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Government policy and the evolving networks of innovation in Japan's photovoltaic industry, 1961-2014

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Abstract

In the context of the renewed interest on innovation in renewables, this paper examines the evolution of Japan's photovoltaic industry. Over the decades, government policies on renewables have focused on photovoltaics, which convert solar rays into electricity. This paper identifies several policy regimes over the history of the Japanese industry. Using patent data, this research looks at the relationship between the changes in policy regimes and the evolving networks of innovation; from autarkic to more open innovation within and beyond national borders. This paper may be of use for firms who wish to examine the relationship between government policy and the evolution of innovation networks in the Japanese context. For academics and policymakers, it may be of use in considering the relationship between policy regime changes and its impact on innovation networks.

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Introduction

Amidst recent concerns over energy security, there has been a growing call for a diversified energy mix, away from traditional fossil fuels and nuclear energy, toward green energy: from wind to biomass. This call for alternative sources of energy has intensified in the wake of Japan's Fukushima nuclear accident on 11 March 2011. Public opinion in Japan – as well as overseas – came to cast greater doubt on our over reliance on nuclear energy. Part of the solution might be to invest in innovation that might improve the safety and efficiency of nuclear power plants. Another part of solution may be to invest in innovation concerning renewable energy, such that these might become a viable alternative to the dominant energy sources. Innovation in this context might manifest in a number of ways: from lowering the cost of production; enhancing the safety of devices; developing/using better materials; to increasing the efficiency of energy generation.

The concerns over energy security has led many in Japan, including policymakers, to call for a more diversified energy mix and a shift away from traditional fossil fuels and nuclear energy, toward green energy, including photovoltaics. This push for alternative sources of energy has intensified in the wake of Japan's Fukushima nuclear accident on 11 March 2011, which caused public opinion in Japan, as in some other countries, to turn against nuclear energy. An awareness of the drawbacks of current solar electric technology, which include high cost, has prompted Japanese policymakers to encourage innovation in photovoltaics so that the technology can become a viable alternative to traditional energy sources. Innovation in this context might manifest in a number of ways: from lowering the cost of production; enhancing the safety of devices; developing/using better materials; to increasing the efficiency of energy generation.

The attempts to encourage innovation in Japan's renewable energy sector have taken place against a backdrop of deregulation in the electricity industry. Inspired by the examples of the US and the UK, Japan is deregulating its electricity industry, which will break the 10 regional monopolies that have long dominated the Japanese market. There are multiple reasons behind this move, from lowering electricity costs to stimulate the economy to ensuring a stable supply of electricity on the national grid in the wake of the Fukushima nuclear disaster. In April 2015, the government initiated the first of a three-stage process of deregulation, creating an independent regulator referred to as Organization for Cross-regional Coordination of Transmission Operators (OCCTO). The second phase of electricity deregulation in Japan is planned for 2016, and will permit new firms to enter the sector. The third phase is expected in 2020, when generators and transmitters of the grid are to be operated by different firms. It is the second phase of retail electricity deregulation commencing in 2016, which will also enable innovative renewable energy firms to expand their presence in the Japanese market.

In the context of the renewed interest on innovation in renewables, this paper examines the evolution of Japan's solar energy industry. In particular, it looks at the role of public

innovation policies in photovoltaics, which are devices that convert sunlight into electricity. In Japan, the photovoltaic industry is now over half a century old, and its trajectory – as in other countries – is intricately entwined with the evolution of government policy, external shocks (whether energy crises or natural disasters) and globalization. In fact, around the millennium, Japan had the world's largest market for photovoltaics, and leading firms such as Sharp and Kyocera remain one of the leading global players in this industry to date. As Japanese firms transition from firm-based to network-based innovation, the paper also hopes to examine the relationship between government policies and the evolving networks of collaboration between research organizations (universities and national laboratories) and the private sector.

In the following pages, the paper will first outline the research aim, then discuss the relevant literature. It will then elaborate on the research methodology employed to examine the evolution in the networks of innovation in Japan in the photovoltaics industry. The article will provide an overview of industry evolution in Japan, based on a combination of existing primary and secondary sources. The paper will conclude by summarizing the empirical and theoretical contributions of the research.

Research questions

This research project is concerned with the role of the government policies in the development of new knowledge intensive industries through a case study of the photovoltaics industry. My first research question is: how have Japan's policies governing solar energy evolved between 1990 and 2014? My second research question is: how have networks of innovation evolved in the solar energy industries? With patent data, I wish to look specifically at how networks of collaboration between research organizations and the private sector have evolved. I plan to examine the relationship between changes in collaboration patterns over time, and the significance of factors such as government funding, corporate entity, or geographic location. I will further consider whether the nature of innovation in this industry has evolved over time, and to what extent that has remained compatible to the institutional environment in Japan.

