CEMAC
Clean Energy Manufacturing Analysis Center

Benchmarks of Global Clean Energy Manufacturing, 2014–2016

Summary of Findings

Benchmarks of Global Clean Energy Manufacturing provides an assessment of the global state of clean energy manufacturing over 3 years from 2014 through 2016. 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. The analysis evaluated each technology's manufacturing supply chain, from processing raw materials to producing required subcomponents to assembling final products, evaluated across 13 economies that are the primary manufacturing hubs for these technologies.

Snapshot

- **Manufacturing Capacity and Utilization:** To meet anticipated demand growth, all benchmarked economies added clean energy manufacturing capacity from 2014 through 2016, with China adding the largest amount. Overall utilization of global production capacity for the clean energy technology end products declined over the period, except for LED chips.
- **Global Supply Chains:** Across the benchmarked economies, clean energy manufacturing supply chains added more value, both domestically and globally, than the manufacture of the end products. 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. China was the only benchmarked economy able to meet domestic demand for the four end products with domestic production alone.
- **Value Added:** The United States moved from third- to second-highest economic total value added from production of the four clean energy technology end products from 2014 through 2016. China accounted for the largest demand for and production of each of the four end products over the period, with total value added three to four times higher than that of each of the next three economies (the United States, Japan, and Germany).

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

Scope and Approach of the Benchmark Analysis

Although development and deployment of the four technologies make tremendous contributions to the economy, this report focuses on the value added by and opportunities found in the manufacturing supply chain, which includes processing raw materials, producing required subcomponents, and assembling final products.

The 13 economies CEMAC researchers assessed 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.

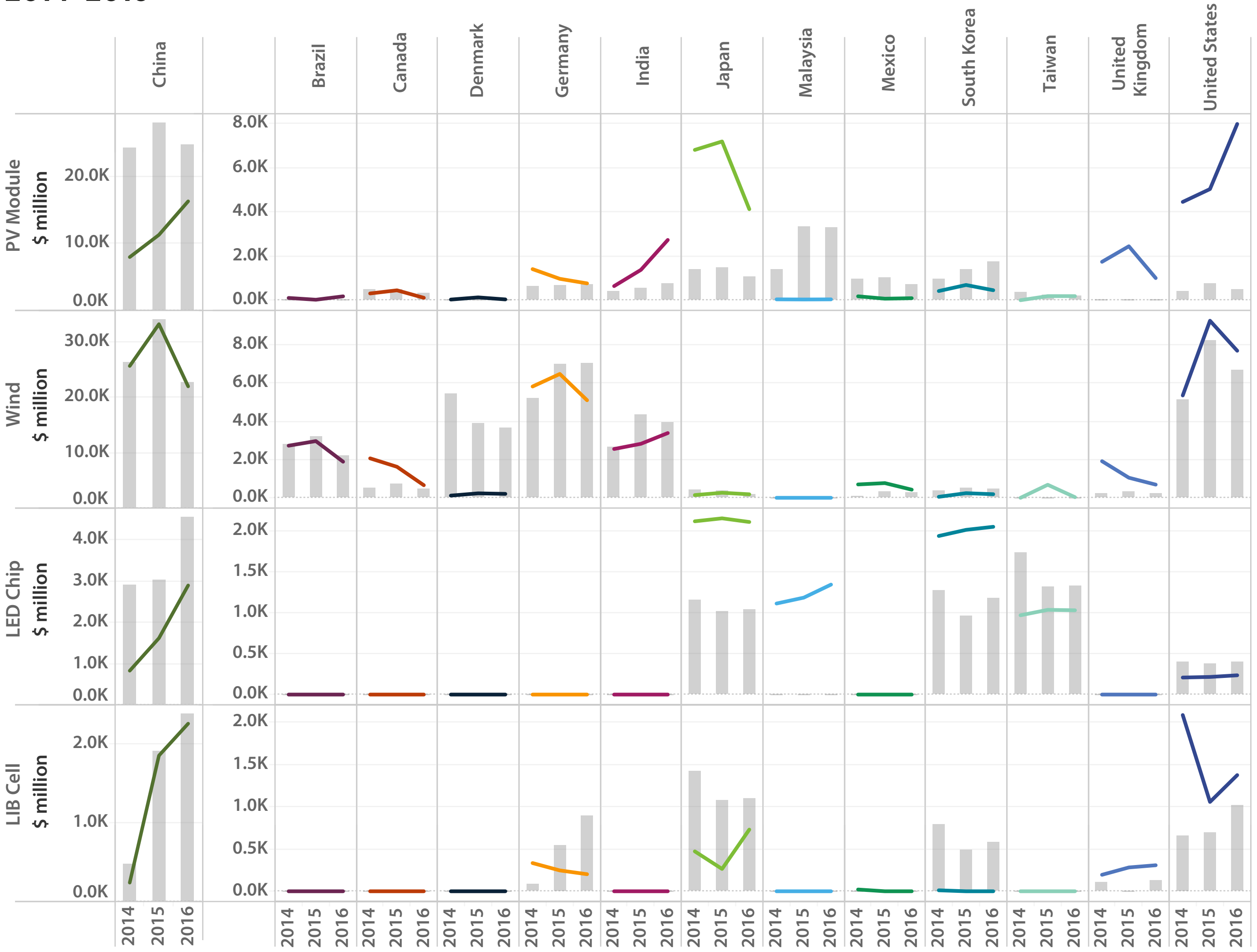
The impacts of the manufacturing supply chain for these four technologies were assessed in terms of three common points of reference—benchmarks—to provide a standardized basis for comparing key economic aspects of clean energy technology manufacturing on a national and global basis, and for tracking changes as markets and manufacturing processes evolve.

