CEMAC Clean Energy Manufacturing Analysis Center

Energy Innovation Clusters and their Influence on Manufacturing: A Case Study Perspective

Derek Hill
National Science Foundation

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CEMAC is operated by the Joint Institute for Strategic Energy Analysis for the U.S. Department of Energy's Clean Energy Manufacturing Initiative.

Technical Report
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September 2017

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Summary

Over the last decade, the wide-scale adoption of solar photovoltaic (PV) and wind energy—and the emergence of mature and global industries for these two technologies—has coincided with renewed interest in regional innovation clusters. Innovation clusters are geographic concentrations of specialized industries and technologies. Governments seek to develop innovation clusters in their location though policies and funding in order to capture economic value in innovation of advanced energy and other clean technologies.

Innovation clusters have been important for recent development of clean energy technologies and their emergence as mature, globally competitive industries. However, the factors that influence the co-location of manufacturing activities with innovation clusters are less clear. A central question for government agencies seeking to grow manufacturing as part of economic development in their location is how innovation clusters influence manufacturing. Thus, this paper examines case studies of innovation clusters for three different clean energy technologies that have developed in at least two locations: solar PV clusters in California and the province of Jiangsu in China, wind turbine clusters in Germany and the U.S. Great Lakes region, and ethanol clusters in the U.S. Midwest and the state of São Paulo in Brazil. These case studies provide initial insight into factors and conditions that contribute to technology manufacturing facility location decisions.

Key findings from this case study analysis include the following:

- Manufacturing is generally perceived by government decision makers as a key element of an innovation cluster and a tool for economic development through creating jobs, attracting related industries, and increasing tax revenue.
- Co-location of innovation centers with manufacturing activities is more important when product design and manufacturing process technology require close integration, often in early stages of development and commercialization.
- Manufacturing of clean energy components and equipment that have low transportation costs can more easily occur geographically separate from innovation.
- Governments with overlapping jurisdiction over regional clusters may accelerate cluster and subsequently technology development by coordinating regional policies.
- Intrinsic factors such as low-cost labor are widely perceived as important for attracting manufacturing; however, the scale of production and an extensive domestic supply chain appear to be more important factors in capital-intensive clean energy technology manufacturing industries.

This study presents a largely qualitative case study approach to evaluating the relationship between innovation clusters and manufacturing. Because advanced energy technologies represent a discrete and growing sector, patent, trade and market data exist that could be utilized in a geographic information system to better quantify the relationship, which could be a subject of future study for these case locations.

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1 Introduction and Approach

Clean energy technology deployment and associated manufacturing has grown rapidly over the last decade and a half, particularly for solar photovoltaics (PV) and wind turbines. This growth has generally been driven by government policies, rapid improvements in the cost and performance of these technologies, and expansion of large-scale manufacturing capacity. Innovation clusters in solar PV and wind have been important contributors to the development of these technologies and the emergence of mature global industries that manufacture and deploy them.

Over the last decade, the wide-scale adoption of solar PV and wind energy and the scaling up of manufacturing in these industries have coincided with renewed interest in regional innovation clusters. Innovation clusters are geographic concentrations of specialized organizations related to a single technology that have mobile assets—people, money, and information—that facilitate entrepreneurship, innovation, and collaboration (Engel and del-Palacio 2009). Many local and country-scale governments are seeking to support and develop innovation clusters in clean energy and other technologies to generate jobs, economic growth, and tax revenue. The federal government in the United States has implemented new policies since the 2008–2009 recession to support regional innovation clusters, including the National Network Manufacturing Initiative (which includes funding to support advanced clean energy manufacturing).

Today's manufacturing supply chains of clean energy and other technologies are global and highly competitive (Sandor et al. 2017). Manufacturing activities, especially final assembly and low-value production of lighter-weight commodities, increasingly occur in locations geographically separate from innovation activities, such as technology design and research and development. This is particularly true for manufacturing in developed countries. For example, global solar PV companies that have headquarters or operations in the United States have more than 90% of their module manufacturing capacity located outside the United States (Goodrich et al. 2013).

National and regional governments worldwide are striving to develop and enhance their innovation clusters. An important question for these governments is how these clusters may or may not have an impact on the location of manufacturing. The co-location of manufacturing with innovation is generally considered desirable to spur innovation in technological development and manufacturing processes, especially in emerging technologies. Recent research suggests that offshoring manufacturing, especially advanced manufacturing activities, may reduce domestic and global innovation (Fuchs 2014). Regardless of the impact on innovation, national and regional governments may want manufacturing co-located with innovation because they believe manufacturing can generate jobs and other economic benefits for their economies. However, for innovation clusters in commercialized technologies in developed countries, the offshoring of low-value and routine manufacturing activities may make economic sense and may not impair domestically-located innovation (Pisano and Shih 2012).

To consider the influence of innovation clusters on manufacturing, this research looked at case studies of clusters in three clean energy technologies in varying locations—solar PV in California and the Chinese province of Jiangsu, wind turbines in Northwest Germany and the Great Lakes region, and ethanol in the Midwest states and the Brazilian state of São Paulo—to gain insight into factors and conditions related to co-locating or offshoring manufacturing from innovation clusters. Our approach included an extensive literature review of cluster development in general, including theory, history, and associated supporting policies. Particular attention was paid to the current focus of governments on developing innovation activities in clusters and the impact of the globalization of manufacturing on clusters.