My third research question is: how have changes in the Japanese government's solar-energy policies affected networks of innovation in the sector in the period 1990 to 2014? The solar-energy policies of the Japanese government changed dramatically at several points covered by my historical study, with support being alternatively offered, withdrawn, reintroduced, and then restructured. As the country switched from one solar-power energy regime to another, how did innovation networks respond?

Literature review

On innovative competences

The paper is informed by the discussions on innovation debated in the comparative capitalism literature. Numerous scholars have suggested that differences in institutional arrangements shape innovative behavior (Hall and Soskice, 2001, Whitley, 2002, Allen, 2013). In their seminal paper, Hall and Soskice (2001) outlined two ideal types of capitalist variety: "liberal market economies (LMEs)" such as the United States and Britain, and "coordinated market economies (CMEs)" such as Japan and Germany.

This scholarship has suggested that LMEs, or countries whose markets that feature arms-length transactions, competitive relationships and formal contracting, will engage in radical innovation. Conversely, those located in coordinated market economies, or countries that feature extensive relational and incomplete contracting, network monitoring, and collaborative relationships, will engage in more incremental innovation. Subsequent scholarship has questioned this association, not least due to the small number of countries studied to arrive at this proposition.

As well, Japanese innovation in the second half of the twentieth century was generally characterized as being led by private, rather than government investment, through large rather than small firms, and via intra firm rather than inter firm collaboration. The long-term employment patterns observed in Japan also encouraged firms to develop firm specific forms of tacit knowledge and enhance strengths in incremental innovation (Odagiri and Goto, 1993, Goto 2000). Robert Kneller, for instance, referred to an "autarkic" form of innovation (Kneller 2003) In this context, the nature of innovation required in the photovoltaics industry were more compatible to Japan's institutional environment compared to industries such as biotechnology of software. Yet given the opportunities and competition arising from globalization, firms have increasingly engaged in more open and network based innovation so as to compete with ever-increasing technological complexity. In this regard, it is also timely to ask the role of the state in nurturing innovation in a frontier industry in a global environment, where firms are able to leverage institutional diversity at regional and international levels.

On the evolution of the energy industry

Given the growing public interest in climate change, environmental issues and energy security, numerous scholars have elaborated on the evolution of the energy industry in recent years (Yergen 1994, 2008, Schmid 2015, Clayton 2015). For instance, business historians in recent years have increasingly looked at the dynamic interactions between the state, business

and institutions in the evolution of industry around the world, whether in Italy (Schisani and Caiazzo 2016), Sweden (Eriksson 2015) or the United States (Hausman and Neufield, 2011).

Scholars of energy have also referred to an energy transition (Smil 2010, Lewis 2012) and the shift toward renewables. Among these are writings that have elaborated on the lessons that could be drawn from past policies of various countries. These include: an assessment of the Germany experience in renewable energy policy for Post Fukushima Japan (Huenteler, Schmidt and Kanie 2012); an analysis of the US experience regarding innovation incentives in energy technologies Norberg-Bohm, V. (2000); or an examination into the reasons behind the diffusion of renewable energy technology (Jacobsson and Lauber 2006). Scholars have also documented the various innovative activities carried out by firms around the world (Watanabe, Wakabayashi and Miyazawa 2000, De La Tour, Glachant and Ménière, 2011, Dewald and Truffer 2011). The rising interest in specific segments of renewables – such as photovoltaics – is also palpable from the growing scholarship in recent years (Bradford 2008, Jones and Bouamane 2012, Perlin 2013, Varadi 2014) .

The leading scholar on the evolution of Japan's energy industry is Takeo Kikkawa. Kikkawa has written numerous works in the field, whether from the perspective of industry (1995, 2004, 2009, 2015); individual corporations such as Tokyo Electric (2011); or on specific energy sources such as nuclear (2011) or energy policy (2012). Other scholars have written on more specific themes, such as the evolution of industrial structure in the coal sector (Odano and Araya 2007). Shimamoto has written on this specific theme of innovation in the Japan PV industry (2007), as well as an in-depth study of Japan's national Sunshine Project in the 1970s to develop this sector (2014). Shimamoto has argued that the strategic needs of individual corporations were important in the adoption of photovoltaic technology, and for understanding the evolution of this sector in relation to public innovation policy (2012).