The clean energy manufacturing benchmarks include:

- **Market (Demand, Manufacturing Capacity, and Production)—**Relative concentration of consumption of clean energy technologies and distribution of manufacturing activity
- **Trade Flow—**Snapshot of trade activity among economies across the supply chain
- **Value Added—**Estimate of clean energy manufacturing contribution to national economies and relative interconnectedness and strength of manufacturing supply chains.

This analysis summarized trends of these benchmarks between 2014 and 2016, building on the original report, *Benchmarks of Global Clean Energy Manufacturing*, published in 2017.

Clean energy technology end product global demand and production shares 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.

Market Trends

Production and Demand

Between 2014 and 2016, China had the highest demand for and production of the four benchmarked clean energy technologies. Over the period, total global demand (on a dollar basis) for the four clean technology end products decreased slightly—from $98.2 billion to $97.1 billion, with a peak of $116.8 billion in 2015.

For some clean energy technologies in some economies, market demand and production decreased on a dollar basis over the period while actual physical units produced and sold increased, due to rapidly dropping prices for end products. This situation was also reflected in the decline in global end product imports and exports in aggregate dollar terms over the period.

Of the benchmarked countries, only China had sufficient production to meet domestic demand for the four clean technology end products over the period. 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.

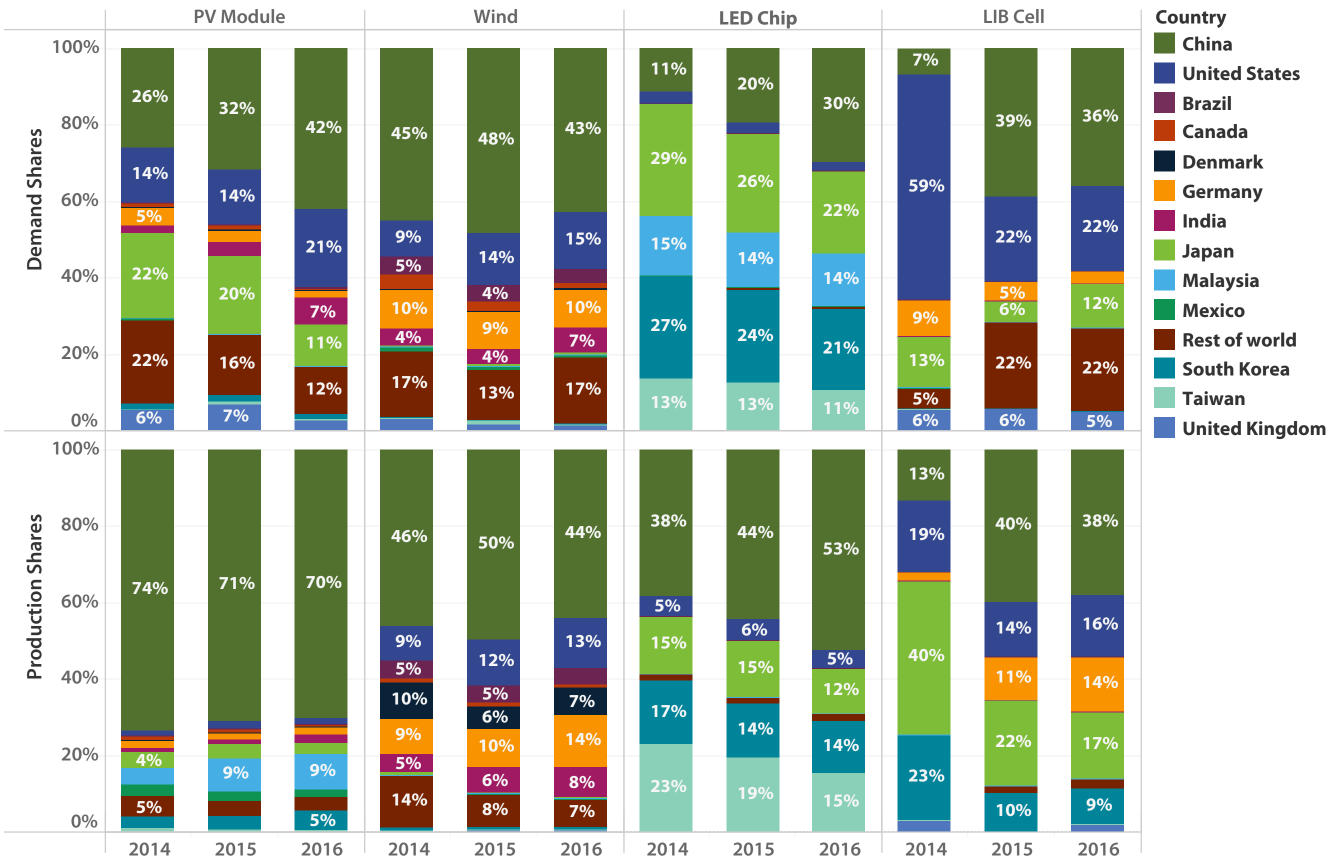
Global Distribution of Production and Demand

The global distribution of production and demand for the four end products provides additional insight into the shifting clean energy manufacturing landscape over the period. By 2016, China had the largest shares of demand for and production of the four clean energy technologies.

Demand for PV modules and wind turbine components was more widely distributed than demand for LED packages and LIB cells. Demand for LED packages was particularly concentrated, with nearly all 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. About 75% of LIB cell aggregate demand was in four economies—China, the United States, Japan, and Germany—the top four automotive manufacturers globally.

Distribution of production for PV modules and wind turbine components remained relatively constant over the period, with China accounting for the largest shares. C-Si PV module production outside China was dispersed across all but three of the benchmarked economies. Wind turbine component demand and production were generally co-located 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.