For the various case studies, we collected information from the research literature and relevant reports representatives of government agencies (U.S. Department of Energy [Office of Energy Efficiency and Renewable Energy], Ministry of Energy [Ontario]), the U.S. national laboratories involved in research and analysis of the specific technologies (Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory), and industry trade associations (American Wind Energy Association, Canadian Wind Energy Association, Great Lakes Wind Network, and the Solar Energy Industries Association). We examined the six clusters based on the following factors:

- Level of regional economic development
- Type of network—local, regional, integrated within a country or geographic area
- Innovation activities—research and development (R&D), technology transfer, patenting, and access to venture capital, related to both the technology end products as well as the processes used to manufacture them
- Manufacturing location—co-located or geographically separate from innovation cluster
- Type of manufacturing—limited (concept or prototype), selected links of supply chain, or entire economic value chain
- Location of suppliers/range of supply chain—size, local, same country, or international
- Location and size of market for end products and services—local, regional, same country, or international
- Cluster performance—development, nature of competition with other clusters, enduring competitive advantage over other clusters, contributing factors to success or failure, duration of success.

Our case study approach is exploratory and intended to stimulate further and more in-depth research into the factors and conditions that influence the siting of manufacturing in innovation clusters in clean energy and other technologies. The findings from this research are suggestive and derive solely from these six case studies of innovation clusters in three clean energy technologies.

2 Background: Clusters and the Globalization of Manufacturing

Clusters have long been a subject of research and policy interest, dating back to the pioneering study of industrial clusters in the late 19th century by British economist Alfred Marshall. Marshall identified three basic advantages to clusters—a pool of skilled labor, knowledge spillovers, and linkages between and within firms (Wesner and Wolff 2012). Romer (1986) expanded on the concept that knowledge is a form of capital and accumulation of new knowledge is essential for and enables economic growth. Michael Porter's research, starting in the 1990s, stimulated much of the current interest and research in innovation clusters. Porter defined innovation clusters as "geographic concentrations of interconnected companies and institutions in a particular field" (Porter 1998). Clusters include "an array of linked industries and other entities important to competition," including specialized inputs such as components, machinery, services, and providers of specialized infrastructure (Porter 1998).

A number of contemporary scholars have argued that Porter's model does not adequately capture the dynamics of innovation clusters in today's world where human capital, money, and knowledge flow easily across regional and national boundaries. Engel and del-Palacio (2009) define innovation clusters as geographic concentrations of specialized industries and technologies that have mobile assets—talented and highly skilled people, money, and information, including know-how and intellectual property—that facilitate entrepreneurship, rapid innovation, and international collaboration. Innovation clusters utilize their mobile assets in interconnected organizations, including new and existing firms, service providers, financial institutions, research universities, and trade associations. Government may provide support to clusters through enforcement of intellectual property laws, funding of technological development, R&D funding, and financing of research parks, incubators, and public research universities.

Innovation clusters are typically found in areas with a population with scientific and technical skills, often in association with one or more research universities in the region. Early U.S. innovation clusters, such as Silicon Valley for computing and information technology, emerged from interaction of the private sector with major universities that received substantial research funding without organized intervention or coordination by regional, state, or the federal governments (Wesner and Wolff 2012). In other cases, direct public funding, planning, and regulatory support was instrumental for success, such as the Research Triangle in North Carolina (Wesner and Wolff 2012). Countries and regions across the world frequently aim to mimic successful clusters with varying degrees of attainment. Although specific U.S. states and localities have encourage clusters, the U.S. federal government has until recently done little to directly support the formation of state-level innovation clusters, and U.S. federal technology initiatives have tended to be "siloed" and "uncoordinated" (Wesner and Wolff 2012, 438).

The sweeping changes in manufacturing over the last four decades have had a major impact on clusters and government policies that support them. Manufacturing is a critical part of the economic value chain of a technology, which is the system of activities that businesses and workers perform to make a product, deliver it to the market, and support it until the end of its lifecycle (Donofrio and Whitefoot 2015). The globalization of manufacturing has often resulted in the geographical separation of manufacturing activities from innovation activities in many clusters (OECD 2008). Manufacturing activities that are routine or low value have at times been offshored to locales in developing countries that have lower production costs in labor, land, and raw material and/or generous financial incentives.

Innovation clusters in some developed countries have lost manufacturing jobs due to the offshoring of jobs to lower-cost locations, as well as increased efficiency and productivity of manufacturing processes (Donofrio and Whitefoot 2015). For example, the Detroit automobile cluster used to have final-assembly plants located around Detroit, with an entire manufacturing value chain located in Michigan and neighboring Midwest states. Over time, the Detroit "Big 3" automakers began expanding their manufacturing to rural states and Canada, and later, to Mexico, China, and other Asian countries to be closer to markets and to take advantage of other trade and financial benefits (Klier and McMillen 2006). Detroit continues to be a leading innovation cluster with R&D performed by the U.S. and foreign automakers, and with manufacturing strategically located around the world. Because the technology was mature, and as communication systems advanced, manufacturing became geographically disassociated from its innovation center.