In the past few years, scholars have also followed the evolution of Japan's photovoltaic industry, such as from the perspective of policy (Kimura and Suzuki 2006) as well industry (Habuya, 2014). Public bodies have also recorded their own project histories. For instance, the Kogyo Gijutsuin , or the Agency of Industrial Science and Technology of the former Ministry of International Trade and Industry, chronicled an official history of the national Sunshine Project in 1984 (Kyogo Gijutsuin, 1984). The New Energy and Industrial Technology Development Organization (NEDO), the government agency tasked with the execution of energy policy, has also documented the evolution of the photovoltaic industry in Japan (NEDO, 2000, 2007). Furthermore, companies such as Kyocera have also documented their engagement in the development of photovoltaic cells (Kyocera, 1994).

Justification of case

The solar energy industry offers a good case to investigate the role of state policies on innovative activity for three main reason. First, as represented by companies such as Sharp, Kyocera and Panasonic, the photovoltaics industry is a segment in which Japanese firms have been recognized as leading global players. Japanese firms' very success in this sector also allows us to consider the reasons behind the success of Japanese firms in an innovative sector during a particular time period.

Second, and in a similar vein to the first point noted above, many Japanese companies have operated in this space. To compete with domestic and overseas rivals, Japanese photovoltaic companies had to innovate to survive. The sector thus offers a forum to investigate the competences of firms that are rigorously engaged in innovative activity.

Third, as in many green energy industries worldwide – from wind to biomass –the photovoltaics industry has been heavily supported and shaped by government policy. The sensitivity of both market size and firm performance to changes in government policy is testament to this fact, and thus lends easily to an examination on the role of government policy in shaping an innovative industry. Given the recent push to revitalize this industry in Japan in the wake of the Fukushima nuclear disaster, this paper is also topical in its observation of the extent to which these policies shape firm responses.

Definition

This paper refers to the solar electric industry in terms of the photovoltaic solar energy industry; the industry offering devices that convert the sun's light into electricity. It does not refer to other industries based on solar technology, such as the solar thermal industry. It should be noted that the smallest unit of a photovoltaic system is a cell, or solar cell. Numerous different types of cells together combine to form a photovoltaic module. One or more of these modules then comprise a photovoltaic system, which may be on or off grid. The figure below illustrates the photovoltaic value chain.

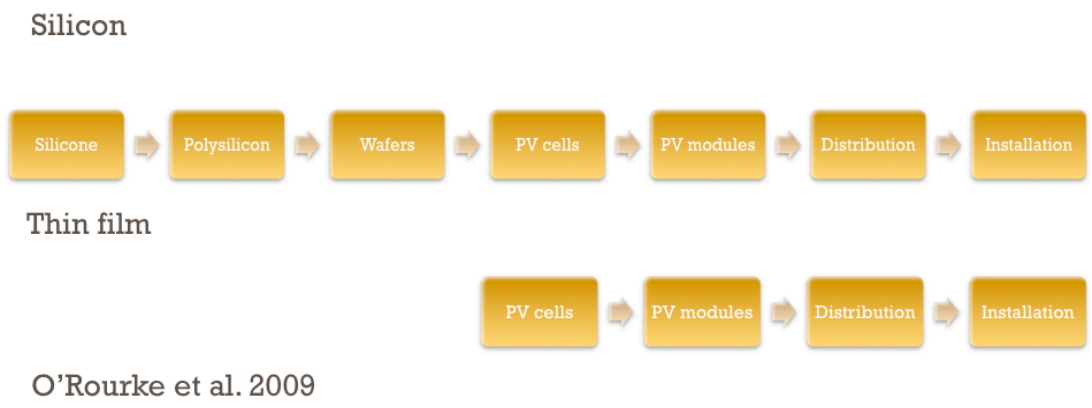

Figure 1. Photovoltaic industry value chain

As Figure 1 suggests, there are competing technologies among photovoltaic cells, largely differentiated between the first generation cells made out of monocrystalline and polycrystalline silicon; and the second generation thin film cells made by a range of materials, such as amorphous silicon. Many second generation cells, such as nonocrystalline, have yet to become commercially successful. Research on new materials has been conducted but many are still technologically immature for the market.

One of the most significant barriers to commercialization in photovoltaics is the high cost of the first generation technologies. Innovation in this industry therefore involves, for example, the lowering of manufacturing costs using existing materials. It may also involve the location of new, lower cost materials, and the development of stable, durable, and low cost photovoltaic cells with high conversion rates from such materials.

Discussion over the first and second technologies is also pertinent to the discussion of industry evolution and innovation in the context of globalization, given the difference in value chain. The older silicon technology features more phases in the manufacturing process, while the newer technology feature a two step process for producing cells and modules, respectively – before distribution and installation (O'Rourke 2009).