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



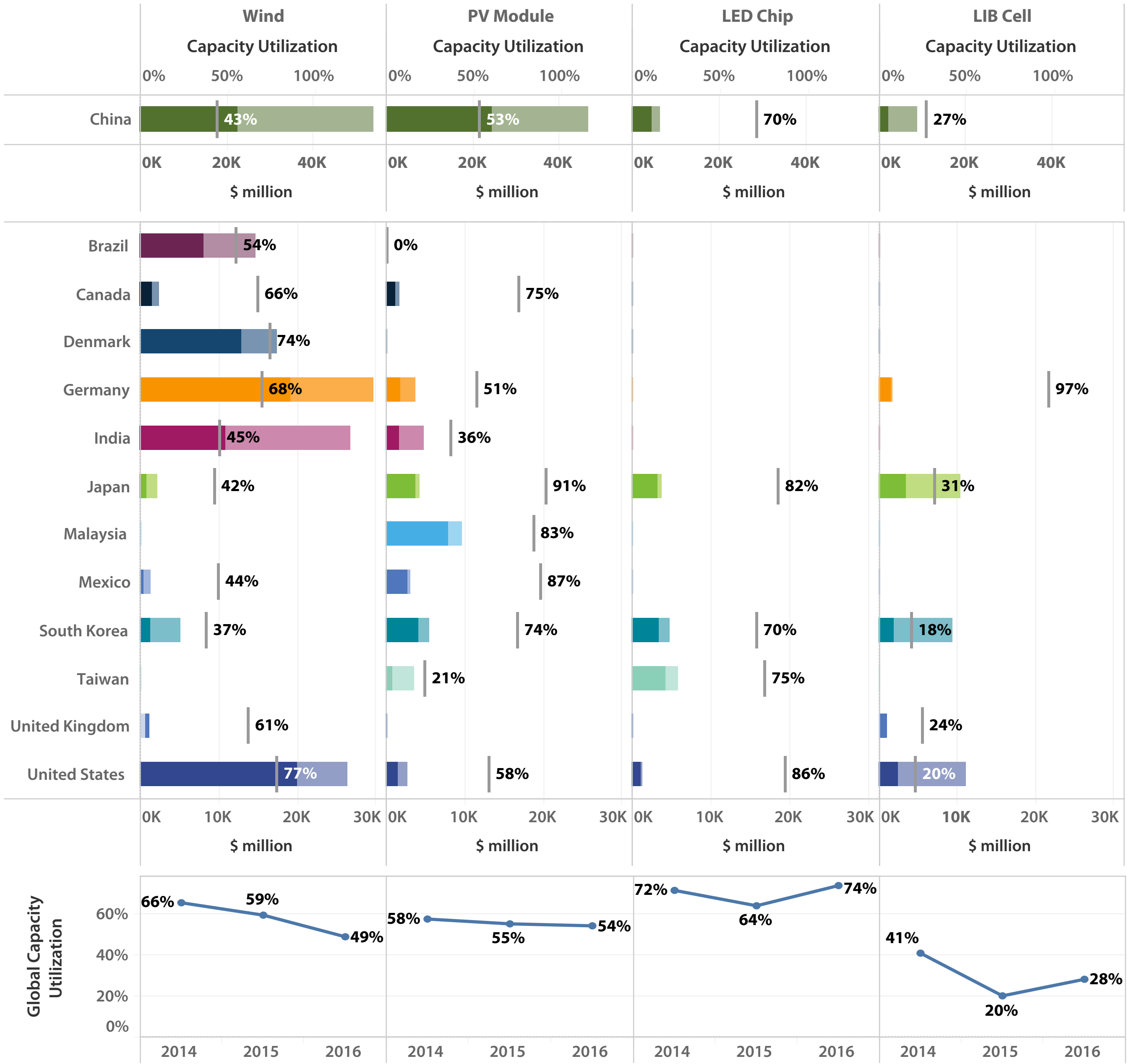
Breakdown (in %) of global demand (top) and production (bottom) by economy for benchmarked clean energy technology end products. Note that LED chip data are presented in place of LED package data. (Due to a lack of availability of economy-specific demand data for LED packages, the benchmark analysis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

Manufacturing Capacity and Utilization

Global manufacturing capacity increased to meet anticipated demand growth for all four technologies over the period. The capacity expansion was driven in part by domestic policies that set targets for renewable energy production and provide incentives to offset costs. Although all economies added new clean energy manufacturing capacity over the period, China added the largest amount.

Overall capacity utilization relative to global production for clean energy benchmark technology end products declined from 2014 through 2016, except for LED chips. 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.

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.

