Why did the solar power sector develop quickly in Japan?

by

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Abstract

The solar power sector grew quickly in Japan during the decade 1994 to 2003. During this period, annual installations increased 32-fold from 7MW in 1994 to 223MW in 2003, and annual production increased 22-fold, from 16MW in 1994 to 364MW in 2003. Over these years, the growth of Japan's solar power sector outpaced the global industry's growth, which is puzzling because Japan was in a recession during this period. At the same time, the U.S. was experiencing considerable economic expansion, yet the U.S. solar industry's growth was significantly slower than Japan's.

This thesis focuses on the rapid development of Japan's solar power sector in order to address the central question, "Why did the solar power sector develop quickly in Japan?" To address this question, this thesis develops two comparative case studies: (1) Japan's solar power sector: 1994 to 2003 and (2) U.S. solar power sector: 1994 to 2003. These case studies provide detailed descriptions of the historical development of the solar power sectors in Japan and the U.S. based on data collected from International Energy Agency's PVPS program, Japan's New Energy Development Organization and the U.S. Energy Information Administration, among other sources.

A comparative analysis of these cases suggests that the rapid growth of Japan's solar power sector was enabled by interplay among (a) decreasing gross system prices price, (b) increasing installations, (c) increasing production and (d) decreasing costs. The second-order explanation for this interplay is that a mosaic of factors led to (a) decreasing prices, (b) increasing installations, (c) increasing production and (d) decreasing costs. This mosaic included the extrinsic setting (solar resource, interest rate, grid price), industrial organization (including the structure of the electric power sector and the structure within the solar power sector), demand-side incentives that drove down the "gap" with and provided a "trigger" for supply-side growth, and supply-side expansion that enabled significant cost reductions and price reductions that more than offset the decline in demand-side incentives. Within this complex interplay of numerous factors, roadmapping and industry coordination efforts played an important role by shaping the direction of Japan's solar power sector.

This thesis concludes with "lessons learned" from Japan's solar power sector development, how these lessons may be applicable in a U.S. context and open questions for further research.

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Table of Contents

List of Figures

List of Tables

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- SECTION 1 -

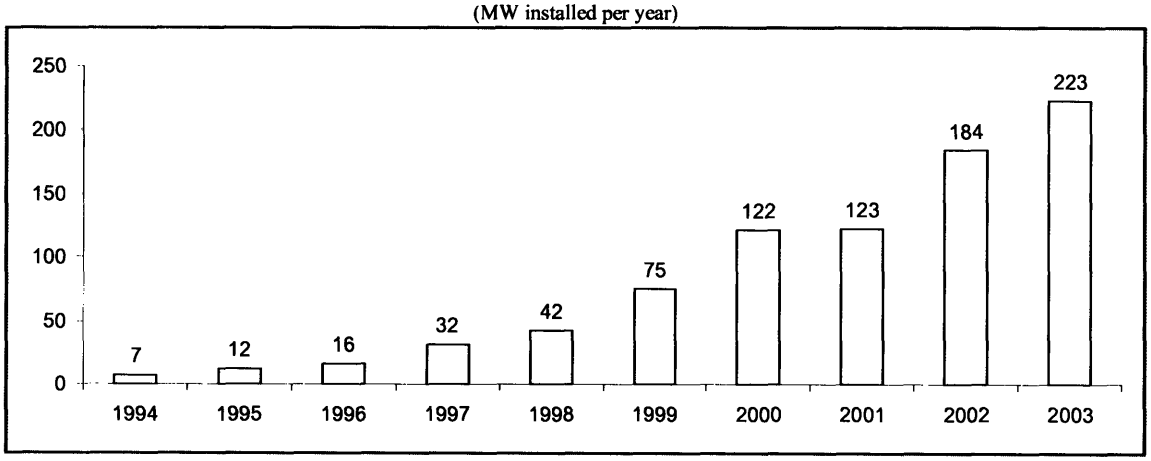
INTRODUCTION: WHY DID THE SOLAR POWER SECTOR DEVELOP QUICKLY IN JAPAN?

Introduction:

Why did the solar power sector develop quickly in Japan?

The decade leading up to 2004 was a period of rapid growth for the solar power sector in Japan. During this period, annual solar power installations increased 32-fold, from 7MW/year in 1994 to 223MW/year in 2003.[1] (FIGURE 1) This growth was driven primarily by residential rooftop installations, which expanded nearly 100-fold from 539 installations in 1994 to 46,760 installations in 2003.[2] Over this period, Japan moved from being the OECD's third largest solar power installation market, with 25% of OECD installations in 1994, to being the largest, with 47% of OECD installations in 2003.[3] (FIGURE 2)

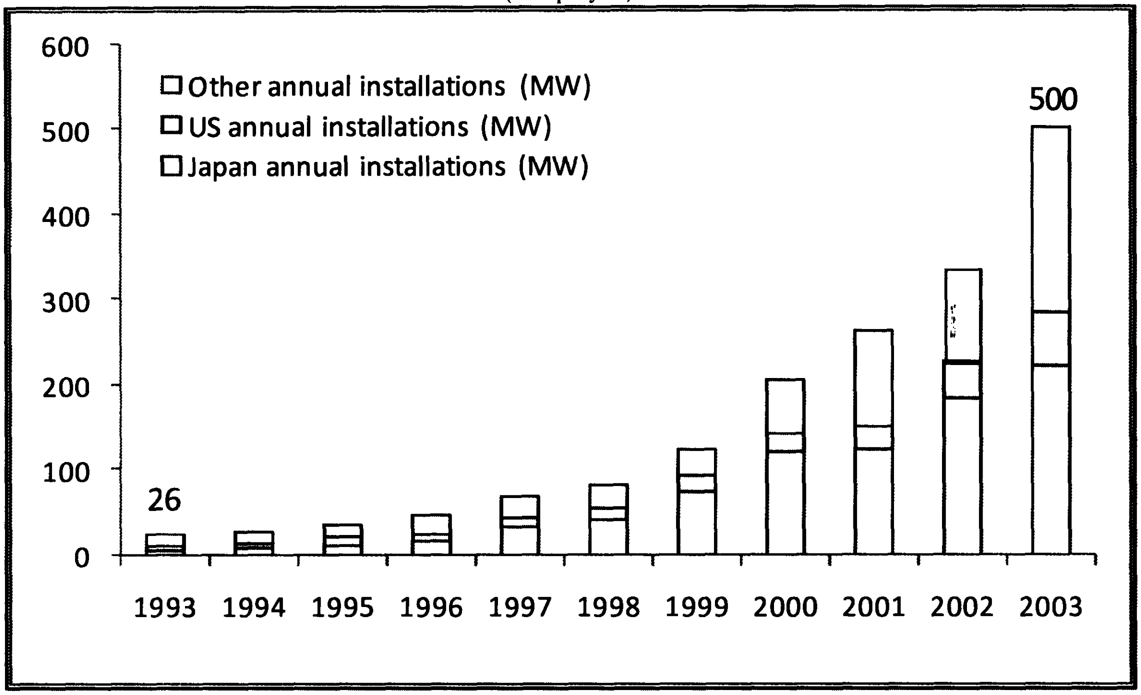
FIGURE 1: Annual solar power installations in Japan 1994-2003
(MW installed per year)



Source: IEA PVPS 2004

[1] IEA PVPS (2004) page 5.
[2] New Energy Foundation (www.solar.nef.or.jp/josei/setti_kensuu.xls)
[3] IEA PVPS (2004) page 5.

FIGURE 2: Annual solar power installations in OECD by country 1994 to 2003
(MW per year)



Source: IEA PVPS 2004

The scale of these installations – hundreds of megawatts and tens of thousands of individual Japanese homeowners – is puzzling for several reasons.

- **Solar power appears suited for remote applications.** Intuition suggests that rural villages in less developed countries where traditional sources of electricity are prohibitively expensive due to logistical difficulties are a more likely location for solar installations. In contrast, Japan's solar installations were in relatively wealthy urban and suburban areas that already had electricity provided via a power distribution grid.

- **The price of generating solar power is much higher than traditional sources.** On a levelized basis, the price of solar power per kWh is typically $0.30 to $0.40 per kWh in Japan in 2003[4], compared to a typical range of $0.02 to $0.08 per kWh cost for electricity

[4] Estimate based on calculations. Methodology for calculations described in Section 2. These estimates are consistent with typical range identified during interviews with Japanese solar executives and policy managers.

generation using coal, natural gas, hydro and nuclear and to roughly $0.20/kWh for grid-based residential electricity.[5]

- **The price of a solar power installation was quite high.** In 2003, a typical 3.7kW installation had a price tag of roughly $24,000.[6] This represented more than 60% of average Japanese per capita income in 2003.[7] At this price level, a solar power installation would have been a significant expenditure for most Japanese, creating a customer financing hurdle and making it surprising that so many households purchased solar power systems.

It is also puzzling that large Japanese companies such as Sharp, Kyocera, Mitsubishi, Sanyo and Sekisui Chemical invested more than $2 billion to expand the supply chain for solar power systems.[8] This was surprising because many solar power players had low or negative operating profit from their solar divisions through the 1990s.[9] It was also surprising because leading solar power companies in other parts of the world made business decisions (e.g. exiting the business or pursuing slower growth rates) that differed significantly from their Japanese competitors. Despite these factors, investments in solar cell/module capacity led to a 22-fold increase in production by Japanese solar power companies increased, from 17MW in 1994 to 365MW in 2003.[10] By the end of this period, Japanese firms accounted for nearly half (49%) of global cell/module production, up from only 24% at the start of the period.[11] In addition, the largest players (Sharp, Kyocera, Mitsubishi, Sanyo) planned to significantly expanding their production in the coming years.[12]

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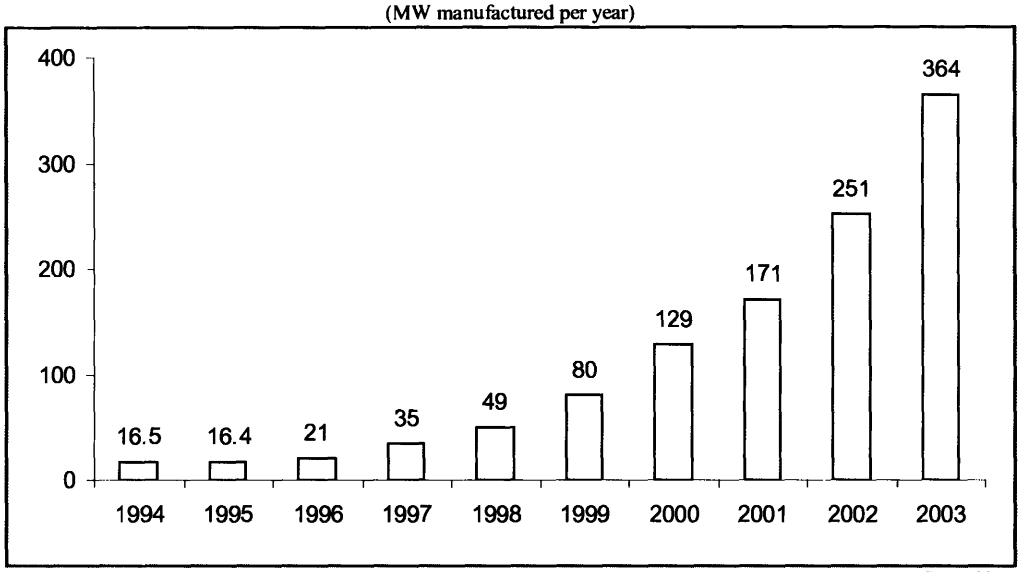
[5] There are wide ranges of levelized costs in the literature. For a standard methodology for estimating the levelized cost of electricity, see web.mit.edu/1.149/www/lecture04/lec04notes.doc. For "Cost and Performance Characteristics of New Central Station Electricity Generating Technologies" see, for example, www.eia.doe.gov/oiaf/aeo/assumption/pdf/electricity.pdf#page=3.
[6] New Energy Foundation (www.solar.nef.or.jp/josei/setti_kensuu.xls)
[7] World Bank (www.iaea.org/inis/aws/eedrb/data/JP-gdpc.html)
[8] This is a rough estimate of the capital expenditure by Japanese solar power companies. This estimate is likely too low. Japanese producers increased capacity by nearly 500MW from 1994 to 2003 according to PV News/Paul Maycock and RTS/Osamu Ikki. See, for example, "Overview of PV Activities in Japan: Current Status and Future Prospects" (2004) Capex per watt for the supply chain decreased from at least $20/watt in 1994 to roughly $3/watt in 2003, according to interviewees. Assuming a steady annual decrease in capex per watt, this implies that total capex of at least $2bn during the period. This likely understates the actual expenditures because it does not include expenditures that did not lead to production such as pilot lines, failed production attempts and R&D. Together, these increase the total by at least $1 billion based on data from Sanyo, Kyocera, Sharp, Kaneka, Fuji Electric, Sekisui Chemical, Hitachi, Mitsubishi, Sumitomo and other companies. This capital expenditure by companies was partially offset by government cost sharing programs in some areas.
[9] Several interviewees said that most Japanese solar companies were had low or negative profitability from 1994 to 2003. There were some exceptions, but this was the dominant view shared by interviewees during interviews (Rogol 2004).
[10] Maycock (2004)
[11] Maycock (2004)
[12] Company annual reports and press releases. See, for example, Maycock (2004).

FIGURE 3: Solar power cell/module production in Japan 1994-2003
(MW manufactured per year)



Source: Maycock (2004)

A significant body of academic and non-academic literature explores the development of the solar power sector in Japan and in other countries.[13] This literature provides explanations for the rapid development of Japan's solar power market, including:

- **Strong demand-pull incentives.** A decade-long government program launched by the Japanese government to support dissemination of solar power systems. From 1994 to 2003, the New Energy Foundation (NEF) under the Ministry of Economy, Trade, and Industry (METI) oversaw a program that spent more than $1 billion to support residential solar power installations.[14] This program was responsible for more than the bulk of the capacity installed during this period, and made Japan a model of how demand-pull incentives can build an industry.[15]

- **Rapid decrease in solar power system prices.** During the period 1994 to 2003, installed system prices without incentives decreased by nearly 70% from $20/watt in

[13] Several examples are provided in "Appendix: References"

[14] Data on government spending provided in IEA PVPS (1998, 1999, 2000, 2001, 2002, 2003, 2004). Scale of spending (more than $1bn) confirmed with data from Ministry of Economy, Trade and Industry (METI) and U.S. Energy Information Administration (EIA), though there is some divergence in the specific annual and cumulative spending estimated by different sources.

[15] Bolinger and Wiser (2002) and Algoso, Braun and Del Chiaro (2006) provide details on the Japanese program in case study formats. As Algoso et al write, "Japan provides a prime example of how demand-pull incentives can build an industry and bring solar PV to the point of cost-competitiveness for consumers." (page 15)

1994 to $6/watt in 2003.[16] These price reductions have been explained in the literature as being the result of learning and scale that enabled significant manufacturing and installation cost reductions for manufacturers and service providers throughout the solar supply chain.[17]

- **High grid prices.** Japan has the highest residential grid prices in the OECD, with average residential prices of $0.19 per kWh in 2003.[18] Residential solar power systems in Japan are normally grid connected and net metered, making solar power a direct substitute for grid-based electricity.

- **Coordination of diverse actors by the government.** Efforts to "roadmap" important technical, economic and policy milestones and to coordinate implementation of government incentive programs, corporate expansion plans and research priorities are also cited in the literature as important ingredients driving the growth Japan's solar power sector. For example, according to a leading researcher on Japan's solar sector, the strong growth of Japan's solar power sector was achieved because "various sectors have been working on deployment of PV systems. The Government has been promoting programs for R&D, dissemination and demonstration/ field test, and successfully created the infrastructure for introduction of PV systems. In addition, efforts of technical development and cost reduction through enhancement of production capacity by PV manufacturers and the housing industry and other user industries involved in the PV business also serve as the driving force."[19]

While the literature provides explanations for the rapid development of Japan's solar power sector during the years 1994 to 2003, there are several important issues that have not received consideration.[20] For example, on the demand side, neither the decline in average residential grid prices (26% decrease from 1994 to 2003[21]) nor the decrease in interest rates (1.7 percentage points decrease from 1994 to 2003[22]) are discussed despite their impact on end-customer economics. Similarly, on the supply side, the literature does not explain why Japanese solar power companies were rapidly expanding despite low profit levels. Also, the literature does not explore solar power as a substitute for grid-based electricity, provide estimates of demand elasticities or discuss solar power as a disruptive technology.