In terms of business model, firms that have adopted first generation technologies – such as Sharp, Kyocera, Panasonic, Mitsubishi – are able to adopt a business model that separates the cell from module production, and may produce solar cells in Japan but assemble solar modules overseas. By comparison, companies that have adopted the thin film technologies – such Solar Frontier and Kaneka – cannot separate the cell production from module assembly and are produce them in one location, [usually in Japan]. The difference in business model

suggests that first generation technology firms have more open and international innovation networks than second-generation technology firms.

Methodology

This paper uses patent information to examine the evolution in the networks of innovation in Japan's photovoltaic sector across several photovoltaic policy regimes. The paper follows changes in collaboration patterns over time and identifies the relative importance of factors such as government funding, affiliated research organization, and geographic location – both in the form of geographic concentration as well as international collaboration.

This paper considers patent data as a tangible form of collaborative knowledge production from industry that is essential to develop an innovative industry. Whilst the paper recognizes that there are problems in patent counts that have been elaborated elsewhere, the paper believes that it is nevertheless one of the best available sources to investigate changes in collaborative innovation networks over time. The research will supplement the computer-based research methods with interviews to help confirm research results.

Historical background and current overview of industry

Before the oil shock

As documented elsewhere (Kikkawa, 2012, The Federation of Electric Companies of Japan, 2015), it is important to remember that the broader structure of the Japanese electricity industry featuring stable, regional monopolies, is a distinctly "recent," phenomenon. The post 1951 industry bears no resemblance to Japan's electricity in the first half of the 20th century, which itself experienced several phases of evolution: from fierce market competition to national consolidation. The industry's beginnings with Tokyo Electric Lighting in 1878 was followed by a great number of private initiatives. In fact, when the government restructured the industry into five major utilities after the First World War, hundreds of firms disappeared. Further industry consolidation followed the trend toward the state control and rationalization of industries during the war period, and the national Nihon Hatsusoden, distributed electricity through nine companies during the Second World War. With the restoration of Japan's independence in the 1950s, that industry was deliberately rebuilt wit the creation of nine private regional monopolies in 1951. Aside from the addition of Okinawa Electric in 1972, the fundamental structure of Japan's electricity sector was sedimented in 1951, with limited change over the following decades.

It is important to remember that it was early entrepreneurial initiatives that preceded government policy and pioneered Japan's photovoltaic industry occurred shortly after the discovery of photovoltaic cells at Bell Laboratories in 1954. As was typical of the times, Japanese firms imported foreign technology to develop a photovoltaic business, within the aforementioned broader context of a stable electricity industry. Japanese companies that pioneered this sector were largely electronic companies such as Sharp and Hitachi whose visionary founders and senior managers were dedicated to the commercialization of an green technology that would be unprofitable for years to come (Kimura and Suzuki 2006, Jones and Bouamane 2012). As Shimamoto remarks, they were also firms with slightly less deeper pockets and technological sophistication of firms such as Toshiba or Hitachi who would later become more interested in investments in semiconductor technologies (Shimamoto, [2010]).

After the oil shock, three decades of policy support

Even before the 1970s, Japanese policymakers had expressed interest in the development of alternative energy sources, given the country's lack of natural resources. Thus, the 1973 oil shock, not only prompted change in energy policy – as it did not other countries – it precipitated a large scale national "Sunshine Project" dedicated to the development or renewable energy. As subsequently detailed in the documents of the Ministry of International Trade and Industry (MITI), subsequent policy histories and academic papers, the Sunshine policies included: electricity taxes to execute policy; the creation of a special account dedicated to alternative energy development; and the establishment of the New Energy Development Organization (NEDO) to help develop energy technologies (Kogyogijutsuin, 1984, 1997; NEDO ; Kimura and Suzuki 2006, Shimamoto 2014).

Sharp Matsushita, Hitachi, Toshiba and NEC, who expressed interest in developing photovoltaic technologies originating from Japan were initial project participants. Kyocera, Sanyo and other manufacturers joined later. As a frontier industry, the growth of the photovoltaics sector was a complex interplay between the creation of policies and regulations that were negotiated between different government ministries and corporations. Indeed, corporate interests formed the Japan Photovoltaic Energy Association in 1987 to lobby the government to help support industrial development. Whilst the government had offered procurement program, many firms foresaw the limited market potential of this sector for years to come. Indeed, equipped greater funds and technological capabilities, firms such as Hitachi, Toshiba and NEC parted from the photovoltaic industry and shifted to the semiconductor industry in the 1980s (Shimamoto, 1998).