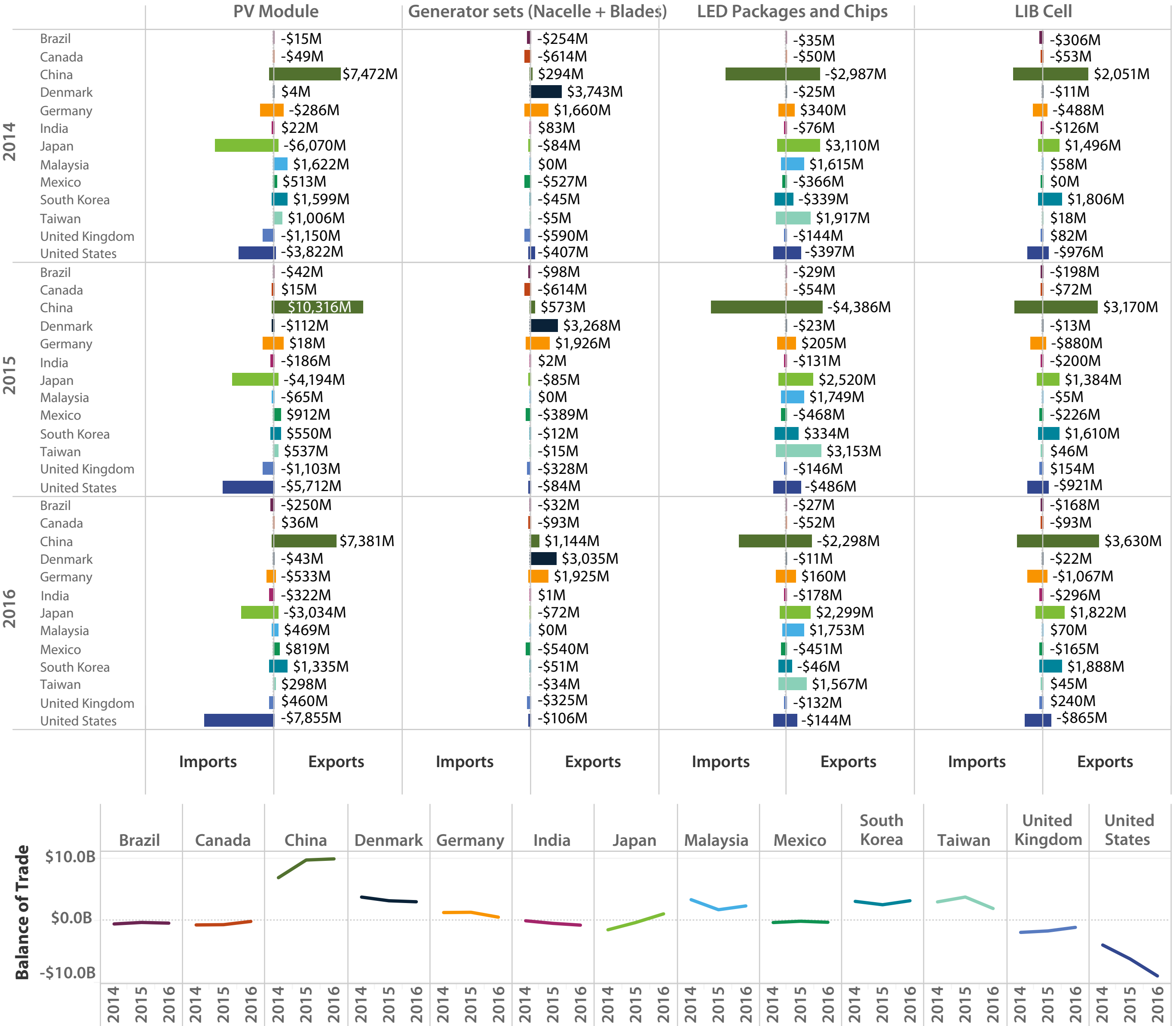
Trade Trends

Clean Energy End Products

Trade is a significant component of gross domestic product (GDP) in many economies. Balance of trade (exports less imports) is one element of GDP and is influenced by production capacity, capacity utilization, and domestic demand for manufactured products.

From 2014 through 2016, aggregate exports for the 13 economies declined 7.3% from $39.5 billion to $36.6 billion, whereas imports declined 9.2% from $51 billion in 2014 to $46.3 billion in 2016. China was the largest exporter of the benchmark technologies, and 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), whereas exports of LIB cells expanded (19.4%) over the period.