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[16] New Energy Foundation (www.solar.nef.or.jp/josei/setti_kensuu.xls) for prices in yen, World Bank (2005) for exchange rate.

[17] For example, see "Positive Cycle of Cost Reduction and Demand Increase" (FIGURE 4) in Chiba (1996).

[18] U.S. Energy Information Administration. Note: The *cost* of generating electricity from traditional sources (mentioned on the previous page as $0.02 to $0.08/kWh is significantly lower than the *price* of electricity paid by consumers. The price paid by consumers also incorporates transmission, distribution, fees, taxes and profits. As a result, prices for customers, especially smaller residential and commercial customers in the OECD countries, are typically much higher than the cost of electricity.

[19] Ikki (2004) page 1.

[20] This sentence applies only to the English-language literature. A thorough review of the Japanese-language literature was not undertaken.

[21] U.S. Energy Information Administration. Note this decrease in average residential grid-price is based in U.S. dollars. In yen, the decline was roughly 16% from 1994 to 2003.

[22] Interest rate data including long-term consumer lending rates provided by CLSA, a financial services firm, based on proprietary sources.

Overall, the English-language literature fails to adequately address questions like, "Why did the rate of development for the solar power sector in Japan outpace the growth in the rest of the world?", "Why did Japanese companies expand solar power production faster than companies outside Japan (including U.S. companies)?" and "Why did solar power prices fall faster in Japan than in any other major solar market?" Conversely, the literature fails to fully explain why the experience of the U.S. solar power sector was dissimilar to Japan, with lost market share in both demand-terms (% of annual megawatts installed) and supply-terms (% of annual megawatts manufactured), and solar power price declines that were much slower than in Japan.

Comparative case studies of Japan and U.S. solar power sector development

This thesis attempts to explain the rapid development of Japan's solar power sector during the period 1994 to 2003 in order to shed light on potential lessons that may be applicable in a U.S. context. To do this, comparative case studies of the Japanese solar power sector from 1994 to 2003 and of the U.S. solar power sector from 1994 to 2003 are presented and analyzed. The period 1994-2003 was selected for the case studies because this was the main focus period for Japan's New Sunshine program.[23] Following 2003, incentives under this program were phased out with the belief that solar power in Japan had become economic without incentives.[24] The same period was selected for the U.S. in order to provide a basis of comparison and contrast with the Japanese experience.

These case studies provide detailed descriptions of the historical development of the solar power sectors in Japan and the U.S. based on data collected from the International Energy Agency's PVPS program, the Japanese Ministry of Industry, Trade & Economy's New Energy Development Organization and the U.S. Department of Energy's Energy Information Administration, among other sources. After developing each case study, this thesis compares the development of the Japanese and U.S. solar power sectors in order to identify and attempt to explain similarities and differences, and also to draw potential lessons-learned that may be applicable in a U.S. context.

[23] Details on the Japanese policies are provided in Section 3.
[24] For example, see Ikki (2004) page 5. Phase out of incentives was planned for end of FY2005.

Key conclusions from case comparative case studies

The central question for this thesis is, "Why did the solar power sector develop quickly in Japan?" The first-order response to this question is that the rapid growth of Japan's solar power sector was enabled by *interplay* among (a) decreasing gross system prices price, (b) increasing installations, (c) increasing production and (d) decreasing costs. The second-order explanation for this interplay is that a mosaic of factors led to (a) decreasing prices, (b) increasing installations, (c) increasing production and (d) decreasing costs. This mosaic included the extrinsic setting (solar resource, interest rate, grid price), industrial organization (including the structure of the electric power sector and the structure within the solar power sector), demand-side incentives that drove down the "gap" with and provided a "trigger" for supply-side growth, and supply-side expansion that enabled significant cost reductions and price reductions that more than offset the decline in demand-side incentives.

Within this complex mosaic of factors, industry roadmapping and coordination efforts played an important role in several respects: (i) identification of target segments/markets and barriers to growth in specific segments; (ii) data/information/feedback on customer adoption (price, volume, etc.); (iii) data/information/feedback on in-field problems that led to the adaptation of supply-side R&D incentives; and (iv) precise manipulation of demand-side incentives. This was an important role because it helped shape the evolution of Japan's solar power sector. This shaping influence included: focusing on small-scale grid-connected systems; enabling learning spillovers; supporting supply-side and demand-side policies that pursued grid parity; recognizing the stronger-than-expected growth potential from crystalline silicon technologies; and focusing on BIPV applications that had stronger economic benefits than non-building integrated applications.

The mosaic of factors in Japan – including extrinsic factors, industrial organization factors, end-customer economic factors, supplier economic factors and policy factors – led to fast growth of solar power installations in Japan *and* fast growth of solar power manufacturing in Japan *and* fast decreases in solar power prices in Japan. In contrast, the U.S. during the years 1994 to 2003 had slower growth in installations, slower growth in solar power manufacturing and slower decreases in solar power prices compared to Japan. The comparative case studies suggest that these differences (slower demand side growth, slower supply side growth and slower price reductions in the U.S.) resulted from a mosaic of factors, including: less attractive extrinsic environment (e.g. lower grid prices and higher interest rates); less conducive industrial organization (e.g. inconsistent and/or non-existent grid-connection rules in many geographies); less compelling end-customer economics (e.g. slower reduction in "gap"); unattractive supply-side economics (e.g. negative NPV for many investments); lower funding for and less consistency in supply-side incentives; later and less geographically consistent funding for demand-side incentives; and less consistent policies and less robust coordination policies in the U.S.

One key implication from this analysis for U.S. policies is that an integrated approach to solar power policies that takes into account grid-connection policies, demand-side policies, supply-side policies and coordination policies may have benefits. In addition to this high-level conclusion, there are also more specific lessons-learned from the Japanese experience that may be applicable in a U.S. setting. For example, U.S. policy makers might attempt to:

- Focus supply-side and demand-side policies in areas where parity with the substitute price is most likely to be achieved (e.g. higher price electricity markets);
- Establish federal grid-connection and net metering rules that are simple for solar power system integrators to implement;
- Set demand-side incentives that are commensurate with the "gap" between levelized solar power prices and grid prices;
- Institute demand-side incentives that decline over time so that supply-side cost reductions enable end-customer prices to decline at the same time that government incentives also decline;
- Establish a reliable budget for demand-side incentives that increases confidence among suppliers and customers;
- Pursue policy instruments that enable careful manipulation of demand-side incentive levels with a goal of driving down solar power prices;
- Pursue programs that reduce the interest rate for long-term loans to pay for solar power systems because interest rates may have a significant impact on the levelized price of solar power for end-customers;[25]
- Collect, analyze and react to data on demand elasticity and, more specifically, changes in demand elasticity as the levelized net system price of solar power approaches the price of its substitute (i.e. approaches parity with grid price);

[25] This specific potential policy lever is highlighted because interviewees often overlook it as a potentially high-impact lever for policy intervention to support solar power installations.

- Establish a reliable budget for supply-side incentives that increases confidence among suppliers and enables the development of a deep knowledge base that can be tapped to reduce costs;

- Pursue programs that are commensurate with the stage of technological understanding. And, more specifically, do not pursue *deployment* programs for technologies that are not well understood;

- Focus on cell-level efficiency gains in order to drive down the cost of the total system;

- Focus on cost reduction efforts in non-module system inputs that have significant potential for cost compression;

- Establish a systematic coordination effort for supply-side research, development and demonstration projects similar to Japan's PVTEC with a consortium of industry, academic and government participants; and

- Make reliable data collection, analysis and dissemination a priority since cognition is necessary from a diverse set of actors (industry, customers, policy makers).

While the case studies presented in this thesis suggest that there are insights to be gained from a comparative analysis of the U.S. and Japanese solar power sectors that may be applicable for U.S. policy makers, these results are based on a limited analysis. Further research might:

- Provide detailed description and analysis of the Japanese PVTEC consortium's industry roadmapping and roadmapping activities and their impact: How *exactly* did this consortium come into existence, operate and influence the growth of Japan's solar power sector?

- Compare the Japanese experience in roadmapping the solar power sector with experience in other sectors. How, for example, did industry coordination efforts occur in a non-commodity sector such as biotech?

- Refine the case studies to include more focus on industrial organization: Why was production growth largely the focus of electronics companies in Japan and of smaller companies/energy companies (i.e. not large electronics manufacturers) in the U.S.? Does this manufacturing expertise explain the difference in the faster growth of manufacturing in Japan? Was the emergence of electronics sector players as leading solar power players a result of Japanese policy? Are there lessons for U.S. roadmapping/coordination efforts on the supply-side?[26]

[26] As Professor Moniz pointed out during discussion (March 2007), "Another issue is the role of industrial organization. It seems to me that the focus of building off the semiconductor/microelectronics industry provided a different industry organization, one that was much more amenable than the U.S. industry organization. How would you roadmap an industry that has behemoths and little start-ups? If you want to go from the case studies to focus on industry roadmaps, then you much incorporate the industrial organization in Japan. The industrial organization may have been the key in Japan. If so, roadmapping was a much easier tool to apply…"

- Build-up comparative case studies of the development of the solar power sector in additional geographies: In terms of further research, Germany is a top priority. This is (a) because Germany became the world's largest solar power market from 2004 as the result of introduction of a significant demand-side incentive and (b) because the German policy was a feed-in tariff not a buy-down incentive program. Evaluating the similarities and differences among Japan, the U.S. and Germany will almost certainly yield deeper insights to address questions such as, "Why did the solar power sector develop quickly in Japan?"

- Build-up comparative case studies of the development of other, similar industries: What are the similarities, differences and lessons learned by comparing the development of the solar power sector to the development of the semiconductor industry in U.S. and Japan and/or coalbed methane in U.S.? What was the role of roadmapping and industry coordination efforts in these other cases?

- Develop a theoretical framework for a system dynamics model of the development of the solar power sector: What are the key parameters for this model? How can research begin to estimate these parameters?

This section provided an introduction to the thesis topic and an overview of the implications suggested by the cases studies within the thesis. The next section provides details on the data and methods employed in this thesis.

- SECTION 2 -

OVERVIEW OF DATA AND METHODOLOGIES

Section 2: Overview of data and methodologies

This thesis develops comparative case studies of the Japanese and U.S. solar power sectors from 1994 to 2003. To develop these case studies, I collected and analyzed data from several sources in order to provide an overview of the solar power sector in each country, including installations, end-customer economics, cell/module production, supplier economics, policy spending and other areas. One challenge in developing case studies on the Japanese and U.S. solar power sectors is that data sources are diverse, inconsistent and sometimes difficult to access. As such, this section provides information on the specific data sources, data collection process and analysis that underpins this thesis. In addition to quantitative analysis, interviews were conducted with solar power executives, policy makers and technologists in order to provide qualitative feedback on the quantitative analysis. Finally, this thesis was peer reviewed by five people with significant experience in the solar power sector, and feedback from this peer review was incorporated into the document.

(A) Installation data

As a starting point for developing the case studies, demand-related data on the solar power sector were reviewed and organized. Part of the data collected was segment-by-segment estimates for solar power installations from 1994 to 2005 based on data sources such as IEA PVPS, U.S. EIA, PV News/Paul Maycock, RTS/Osamu Ikki, Photon Magazine and other sources. These data include segment-by-segment estimates of solar installations in Japan and the U.S. from the IEA PVPS's annual "Trends in Photovoltaic Applications" available from www.iea-pvps.org. TABLE 1 presents the cumulative installed base of solar power installations at the end of 2003 for Japan and the U.S. These segment-by-segment data were analyzed to determine the types of installations occurring in Japan and the U.S. over the study period. By the end of the study period (2003), the data show a high portion of grid-connected systems in both Japan and the U.S., which was a contrast to the years leading up to the study period (prior to 1994) during which grid-connected systems were a small portion of the solar power markets in both countries.[27]

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[27] IEA PVPS (2004) compared with IEA PVPS installation data from 1993.

TABLE 1: Solar power installations by segment in Japan and U.S. 2003
(Cumulative and annual 2003 kW and kW per capita)

	CUMULATIVE						ANNUAL	
COUNTRY	Off-grid domestic (kW)	Off-grid non-domestic (kW)	Grid-connected distributed (kW)	Grid-connected centralized (kW)	Total installed (kW)	Total installed per capita (W/capita)	Installed 2003 (kW)	Grid connected installed 2003 (kW)
Japan	1,101	77,792	777,830	2,900	859,623	6.7	222,781	216,535
U.S.	67,900	93,700	95,600	18,000	275,200	0.9	63,000	38,000
IEA PVPS TOTAL	**158,804**	**249,232**	**1,347,269**	**54,379**	**1,808,964**		**475,887**	**428,486**

Source: IEA PVPS (2003).
Note: "IEA PVPS TOTAL" is the total volume of cumulative and annual installations in the countries that report to IEA PVPS. This includes most of the OECD nations.

The installation database also includes country-by-country estimates for solar power installations from 1980 to 2005. Data sources include the IEA PVPS, U.S. Energy Information Administration (U.S. EIA), PV News by Paul Maycock, RTS led by Osamu Ikki, Photon magazine and other sources. In addition to country-level data, sub-country-level data were also collected for regions with sizeable installation levels, such as California. TABLE 2 provides installation data for Japan, the U.S. and California during the years 1994 to 2003. These years were selected they represents duration of the core years of the New Sunshine Program.[28]

TABLE 2: Solar power installations by country
(MW of cumulative and annual installation)

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Japan annual installations (MW)	5	7	12	16	32	42	75	122	123	184	223
Japan cumulative installed base (MW)	24	31	43	60	91	133	209	330	453	637	860
US annual installations (MW)	6.8	7.5	9	9.7	11.7	11.9	17.2	21.5	29	44.4	63
California grid connected	*0*	*1*	*0*	*1*	*1*	*1*	*2*	*3*	*10*	*22*	*32*
Other USA	*0*	*7*	*9*	*8*	*11*	*11*	*16*	*19*	*19*	*22*	*23*
US cumulative installed base (MW)	50	58	67	77	88	100	117	139	168	212	275
IEA PVPS countries annual installations (MW)	26	28	35	46	69	82	124	206	264	338	500
IEA PVPS countries cumulative installed base (MW)	136	164	199	245	314	396	520	726	990	1328	1828

Source: IEA PVPS (2004) for Japan, U.S. and IEA PVPS countries annual and cumulative installations. Maycock (2004) for "California grid connected."
Note: "Other USA" calculated by subtracting "California grid connected" from "US annual installations."

(B) Grid-connection and net metering rules

Because grid connection and net metering rules appear to have been a necessary condition for the rapid expansion of solar power installations (particularly grid-connected solar power installations), a literature review was conducted of grid connection and net metering rules in Japan and the largest U.S. market of California. This review yielded some information on the

[28] Note: The New Sunshine Program continued into 2005, but phase-out began in 2004.

historical evolution. However, the literature did not include a detailed description grid connection and/or net metering rules for Japan, California or the U.S. overall. As a result, interviews were conducted with members of Japan's New Energy Foundation[29] and the U.S.'s National Renewable Energy Laboratory.[30] The purpose of these interviews was to determine the timing, scale, geographic scope and details of grid connection and net metering rules in Japan, California and the U.S. overall.

(C) Price data

The data collected also include historical prices of silicon, cells, modules, inverters, systems and incentives for solar power systems and historical grid prices for residential, commercial and industrial customers. Data sources include IEA PVPS, U.S. EIA, PV News/Paul Maycock, RTS/Osamu Okki, Photon Magazine, company data and other sources. TABLE 3 provides the historical solar price data used for analysis in this thesis along with sources. In addition, average residential, commercial and industrial electricity prices were collected in order to have a rough estimate of the price for solar power's direct substitute. TABLE 4 provides historical average residential electricity prices in Japan, the largest U.S. installation market, California.[31] It is important to emphasize that use of *average* grid prices is being used because this is the most readily available data, but more accurate analysis would take into account the distribution curve for grid prices in each electricity market. This is important because the results of this thesis are based on average prices for typical customers, whereas *specific* end-customer economics will depend on specific end-customer prices that may vary significantly from the average. As such, the results presented in this thesis should be seen as an attempt to evaluate end-customer economics for solar power in a directional sense rather than with a high degree of precision. More detailed analysis using more precise customer-specific estimates of prices is an area for additional research.[32]

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[29] Mr. Masamitsu Obashi.
[30] Mr. Dick DeBlasio
[31] See Section 4 for description of U.S. solar power market and rationale for focus on California within the U.S. market.
[32] The result of using average grid prices is that it likely *under*estimates the market potential of solar power by ignoring the potential for earlier adoption by higher-than-average grid price customers.