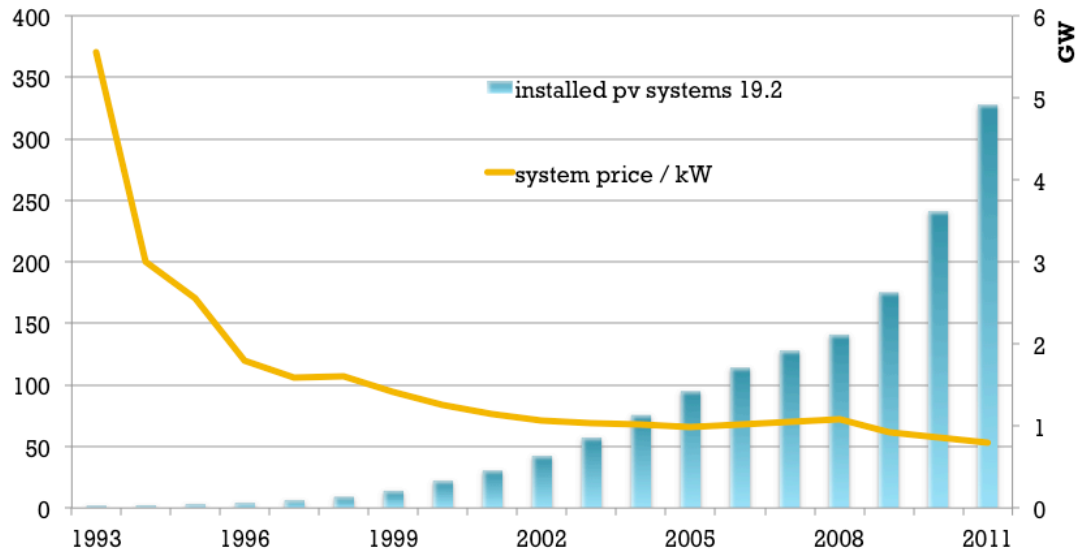

Figure 2. Price trends of photovoltaic systems in Japan, in millions of yen per kWH; Cumulative installed pv systems in Japan (GW)
Source: Agency for Natural Resources and Energy, METI

The Japanese photovoltaic industry continued to grow with the support of government programs over the 1990s. One of the most effective incentive programs introduced at the time the government subsidy for residential photovoltaic systems that was in effect between 1994 and 2005. This particular policy was driven by the need to demonstrate the commercial success of the Sunshine Project as well as assist in the development of mass production capabilities among Japanese firms. As Figure 2 shows, the program was influential in the rapid fall of photovoltaic system prices in Japan. However, the number of installations remained limited because the cost of photovoltaic electricity remained high. In effect, most photovoltaic systems in Japan over the 1990s and 2000s were installed in the individual residences of higher income families.

A brief period of policy withdrawal and transformation of the global industry

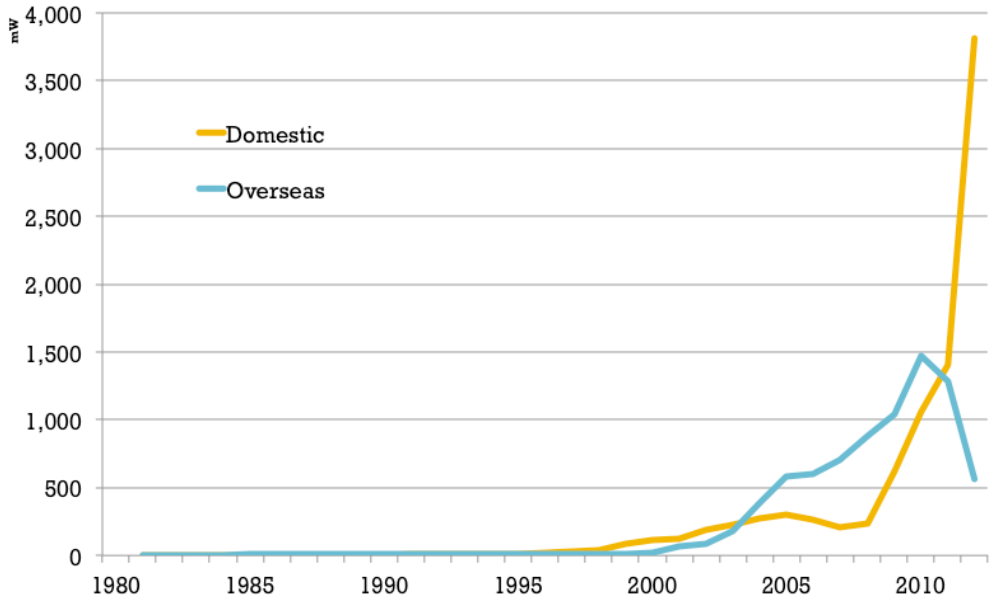

Figure 3. Domestic versus overseas shipments
Source: Japan Photovoltaic Energy Association