Clean energy technology end product trade, 2014–2016

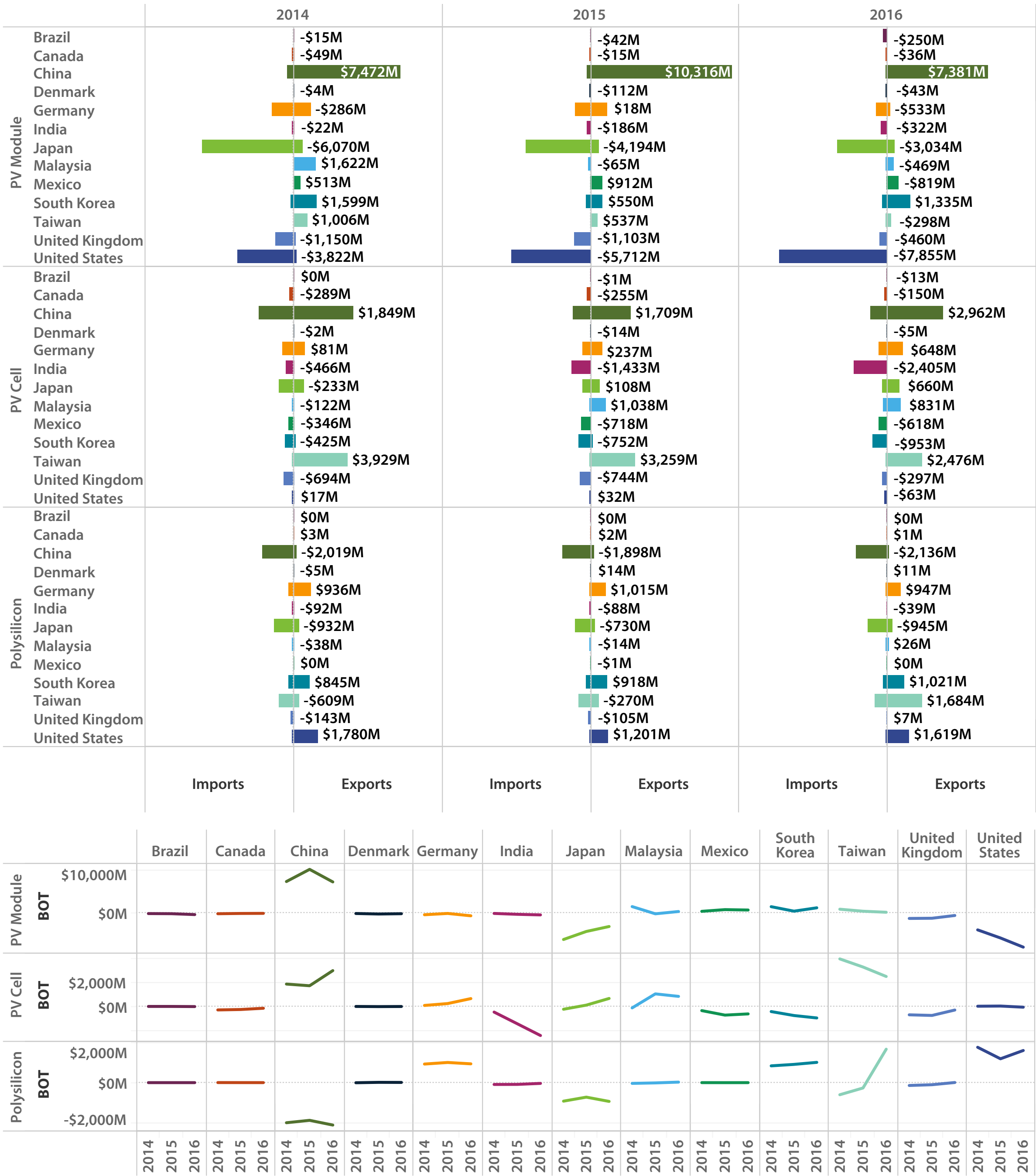


Bar chart (top) shows imports (negative values), exports (positive values), and balance of trade (exports less imports) in US dollars US$(2014) by economy for four clean energy end products: wind turbine nacelles and blades, PV modules, LED chips and packages, and lithium-ion cells. Line chart (bottom) 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).

Clean Energy Intermediates

Manufacturing of clean energy technologies is a complex global enterprise with extensive trade among economies to support the geographical distribution of production and demand across the links in the supply chain. Economies that are net importers of end products may be major exporters of upstream processed materials and subcomponents of those same technologies. For example, China maintained its position as the largest PV module and cell exporter—primarily to the United States, Japan, and India—with decreases in exports in 2016 driven in part by a buildup of manufacturer and installer inventory levels. At the same time, China continued to be the largest net importer of polysilicon, largely from South Korea, Germany, Taiwan, and the United States. The United States continued to be one of the major exporters of polysilicon but moved to second place after South Korea in 2016. Downstream, the United States and Japan were the two largest net importers of PV modules over the period. U.S. PV module net imports doubled, whereas Japan's net imports decreased by 50%.

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.

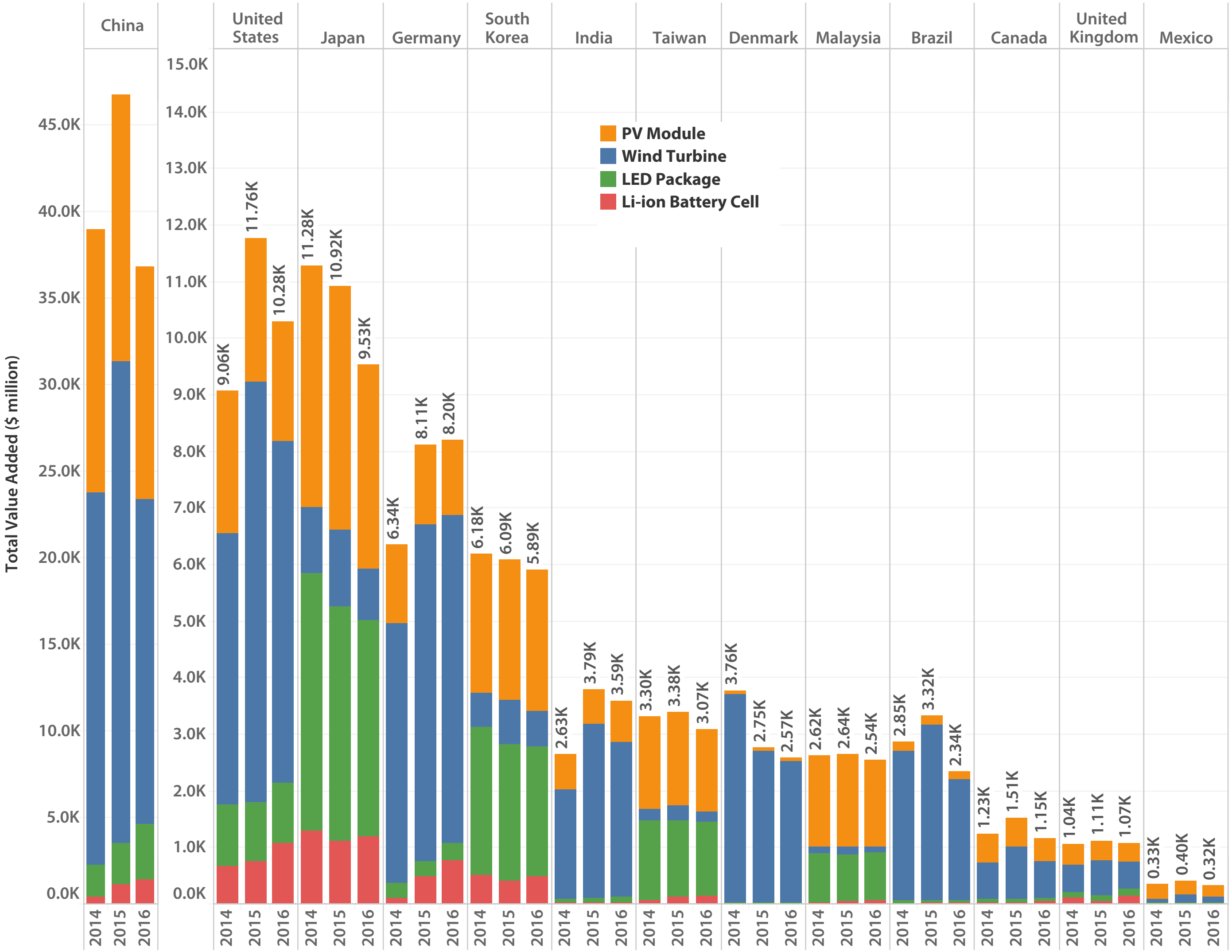
Value-Added Trends

Global Landscape

Total value added (tVA) from production of the four benchmark technologies increased from $89.6 billion in 2014 to $102.4 billion in 2015 across the benchmarked economies and then dropped to $87.3 billion in 2016. Note that total value added declined at the same time actual physical unit production increased due to rapidly dropping prices for end products. From 2014 through 2016, China accrued the largest tVA from manufacturing the four clean energy end products—three to four times higher than that accrued by the next three economies (the United States, Japan, and Germany).