TABLE 3: Module, non-module, incentives and system prices 1994 to 2005
($/Watt)

JAPAN	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Exchange rate (yen/US$)	102	94	109	121	131	114	108	122	125	116
Module price ($/watt)	$9.07	$8.37	$5.94	$5.42	$5.11	$5.28	$5.08	$3.98	$3.70	$3.83
Module price (yen/watt)	927	764	646	656	670	600	548	484	463	446
Non-module price ($/watt)	$10.50	$9.96	$5.09	$3.34	$3.05	$2.98	$2.75	$2.25	$1.97	$2.10
Non-module price (yen/watt)	1073	936	554	404	400	339	296	274	247	244
Gross system price ($/watt)	$19.57	$18.09	$11.03	$8.76	$8.17	$8.26	$7.83	$6.24	$5.67	$5.95
Gross system price (yen/watt)	2000	1700	1200	1060	1070	939	844	758	710	690
National incentives ($/watt)	$8.81	$9.05	$4.60	$2.81	$2.60	$2.90	$1.86	$0.99	$0.80	$0.78
National incentives (yen/watt)	900	850	500	340	340	330	200	120	100	90
Local incentives ($/watt)	$0.00	$0.05	$0.10	$0.15	$0.20	$0.25	$0.30	$0.35	$0.40	$0.40
Local incentives (yen/watt)	0	5	11	18	26	28	32	43	50	46
Total incentives ($/watt)	$8.81	$9.10	$4.70	$2.96	$2.80	$3.15	$2.16	$1.34	$1.20	$1.18
Total incentives (yen/watt)	900	855	511	358	366	358	232	163	150	136
Net system price ($/watt)	$10.77	$9.00	$6.34	$5.80	$5.37	$5.10	$5.67	$4.90	$4.47	$4.77
Net system price (yen/watt)	1,100	845	689	702	704	581	612	595	560	554
CALIFORNIA	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Module price ($/watt)	$4.00	$4.00	$4.00	$4.15	$4.00	$3.50	$3.75	$3.50	$3.25	$3.00
Non-module price ($/watt)	$8.00	$7.50	$7.00	$6.85	$6.50	$6.50	$5.25	$4.50	$4.50	$4.25
Gross system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$10.50	$10.00	$9.00	$8.00	$7.75	$7.25
National incentives ($/watt)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Local incentives ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Total incentives ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Net system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$7.50	$7.00	$6.00	$3.50	$3.25	$3.50

Source: World Bank (exchange rate), U.S. EIA (grid prices), NEDO via www.solar.nef.or.jp/josei/zissi.htm (Japan national incentives, Japan gross system price, Japan module prices), interviews (estimate of local incentives in Japan); IEA PVPS (U.S. module and gross system prices); CEC (California incentives) www.energy.ca.gov/electricity/statewide_weightavg_sector.html. Note: Non-module price calculated by subtracting module price from gross system price. Net system price calculated by subtracting total incentives from gross system price.

TABLE 4: Average price of residential grid-based electricity
(Price per kWh in local currency)

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Exchange rate (yen/US$)	102	94	109	121	131	114	108	122	125	116
Japan residential electricity price ($/kWh)	$0.25	$0.27	$0.23	$0.21	$0.19	$0.21	$0.21	$0.19	$0.17	$0.19
Japan residential electricity price (yen/kWh)	25.5	25.4	25.0	25.1	24.4	24.2	23.1	22.8	21.8	21.5
U.S. residential electricity price ($/kWh)	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.09	$0.08	$0.09
California residential electricity price ($/kWh)	$0.12	$0.12	$0.12	$0.12	$0.11	$0.11	$0.11	$0.12	$0.13	$0.13

Source: World Bank (exchange rate); U.S. EIA (Japan residential electricity price - www.eia.doe.gov/emeu/international/elecprih.html; U.S. residential electricity price - www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html); www.energy.ca.gov/electricity/statewide_weightavg_sector.html (California residential electricity price).

(D) Levelized price modeling and analysis

Following Lester and Deutch[33], a 16-variable spreadsheet model was developed to estimate the levelized price of solar power in U.S. cents per kilowatt-hour.[34] This model incorporates the key costs and benefits associated with a solar power system over its lifetime, and then discounts these costs and benefits to estimate the net present value per kilowatt-hour. The purpose of this

[33] Based on levelized price methodology taught in Applications of Technology in Energy and the Environment (1.174) class at MIT during Fall 2003 semester.

[34] Model developed in cooperation with Joel Conkling, MIT Sloan MBA 2007.

modeling effort was to evaluate the price of solar power as perceived by end customers and then to compare it with the price of the substitute (i.e. grid-based residential electricity prices). This model estimates both the levelized gross system price (LGSP) of solar power without incentives and the levelized net system price (LNSP) of solar power with incentives. The model enables identification of areas of price reduction during the period 1994 to 2003. Source data for this model include the price of solar modules and other system inputs (NEDO, IEA PVPS), the level of solar incentives (NEDO, IEA PVPS, U.S. DOE, other) and long-term residential interest rates (CLSA). Other model inputs (e.g. historical system degradation rates, historical DC-AC conversion factors) were based on interviews with numerous solar power company executives to determine rough estimates of typical rates. While this modeling approach is not unique, the reviewed literature does not include any modeling of the levelized solar power price in major solar power markets that enables consistent comparison across these markets. This was a valuable exercise because the LGSP and LNSP are measures of the price of solar power that can be compared across markets. Assumptions and output from this model are provided in TABLE 5 and TABLE 6, with additional details in the relevant sections of this thesis.

TABLE 5: Key assumptions & output of LNSP model for Japan

KEY ASSUMPTIONS										
	1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Installation size (kW DC)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Gross system price ($/watt)	$19.57	$18.09	$11.03	$8.76	$8.17	$8.26	$7.83	$6.24	$5.67	$5.95
National incentive ($/watt)	$8.81	$9.05	$4.60	$2.81	$2.60	$2.90	$1.86	$0.99	$0.80	$0.78
Local incentive ($/watt)	$0.00	$0.05	$0.10	$0.15	$0.20	$0.25	$0.30	$0.35	$0.40	$0.40
Total incentive ($/watt)	$8.81	$9.10	$4.70	$2.96	$2.80	$3.15	$2.16	$1.34	$1.20	$1.18
Net system price ($/watt)	$10.77	$9.00	$6.34	$5.80	$5.37	$5.10	$5.67	$4.90	$4.47	$4.77
System lifetime (years)	25	25	25	25	25	25	25	25	25	25
Inverter replacement price ($/watt)	$0.50	$0.48	$0.45	$0.43	$0.41	$0.39	$0.37	$0.35	$0.33	$0.31
Inverter replacement frequency (years)	6.0	6.4	6.7	7.1	7.6	8.0	8.5	9.0	9.6	10.1
Annual O&M (% installed price)	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
Solar resource (kW/m^2/day)	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25
AC conversion factor (%)	71%	72%	73%	74%	75%	76%	77%	78%	79%	80%
Annual output degradation (%)	0.30%	0.29%	0.29%	0.28%	0.28%	0.27%	0.27%	0.26%	0.26%	0.25%
Residential electricity price (yen/watt)	25.5	25.4	25.0	25.1	24.4	24.2	23.1	22.8	21.8	21.5
Residential electricity price ($/watt)	$0.25	$0.27	$0.23	$0.21	$0.19	$0.21	$0.21	$0.19	$0.17	$0.19
Electricity price inflation for DCF forecast (%)	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Exchange rate (yen/$)	102	94	109	121	131	114	108	122	125	116
Nominal interest rate (%)	4.0%	3.6%	3.2%	3.1%	2.6%	2.5%	2.8%	2.6%	2.6%	2.3%
LEVELIZED SYSTEM PRICE										
	1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Levelized gross system price ($/kWh)	$1.23	$1.10	$0.65	$0.51	$0.46	$0.46	$0.45	$0.35	$0.32	$0.33
Levelized gross system price (yen/kWh)	126	103	71	62	60	52	49	43	40	38
Levelized net system price ($/kWh)	$0.70	$0.57	$0.39	$0.36	$0.32	$0.30	$0.34	$0.29	$0.26	$0.27
Levelized net system price (yen/kWh)	72	54	42	44	42	34	37	35	33	31

Source: New Energy Foundation www.solar.nef.or.jp/josei/zissi.htm (gross system price, national incentive); Rogol (2004) (local incentives, system lifetime, inverter replacement frequency and price, annual O&M, solar resource, AC conversion factor, annual output degradation), U.S. EIA (residential electricity price); World Bank (exchange rate); CLSA (interest rate). Note: See Section 3 for more details on LNSP modelling for Japan.

TABLE 6: Key assumptions & output of LNSP model for California

KEY ASSUMPTIONS										
	1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Installation size (kW DC)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Gross system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$10.50	$10.00	$9.00	$8.00	$7.75	$7.25
National incentive ($/watt)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Local incentive ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Total incentive ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Net system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$7.50	$7.00	$6.00	$3.50	$3.25	$3.50
System lifetime (years)	25	25	25	25	25	25	25	25	25	25
Inverter replacement price ($/watt)	$0.50	$0.48	$0.45	$0.43	$0.41	$0.39	$0.37	$0.35	$0.33	$0.32
Inverter replacement frequency (years)	6.0	6.4	6.7	7.1	7.6	8.0	8.5	9.0	9.6	10.1
Annual O&M (% installed price)	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
Solar resource (kW/m^2/day)	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
AC conversion factor (%)	71%	72%	73%	74%	75%	76%	77%	78%	79%	80%
Annual output degradation (%)	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Residential electricity price ($/watt)	$0.12	$0.12	$0.12	$0.12	$0.11	$0.11	$0.11	$0.12	$0.13	$0.13
Electricity price inflation for DCF forecast (%)	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Nominal interest rate (%)	7.5%	7.8%	7.7%	7.7%	7.1%	7.3%	7.9%	7.0%	6.5%	5.8%
LEVELIZED SYSTEM PRICE										
	1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Levelized gross system price ($/kWh)	$0.85	$0.84	$0.79	$0.79	$0.71	$0.69	$0.65	$0.54	$0.50	$0.44
Levelized net system price ($/kWh)	$0.85	$0.84	$0.79	$0.79	$0.52	$0.49	$0.44	$0.25	$0.23	$0.23

Source: IEA PVPS (gross system price), CEC (national and local incentive), Rogol (2004) (system lifetime, inverter replacement price and frequency, annual O&M, solar resource, AC conversion factor, annual output degradation, AC conversion factor); U.S. EIA (residential electricity price); CLSA (interest rate). Note: See Section 4 for more details on LNSP modelling for California.

(E) "Solar gap" analysis, demand elasticities and price drivers

Solar power is a direct substitute for electricity from other sources and, more specifically, grid-connected solar power systems are a direct substitute for grid-based electricity. As a result, analysis was conducted on the data described above (a) to compare the "gap" between the price of solar electricity and the price of its main substitute (grid-based electricity), (b) to identify the key drivers of reductions solar power prices and (c) to evaluate the impact on demand of price reductions by estimating demand elasticities. TABLE 7 presents estimates of the "gap" (measured in \$/kWh) between solar power price for the end customer (estimated as levelized net system price) and average residential electricity price.[35] TABLE 8 presents estimates of demand elasticities in Japan and California assuming various definitions of price during the years 1994 to 2003. In all cases, the estimate of demand elasticity is -2.6 or greater, meaning that a 1% decrease in price coincided with at least a 2.6% increase in installations. TABLE 9 presents estimates of the key drivers of reduction in the solar power system prices (in \$/W terms) in Japan and California. It is noteworthy that non-module price reductions were significant in all three markets during the period 1994 to 2003.

TABLE 7: "Solar gap" analysis 1994-2003
(\$/kWh)

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	CAGR
Japan average residential grid price (\$/kWh)	\$0.25	\$0.27	\$0.23	\$0.21	\$0.19	\$0.21	\$0.21	\$0.19	\$0.17	\$0.19	-3%
Japan levelized net system price (\$/kWh)	\$0.70	\$0.57	\$0.39	\$0.36	\$0.32	\$0.30	\$0.34	\$0.29	\$0.26	\$0.27	-10%
Japan "gap" (\$/kWh)	\$0.45	\$0.30	\$0.16	\$0.15	\$0.13	\$0.09	\$0.13	\$0.10	\$0.09	\$0.08	-17%
	1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**CAGR**
California average residential grid price (\$/kWh)	\$0.12	\$0.12	\$0.12	\$0.12	\$0.11	\$0.11	\$0.11	\$0.12	\$0.13	\$0.13	1%
California levelized net system price (\$/kWh)	\$0.85	\$0.84	\$0.79	\$0.79	\$0.52	\$0.49	\$0.44	\$0.25	\$0.23	\$0.23	-14%
California "gap" (\$/kWh)	\$0.73	\$0.72	\$0.67	\$0.67	\$0.41	\$0.38	\$0.33	\$0.13	\$0.10	\$0.10	-20%

Source: Michael Rogol calculations.
Note: "Gap" is defined as levelized net system price minus average residential grid price.

[35] One way to improve this analysis would be to incorporate the full distribution curve of residential grid prices instead of using the simplistic assumption of weighted average residential grid price. Using the distribution curve would enable identification of customers paying above average grid prices for whom solar power reaches grid parity more quickly. Future research may incorporate a distribution of grid electricity prices.

TABLE 8: Demand elasticity analysis 1994-2005

	Price change 1994-2003 (CAGR %)	Installation growth 1994-2003 (CAGR %)	Elasticity (Change in installation/ change in price)
Japan gross system price	-12%	47%	-3.8
Japan net system price	-7%	47%	-6.4
Japan levelized net system price	-10%	47%	-4.7
Japan "gap" of LNSP minus grid price	-17%	47%	-2.8
U.S. gross system price	-5%	27%	-4.9
U.S. net system price	-5%	27%	-4.9
U.S. levelized net system price	-7%	27%	-3.7
U.S. "gap" of LNSP minus grid price	-8%	27%	-3.3
California gross system price	-5%	51%	-9.4
California net system price	-13%	51%	-4.0
California levelized net system price	-14%	51%	-3.8
California "gap" of LNSP minus grid price	-20%	51%	-2.6

Source: Michael Rogol calculations.
Note: The column in yellow (elasticity) equals the third column (installation growth) divided by the second column (price change).

TABLE 9: Drivers of reduction in the solar power system prices 1994-2003

JAPAN	1994	2003	Change ($/W)
Module price ($/W)	$9.07	$3.83	-$5.24
Non-module price ($/W)	$10.50	$2.10	-$8.40
Gross system price ($/W)	$19.57	$5.94	-$13.64
Incentive ($/W)	$8.81	$1.18	-$7.63
Net system price ($/W)	$10.77	$4.76	-$6.00

CALIFORNIA	1994	2003	Change ($/W)
Module price ($/W)	$4.00	$3.00	-$1.00
Non-module price ($/W)	$8.00	$4.25	-$3.75
Gross system price ($/W)	$12.00	$7.25	-$4.75
Incentive ($/W)	$0.00	$3.75	$3.75
Net system price ($/W)	$12.00	$3.50	-$8.50

Source: Michael Rogol calculations.
Note: The fourth column (Change) equals the third column (2003) minus the second column (1994).

(F) Discounted cash flows of solar players

In 2003-2004, detailed financial models for 15 leading solar companies were developed using standard financial modeling practices similar to those discussed in "Valuation"[36] to build quarterly discounted cash flow models. This modeling was based on disclosed financial information (annual reports, quarterly reports, analyst briefings, etc.). In 2005-2006, this modeling was extended to cover more than 30 solar power companies. These are quarterly/ annual discounted cash flow models include historical trends in the companies' income statements, balance sheets and cash flow statements. Typically, these models cover the years 2003 to 2010. These models were developed in order to evaluate the cost structures, cash flows and market valuations of traded solar power companies. In addition, in 2007, a detailed study of the cost structure of the solar power sector was conducted with co-author Joel Conkling. This study provides a detailed examination of the cost structure at each step of the solar supply chain.[37] Together, this research provides a strong body of data for cost structures for solar power players along the supply chain during the period 2003 to 2007.

