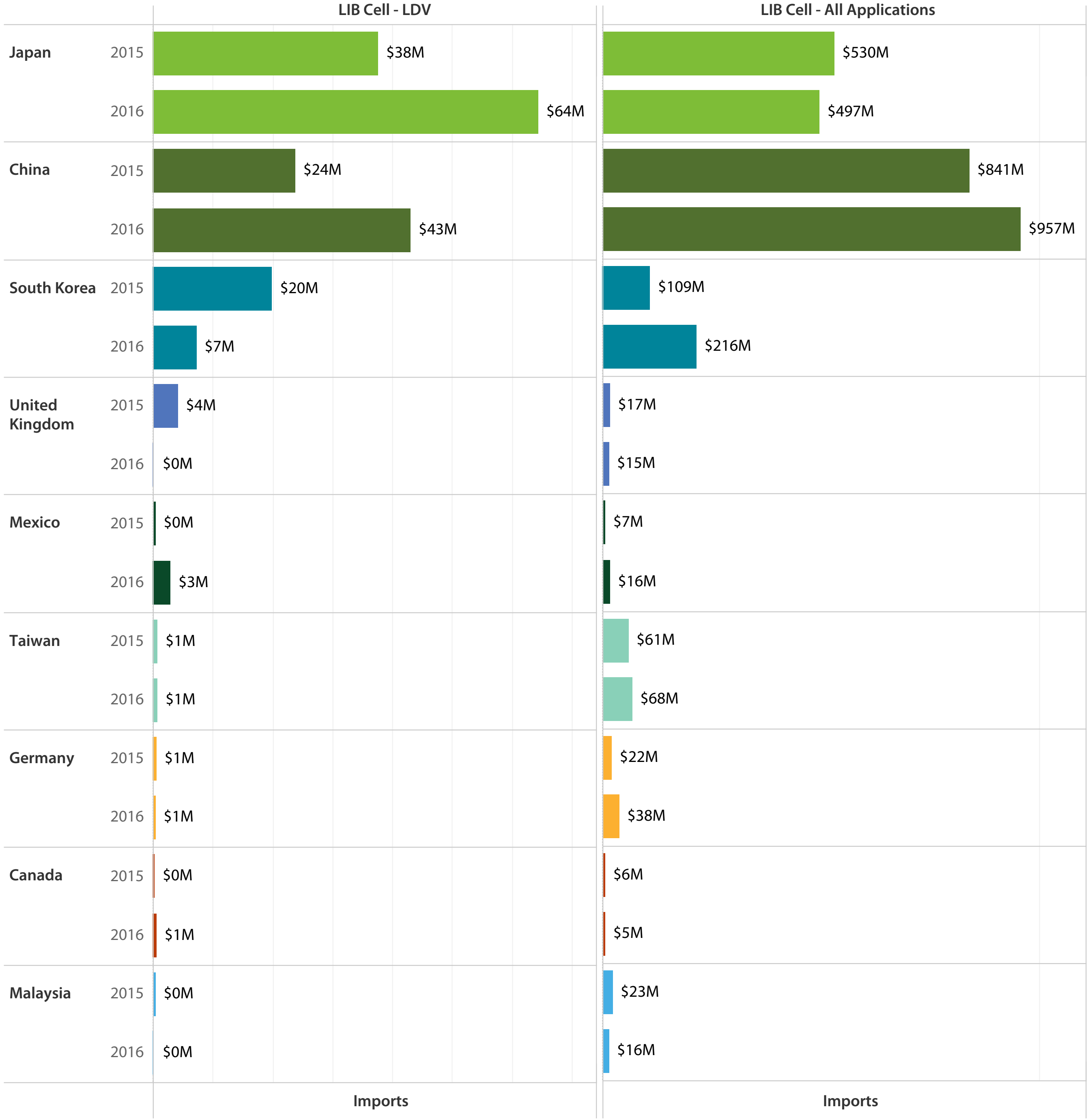


Bars show trade (exports positive and imports negative) and numerical value indicates balance of trade (BOT, exports minus imports) for LED packages by economy. All data are in US$(2014).

Between 2014 and 2016, the distribution of trade among the five key LIB economies remained relatively stable over the period, with China, Japan, and South Korea the top exporters and the United States and Germany the largest importers.

The top three destinations for exports from China in 2016 were the United States, Japan, and Germany. China's imports in 2016 came primarily from South Korea, Japan, and Malaysia. The top three destinations for exports from Japan and South Korea in 2016 were China, Germany, and the United States. The United States imported LIB cells primarily from China, Japan, and South Korea in 2016.

U.S. imports of LIB cells for use in EVs, 2015–2016



Bars show U.S. imports of LIB cells for EVs (left) and all applications (right) in US$(2014). Note that data for All Applications are shown on a different scale.

U.S. LIB cell imports for EVs accounted for a small but increasing share of LIB imports for all applications—5.3% in 2015 and 8.4% in 2016.

In 2015, the United States added a new Harmonized System (HS) code[29] to track imports of LIB cells for use in LDVs (EVs specifically). Overall, U.S. imports of LIB cells increased from $1.7 billion in 2015 to $2.0 billion in 2016, while imports of LIB cells for EVs increased from $90.5 million to $167.3 million. The majority of U.S. LIB cell imports for EVs came from Japan and China.

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[29] Code 850760-0010 : Lithium-ion storage batteries of a kind used as the primary source of electrical power for electrically powered vehicles of subheading 8703.90

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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.

NREL/TP-6A50-78037
January 2021