The United States moved from third- to second-highest tVA from clean energy manufacturing of the four technologies over the period. Of the clean energy technologies studied, manufacturing of wind turbine components added the most value to the benchmarked economies, contributing a total of $50.6 billion in tVA to the 13 economies in 2016.

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



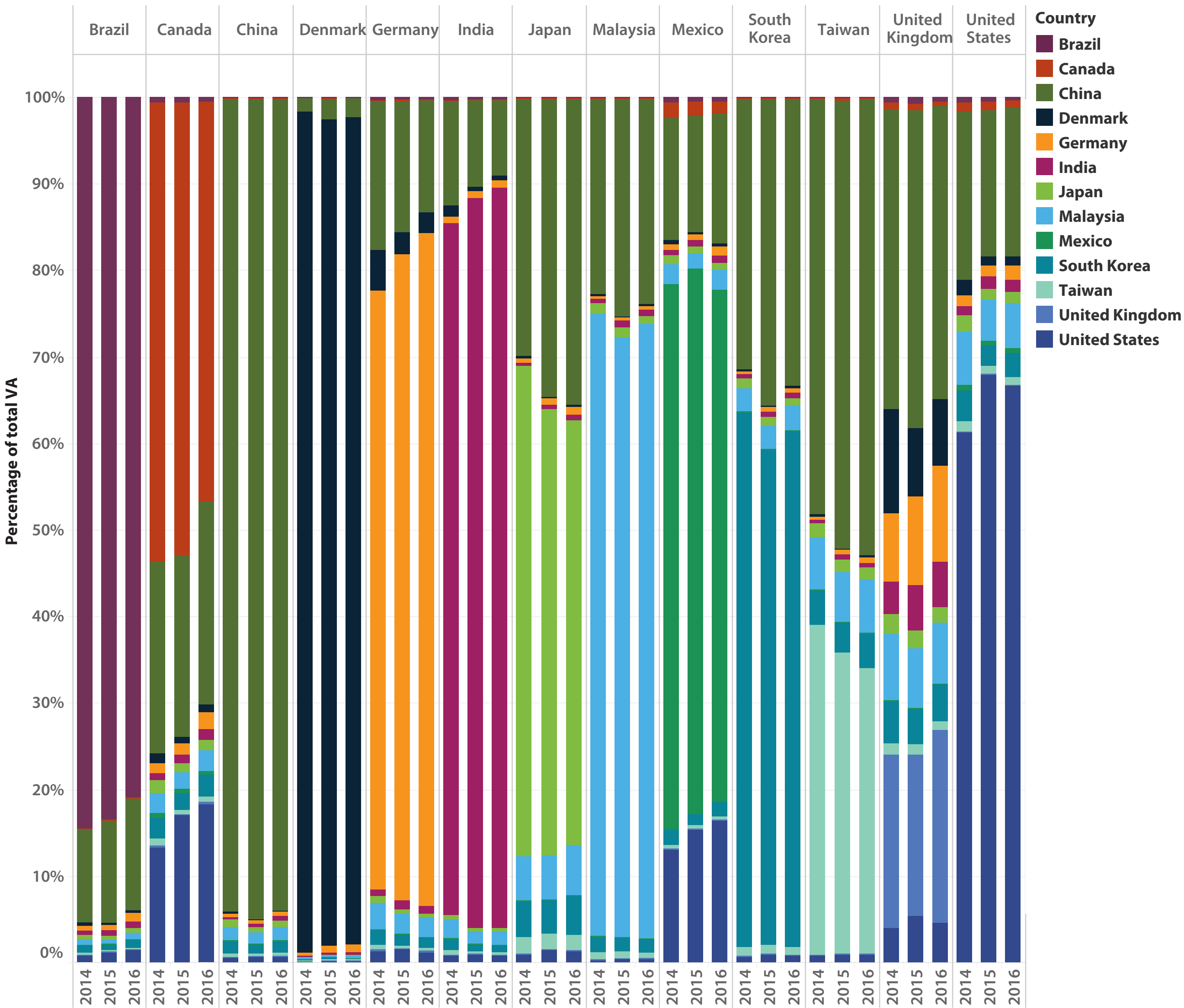
Total value added (tVA) trends in US$(2014) million from manufacturing of four clean energy technology end products in 13 key economies. Economies are ordered by tVA. Note that tVA for China is displayed on a different scale. Data are listed in order of 2016 tVA.

Global Supply Chains

In the benchmarked economies, the greatest share of tVA is generally accrued from domestic production of clean energy technology end products. For most of the studied economies, indirect value added (iVA) from manufacturing raw material and intermediates was greater than direct value added (dVA)[1] over the period, indicating that participation in the broader supply chain that supports clean energy technology end product manufacturing at home and abroad was more important than domestic production of the end product.

Due to global supply chains associated with the production of the four benchmark technologies, all analyzed economies received iVA2 from the production of intermediate materials, subcomponents, or services related to end product manufacturing of PV modules, wind turbine components, LED packages, and LIB 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.