Unfortunately, detailed estimates for the cost structure of the solar power supply chain in the mid-1990s (e.g. 1994) are not publicly available. As a result, assumptions believed to be conservative were applied to 2003-2006 cost estimates in order to make an estimate of the net present value of a 100MW cell/module production facility investment by a Japanese player in 1994 to supply modules in the Japanese market. These assumptions were reviewed with senior executives in the Japanese and U.S. solar power sectors. In this case, as $90mn investment would have yielded an NPV of roughly $114mn.[38] In contrast, in 1994 the U.S. manufacturers likely had lower cost structures but also faced much lower domestic module prices. As a result, the NPV of $72mn investment in a 100MW cell/module production facility in the U.S. in 1994 to supply modules to the U.S. market appears to have yielded an NPV of roughly negative $120mn.[39] These assumptions and NPV estimates are provided in TABLE 10 and TABLE 11.

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[36] Copeland, Koller, Murrin (1995)

[37] Conkling and Rogol (2007).

[38] Official Japanese government estimates for 600 yen/watt ($6/W) for the fully loaded cost of solar module manufacturing are consistent without my estimates. Unfortunately, public data supporting the Japanese government estimates are not available. See Chiba, M "New Sunshine Program: Comprehensive Approach to the 21st Century" Journal of Energy Engineering December 1996 pages 93-101.

[39] Note: This NPV estimate for a 100MW U.S. plant cell/module facility to supply the U.S. market likely overstates the negative NPV. In reality, U.S. manufacturers exported the bulk of their production (nearly 80% in 1994). Assuming that a U.S. manufacturer would export a significant portion of their production to higher price markets makes the NPV calculation significantly more attractive than the negative estimate provided here. However, the NPV was likely lower than the NPV for a Japanese manufacturer supplying the Japanese market due to higher costs (business development, marketing, selling, shipping, etc.) for product manufactured in the U.S. then exported to other markets such as Japan.

TABLE 10: NPV analysis of 100MW cell/module investment in 1994 in Japan to supply modules to the Japanese market

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Index of capex/W (2006 = 100)	225	210	197	184	172	161	150	140	131	123	114	107	100
Capex/W ($/W)	$0.90	$0.84	$0.79	$0.74	$0.69	$0.64							$0.40
Index of silicon usage (2006 = 100)	225	210	197	184	172	161	150	140	131	123	114	107	100
Silicon usage (grams/W)	23	21	20	18	17	16	15	14	13	12	11	11	10
Silicon price ($/kg)	$40	$40	$40	$40	$40	$40							
Si cost per W	$0.90	$0.84	$0.79	$0.74	$0.69	$0.64							
Index of ingot/wafer cost/W ($/W)	225	210	197	184	172	161	150	140	131	123	114	107	100
Ingot/wafer cost/W ($/W)	$1.46	$1.37	$1.28	$1.19	$1.12	$1.04							$0.65
Ingot/wafer mark-up (%)	10%	10%	10%	10%	10%	10%							
Ingot/wafer price ($/W)	$1.61	$1.50	$1.41	$1.31	$1.23	$1.15							
Index of cell/module non-equipment, non-wafer cost (2006 = 100)	225	210	197	184	172	161	150	140	131	123	114	107	100
Cell/module non-equipment, non-wafer cost/W ($/W)	$2.70	$2.53	$2.36	$2.21	$2.06	$1.93							$1.20
Cell/module cost including everything except equipment ($/W)	$5.21	$4.87	$4.55	$4.26	$3.98	$3.72							
Cell/module plant size (MW)	100												
Capex ($mn)	-90												
Proudction (MW)	0	100	102	104	106	108							
Expected annual module price decrease (%)		20%	20%	20%	20%	20%							
Expected module price in Japan from 1994 perspective ($/W)*	$9.07	$7.26	$5.81	$4.64	$3.72	$2.97							
Revenue ($mn)	$0	$726	$592	$483	$394	$322							
Manufacturing and other cash expenses ($/W)	-$5.2	-$4.9	-$4.6	-$4.3	-$4.0	-$3.7							
All in operaitng cost ($mn)	$0	-$487	-$465	-$443	-$422	-$402							
Tax rate (%)	30%	30%	30%	30%	30%	30%							
Taxes on income ($mn)	$0	-$72	-$38	-$12	$8	$24							
Cash flow ($mn)	-$90	$167	$89	$28	-$19	-$56							
Discount rate (%)	5%												
Present value of cash flow ($mn)	($90)	$159	$81	$24	($16)	($44)							
Net present value ($mn)	**$114**												

Source: Michael Rogol calculations. *Note: "Expected module price in Japan from 1994 perspective ($/W)" is estimate for how price of modules might evolve in the years following 1994 from the perspective of 1994.

TABLE 11: NPV analysis of 100MW cell/module investment in 1994 in U.S. to supply modules to the U.S. market

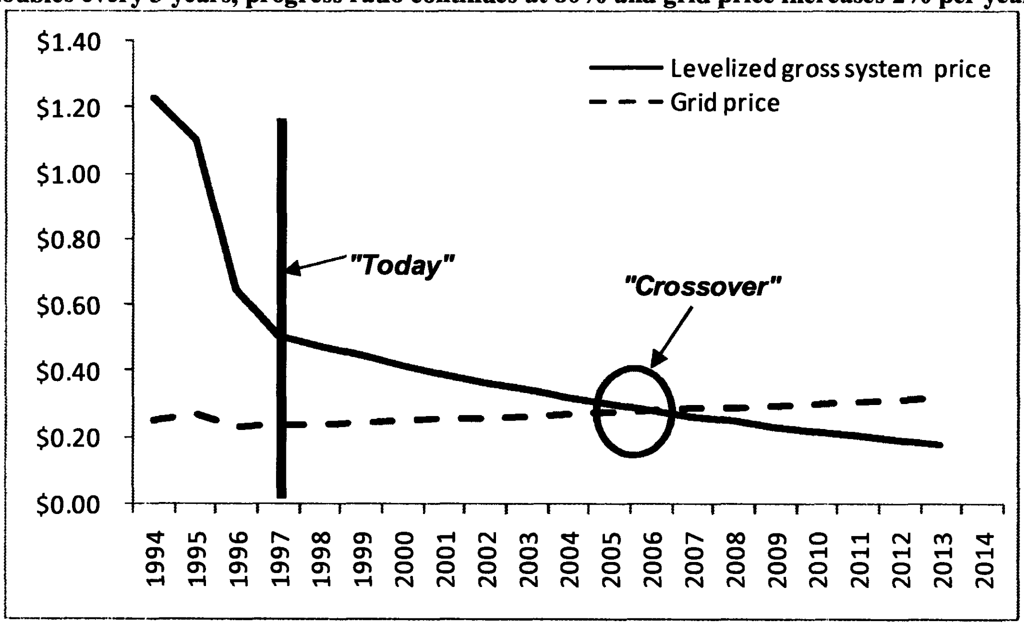
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Index of capex/W (2006 = 100)	180	171	163	155	148	141	134	128	122	116	110	105	100
Capex/W ($/W)	$0.72	$0.68	$0.65	$0.62	$0.59	$0.56							$0.40
Index of silicon usage (2006 = 100)	180	171	163	155	148	141	134	128	122	116	110	105	100
Silicon usage (grams/W)	18	17	16	16	15	14	13	13	12	12	11	11	10
Silicon price ($/kg)	$40	$40	$40	$40	$40	$40							
Si cost per W	$0.72	$0.68	$0.65	$0.62	$0.59	$0.56							
Index of ingot/wafer cost/W ($/W)	180	171	163	155	148	141	134	128	122	116	110	105	100
Ingot/wafer cost/W ($/W)	$1.17	$1.11	$1.06	$1.01	$0.96	$0.91							$0.65
Ingot/wafer mark-up (%)	10%	10%	10%	10%	10%	10%							
Ingot/wafer price ($/W)	$1.28	$1.22	$1.16	$1.11	$1.06	$1.01							
Index of cell/module non-equipment, non-wafer cost (2006 = 100)	180	171	163	155	148	141	134	128	122	116	110	105	100
Cell/module non-equipment, non-wafer cost/W ($/W)	$2.16	$2.05	$1.95	$1.86	$1.77	$1.69							$1.20
Cell/module cost including everything except equipment ($/W)	$4.16	$3.96	$3.77	$3.59	$3.42	$3.26							
Cell/module plant size (MW)	100												
Capex ($mn)	-72												
Proudction (MW)	0	100	102	104	106	108							
Expected annual module price decrease (%)		5%	5%	5%	5%	5%							
Expected module price in U.S. from 1994 perspective ($/W)*	$4.00	$3.80	$3.61	$3.43	$3.26	$3.10							
Revenue ($mn)	$0	$380	$368	$357	$346	$335							
Manufacturing and other cash expenses ($/W)	-$4.2	-$4.0	-$3.8	-$3.6	-$3.4	-$3.3							
All in operaitng cost ($mn)	$0	-$396	-$385	-$374	-$363	-$353							
Tax rate (%)	30%	30%	30%	30%	30%	30%							
Taxes on income ($mn)	$0	$5	$5	$5	$5	$5							
Cash flow ($mn)	-$72	-$11	-$12	-$12	-$12	-$12							
Discount rate (%)	5%												
Present value of cash flow ($mn)	($72)	($11)	($10)	($10)	($10)	($10)							
Net present value ($mn)	**($122)**												

Source: Michael Rogol calculations. Note: This NPV estimate does not take into account potential for exports at higher prices. *Note: "Expected module price in U.S. from 1994 perspective ($/W)" is estimate for how price of modules might evolve in the years following 1994 from the perspective of 1994.

(G) "Cross-over" analysis

Several interviewees in Japan and the U.S. mentioned their view that achieving grid parity is the long-term goal of the solar power sector.[40] Interviewees would often share "mental exercises" for estimating the time (in years) that it would take solar power to reach parity with (or "cross-over") average residential grid prices in various markets. Typical assumptions for the "mental exercise" were the volume growth rate of the sector ("cumulative production doubling every X years" or "annual year-on-year growth of Y%"), the cost reduction associated with learning and scale ("X% progress ratio" or "Y% annual cost reductions") and the annual increase in nominal average residential grid prices. Using data on average residential grid prices, estimates for LNSP and simplistic assumptions about the pace of growth (doubling every 3 years consistent with historical growth rates[41]), the rate of cost reductions (80% progress ratio consistent with the literature[42]) and rate of nominal grid price increases (assumed 2%/year based on interviews with electricity market modelers at DOE and Cambridge Energy Research Associates) to estimate the number of years in the future LNSP would reach parity with grid price. The value of this analysis is that it provides a simple-to-understand quantification of "time to parity" that is comparable across markets.

FIGURE 4: "Cross-over" analysis – Japan from perspective of 1997 assuming cumulative production doubles every 3 years, progress ratio continues at 80% and grid price increases 2% per year



Source: Calculations by Michael Rogol.

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[40] Research conducted for Rogol (2004) and Rogol (2005)
[41] IEA PVPS (2004)
[42] Margolis (2002a)

(H) Government spending on solar power

For both the U.S. and Japan, data was collected on government spending for solar power R&D, demonstration and deployment budgets in order to identify trends and changes in trends. Analysis was then conducted on quantitative and qualitative aspects of government spending in the solar power sector during the years 1994 to 2003. The basic data analyzed are presented in TABLE 12.

TABLE 12: Government spending on solar power 1994-2003
(Nominal US$ millions and yen billons)

R&D	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	1994-2003
Japan (nominal US$mn)	67.0	80.0	69.0	58.0	71.1	90.7	85.7	51.0	59.1	84.5	716
Japan (nominal yen bn)	6.8	7.5	7.5	7.0	9.3	10.3	9.2	6.2	7.4	9.8	81
US (nominal US$mn)	70.0	84.0	84.0	60.0	35.0	35.0	35.0	35.0	35.0	65.7	539
DEMONSTRATION	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**1994-2003**
Japan (nominal US$mn)	10.1	18.1	17.7	11.2	21.4	23.6	36.6	16.5	35.9	32.4	223
Japan (nominal yen bn)	1.0	1.7	1.9	1.4	2.8	2.7	3.9	2.0	4.5	3.8	26
US (nominal US$mn)											0
DEPLOYMENT	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**1994-2003**
Japan (nominal US$mn)	18.1	35.2	37.3	91.8	132.5	149.9	129.3	188.4	185.5	90.6	1059
Japan (nominal yen bn)	1.9	3.3	4.1	11.1	17.4	17.0	13.9	22.9	23.2	10.5	125
US (nominal US$mn)					29.7	31.5	84.6	84.6	79.6	273.7	584
RDD&D TOTAL	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**1994-2003**
Japan (nominal US$mn)	95.2	133.3	124.0	160.9	225.0	264.1	251.5	255.9	280.5	207.5	1998
Japan (nominal yen bn)	9.7	12.5	13.5	19.5	29.5	30.0	27.1	31.1	35.1	24.1	232
US (nominal US$mn)	70.0	84.0	84.0	60.0	64.7	66.5	119.6	119.6	114.6	339.4	1122

Source: IEA PVPS (1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004)[43]

(I) Coordination, roadmapping and government policies

A preliminary review of the literature on Japan's solar power sector development suggests that the combination of policies and corporate activities observed in Japan was part of a coordinated exercise to support the growth of the solar power sector.[44] However there is not much information on this roadmapping in the literature on Japan's solar power sector. From the literature, it appears that roadmapping incorporated technology milestones, R&D requirements, capacity expansion, supply chain developments, end customer installations, cost and price milestones, etc.

[43] One peer reviewer suggested using other data sources for government spending on solar power due to inconsistencies between IEA PVPS data and data from official government sources in both Japan and the U.S. Identifying more accurate data sources is an area of current research.

[44] For examples of the diverse activities that were involved in this coordinated effort, see description of coordinated efforts by various players in Kurokawa (1994), "The Japanese Experiences with National PV Systems Programmes" by Kurokawa and Ikki (2001) and Foster (2005).

Roadmapping appears to have formally commenced in 1990 with the formation of a consortium of companies and public institutes focused on commercialization efforts including reducing solar cell production costs. This consortium, named the Photovoltaic Power Generation Technology Research Association (PVTEC), included many of Japan's largest companies, such as Asahi Glass, Fuji, Hitachi, Kawasaki Steel, Kyocera, Matsushita, Mitsubishi, Mitsui, Nippon Sheet Glass, Sanyo, Sharp, Shinetsu, Showa Shell, Sumitomo and Teijin. Funding for research activities was provided by the Japanese government, including the Ministry, Economy, Trade and Industry (METI). PVTEC's mission was to help Japan stay ahead of other countries in the PV sector. To pursue this mission, PVTEC sought to accelerate the development of the commercialization of solar power technologies by coordinating the R&D activities of member companies, organize projects assigned by the Japanese government (via NEDO under METI) and promote cooperation among universities, national research institutions, and overseas organization such as foreign research laboratories.[45]

This thesis attempts to highlight the available literature on Japan's solar power sector roadmapping and coordination efforts. It also attempts to identify and describe activities in the U.S. that were both similar and dissimilar to those in Japan. Unfortunately, there is not a great deal of publicly available information in the English-based literature on Japan's coordination and roadmapping. One contribution of this thesis will be simply to provide a high-level picture of Japan's coordination efforts within the solar power sector and to identify important questions for further research.

The data and analysis described so far in this section was organized into two case studies: Japan 1994 to 2003 (Section 3) and the U.S. 1994 to 2003 (Section 4). The structure of these case studies is: grid connection; demand; supply and coordination. A comparative analysis of the two case studies is conducted in Section 5 to evaluate similarities and differences between the

[45] PVTEC was organized under NEDO with the purpose of "co-ordinating R&D contracts in terms of the mass-production technology of low-cost, high-efficiency PV cells, and the development of BIPV modules." (Kurokawa and Ikki (2001)). While PVTEC appears to have played an important coordination role, Kurokawa and Ikki's description emphasizes a broad number of organizations were involved in the development of Japan's solar power sector, so that PVTEC was not the only organization involved in coordination activities. However, the English-language literature does not provide detailed descriptions of the precise roles and activities. Foster (2005) also stresses that, "The government research program has been tightly coordinated with Japanese industry and academia." However, the details of the coordination among the various organizations are not elaborated. Providing a more granular and descriptive overview of the coordination process, players and impact is a potential focus for further research.