Over the last decade, the development of clusters has become a major priority for many countries and regions across the world. In developed countries, governments generally seek to attract or retain high-value or advanced manufacturing activities co-located with innovation activities because past research suggests that manufacturing in proximity to R&D and other innovation activities can help accelerate innovation and technological development (Fuchs 2014). In addition, states or other localities view manufacturing as a tool of economic development that generates jobs, increases economic growth, attracts other industries, and increases tax revenue. More recently, the geographical fragmentation of production and the emergence of globally distributed value chains have allowed countries to enter global markets as component or service suppliers without having to build an entire value chain (OECD/WTO 2013). The participation of many developing countries has allowed them to industrialize faster and has increased global competition for the siting of manufacturing activities (OECD/WTO 2013).

In the United States, the federal government became more engaged in developing and supporting innovation clusters following the 2008–2009 recession. Congress allocated funding through the American Recovery and Reinvestment Act to support regional clusters (Donofrio and Whitefoot 2015). For example, the National Network Manufacturing Initiative (NNMI), started in 2013, is modeled after Germany's Fraunhofer Institutes. The NNMI is focused on developing and commercializing manufacturing technologies through public-private partnerships between U.S. industry, universities, and federal government agencies. Individual U.S. states, including New York, South Carolina, Ohio, New Mexico, and Michigan, have developed comprehensive cluster-development strategies over the past decade (Donofrio and Whitefoot 2015).

In 2009, 26 of the 29 European Union member countries had cluster-development programs at the national level, and since then many Asian and Latin American countries have also implemented cluster strategies (Donofrio and Whitefoot 2015). These strategies include tax incentives and subsidies, heavy investment in university research funding, public-private research collaborations, workforce training programs, early-stage capital funding, and modern science parks.

In developing countries, such as China and India, government cluster policies have targeted the development of both innovation and higher-value manufacturing activities to increase indigenous innovation and economic growth. For example, China's "Made in China 2025 Plan" will provide $300 billion in government assistance for Chinese companies to become global leaders in innovation and production in ten emerging high-technology manufacturing industries (New York Times 2017). The plan provides subsidies for R&D and assistance for Chinese companies to acquire foreign companies in these industries, and create domestic employment in high paying and skilled jobs in areas including R&D, design, and marketing.

3 Case Studies of Innovation Clusters of Three Clean Energy Technologies

The following case studies explore clusters of innovation and technologies and their influence on manufacturing.

3.1 California and Jiangsu Solar PV Clusters

California's solar PV innovation cluster is a leading-edge technology cluster that currently has no associated large-scale manufacturing. The cluster originated more than four decades ago driven by state government policies supporting solar. California is a leader in solar PV electricity generation, with a 5% share of global solar PV cumulative capacity installed as of 2015.[1] California is also a knowledge center, with top-tier research universities, federal laboratories, and businesses that conduct R&D in advanced semiconductor-related technologies. Silicon Valley's venture-capital investment in solar PV technologies, and knowledge spillovers from established solar PV companies, new start-ups, and entrepreneurs, have enhanced its knowledge base and technological development (Gibson et al. 2013). However, California's current PV manufacturing activity is limited to small-scale fabrication of prototypes of next-generation solar PV technologies. Although several multinational solar PV companies have offices in California, their solar PV manufacturing primarily occurs offshore in Asian countries.

California's more than 40-year-old solar PV cluster had a global first-mover advantage largely driven by concerted and supportive policies by the state government (Gibson et al. 2013). The state government has provided a number of market-based and financial incentives over the last four decades to encourage residential and commercial solar PV installation (Yudken 2011). The federal government's investment tax credit also stimulated installation of solar PV. California became a major solar PV manufacturing center in the 1980s and 1990s when the United States was a major global solar PV manufacturer (Figure 1). Starting in the early 2000s, California lost market share to other countries as well as to other U.S. states as PV manufacturing outside of California dramatically increased. California also did not provide sufficient incentives to manufacturers to maintain its solar PV manufacturing base (Gibson et al. 2013). Several other U.S. states provided more appealing tax and other financial incentives and were successful in attracting solar PV manufacturing (PV Magazine 2015),[2] with manufacturing centers now in Washington, Oregon, Michigan, and Mississippi,[3] with the bulk of global manufacturing in Asian countries (Figure 2).

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[1] According to SEIA/GTM Research, California had installed 11,987 megawatts (MW) at the end of 2015 compared to 225,600 MW globally (source: International Energy Association).

[2] PV Magazine (2015). Solar PV manufacturing has recently expanded in Ohio, Oregon, Michigan, New York, and Texas. Three of these states—Michigan, New York, and Texas—have financial incentives or provided cash for solar PV manufacturing.

[3] See map at Clean Energy Manufacturing Analysis Center weblog, PV in the USA, March 2017, http://www.manufacturingcleanenergy.org/blog.html.