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 through 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).

1. dVA comes solely from domestic manufacturing of clean energy end products.

2. iVA has two components: (1) domestic iVA comes from the broader supply chain that provides domestic inputs used by manufacturers, and (2) non domestic iVA comes from goods and services exported to support manufacturing that takes place in other economies.

Raw Materials in the Manufacturing Supply Chain

Cobalt

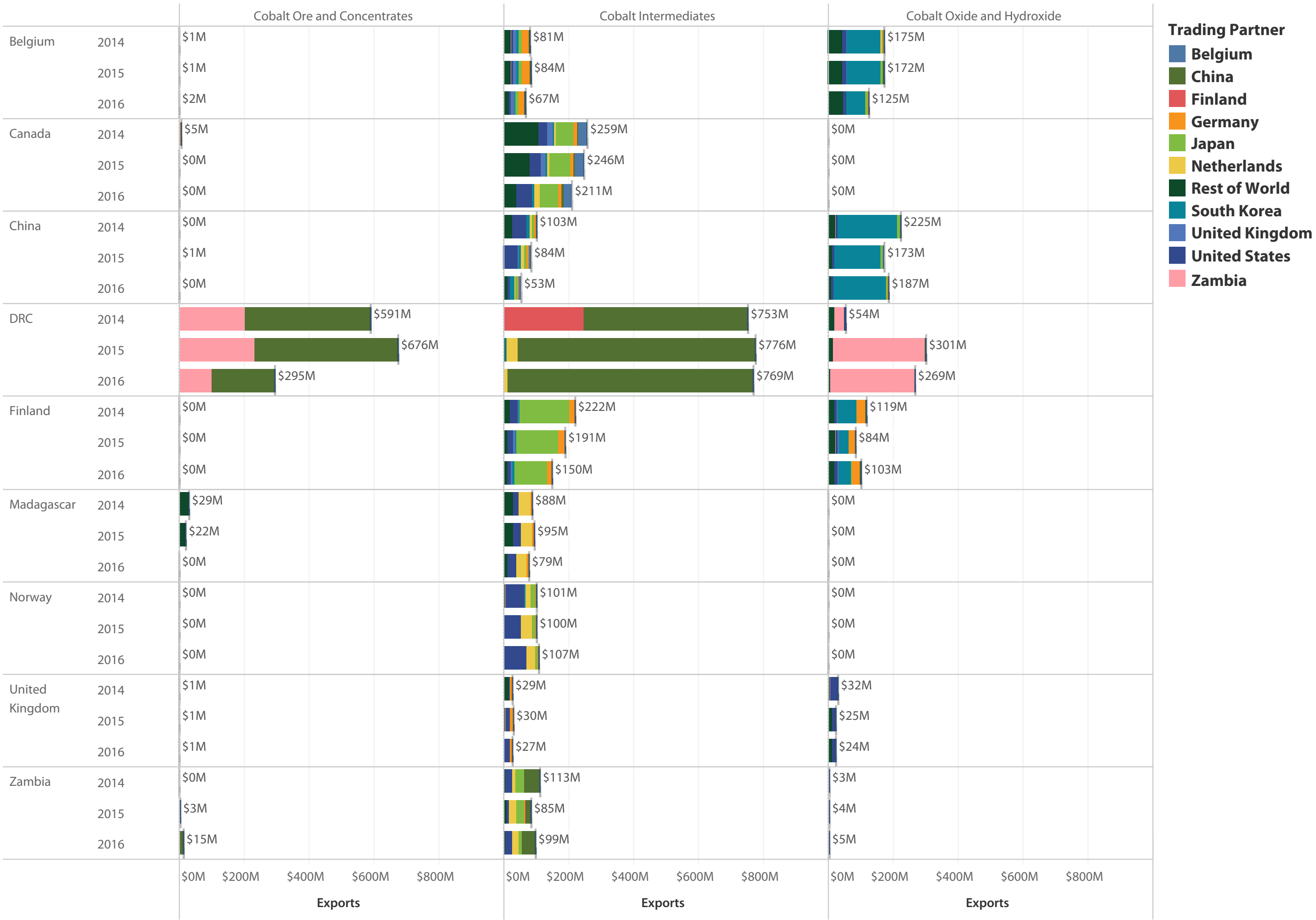
Some of the key raw materials used in manufacturing LIBs include lithium, graphite, cobalt, and manganese. These materials are used to manufacture a range of products, from LIBs for consumer electronics and vehicles to superalloys, hard metals, ceramics, and polymers. Increased deployment of electric vehicles (EVs) with LIBs is driving demand for the raw materials.

Although it is challenging to obtain data, understanding these materials' markets is critical to comprehending the impact of continued EV deployment on mineral production and vice versa. In addition, 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. For the first time, the benchmark report was able to track raw materials for light-duty vehicle LIB cells.

The cobalt supply chain encompasses mining, ore processing to produce concentrates and intermediates, and metal and chemical refining to extract precursor materials. Globally traded cobalt materials include ores and concentrates; intermediate products of cobalt metallurgy, unwrought cobalt, and powders; and oxides and hydroxides. The Democratic Republic of the Congo (DRC) was the leading exporter of cobalt materials, whereas China was the leading importer. From 2014 through 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 billion worth of cobalt materials, almost entirely from the DRC.

Most economies experienced a slight decrease in exports and imports of cobalt over the period, 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.