Japanese and U.S. experiences, identify "key learnings" and formulate questions for further analysis.

- SECTION 3 -

CASE STUDY:

JAPANESE SOLAR POWER SECTOR 1994-2003

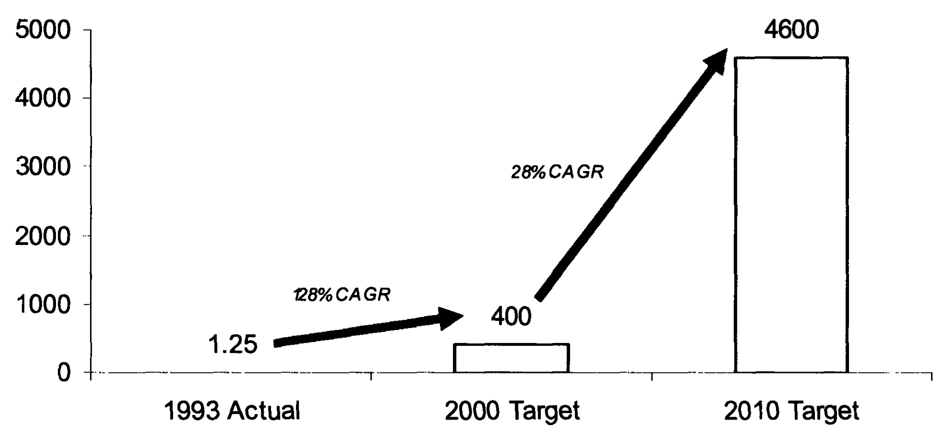
Section 3

Case study: Japanese solar power sector 1994-2003

(A) Introduction

In 1993, the Japanese government laid out formal, long-term goals for the solar power sector. In the "Basic Guidelines for the New Energy Introduction," the cabinet approved overarching goals for PV that included official targets for cumulative installations of 400MW by 2000 and 4600MW by 2010.[46] From the perspective of 1993, these goals appeared aggressive because the cumulative base of PV in Japan in 1993 was only 1.25 MW. As such, achieving the official government target would require 128% compound annual growth from 1994-2000 and 28% compound annual growth 2001-2010.

FIGURE 5: Cumulative installed solar power installations
MW (actual for 1993, targets for 2000 and 2010)



Source: 1993 from IEA PVPS. 2000 and 2010 Target from Kurokawa and Ikki (2001). CAGR% calculated by Michael Rogol.

These goals and the strong growth rates they required were supported by the "New Sunshine Program" which went into effect from 1993.[47] The New Sunshine Program was an aggressive effort to:

- Accelerate R&D on innovative technology essential to stabilizing per capita CO2 emissions at 1990 levels by the year 2000;

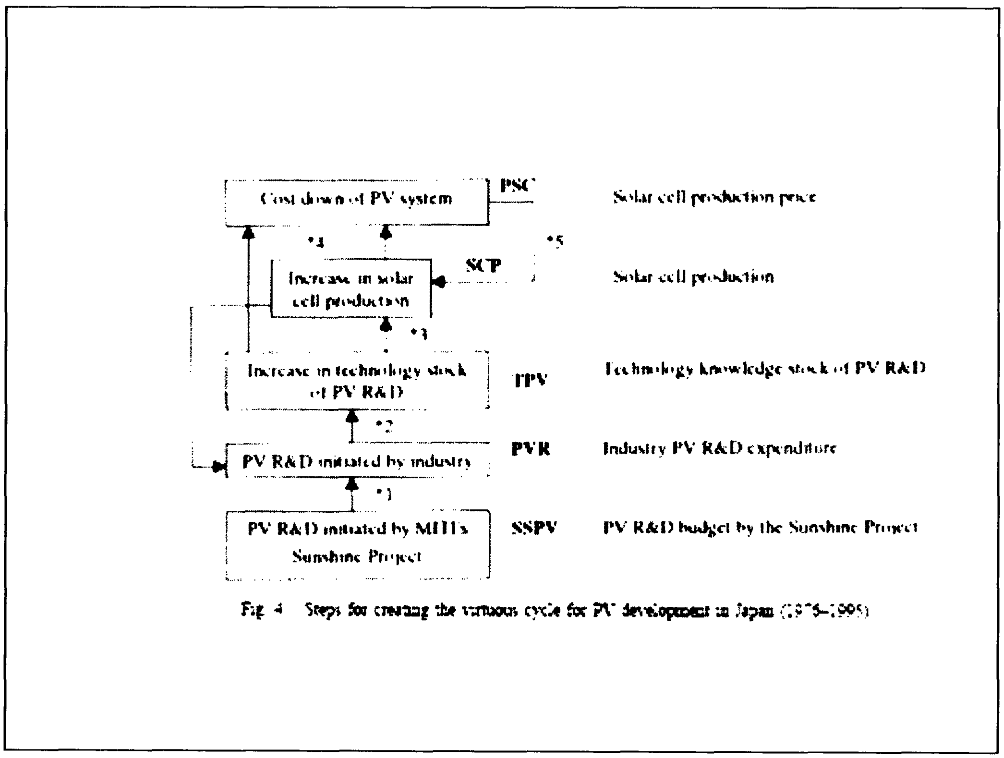
[46] Kurokawa and Ikki (2001) pages 2-3.
[47] Kurokawa and Ikki (2001) Table 2.

- Initiate large international R&D projects in areas that could contribute significantly to reducing greenhouse gas emissions; and

- Develop and diffuse appropriate technologies needed in neighboring developing countries through cooperative R&D on technologies originating from the previous Sunshine Project and the Moonlight Project.[48]

The New Sunshine Program supported projects to accelerate technologies for which a "virtuous cycle for PV development in Japan" might be triggered. This "virtuous cycle" involved the expectation of technological improvement decreasing cost, leading to increase in demand, leading to mass production and further cost reduction.[49] A schematic overview of this process is provided by Watanabe et al (2000) in the following figure.

FIGURE 6: "Steps for creating a virtuous cycle for PV deployment in Japan 1976-1995"



Source: Wantanbe et al (2000). Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see original source for clearer image.

[48] Richards and Fullerton (1994)
[49] Watanabe et al (2000)

Japan's solar power sector delivered impressive results in the decade that followed. At the start of the period (1994), the Japanese solar power sector was small in terms of installations (7MW equating to 10% of global installations), modest in terms of production (17MW equating to 23% of global annual cell/module production) and expensive (typical installation prices of $20/watt compared to $12/watt in larger markets such as the U.S.). By 2003, installations had increased 32-fold (47% compound annual growth rate), annual cell/module manufacturing had increased 22-fold (41% CAGR) and gross system prices had decreased 70% (-12% CAGR).[50]

By early 2004, there was general belief among Japanese policy makers and solar power executives that the goals of the New Sunshine Program were being achieved.[51] Specifically, "creation of the initial market for PV system[s]" was viewed as complete and the government began phasing out the core programs of the New Sunshine Program. In 2004, the government revised its "Long Term Energy Supply and Demand Outlook." With this revision, the programs under the New Sunshine Program were to be reduced and eliminated by 2006-2007. According to Ikki et al (2004), Japan's solar power market appeared likely to continue growing despite the end of the government incentive programs: "Although the amount of subsidy [will be] reduced, the sales of PV systems for individuals and private companies are growing, as [customers] profoundly understand the value of PV power generation. From these trends, further dissemination of PV systems is expected with the progress of cost reduction of PV systems and development of PV."[52]

Given the strong government support for solar power sector development under the New Sunshine Program during the years 1994 to 2003, this chapter provides a detailed review of the Japanese solar power sector during these years with emphasis on Japan's solar power policies. One key point made in this case study is that efforts to coordinate the development of Japan's solar power sector were an important factor in the rapid growth achieved from 1994 to 2003. The remainder of Section 3 will provide details on grid connection rules, demand, supply and industry coordination efforts.

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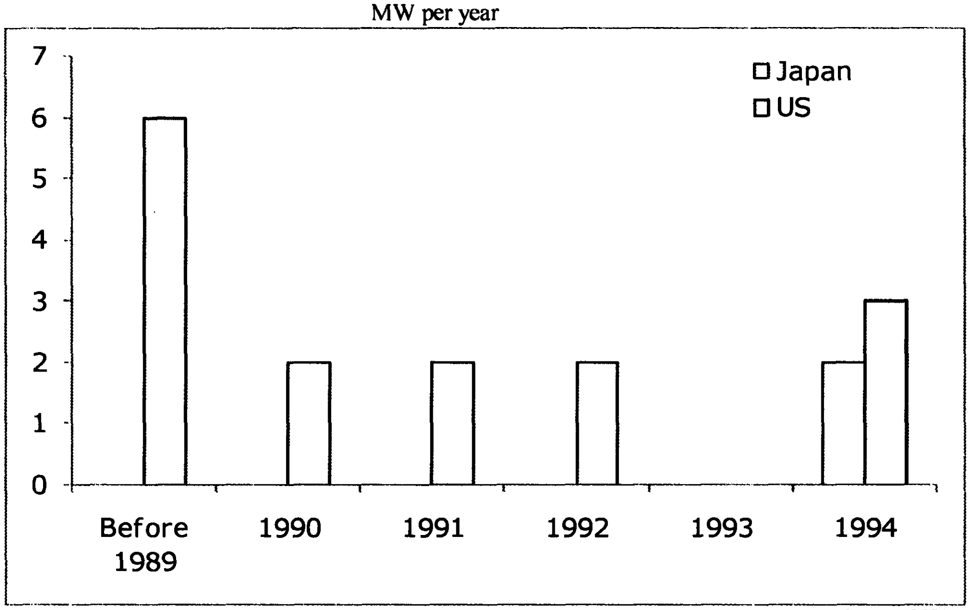
[50] Installation volume data from IEA PVPS, production volume data from Paul Maycock/PV News, price data from IEA PVPS and NEDO. For data, see Section 2.
[51] Interviews with NEDO, Sharp, Kyocera Solar and RTS, among others, during summer 2004.
[52] Ikki, Ohigashi, Kaizuka and Matsukawa (2004)

(B) Grid connection

In the years leading up to 1994, no small-scale solar power systems were connected to the electric power network in Japan.[53] The lack of installations is displayed in FIGURE 7 in which there is no yellow (Japan) prior to 1994. In contrast to the absolute lack of small-scale installations in Japan, the U.S. had several megawatts of cumulative small-scale solar system installations prior to 1994. Interviews with managers in Japan's New Energy Development Organization (NEDO) indicated that the non-existence of small-scale systems installations was due to a lack of regulations and standards for connecting a small-scale system to the existing electric power networks.[54]

FIGURE 7: Annual installations of small-scale solar power systems in Japan and U.S.

MW per year



Source: AGORES (1994)

Small-scale installations had been the focus of considerable attention from policy makers in the years leading up to 1994. From the late-1980s, household rooftop solar power systems had been identified as a promising area for deployment of solar power. In 1990, official government estimates were that the "...potential contribution of PV rooftop power would be roughly 950

[53] AGORES. This description does not include a small number of systems built and operated by utilities. For a more detailed description see Ramakumar and Bigger (1993) pages 370-371.

[54] Interviews with NEDO during 2004 while researching Rogol (2004). Note: Interviewees also mentioned "high prices" as a reason why solar power systems had not been installed prior to 1994, but said that even at high prices, some small number of systems would have been installed if they connection rules had been in place. It is also worth noting that larger grid-connected government demonstration projects and several test projects within the Japanese electric power utilities had taken place prior to 1994. The most important of these was the Rokko Island test facility installed starting in 1986. Per previous footnote, see Ramakumar and Bigger (1993) for details.

kWh/year per inhabitant equalling [sic] nearly 14% of Japanese final electricity consumptions"[55] and forecasts were discussed of market potential of 5GW cumulative installed capacity by 2010.[56]

In April 1990, a ministerial ordinance laid out high level standards for grid connection of solar power systems. This ordinance added rules for solar power systems within the existing legal framework for the electric utility industry. The change provided general voltage specifications for solar power systems, installation methods for solar power systems and definitions for solar power system operation without a full time supervisor.[57] Also in April 1990, standards and processes for construction plan approval, definitions of qualified engineers and other regulations were revised. This eliminated need for legal formalities for grid connecting solar power systems of under 100kW, reduced formalities for grid connecting solar power systems of 100 to 500kW and reduced the engineering requirements for systems under 500kW. In the three years that followed, more specific technical guidelines for grid connection were established that dealt with reversal of power flow for low and high voltage lines and protective devices to address technical issues such as islanding.[58] In addition, by mid-1992, clear rules for net metering[59] were established under which the existing electric utilities accepted the flow of power from distributed solar power system and agreed to purchase the electricity at the same price level at which the electricity was being sold to the customer generating the solar electricity.[60] Overall, from 1990 to 1993, interconnection rules and standards were streamlined and simplified to a degree that small-scale solar power installations were feasible in Japan.

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[55] AGORES (1994) p214
[56] AGORES (1994)
[57] Kurokawa (1994)
[58] "Islanding is a condition in which a portion of the utility system, which contains both load and generation, is isolated from the remainder of the
utility system and continues to operate via a photovoltaic power source." For a description of islanding, detection of islanding and potential impacts, see Bower and Ropp (2002).
[59] There are numerous definitions of net metering with minor vairations. One example is: "Net-metering is a simplified method of metering the energy consumed and produced at a home or business that has its own renewable energy generator, such as a wind turbine. Under net metering, excess electricity produced by the wind turbine will spin the existing home or business electricity meter backwards, effectively banking the electricity until it is needed by the customer. This provides the customer with full retail value for all the electricity produced." Source: en.wikipedia.org/wiki/Net_metering
[60] This paragraph based on Kurokawa (1994).

TABLE 13: Relaxation of regulations and codes relating to PV system utilization in Japan

Item	Date	Outline	Remarks
Revision of ministerial ordinance prescribing technical standards of electrical facilities relating to electric utility industry law	April 1990	Addition of definitions and rules for PV systems, etc. to the standard	Withstand voltage specification; Installation method of PV modules; PV power system without a full-time supervisor
Revision of ministerial ordinance prescribing technical standards of electrical facilities relating to electric utility industry law	April 1990	Revision of enforcement regulations (construction, plan approval, qualified engineer assignment, etc.)	No legal formalities for construction plan lower than 100kW; prior notification of plan for higher than or equal to 100kW and lower than 500kW; no assignment of qualified engineer for a system less than 500kW
Guidelines for technical requirements of utility interconnection	June 1990 through April 1993	Description of protective devices	With/without reversal power flow connected with EHV transmission line and HV exclusive line; with/without reversal power flow with low/high voltage general line; without power flow reversal with spot network
Revision of ministerial rodinance under electric appliances regulatory law	October 1991	Addition of electric air cooler and dehumidifier having PV modules	
Surplus electricity purchase by electric utilities	April 1992	Reversal power flow is accepted by the utility	Purchase at the same level price to selling one

Source: Kurokawa (1994)

Grid-connection and/or net metering rules were an important precursor for the rapid expansion of Japan's solar power market. This assessment is based on the fact that there had been no grid-connected small-scale systems in Japan prior to the introduction of the streamlined and simplified connection and net metering rules but there was rapid expansion of grid-connected small-scale systems following the grid connection rules. This view is supported by interviews. Members of the NEDO team suggested that connection and net metering rules were a necessary condition for the adoption of small-scale grid-connected solar power systems in Japan. Similarly, executives at solar power companies stated in interviews that grid connection and net metering rules were necessary for large-scale adoption of small-scale systems.[61]

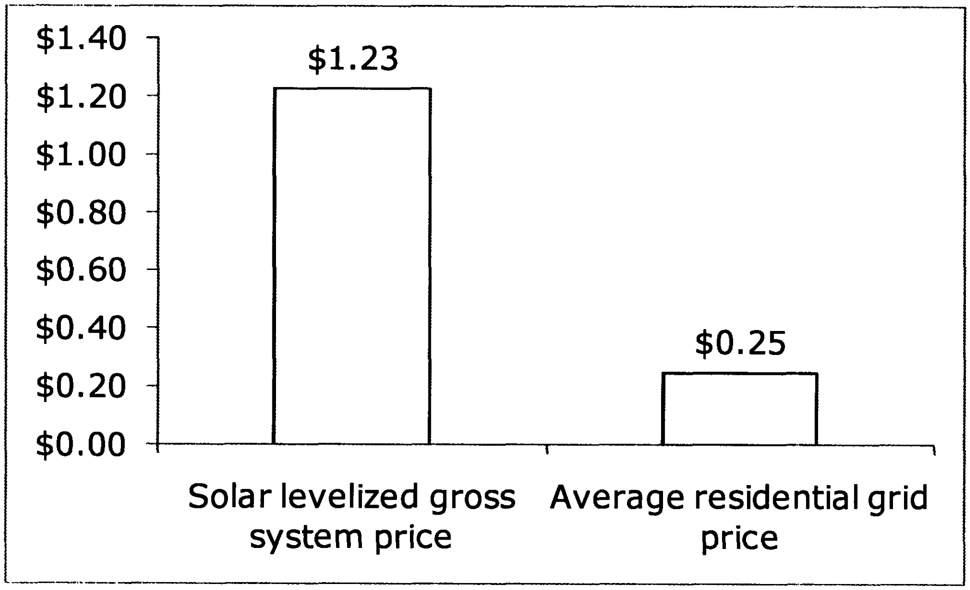
Yet the grid connection and net metering rules by themselves do not appear to have been sufficient for customer adoption of small-scale solar power systems. In interviews, executives at solar power companies stressed that the price of solar power systems in the early 1990s was much

[61] Interviews with NEDO and with dozens of Japanese solar power companies during 2004 while researching Rogol (2004).

too expensive for mass-market adoption without significant government incentives, regardless of the implementation of streamlined grid connection and net metering rules. They estimated that the price of solar electricity to end-customers in the early 1990s was over $1.20/kWh even with simplified grid connection and net metering, compared to average residential grid prices under $0.30/kWh. The "gap" between the two columns in FIGURE 8 was simply too large for mass-market customers to accept.