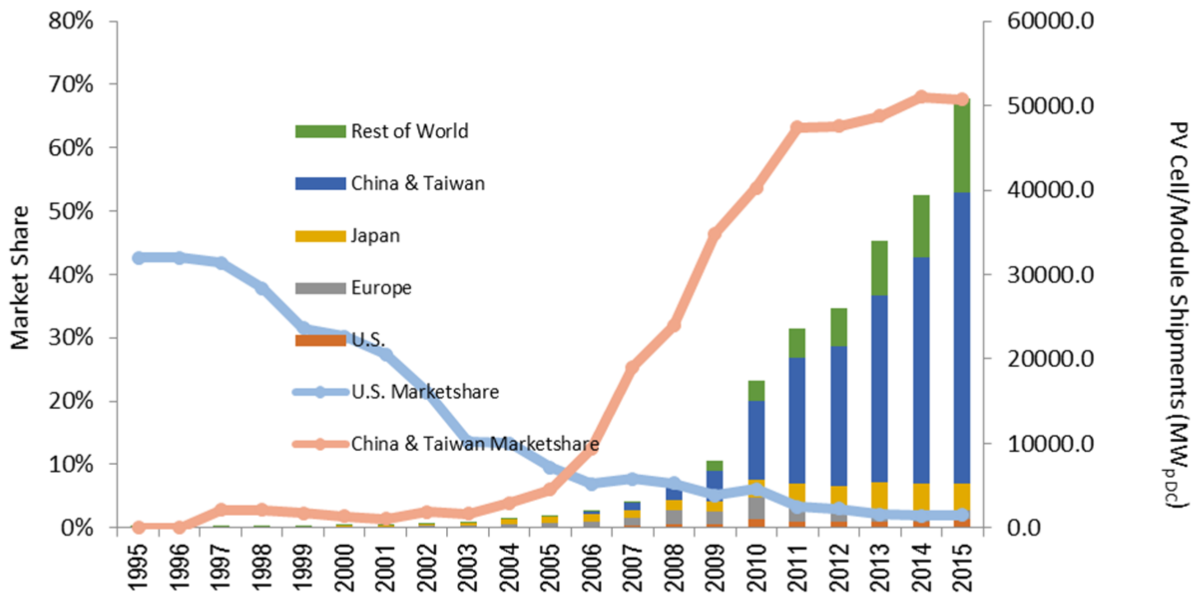

Figure 1. Photovoltaic manufacturers' shipments by selected region/country: 1995–2015
(Sources: Mints 2011; Mints 2016)

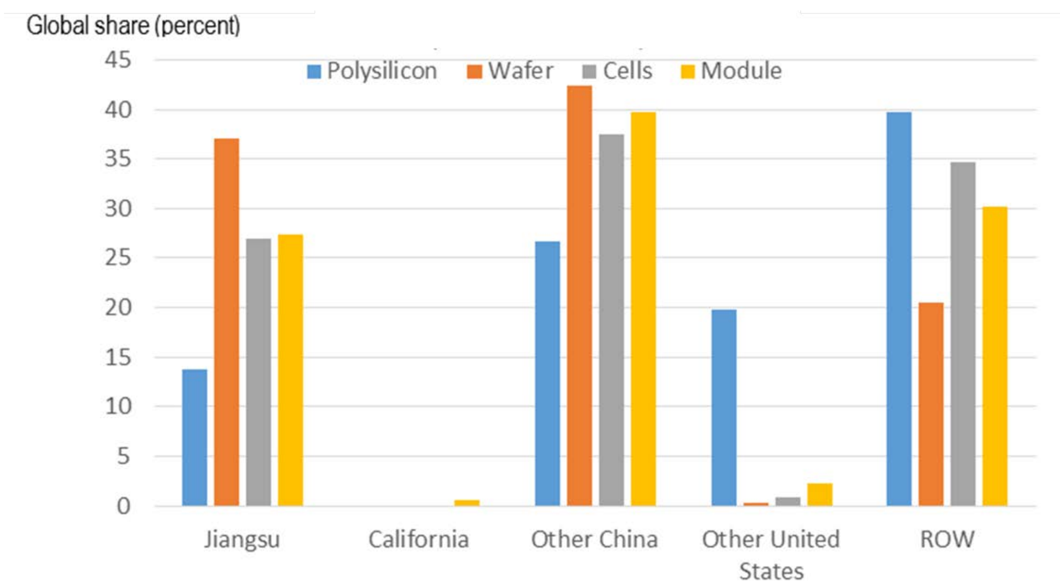

Figure 2. Solar PV manufacturing capacity of California and Jiangsu, by major component: 2013–2014
(Source: National Renewable Energy Laboratory 2013/2014)

The Chinese province of Jiangsu is a leading global manufacturer of solar PV cells and modules driven by supportive government policies. Jiangsu has solar PV production plants that have among the largest capacity in the world and an extensive supply chain of supplier companies and raw materials inputs. Jiangsu is an emerging technology center, with R&D conducted by universities, firms, and government laboratories.[4] The province has several science parks with

[4] For more information on Jiangsu's knowledge cluster, see Lan, Chen, and Wu Bo (2013).

solar PV companies and R&D firms. The huge increase in global demand for solar PV in the mid-2000s, resulting from rapid expansion of PV deployment in Germany and other countries, including China, led to rapid growth of the Jiangsu manufacturing cluster, which had much lower labor costs relative to developed countries (Quiang et al. 2014). The provincial government provided subsidies for land, installation of factories, electricity, and finance (Goodrich et al. 2013). Jiangsu also rapidly scaled up its manufacturing capacity and built an extensive domestic supply chain (Goodrich et al. 2013). However, the glut in solar PV manufacturing in 2011 led to financial difficulties, bankruptcy, and consolidation of the PV manufacturing industry in Jiangsu (Ball 2013). In addition, the United States and the European Union imposed anti-dumping tariffs on imports of solar PV products from China beginning in 2012, which adversely affected Jiangsu-based manufacturers. Following a two-year slump, the Jiangsu solar PV manufacturing cluster began to recover, helped by the growing demand for solar PV installations in China.

Although larger Jiangsu-based solar PV firms made important incremental engineering advances in solar PV production, Jiangsu's capacity for developing next-generation technologies remains limited (Deutch and Steinfeld 2013). In this way, the Jiangsu cluster began with manufacturers and is building its innovation capacity, whereas California started with innovation, built co-located manufacturing, then lost its dominance in manufacturing.