The termination of subsidies for residential photovoltaic systems in 2005 led to a fall of photovoltaic module shipments from Japanese firms. German firms such as Q Cells and Solon benefitted from the German government's introduction of the feed in tariff in 2004, and became the leading global producers of photovoltaic cells in the mid 2000s. The German feed in tariff made solar energy much more appealing to consumers compared to Japan's RPS system. In fact, the Japanese increase in overseas shipments in the 2000s appears accompanies the introduction of favorable subsidies schemes available in European markets, such as Germany. The later decline of overseas shipments follows the 2008 financial crisis and subsequent cuts or modification to European schemes.

The entry and rapid rise of Chinese firms such Trina Solar and Yingli Green Energy contributed to a fall in solar panel prices and transformed the competitive dynamics of the global industry in the late 2000s. The Chinese photovoltaic industry was supported by various government schemes: from subsidies for photovoltaic installation; a feed in tariff from 2009; to favorable loan terms for state owned companies. As Chinese firms developed expertise in producing high quality photovoltaic cells at low cost, they replaced the American and

European firms. In the meanwhile, Japanese firms shifted their focus to the offering of photovoltaic systems and solutions

Much has been made of the falling prices of solar cells. By the mid 2000s, the price of solar cells has fallen to almost a hundredth of the price in the late 1970s. Indeed, while price levels differ somewhat between countries and technology material, the prices of photovoltaic cells, modules and systems have fallen precipitously since the 1970s, and have continued to do so in the 2000s. While Japanese residential photovoltaic programs were initiated in the 1990s, what is rather striking is the particularly rapid rise of installations from the late 2000s (Japan Photovoltaic Energy Association, various years).

Post Fukushima, a revival of policy support

While a limited feed in tariff had been introduced in 2008, the Fukushima nuclear disaster in 2011 reignited debates for the introduction of alternative non-fossil fuel, and non-nuclear energy for future generations. In 2012, a new feed in tariff was introduced at 42 yen/kwH, and stimulated rapid re-expansion of Japan's photovoltaics industry. While the incentives introduced have since received considerable criticism regarding poor planning and problems with grid access, they nevertheless led to a surge of photovoltaic installations after 2012. By the end of 2014, photovoltaic installations in Japan (9.7GW) was only second to China (10.2GW) in that year; third after Germany (22%) and China (16%) in terms of cumulative photovoltaic capacity. At the same time, it should be remembered that photovoltaics account for merely 2.5% of total electricity consumption, while greater than most developed countries, is less than countries such as Germany or Italy (IEA-PVPS, 2015).

Table 1. Leading photovoltaic module suppliers, 2014

	Supplier
1	**Trina Solar**
2	**Yingli Green Energy**
3	**Canadian Solar**
4	**Hanwha SolarOne**
5	**Jinko Solar**
6	**JA Solar**
7	**Sharp**
8	**ReneSola**
9	**First Solar**
10	**Kyocera**

Source: IHS Inc.

It may be worth noting that the global market for photovoltaics is, in reality, concentrated in only a few countries. In fact, over the past few years, the top five countries – China, Japan, United States, Britain and Germany – have comprised over three quarters of global photovoltaic installations (IEA-PVPS, 2010-15). One of the prominent features of the Japanese market is the prevailing dominance of large firms, compared to other markets. For instance, the leading Japanese players in this field are Sharp, Kyocera, Panasonic, and Mitsubishi, who use first generation technology. The thin film makers Kaneka and Showa Shell (through its subsidiary Solar Frontier), are also major players in Japan (Fuji Keizai 2014). As can be observed in Figure 4, while thin film and other newer materials have been developed since the 2000s, the market is much dominated by first generation technology (monocrystalline and polycrustalline silicon) and much less by thin film and other materials.