FIGURE 8: Solar levelized gross system price without incentives vs. average residential grid price

Nominal $/kWh in 1994



Source: Grid price from EIA. Solar levelized gross system price estimate from Michael Rogol based on data from various sources.
Note: Description for calculation of solar levelized gross system price later in this section.

While the establishment of streamlined grid connection and net metering rules appears to have been a necessary precursor for the rapid growth of Japan's solar power market, it is worth noting that the relative value and impact of the different rules (i.e. grid connection rules versus net metering rules) was unclear. Most interviewees said that both grid connection *and* net metering rules were necessary conditions for mass market adoption of small-scale solar systems. Both appear to improve the end-customer economics of solar power. On one hand, the ability to connect a small scale system to the existing grid reduces the need for battery/storage, thereby decreasing the gross price of a solar system by roughly $2/watt (approximately $0.10/kWh) in the early 1990s.[62] On the other hand, the treatment of excess electricity put onto the grid from a solar

[62] Estimating the cost per watt or cost per kWh of storage in 1994 is difficult for two reasons. First, there is little available data in the literature. Second, costs for storage systems have a wide range depending on the characteristics of the storage. Cost reduction of roughly $2/watt for cost of storage in 1994 estimated based on interviews with Japanese executives in 2003-2004 as part of research

power system as having the same price as electricity consumed from the grid also improves the economics of a solar power system for the end-customer, though the value of net metering varies for different end-customers depending on the grid electricity price and the volume of excess electricity involved in net metering. While both grid connection rules and net metering rules appear to improve end-customer economics, it is unclear what the relative impact of the various rules was. As such, the most that can be said from this review of grid connection and net metering rules is that, collectively, they significantly reduced the gross price of solar power from small-scale solar installations and appear to have been a necessary but not sufficient condition for the rapid growth of Japan's solar power market.

(C) Demand

From 1994, installations of solar power systems grew rapidly in Japan. This followed the adoption of grid connection and net metering rules, and coincided with the implementation of significant demand-side incentives for solar power system installations. This sub-section attempts to answer the question, "What were the economics of solar power for end-customers in Japan during the period 1994 to 2003?" In order to address this question, this sub-section presents:

i. Overview of the product
ii. Solar power system prices
iii. Levelized system prices (LSP)
iv. Comparison of LSP with the main substitute ("gap" analysis)

The key point of this sub-section is that evaluating the economics of solar power requires comparing the levelized net system price (LNSP) of solar power with the price of the main substitute, grid-based electricity. The LNSP is calculated using the methodology suggested by Deutch and Lester[63], taking into account the impact of government incentives on the economics of solar power. Then the LNSP is compared to the price of the main substitute (grid electricity) in order to determine the "gap" between LNSP and grid price ("gap analysis"). Finally, estimates are made for the elasticity of demand for solar power as the "gap" decreases and for the relative importance of drivers of solar power price reductions.

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for Rogol (2004). For more recent estimates of storage costs, see "Energy Storage: Role in Building Based PV Systems" by TIAX (2007).

[63] Based on "Applications of Technology in Energy and the Environment" (1.174) taught during Fall 2003 semester.

i. Overview of the product

Solar power products convert sunlight into electricity. During the years 1994 to 2003, the typical product for this sector was a 3-4 kilowatt (kW) solar power system installed on a residential rooftop in Japan.[64] (FIGURE 9) This typical system is connected to the existing electricity grid so that the house draws power from both the solar power system (when the sun is shining) and the electricity grid (when the sun is not shining or when electricity usage exceeds the supply from the solar power system). When electricity is produced by the solar installation in excess of the needs of the house (e.g. sunny day when no one is inside the house), the excess electricity is delivered to the existing electricity grid, and the house's electricity meter rolls backwards. When the house requires more electricity than the solar power system is able to provide (e.g. at night or during a hot day when the air conditioners are running), the house draws electricity from the grid, and the house's meter rolls forward.[65] The bulk of solar power installations use crystalline silicon (c-Si) technologies such as mono-crystalline silicon, multi-crystalline silicon and ribbon/sheet crystalline silicon.[66,67] This case study focuses on solar power installations that were typical in the period 1994 to 2003: grid-connected residential-scale (3-4kW) crystalline silicon systems in Japan.[68]

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[64] http://www.solar.nef.or.jp/josei/zissi.htm in Japanese. Confirmed in literature such as IEA PVPS (1997-2004), Ikki et al (2004) and Maycock (2004).

[65] In response to the question posed by Professor Moniz ("No stranded asset charges?"), my understanding is that there were not any additional charges for grid connection of PV systems under 500kW in Japan. For systems above 500kW, interviewees have told me that grid connection and stranded asset charges exist, but I do not have any information on these charges.

[66] IEA PVPS (2004)

[67] This is a simplistic overview of the solar power market. Other solar power products (beyond residential rooftop applications), other geographic markets (beyond Japan, Germany and the U.S.) and other technologies (beyond crystalline silicon technologies) exist, but the typical solar power product is a residential rooftop installation of a c-Si solar system in Japan, Germany or the U.S. Also, there was no ribbon/sheet c-Si in Japan until after 1999 (Kawasaki-Evergreen Solar deal).

[68] This period is selected for two reasons. First, it coincides with the start and end of a major Japanese residential solar power incentive program. Second, this period has significant available data on installed solar system prices from both the Japanese government and from the OECD's IEA PVPS program.

FIGURE 9: Example of solar power installations in Japan

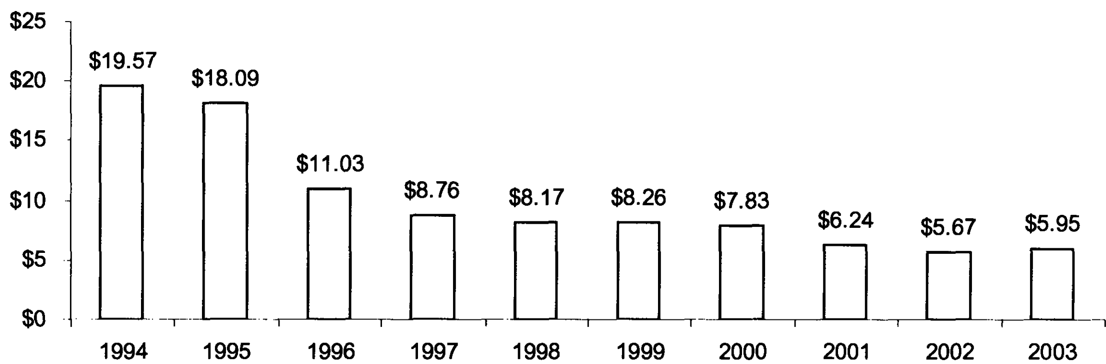
Source: http://web-japan.org/nipponia/nipponia28/images/feature/10_1.jpg

ii. Solar power system prices

The gross price of solar power systems decreased quickly during the period 1994 to 2003. At the start of the period, the price of a 3-kW system was roughly $59,000, or $20/watt. By 2003, the price of a 3-kW system decreased in nominal terms roughly 70% to $18,000, or $6/watt. (FIGURE 10) This equates to negative 12% CAGR for gross system prices over the decade. The decrease in gross system prices resulted from a decrease in module prices and from a decrease in the price of non-module system inputs (wiring, inverter, labor, etc.). Over this period, average module prices declined 58% from over $9/watt in 1994 to under $4/watt in 2003, equating to a negative 9% CAGR for module prices. Similarly, prices for non-module inputs declined 80%

from $10.50/watt in 1994 to $2.10/watt in 2003, equating to a negative 16% CAGR in the price of non-module inputs.[69]

FIGURE 10: Gross price for installed solar power system
(Nominal U.S.$/watt)



Source: NEDO. Note: See TABLE 3 for prices in yen.

Government support for solar power reduced the net price paid by end-customers for solar power systems. From 1994, the Japanese national government provided payments to residential customers of roughly $9 per watt. This "buy-down" incentive program reduced the installed price of solar power systems by nearly 50% in 1994 and 1995. In subsequent years, the per-watt incentive provided by the Japanese national government decreased, reaching a level of $0.78 per watt, or 13% of the installed system price, by 2003.[70] In addition to the national government subsidy for residential solar power system installations, local governments also provided incentive programs. These programs varied over geography and over time, with an estimate of roughly $0.40 per watt by 2003.[71] FIGURE 11 presents estimates for national and regional/local incentives from 1994 to 2003. Taking incentives into account, net system price declined 56% during this period, from $10.77 per watt in 1994 and $4.77 per watt in 2003.[72] (TABLE 14 and TABLE 10)

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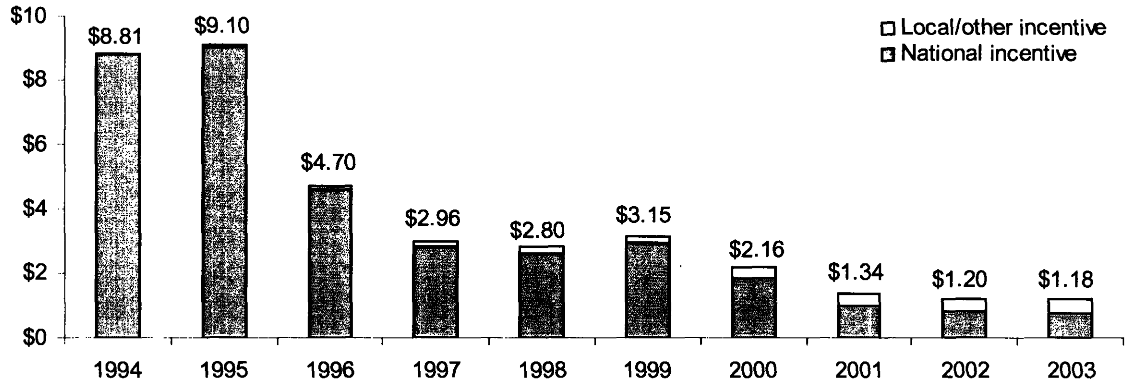
69 Data provided in Section 2 (TABLE 3). Source is NEDO (http://www.solar.nef.or.jp/josei/zissi.htm).
70 Data provided in Section 2 (TABLE 3). Source is NEDO (http://www.solar.nef.or.jp/josei/zissi.htm).
71 By 2004, there was a broad diversity of local/regional incentives, with more than 200 different programs. $0.40/W in 2003 is a rough estimate based on a survey of local/regional incentives and on interviews. For a more complete list of local/regional incentives, see http://www.solar.nef.or.jp/josei/zissi.htm.
72 NEDO.

FIGURE 11: Typical government incentives for residential solar power systems
(Nominal U.S.$/watt)



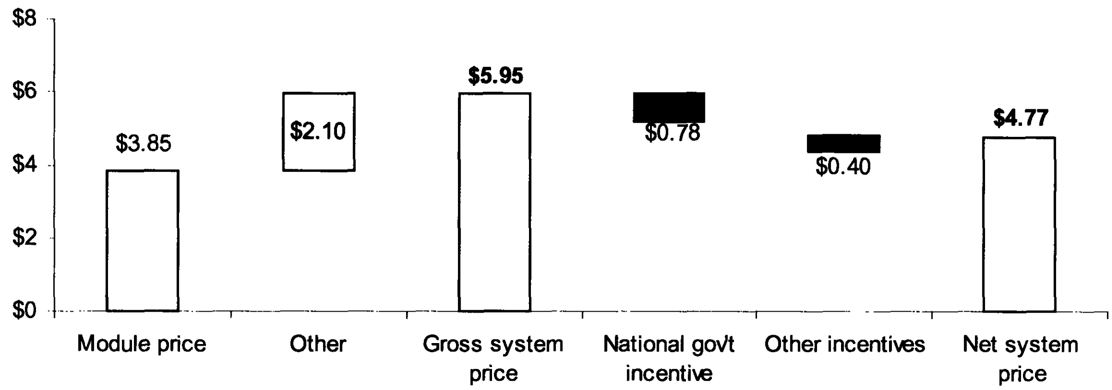
Source: NEDO. Note: The graphic demonstrates the declining per-watt incentive paid to end-customers.

TABLE 14: Gross and net price for installed solar power system 1994 to 2003
(Nominal U.S.$/watt)

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Gross system price ($/watt)	$19.57	$18.09	$11.03	$8.76	$8.17	$8.26	$7.83	$6.24	$5.67	$5.95
Change in gross system price (%)		-8%	-39%	-21%	-7%	1%	-5%	-20%	-9%	5%
National incentives ($/watt)	$8.81	$9.05	$4.60	$2.81	$2.60	$2.90	$1.86	$0.99	$0.80	$0.78
Local incentives ($/watt)	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.4
Net system price ($/watt)	$10.77	$9.00	$6.34	$5.80	$5.37	$5.10	$5.67	$4.90	$4.47	$4.77
Change in net system price (%)		-16%	-30%	-8%	-7%	-5%	11%	-14%	-9%	7%

Source: Michael Rogol calculations based on data from NEDO, IEA PVPS and exchange rates form World Bank.

FIGURE 12: Breakdown of end-customer price for installed solar power system in 2003
(Nominal U.S.$/watt)



Source: Michael Rogol calculations based on data from NEDO and IEA PVPS, and exchange rates from World Bank.

iii. Levelized system prices (LSP)

Assessing the economic competitiveness of solar power requires comparing the price of solar power with the price of the main substitute, grid-based electricity supplied by power generation and distribution companies. Yet an installed solar power system normally has price units of "dollars per watt" while grid-based electricity normally has price units of "cents per kilowatt hour." Comparing these two requires estimating the levelized price of solar power, which is also expressed in price units of "cents per kilowatt hour." Following Deutch and Lester[73], a model to estimate the per kilowatt hour levelized price of solar power was developed, taking into account the large up-front costs, long lifetime and low operating costs of a solar power system.[74] The levelized system (LSP) price is the price of electricity necessary over the life of the solar power system to cover the cost of installing the solar power system, maintaining it over its lifetime, paying for principal and interest on debt and accounting for the time-value of money. This method uses a discounted cash flow model, taking into account benefits and costs over the life of the system, along with the cost of capital.[75]

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[73] Based on "Applications of Technology in Energy and the Environment" (1.174) taught during Fall 2003 semester.