3.2 Northwest Germany and U.S. Great Lakes Region Wind Clusters

Northwest Germany, including the states of Niedersachsen, Nordrhein-Westfalen, Sachsen-Anhalt, and Schleswig-Holstein,[5] is a leading wind turbine innovation cluster that benefited from supportive government policies. Germany today is a leading country in wind energy generation, with a global share of 10% of cumulative installed capacity (REN21 2017). Germany has had long-term, consistent, and supportive policies that made it an early leader in both wind capacity and generation as well as wind technology manufacturing (Boeckle et al. 2010). Most of these government policies have been on the demand side (such as feed-in tariffs), with coordination by federal and state governments and cooperation and input from labor and industry. The wind innovation cluster emerged as installations of wind turbines increased rapidly starting in the 1980s. Turbine manufacturers, wind farm operators, and research institutions agglomerated in a strong cluster in northwest Germany (Boeckle et al. 2010).

Germany's wind turbine innovation cluster is a network of large German and foreign corporations, small and medium-sized firms, federal and state government agencies, and a variety of research organizations. The government's demand-side policies combined with government sponsored economic development in key states with existing but declining industry sectors spurred an increase in wind manufacturing and led to the build-up of an extensive supply chain of subcomponents that utilized and transferred skills and equipment from

[5] German Wind Energy Association, 22 March 2017, https://www.wind-energie.de/en/press/press-releases/2017/wind-industry-strong-employer-germany.

Germany's turbine and machine-building manufacturing industries (Boeckle et al. 2010). This cluster is a major global producer with highly productive and technologically sophisticated firms that manufacture the main components—blades, nacelles, and towers—and an extensive supply chain of firms that manufacture subcomponents. Technology transfer and use of skilled labor, equipment, and plants from Germany's turbine and machine-building manufacturing industries played a key role in this clusters success (Boeckle et al. 2010). Germany is a major exporter of wind turbine components especially throughout Europe, attesting to its high-quality advanced technology and the global competitiveness of its industry (Boeckle et al. 2010). Germany is a major player in the technology and manufacturing of offshore wind turbines that are concentrated in the Baltic and North Sea (The Wind Energy Industry in Germany, 2014).

The Great Lakes region comprises eight U.S. states—Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin—and the Canadian province of Ontario. The Great Lakes region has substantial wind energy capacity, with a 4% global share of cumulative installed capacity.[6] The innovation cluster consists of research institutes, research universities, and industry that perform or fund wind energy R&D and technological development. The U.S. Department of Energy has funded wind R&D activities in several of the Great Lakes states. Western University in Ottawa has the world's most-advanced wind tunnel. The Great Lakes manufacturing cluster primarily manufactures wind subcomponents that supply assembly plants of the main components—blades, nacelles, and towers—located in several states, including Texas, Iowa, and Colorado, and in other countries (Figure 3).

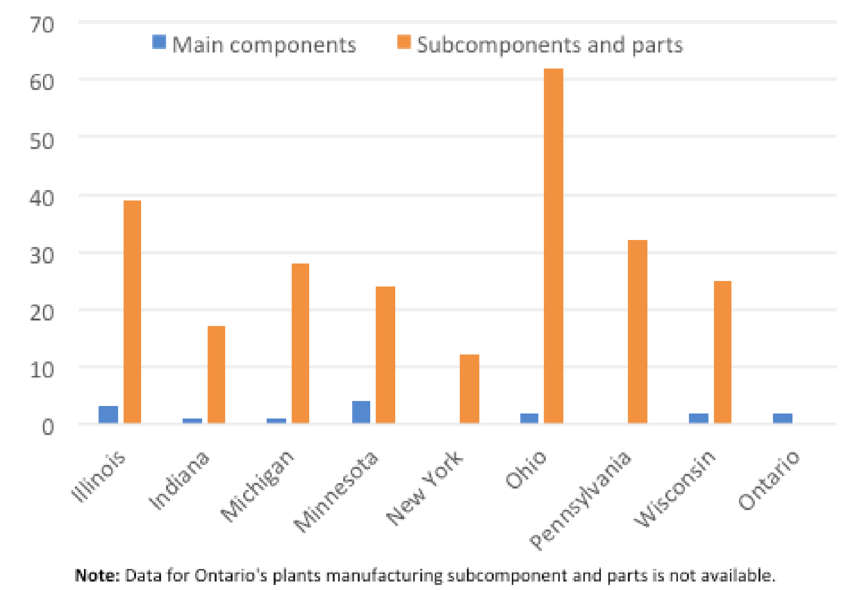

Figure 3. Number of wind manufacturing plants in Great Lakes region
(Sources: AWEA, 2016; Ontario Ministry of Energy, 2016)

[6] Sources: Global Wind Energy Council (global wind energy generation); America Wind Energy Association (wind energy capacity of Great Lakes U.S. states); Canadian Wind Energy Association (wind energy capacity of Ontario).

Key technology demand-side policies that have supported this wind cluster include the renewable portfolio standards adopted by the eight Great Lakes states and other U.S. states, as well as Ottawa's 2009–2013 feed-in tariff program. Government policies that encourage manufacturing have included the U.S. government's investment tax credit and various tax incentives and other programs implemented by the Great Lakes states during and following the 2008–2009 recession. Ottawa's feed-in-tariff program had a domestic content requirement that spurred the construction of wind manufacturing plants.