Cobalt material exports, 2014–2016

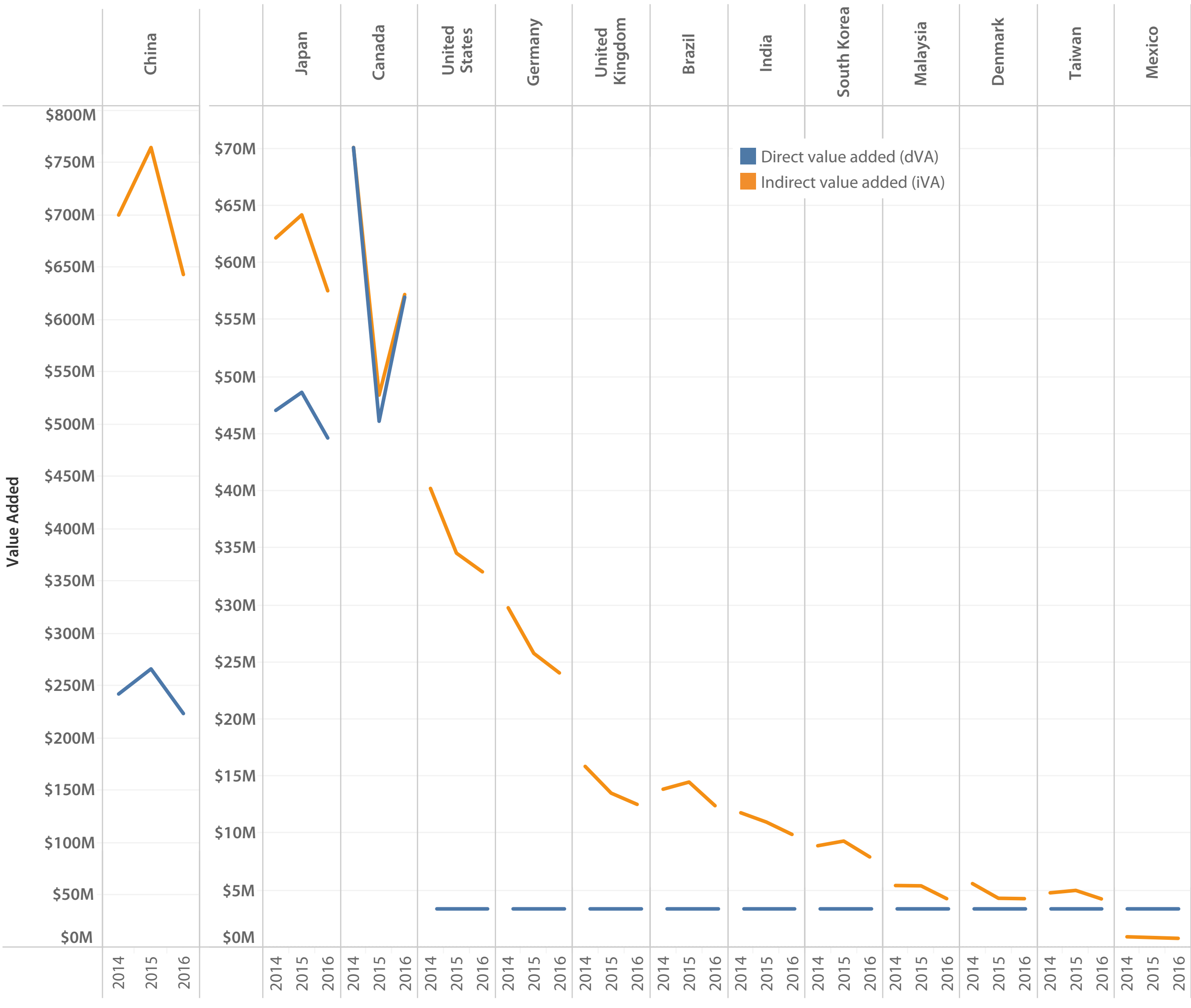


Bars show exports from country listed on left to countries as color coded for three categories of materials: cobalt ores and concentrates (HS-260500); cobalt oxides, hydroxides, commercial cobalt oxides (HS-282200), and cobalt mattes; and other intermediate products of cobalt metallurgy, including unwrought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

Two of the benchmarked economies—Canada and the United States—accrued dVA from domestic cobalt mining, and all 13 benchmarked economies accrued some iVA from cobalt mining in Russia, Australia, Philippines, Canada, and the United States (the five economies for which there is sufficient data). 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.

As the primary cobalt refiner, China accrued the greatest tVA, with $940 billion in 2014, $1 billion in 2015, and $870 million in 2016. U.S. tVA from cobalt refining declined from $40.2 million in 2014 to $32.9 million in 2016. This drop was entirely due to changes in other countries' production levels, because the United States did not refine cobalt during the period.

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.

Conclusion

In the global clean energy economy, manufacturing is the linchpin between technology development and its deployment in the marketplace. As the industry grows and changes based on technology and manufacturing advancements (as well as market forces), data and insights provided by this report can serve as a reference point to track the evolution of clean energy manufacturing across the globe over time. The reported benchmarks over 3 years from 2014 through 2016 provide insight into key trends across clean energy technology manufacturing. These include (1) the relative concentration of global demand for clean energy technologies, (2) global manufacturing capacity and production to highlight opportunities for expansion, (3) global trade activity and interconnectedness across supply chains, and (4) the overall contribution and importance of clean energy manufacturing to national economies. This analysis can inform decisions related to manufacturing facilities for extracting and processing raw materials, producing the array of required subcomponents, assembling final products, research and development planning, and trade.

Learn More

See the CEMAC technical report on this work titled *Benchmarks of Global Clean Energy Manufacturing, 2014–2016*, prepared by Debbie Sandor, David Keyser, Samantha Reese, Ahmad Mayyas, Ashwin Ramdas, Scott Caron, and James McCall. https://www.nrel.gov/docs/fy21osti/78037.pdf.

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.

Front and back page photos from iStock 1018336186

CEMAC
Clean Energy Manufacturing Analysis Center

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 and competitiveness 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.

jisea.org/benchmark.html

NREL/BR-6A50-79692 • May 2021