[74] Note: This thesis presents levelized cost analysis using nominal interest rates, though analysis with both real and nominal interest rates was conducted. While using real interest rates and real prices has minor impacts on specific estimates (i.e. the levelized price of solar power increases/decreases by roughly $0.03 to $0.05/kWh for every 1-percentage point increase/decrease in the interest rate used), the key conclusions of this report remain regardless whether nominal or real interest rates or prices are used in the analysis. The reason that nominal interest rates are used in this write up is that nearly all analysis in the literature and in confidential information provided as background by interviewees is in nominal terms, so that using nominal interest rates and prices enabled easier comparison.

[75] Model developed with Joel Conkling and Scott Roberts with input from several industry experts

There are 16 variables in the spreadsheet model used to estimate the levelized net system price (LNSP) for solar power.[76] (TABLE 15) Of these, the most important drivers of LNSP are typically the gross price of the system, interest rate, amount of solar resource, the electrical output of the system over time and incentives/other benefits. The assumptions used to estimate Japan's LSP during the period 1994 to 2003 are included in TABLE 5.

TABLE 15: Key inputs in LSP model

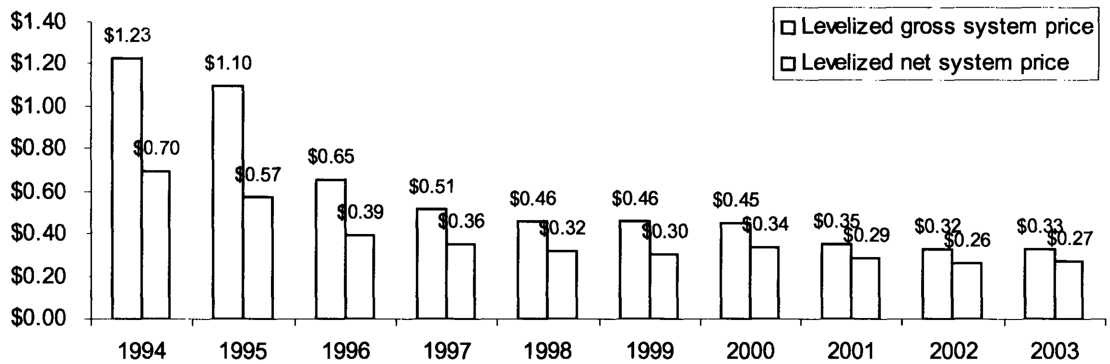
Key model inputs	
AC converstion factor (%)	Inverter replacement frequency (years)
Annual O&M expenses (% installed cost)	Local incentive ($/watt)
Annual output degredation (%)	National incentive ($/watt)
Electricity price inflation after 2003 (%)	Nominal interest rate (%)
Exchange rate (yen/US$)	Residential electricity price ($/kWh)
Gross system price ($/watt)	Solar resource (kilowatts/m^2/day)
Installation size (kW DC)	System lifetime (years)
Inverter replacement cost ($/watt)	Total incentive ($/watt)

Source: Michael Rogol calculations based on numerous sources including IEA PVPS, NEDO, U.S. EIA, World Bank and other source

Under these assumptions, the levelized system price decreased significantly during the period 1994 to 2003. The levelized net system price (LNSP[77]) inclusive of incentives was roughly $0.70/kWh in 1994. By 2003, the LNSP had decreased 61% to $0.27/kWh.[78] (FIGURE 13) This equates to a negative 10% CAGR over the period. It is important to highlight that the impact of incentives diminished over this period as the national government's buy-down rate decreased. As a result, the levelized gross system price (LGSP[79]) excluding incentives diminished more quickly than the LNSP. During this period, the LGSP decreased by 73% from $1.23/kWh in 1994 to $0.33/kWh in 2003. While the ratio of LGSP to LNSP[80] was 176% in 1994 due to the high level of incentives, this difference fell to only 122% in 2003 because the per-watt incentives had decreased.

[76] Key assumptions: Nominal not real... average prices... etc.
[77] Levelized net system price is the levelized system price after accounting for incentives.
[78] This analysis was conducted in both yen and in dollars. A similar trend is observed when conducting the same analysis in yen instead of dollars.
[79] Levelized gross system price is the levelized system price prior to accounting for incentives.
[80] LGSP/LNSP

FIGURE 13: Levelized gross and net system price
(Nominal U.S.$/kilowatt hour)



Source: Michael Rogol calculations.

The change in LNSP during the decade 1994 to 2003 was driven by several factors. (FIGURE 14) In order of importance, these factors include:

- **Non-module system input prices.** The decrease in non-module system input prices from $10.50/watt in 1994 to $2.10/watt in 2003 accounted for roughly $0.41/kWh decrease in LNSP.[81]

- **Incentives.** The decrease of total national and local/other incentives from $8.81/watt in 1994 to $1.18/watt in 2003 accounted for roughly $0.37/kWh *increase* in LNSP.

- **Module prices.** The decrease in module price from $9.07/watt in 1994 to $3.85/watt in 2003 accounted for roughly $0.26/kWh decrease in LNSP.

- **Interest rates.** The decrease in long-term consumer interest rates from 4.0% in 1994 to 2.3% in 2003 accounted for roughly $0.04/kWh decrease in LNSP.

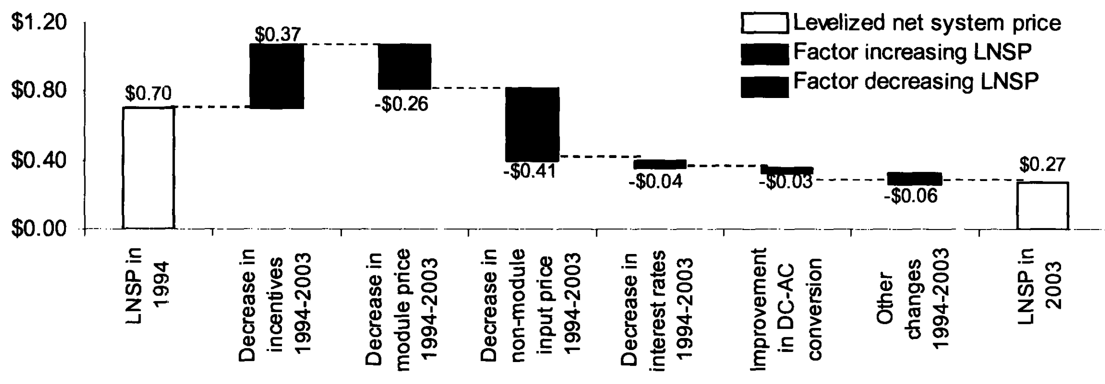
- **DC-AC conversion.** The increase in DC-AC conversion efficiency from roughly ~70% in 1994 to ~80% in 2003 accounted for roughly $0.03/kWh decrease in LNSP.

- **Other factors.** Other factors accounted for roughly $0.06/kWh decrease in LNSP during the period 1994 to 2003.

[81] Non-module inputs include, for example, inverter, wiring, racks, architecting and installation.

It is important to emphasize that non-module input prices, interest rates and system performance together accounted for $0.48/kWh of the decrease in LNSP over this period. This is important because these factors received little attention in the literature on Japan's solar power sector.[82]

FIGURE 14: Impact of selected factors on LNSP during 1994 to 2003
(U.S.$/kWh[83])



Source: Michael Rogol calculations.

iv. Comparison of LNSP with main substitute ("gap" analysis)

The levelized net system price must be compared with the price of grid-based residential electricity in order to fully evaluate the substitution decision facing end-customers.[84] Several researchers have suggested this type of study[85], but detailed analysis comparing Japanese LNSP to Japanese grid price during the period 1994 to 2003 does not appear in the English-language literature on Japan's solar power market. As background, Japan's residential power prices are among the highest in the world, with average residential customers paying $0.19/kWh in 2003. (FIGURE 15) While these prices were high by world standards, they were actually lower than historical prices in Japan. From 1994 to 2003, average residential grid price decreased by 26% in U.S. dollar terms from $0.25/kWh in 1994 to $0.19/kWh in 2003.[86]

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[82] Margolis et al

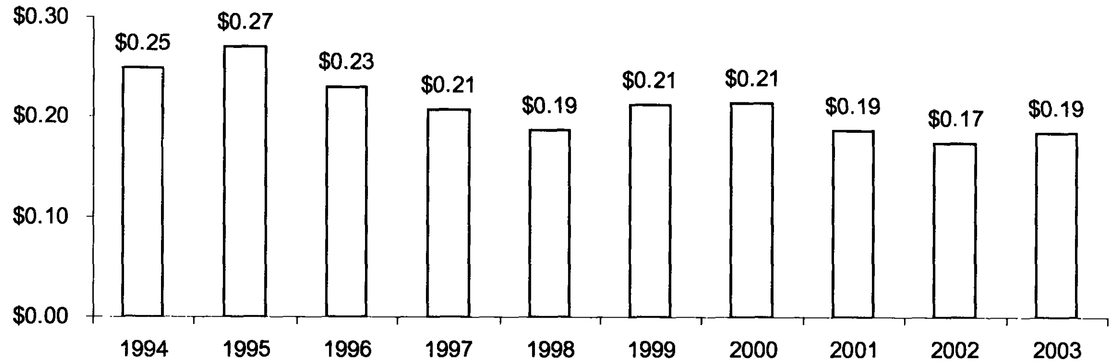
[83] LNSP decreased by $0.48/kWh, from $0.80/kWn in 1993 to $0.32/kWh in 2003.

[84] In less academic terms, a back-of-the-envelope comparison often made by end-customers is the monthly payment they make on a long-term loan on their solar power installation versus their monthly grid-based power bill.

[85] See, for example, Table 3 in Kurokawa (1994) in which the "electricity generation cost" is estimated.

[86] Source: U.S. EIA. Note: Analysis was conducted both in dollar terms and in yen terms. This thesis presents the dollar-based analysis. The results from conducting yen-based analysis do not alter any of the main findings from this thesis, though there are some minor differences. For example, in yen terms, decreased by 16% (compared to 26% in dollar terms), from 26 yen/kWh in 1994 to 22 yen/kWh in 2003.

FIGURE 15: Average residential grid price in Japan 1994 to 2003
Nominal U.S.$ per kilowatt hour

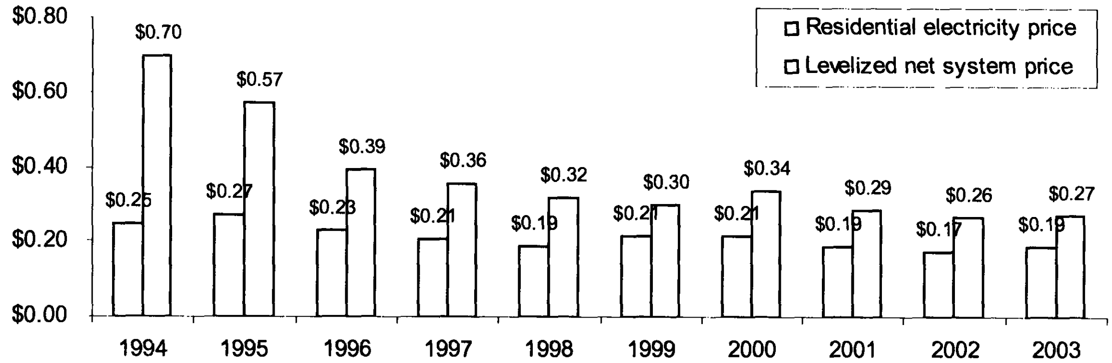


Source: U.S. EIA

Comparing the percentage premium of LNSP to grid price[87] defines a "solar premium" for average residential end customers. During the period 1994 to 2003, the "solar premium" in Japan decreased by three-quarters from 180% in 1994 to 45% in 2003. (FIGURE 17) In per-kilowatt hour terms, the difference between LNSP and grid price defines a "solar gap" for average residential customers. The "solar gap" in Japan decreased from $0.45/kWh in 1994 to $0.08/kWh in 2003. (FIGURE 18) The reduction in "solar premium" and "solar gap" was driven largely by reductions in installed system prices, interest rates and system performance inefficiencies (e.g. losses in conversion from DC to AC), and offset by declines in per-watt incentives and in grid prices.[88]

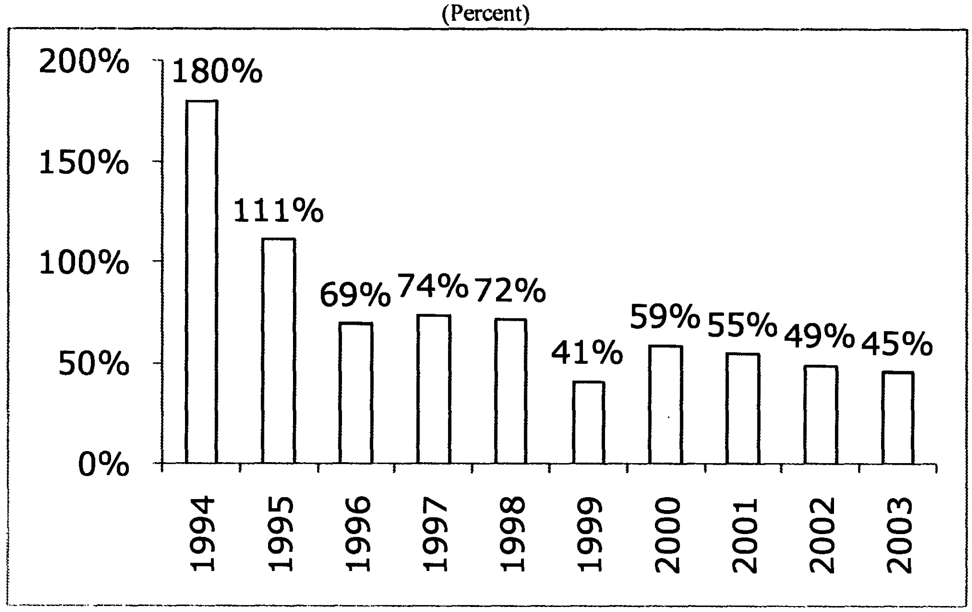
[87] LNSP/grid price - 1
[88] Analysis conducted in yen instead of in dollars leads to similar though not identical results.

FIGURE 16: Average residential grid price compared to LNSP in Japan 1994 to 2003
U.S.$ per kilowatt hour



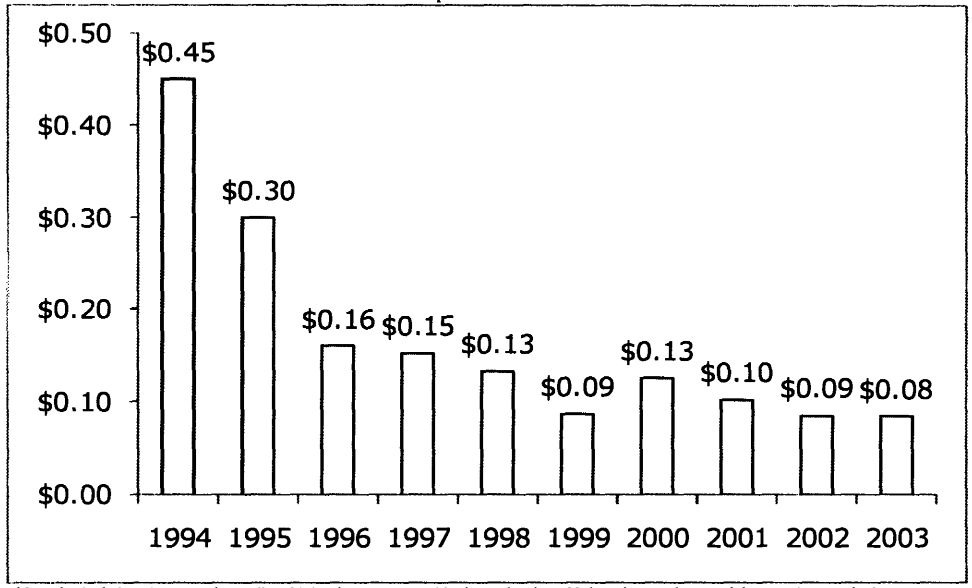
Source: Michael Rogol calculation..