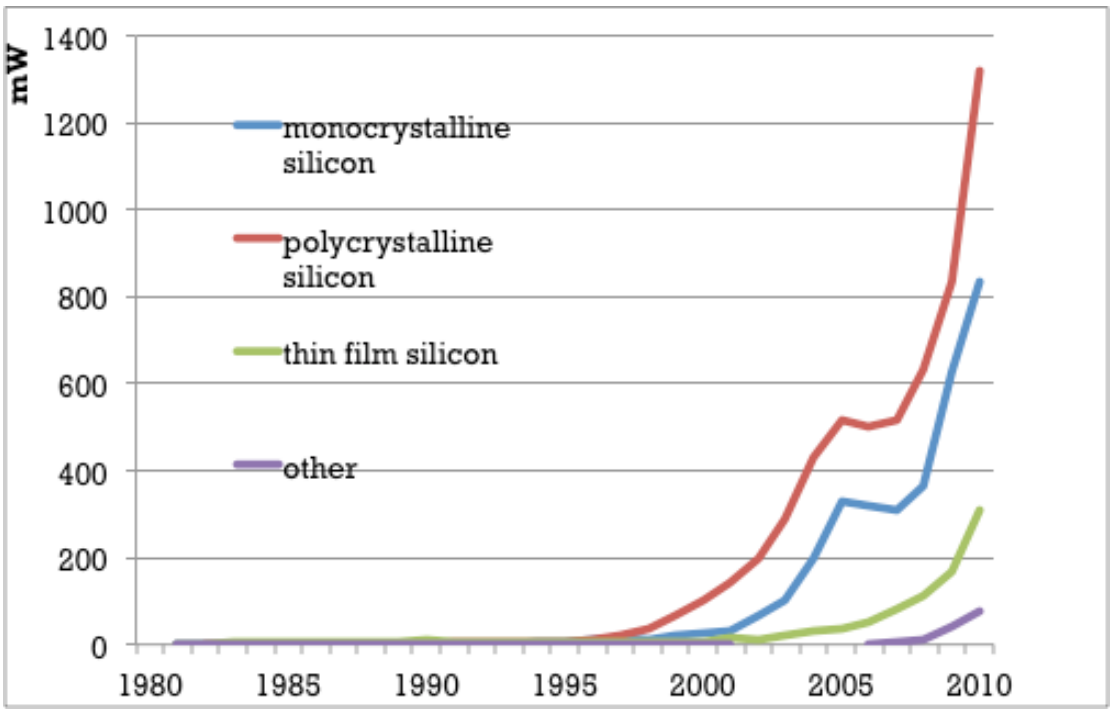

Figure 4. Shipments by technology base
Source: Japan Solar Energy Association

Evolution of policy regimes in Japan's photovoltaic industry

This paper observes five policy regimes:

Phase 1, 1960s-1974

The first phase refers to the nascent period of the global and Japanese photovoltaic industry. During this period, a few Japanese firms become interested in the photovoltaic technologies developed in American firms, and begin importing technology for commercialization in Japan. There is limited government policy concerning this sector during this period.

Stage 2, 1974-1993

The second phase refers to the period after the national Sunshine Project was launched in 1974. As mentioned earlier, this major national project was backed by substantial funds to develop next generation renewable technologies, with a focus on solar energy. The project's reviews have been mixed. Watanabe, Kimura and Suzuki, for instance, have argued that the policies were more important in signaling government support for the industry than specific

policies having a measurable effect per se. After all, private investment in the field always exceeded public investment (Watanabe, Wakabayashi and Miyazawa 2000, Kimura and Suzuki 2006). Jones and Bouamane (2012) have more been more critical. After all, the Sunshine Project: focused not only on solar thermal energy; but also on investments in R&D without support for the translation of academic science to industry. They also point out that the government was more interested in the securing energy supplies; developing nuclear rather than renewable energy; and that Japan's regional electricity monopolies had little interest in developing renewable technologies.

Stage 3, 1994-2005

In the third phase, the government continues to implement various schemes to support the photovoltaic industry. Indeed, as noted earlier, the Japanese government launched one of the largest programs in the world to promote the use of photovoltaic systems on residential homes from 1994. But the New Sunshine Project launched in 1993 a shift in policy focus. In addition to securing stable energy supply, policymakers demonstrated concern over the need to develop technologies that would enable more efficient use of existing energy sources; as well as technologies that would enable firms and individuals to more widely use renewable energy sources. By the time the Kyoto Protocol was adopted in 1997, energy policy had become entwined with increasing concerns over climate change and environmental issues.

From 2003, the Japanese government had also introduced a Renewables Portfolio Standard (RPS) system, which obliged electricity retailers in Japan to use a specified amount of electricity from renewable sources. For example, electricity companies were obliged to either: generate renewable electricity themselves; buy renewable electricity; or buy New Energy Certificates. This scheme, however, was often criticized for the low numbers required of firms to use renewable sources.