Some wind components (blades, towers) are large and difficult to transport thus providing incentive to be made within the country of installation; however, the subcomponents within the nacelle are more easily transported and the retention of the manufacturing of these technologies appears to be supported by a strong cluster of skilled labor and relevant supply chains. The Great Lakes region's pre-eminence in other manufacturing industries—automotive, fabricated metal parts, and machinery manufacturing—played a key role in the development of the wind industry through transfer of technology, use of skilled labor from these industries, and use or conversion of plants in these industries.

3.3 São Paulo and Midwest U.S. States Ethanol Clusters

The state of São Paulo in Brazil is a leading ethanol technology and innovation cluster that originated from government policies. The state of São Paulo produces nearly half of Brazil's sugarcane ethanol. Brazil is the second-largest global producer of ethanol behind the United States and the largest producer of sugarcane ethanol.[7] Sugarcane ethanol is a major source of energy for Brazil, accounting for one quarter of Brazil's fuel consumption in 2016.[8] The federal government and São Paulo's government have both provided supportive long-term policies for many decades that have been instrumental in developing domestic ethanol markets and ethanol production-related knowledge and manufacturing capability (Cortez et al. 2014). The federal government initially intervened in the sugarcane and ethanol markets by establishing price floors and production and fuel-blending mandates for ethanol (DeWitt et al. 2009). The federal government also provided funding for the infrastructure to supply ethanol fuel and subsidized financing for construction of ethanol biorefineries (Berger 2010). After ending its interventionist policies in the 1990s, the federal government continued to support sugarcane ethanol with: a minimum ethanol-blend mandate that is adjusted to market conditions; tax incentives that lowered the cost of ethanol; and tax incentives to develop the technology and usage of flex-fuel engines (DeWitt et al. 2009).

São Paulo's knowledge cluster is a world leader in ethanol production technology development with an extensive network of government agencies, research universities, industry, and research institutes that conduct or fund research on sugarcane ethanol and other biofuels

[7] Sugarcane ethanol has higher energy density and lower production costs than corn ethanol (Pimentol 2007; Mejean 2010).

[8] Total motor fuel consumption in Brazil in 2016 was 27.4 million gallons consisting of 6.7 million gallons of sugar ethanol. Source: Brazilian Sugarcane Industry Association (UNICA).

technologies (DeWitt et al. 2009). São Paulo has an extensive infrastructure for supplying ethanol to its domestic market and is a major agricultural producer of sugarcane. The manufacture of sugarcane biorefineries is largely conducted by a few large multinational firms that produce many of the large components--milling devices, jet-cookers, fermentation tanks, distillation columns, and rotary drum dryers.[9] The high transportation costs associated with these components often means that manufacturing occurs in close proximity to the location of the biorefinery. Government, industry, and firms are now shifting R&D to cellulosic and other second-generation biofuel technologies. In the emerging cellulosic ethanol technologies, R&D and manufacturing process technology are generally closely integrated to spur innovation in both areas.

The Midwest U.S. states have a leading innovation and manufacturing cluster in corn ethanol fuel that is supported by government policies. The Midwest states account for nearly 90% of corn ethanol fuel produced by the United States, the world's largest producer of ethanol,[10] and are the largest agricultural producers of corn in the country.

Federal and state policies have played an important role in developing the U.S. Midwest ethanol cluster. The most important federal policy has been the Renewable Fuel Standard (RFS), which established mandated and progressive increases in ethanol content in fuel (Urbanchuk 2010). The federal government provided credits to automobile manufacturers under the Corporate Average Fuel Economy program to incorporate in new vehicles flex-fuel engines that can run on any combination of gasoline and ethanol. As the federal and state governments have not supported the development of an extensive infrastructure to supply the appropriate gasoline-ethanol blends (up to 85% ethanol) for motor vehicle fuel, the benefits of the flex-fuel engine have not been fully realized (Berger 2010).

The federal government imposed a tariff between the 1980s and 2011 on imports of ethanol, mainly to curb imports from Brazil, effectively shielding the U.S. ethanol industry from competition (Solomon, Barnes, and Halvorsen 2007). Many of the Midwest states have provided tax incentives to encourage both consumption and production of ethanol. Production of ethanol increased rapidly over about a decade through 2015, driven by these government policies, especially the RFS. Production of ethanol plateaued in 2015–2016 due to the plunge in oil prices and the end of large increases in corn ethanol incorporation in fuel as mandated by the RFS. Although the demand and supply-side policies have greatly increased ethanol production, the lack of infrastructure development has hindered the more widespread

[9] Conversation on May 4, 2017, with Liz Gyekye, editor of International Biofuels magazine. Debbie Harding (ICM). ICM is a U.S.-based multinational company that manufactures components and equipment that are used in the majority of U.S. ethanol plants, http://www.icminc.com/index.php.
[10] Renewable Fuels Association, Industry Statistics, http://ethanolrfa.org/resources/industry/statistics/.

adoption of corn ethanol. In 2016, ethanol accounted for 10% of U.S. fuel consumed in the United States, significantly below 25% share of fuel consumption in Brazil[11] (Figure 4).