Stage 4, 2006-2011

The fourth phase refers to a period in which the government withdrew from its earlier support of the photovoltaics industry. In 2005, for example, the government deemed the sector self-sufficient and ended its subsidy scheme for the installation of photovoltaic systems in residential homes. However, as the domestic market stalled and Japanese firms began to struggle against the German and Chinese photovoltaics firms supported by generous government schemes, the government reintroduced this scheme between 2009 and 2014.

Stage 5, Post Fukushima

Following the Fukushima nuclear disaster in 2011, the government launched a renewed effort to develop renewable energy and promote innovation in this industry. As part of this change, a Feed in Tariff replaced the existing RPS system in 2012. The various policy changes were

motivated by the desire to develop non-fossil fuel and non-nuclear sources of energy; reduce Japan's carbon footprint; and create new businesses in the renewables industry. In the end, the policy initiatives particularly stimulated the development of solar electricity, as photovoltaic systems are easier to establish compared to wind, geothermal or biomass systems. By 2014, however, the photovoltaics "boom" began show cracks.. For example, electricity companies suspended purchases from the rush of new installations on the grounds that they could not maintain a stable electricity supply.

Evolution of innovation networks by policy regime

[Images to be inserted for the following stages:

Stage 1, 1950s-1974

Stage 2, 1974-1993

Stage 3, 1994-2005

Stage 4, 2006-2011

Stage 5, post Fukushima

Hypothesis

This paper identified several waves of industry evolution in Japan's photovoltaic industry after the 1950s. In terms of the relationship between government policy and innovation networks, this paper hypothesizes that the following:

Stage 1, Pre Sunshine Policies, 1950s-1974:

In the nascent phase of industry, government policy is limited. A handful of firms seek to import technologies and experiment with the development of a photovoltaics business in Japan. In accordance with the traditional Japanese innovation model (Odagiri and Goto 1993, Kneller 2000) innovation is "autarkic," and conducted in large firms. Firms engaged in this sector show limited domestic networks of innovation, and are reliant on imported technologies – perhaps a embryonic and uni-directional form of an international "network."

Stage 2, Post Sunshine Policies, 1974-1993;

Stage 3, Post Residential Roofs Program, 1994-2005:

The introduction of large-scale government programs to stimulate interest among large corporations and generates a community of firms collaborating on national projects. Large government budgets dedicated to the field, supplemented by demand side policies demonstrates state support for market creation and cultivates further private investment in innovation (Kimura and Suzuki 2006, Shimamoto 2014) Innovation remains firm-based, and conducted within large firms. There is some limited formation of domestic collaborative networks, based on shared technology bases or needs. While companies such as Hitachi and Toshiba depart from this industry in the 1980s, large firms that remain dedicated to the field also form a few collaborative innovation ties with overseas companies. The Japan Solar Energy Corporation established in 1975, for instance, was a joint venture established between Kyocera, Panasonic, Sharp, Mobile Oil and Tyco Laboratories to develop solar cell technologies.

Stage 4, Relative withdrawal of government policies and fall from global leadership, 2006-2011:

The withdrawal of certain government programs leads firms to more aggressively seek expansion into overseas markets. The lower barriers to transactions across national borders, enabled by deregulation and advances in information technology, encouraged firms to seek collaborations in innovation across borders across different stages of the value chain to regain the global competitiveness lost to Asian rivals. The complexity involved in developing solar cells with novel materials encourages firms to develop more international networks of innovation.

Stage 5, Post Fukushima:

The reinstallation of policy initiatives for the photovoltaics industry after Fukushima revived domestic demand in this sector – and encouraged the entry of foreign firms in Japan. Dominant players in Japan remain large firms, with some foreign firms. Domestic innovation networks are limited but international networks of innovation continue to grow, particularly fors novel materials.

Conclusion

This paper builds upon the growing literature on the evolving role of government policy on Japan's solar energy industry. One of the fascinating aspects of Japan's photovoltaics policy is that, the country adopted a large scale, national public policy drive for photovoltaics in the early phase of global evolution of the industry. Yet the rise of Japanese firms in this sector was rather slow, and their prominence was temporal. The paper suggests that the role of government policy – as in other nascent high tech industries, as in all renewable industries around the world – was quite vital to market creation and stimulating innovation in the photovoltaics sector. The policies for support did encourage some degree of open innovation and network based collaboration. However, rather than the policies per se, these collaborations in innovation were driven by the intensification of global competition; growing technological complexity. The degree and nature of innovative collaborations were also shaped and limited by the differences in the value chain that accompanies the shift from first to second generation technologies.

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