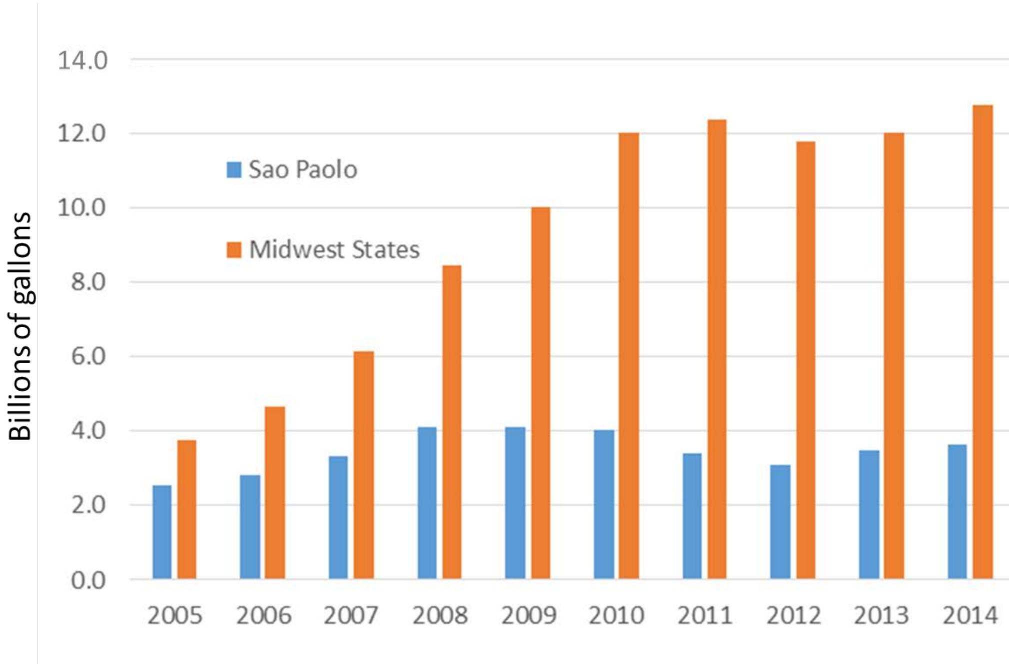

Figure 4. Ethanol fuel produced by U.S. Midwest states and São Paulo: 2005–2015
(Sources: EIA 2016; UNICA 2016)

The Midwest states have an extensive knowledge center, with R&D performed by universities, industries, and other organizations, such as the Great Lakes Bioenergy Research Center. The manufacture of corn ethanol biorefineries in the Midwest is similar to the manufacture of sugarcane biorefineries in Brazil: a few large multinational firms produce many of the large components in generally close proximity to the biorefinery's location.[12] Federal government R&D has shifted to cellulosic and other advanced biofuels technologies. In the emerging cellulosic technologies, as in Brazil, manufacturing is done in close geographic proximity to R&D because R&D and manufacturing process technology must be closely integrated to spur innovation in both areas, as well as transportation of the biomass feedstock.

[11] In 2016, total fuel consumption in the United States was 144.3 billion gallons consisting of 14.4 billion gallons of corn ethanol fuel. Source: Energy Information Association.

[12] Conversation on May 3, 2017 with Debbie Harding (ICM). ICM is a U.S. based multinational company that manufactures components and equipment that are used in the majority of U.S. ethanol plants, http://www.icminc.com/index.php.

4 Findings

Our approach of using case studies is exploratory and intended to stimulate further and more in-depth research in the factors and conditions that influence the co-location of manufacturing with innovation clusters in clean energy and other technologies. The findings from this research are suggestive and derive solely from these case studies of innovation clusters in three clean energy technologies.

Our findings from these three case studies suggest that there are several factors that may influence the geographic proximity of innovation activities and manufacturing:

Manufacturing is generally perceived by government decisionmakers as a key element of an innovation cluster and a tool for economic development through creating jobs, attracting related industries, and increasing tax revenue. Modern manufacturing is globalized and highly efficient, therefore regions and countries compete intensely to attract energy technology manufacturing through supportive government policies. In the Great Lakes wind case study, tax breaks and other financial incentives by the various U.S. state governments and the province of Ontario were instrumental in attracting firms. The advance of ethanol manufacturing in both Brazil and the Great Lakes supported local supply chains from farm to distribution. While California had a lead in PV cell and module manufacturing, the state did not provide as many incentives to retain its manufacturers compared to several other U.S. states and other countries in the late 2000s. As a result, California lost its manufacturing lead while retaining some of its innovation.

Co-location of innovation centers with manufacturing activities is more important when product design and manufacturing process technology require close integration, often in early stages of development and commercialization. For technologies where manufacturing processes and product design must be developed in tandem, the co-location of innovation activities with manufacturing is valuable and may help promote innovation. These types of technologies are typically nascent or emerging and/or have very complex and sophisticated manufacturing processes (Pisano and Shih 2012). On the other hand, for mature or commoditized technologies where the major characteristics of the product are generally not influenced by the production process, R&D and manufacturing can operate independently of each other and the separation of innovation from manufacturing generally does not harm innovation (Pisano and Shih 2012). Crystalline silicon PV technologies initially benefitted from close development of PV cell and manufacturing innovations. In more recent years, module manufacturing became more fully commercial-scale and the innovation centers and manufacturing disassociated. While the more mature ethanol conversion technologies do not require close integration of R&D and manufacturing process technologies, the ethanol case study suggests that the emerging cellulosic technologies may require that R&D and manufacturing be closely integrated, and co-located in the near-term, to ensure continued technology innovation. The large companies in United States and Brazil that are developing demonstration and full-scale cellulosic biorefineries generally have manufacturing located in close proximity to R&D to help drive innovation in both the technology and the manufacturing process.

Manufacturing of clean energy components and equipment that have low transportation costs can more easily occur geographically separate from innovation. The case for geographical separation of innovation from manufacturing is particularly strong where product design, manufacturing process technology, and end consumers do not require close integration. In the manufacture of clean energy technology components or manufacturing equipment that are costly to transport, manufacturing generally occurs near or at the location of both critical supply chain components and the final market or the end product assembly facility. In the PV case study, California and other U.S. states lost initial market share as Jiangsu and other Chinese provinces rose to become global low-cost producers (and consumers) without initial innovation capability. The manufacturing of very large wind turbine blades and towers generally has to occur relatively close to the end market and innovation clusters have often located near the renewable resource. Due to transportation challenges, location decisions for biorefineries have to balance both the location of end use demand for ethanol as well as the location of feedstock supply. Therefore biorefineries cannot always be sited near innovation centers.

Governments with overlapping jurisdiction over regional clusters may accelerate cluster and subsequently technology development by coordinating regional policies. Advanced economies in Western Europe and Asia are reorienting themselves around robust urban clusters of advanced industries, whereas American policy-making is largely formulated by individual states and cities (Khana 2016). The U.S. federal government currently provides minimal support for regional economic efforts and strategies (Khana 2016). The Great Lakes states and the province of Ontario implemented their own separate policies to encourage wind manufacturing within their own political boundaries. In the worst case, the various entities were essentially competing among each other to attract manufacturing; in the best case, the lack of coordination and regionally-consistent policies likely did not maximize the development of manufacturing from a regional perspective. The ethanol case study also suggests that while the demand and supply-side policies of the federal and state governments have greatly increased ethanol production, the Midwest states could have done more to coordinate and make their policies consistent for attracting and developing the biorefining supply chain.

Intrinsic factors such as low-cost labor are widely perceived as important for attracting manufacturing; however, the scale of production and an extensive domestic supply chain appear to be more important factors in capital-intensive clean energy technology manufacturing industries. These latter two factors provide several advantages, including greater access to, and lower cost of, capital, along with direct cost benefits due to enhanced supplier leverage. In addition, average capacity utilization of equipment and use of automation generally rises with scale, reducing output-adjusted capital and labor cost (Goodrich et al. 2013). Manufacturers near clusters may also experience lower operating costs because of the benefits they derive from being in a cluster of dense, specialized production fed by a network of suppliers and supply chains (Goodrich et al. 2013). Labor costs account for less than 10% of production in capital-intensive manufacturing industries such as solar PV and wind (Deutch and Steinfeld 2013). The wind cluster case studies suggest Germany has relatively high labor costs, yet it is a major global manufacturer of wind turbines, benefiting from research advancements and building from robust supply chains to create at-scale manufacturing serving the European region. Public support can also encourage scale-up, especially in a region with existing industry and established leading manufacturers. In the case of Jiangsu, the provincial government subsidized domestic solar-panel production by providing land-use rights, energy subsidies, loan guarantees, tax rebates, and research funds, that spurred the installation of factories with some of the largest capacity in the world (Gang 2015). These measures are routinely used by national, sub-national, and local governments worldwide, including in the United States, to attract business (Deutch and Steinfeld 2013).

5 Conclusions

Manufacturing and deployment of clean energy technologies, along with innovation activities that can improve their performance or reduce their cost, will likely continue grow for the foreseeable future, driven by the increasing competitiveness of clean energy with conventional sources, as well as concern over climate change, regulations limiting atmospheric emissions, and energy security. Countries, regions, and clusters are likely to compete intensely to capture the income and jobs associated with both established and emerging clean energy value chains, which span technology development, manufacturing, and installation. In addition to a focus on manufacturing, many countries have been improving their innovation capabilities through development of a skilled workforce, capital investment in research and manufacturing facilities, collaboration with established innovation clusters, increasing the quality of their universities, and strengthening their institutions, including intellectual property protection. The competition among governments to attract clean energy manufacturing to their jurisdictions will also likely continue to be intense because of the willingness of many national and regional governments to provide financial and policy incentives.

Governments seeking to attract or retain manufacturing in close geographic proximity to an existing innovation cluster or to create a new innovation cluster as a stand-alone activity may carefully consider the following factors in their location: the type of technology (emerging vs. mature); the need for R&D and manufacturing to be co-located to drive innovation in both areas; suitability of their locale for manufacturing, including related industries, skilled labor, access to supply chains, raw materials, and customers; energy costs; and capital costs. Because competition for siting manufacturing is intense, governments may want to carefully weigh the costs and benefits of providing financial incentives.

This study focused on three interesting case studies to make qualitative comparisons, similar to past literature on innovation clusters that has also largely been based on frameworks and case examples. For advanced energy technologies, quantitative databases exist that measure technology development, manufacturing, trade, and deployment, such as patents, global trade flows, manufacturing value, and market reports for manufacturing output and deployment. Conceivably, these data could be used in conjunction with geographic information systems, to model the success of innovation clusters and their relationship to manufacturing facilities, then compare these results to the intrinsic and policy conditions of each region to more precisely identify success factors for clusters and manufacturing. This more quantitative approach would enable an increased level of confidence for policy decisionmakers and manufacturers in advancing clusters as a development strategy.

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