FIGURE 17: "Solar premium" in Japan 1994-2003
(Percent)



Source: Michael Rogol calculation.. Note: "Solar premium" = LNSP/average grid price minus 1. Also, in 1999 the solar premium decreased due to a decrease in the gross system price (in yen terms) with grid prices (in yen/kWh) remaining flat and incentives (in yen/watt) remaining flat. A similar pattern (dip in solar premium in 1999) is observed when measuring in US$-terms, though the decrease is influenced by the change in exchange rates from 1998 to 1999. The result (72% in 1998 and 41% in 1999) is near nearly identical in yen- and US$-terms. This graphic is based on data in US$-terms.

FIGURE 18: "Solar gap" with grid price in Japan 1994-2003
U.S.$ per kilowatt hour



Source: Michael Rogol calculation.. Note: "Solar gap" = LNSP minus average grid price. Also, in 1999 the solar gap decreased due to a decrease in the gross system price (in yen terms) with grid prices (in yen/kWh) remaining flat and incentives (in yen/watt)remaining flat. A similar pattern (dip in solar gap in 1999) is observed when measuring in US$-terms, though the decrease is influenced by the change in exchange rates from 1998 to 1999. The pattern is similar in yen- and US$-terms. This graphic is based on data in US$-terms.

It is important to mention that this assessment of a 45% premium is based on averages. In reality, there is a distribution of levelized net system prices based on differing installed system prices, incentives, grid prices, sun hours, etc. and also a distribution of residential grid prices.[89] By 2003, it appears likely that a small portion of Japanese end customers (those with lower-than-typical LNSP for solar and higher-than-average grid prices) had a "solar premium" that was at or below zero percent and a "solar gap" that was at or below zero cents per kilowatt hour.[90]

It is also important to use the preceding to analyze substitution effects and estimate demand elasticity. This is important because demand elasticity appear to be an important point of "leverage" in the interaction between supplier costs and customer demand. Higher elasticity of demand means that cost reductions on the supplier side that are passed along to consumers have significant, positive impact on demand. Looking at demand elasticity across markets, there is preliminary evidence to support the view that a one percent decrease in price leads an increase of 3% or more in installations.[91] Yet there are many ways to measure price in the solar power sector and, as a result, many potential measures of elasticity. One measure of price is the gross system

[89] For this thesis, data was not collected on the distribution of prices. This is a potential area for further research.
[90] This ("gap" analysis for above-average grid-price/below-average LNSP customers in Japan) is a potential area for further research.
[91] Similarly, this is an area for further research.

price: how much a customer pays for the system in $/W before accounting for incentives). Another is the net system price: how much a customer pays for the system in $/W after accounting for incentives. A third is the levelized net system price (LNSP): how much a customer pays for solar power in cents/kWh using a discounted cash flow model to account for all cash flows including system payments and incentives. A fourth way is the "gap" between solar and grid price: how much larger is LNSP than grid price in cent/kWh terms. A summary of elasticity estimates using these various definitions is presented in TABLE 16. This table presents the CAGR for various prices from 1994 to 2003 in the second column, the installation CAGR for Japan from 1994 to 2003 in the third column and an estimate of elasticity (equal to the third column divided by the second column) in the third column. The point of showing these various elasticities is to provide a rough sense of the range for demand elasticity depending on the price being measured.[92]

TABLE 16: Preliminary estimates of demand elasticity in Japan 1994-2003

	Price change 1994-2003 (CAGR %)	Installation growth 1994-2003 (CARG %)	Elasticity (Change in installation/ change in price)
Japan gross system price	-12%	47%	-3.8
Japan net system price	-9%	47%	-5.5
Japan levelized net system price	-10%	47%	-4.7
Japan "gap" of LNSP minus grid price	-17%	47%	-2.8

Source: Michael Rogol calculation.. Note: "Solar gap" = LNSP minus average grid price

Preliminary analysis of the relationship between changes in "gap" and change in installations in demand during the period 1994 to 2003 suggest an elasticity of demand of roughly 2.8, meaning that a 1 percent decrease in "gap" results in a 2.8 percent increase in installations. During the years 1994 to 2003, the "gap" decreased at a 17% CAGR and solar power installations (in MW) increased at a 47% CAGR. This suggests an elasticity of roughly negative 3. It is important to mention that this estimate of elasticity is applicable when LNSP is above average grid price. When LNSP goes below grid price, elasticity may become much larger. Preliminary estimates suggest an elasticity of at least negative 30 after LNSP moves below grid parity, though data for these estimates is both limited in nature and not publicly available. The reviewed literature lacks detailed analysis of elasticity either before or after LNSP reaches parity with grid prices. As a result, refining these estimates of elasticity is an area of ongoing research.

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[92] Based on preliminary research on elasticities in several solar power markets, it appears that "gap" elasticity is the most consistent measure of change in demand for a given reduction in price.

In summary, understanding the end-customer economics of solar power requires assessing the levelized net system price of solar power and comparing this with the price of the main substitute, residential grid-based electricity. During the period 1994 to 2003, the typical LNSP for residential solar power installations declined by 61%, from $0.70/kWh in 1994 to $0.27/kWh in 2003. Over the same period, the "solar premium" of the LNSP compared to the average residential grid price decreased from 180% to 45%. During this period, the "solar gap" of LNSP minus grid prices decreased from $0.45/kWh to $0.08/kWh, equal to a negative 17% CAGR. In comparison, annual installations of solar power systems in Japan increased from 7MW in 1994 to 223MW in 2003. This increase equates to a positive 47% CAGR. A rough approximation of the elasticity of demand (change in annual installations/change in gap) appears to be approximately negative 2.8.[93]

(D) Supply

The preceding sub-section focused on solar power from a demand (end-customer) perspective. This sub-section turns attention to the economics of solar power from a supply (manufacturer) perspective. This sub-section includes:

(i) Overview of the supply chain for solar power systems
(ii) Cost structure and economics of the Japanese supply chain
(iii) Expansion of the Japanese supply chain

One key point made in this sub-section is that supply-side decisions made by Japanese manufacturers to pursue rapid expansions were highly influenced by demand-side policies. Stated simply, demand-side policies made the economics of supply-side investments more attractive. Further, decisions to expand supply-side production reduced cost, which in turn enabled reductions in gross price, which in turn drove higher levels of demand despite falling per-watt demand-side incentives. The point is that the growth of Japan's solar power sector was dependent on interwoven supply-side and demand-side factors and policies.

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[93] Several open questions remain for further research on end-customer economics for solar power systems in Japan. These questions include: What is the root cause of price declines? What are the drivers of elasticity? (e.g. customer preferences)

(i) Overview of supply chain for solar power systems

The supply chain for solar power is complex, involving several thousand companies at the various stages. A simplistic overview of the solar power supply chain has five steps[94]:

- **Silicon:** The supply chain starts with production of high purity polycrystalline silicon (PCS). PCS is produced by a small number of companies globally, with the top five players accounting for more than 70% of global production in 2003. These companies included Hemlock (U.S.-based JV of Dow Corning of the U.S., Shinetsu Hondotai of Japan and Mitsubishi Materials of Japan), Tokuyama (publicly listed Japanese chemical company), Komatsu (US-based subsidiary of publicly listed Japanese conglomerate) and Mitsubishi (U.S.-based subsidiary of Japanese conglomerate), among others. PCS is sold to both the electronics and solar sectors, with the electronics sector using the vast majority of PCS during the years 1994 to 2003. By the end of this period, though, solar usage of PCS was rising quickly and accounted for roughly 35% of total supply.[95]

- **Ingot/wafer:** High purity PCS is melted and shaped into ingots. The ingots are then cut/blocked and sliced into wafers. During the ingoting, cutting/blocking and slicing, a significant portion of the original silicon is lost as waste. By 2003, a typical wafer was approximately 350-400 microns thick. There were approximately 2 dozen solar ingot/wafer players in the world in 2003. While the world's three largest players were European, Japanese companies participated in this stage of the supply chain. Japanese ingot/wafer makers included Kyocera, M. Setek, JFE and Sumco.[96]

- **Cell/module:** Solar wafers are converted to solar power cells by establishing an electrical field across a junction of positive and negative layers that creates electricity when photons of light are absorbed. The cells then go through a "stringing" process that connects several cells together to form a larger circuit panel. This panel is framed with aluminum, covered with glass for protection and support and backed with laminate and electrical connections. The result is a solar module. In 2003, a typical module had capacity of 100 to 150 watts DC. The largest Japanese cell/module makers included Sharp, Kyocera, Sanyo and Mitsubishi.[97]

- **System components:** Several components are added to modules to make a solar power system. These components include an inverter to change direct current (DC) to alternating current (AC), often with a 15 to 25% loss; batteries to serve as storage, though batteries were not typically used in grid-connected systems; and other components such as wiring and mounting materials. The largest component maker in Japan during the period 1994 to 2003 was likely Omron, which manufactured a sizeable portion of inverters used in Japanese solar power systems.[98]

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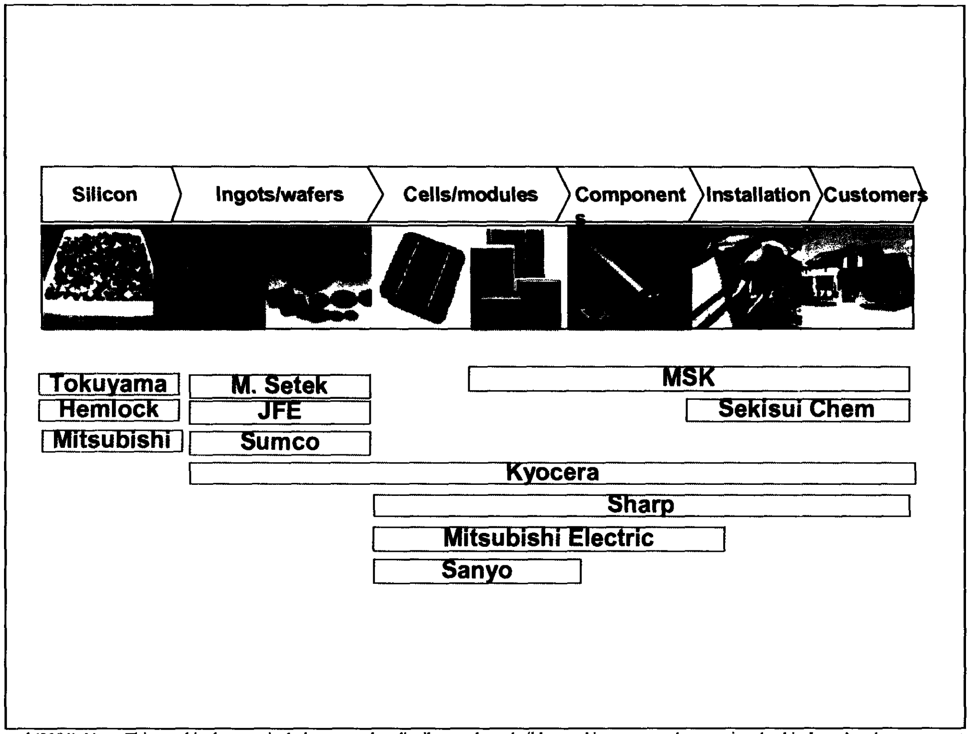
[94] See Rogol (2004) and Rogol (2005) for additional details on supply chain.
[95] Rogol (2005).
[96] IEA PVPS (2004), Maycock (2004).
[97] Rogol (2004), Maycock (2004)
[98] Rogol (2004).

- **Installation and services:** Typical rooftop installations are completed by roofers and electricians. Prior to installation, other services may be required such as architecting to design the system and financing to pay for the system. The largest installer in Japan during the years 1994 to 2003 was Sekisui Chemical, which manufactured prefabricated homes that incorporated solar power systems.[99]

FIGURE 19: Japanese firms' activities within the solar power supply chain



Source: Rogol (2004). Note: This graphic does not include many other distributors, homebuilders and integrators who were involved in Japan's solar power sector. Additional research should focus on identifying and quantifying the size of other downstream players in Japan.

(ii) Cost structure and economics of the Japanese supply chain

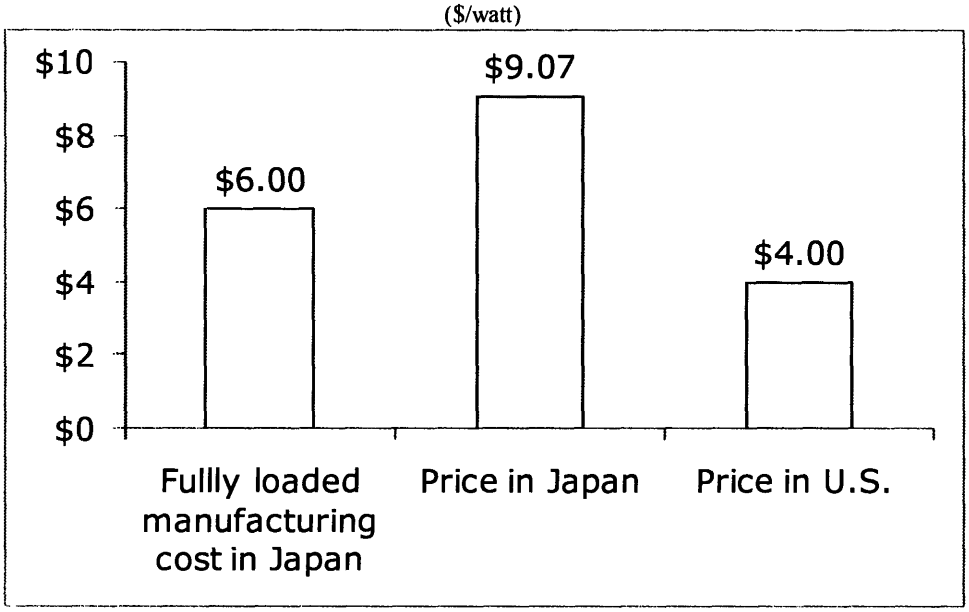
By 1994, the fully-loaded cost for manufacturing a solar power cell/module was roughly $6/watt.[100] This includes all of the costs of buying silicon, making an ingot, slicing a wafer, manufacturing a cell and assembling a module, including equipment, raw materials, electricity, labor, R&D and sales, but excluding return on capital, profit or taxes. This $6/watt cost compared to a price of roughly $9/watt for modules sold in Japan in 1994.[101] This implies a pre-tax margin for modules of roughly 33%, a level at which investments in solar power

[99] Rogol (2004).
[100] This estimate based on both the literature (e.g. Journal of Energy Engineering December 1996) and on estimates made applying an 80% progress ratio backward in time from known 2003 cost structures.
[101] IEA PVPS and NEDO.

manufacturing capacity would have attractive returns *if* prices were to stay at that same level. However, interviewees consistently said that there was broad expectation of significant price decreases. Two factors were identified by most interviewees as driving expectations of price decreases. First, the Japanese government's demand incentive program managers planned to decrease per-watt incentives over time in an effort to push suppliers to compensate for decreasing incentives by reducing the price of their products so that the net price to the end-customer was flat or falling despite decreasing per-watt incentives.[102] Second, Japanese module prices (roughly $9/watt in 1994) were far above international model prices (for example, $4/watt in the U.S. in 1994), meaning that international competitors (especially export-focused U.S. manufacturers) would likely put significant pricing pressure on Japanese module price.[103]

FIGURE 20: Cost and price of solar power module in 1994

($/watt)



Source: NEDO (Price in Japan), IEA PVPS (Price in U.S.). Note: Fully-loaded manufacturing cost is an estimate based on several sources including Chiba (1996).

Despite expectations for significant price decreases, Japanese manufacturers pursued large-scale manufacturing expansions. The most important reason that a large number of Japanese manufacturers made investments in production capacity was that the expected economics were attractive. As an example, a rough estimate for the net present value of a $90mn investment in a

[102] Interviews with NEDO in early 2004.

[103] Note: This paragraph focuses on cell/module production costs instead of the cost of a complete solar power installation because public data on the cost of non-module inputs are not available for the period (1994-2003) under review. This is an area for potential future research.

100MW combined cell/module facility in 1994 with operations starting in 1995 would have had a net present value of roughly $114mn under the following assumptions:

- Capex of $0.90/watt all expended at beginning of 1994
- No production in 1994
- Full production 1995 through 1999
- Manufacturing debottlenecking and creep of 2% per year from 1996
- Silicon usage of 23 grams/watt
- Silicon price of $40/kg
- Fully loaded ingot/wafer manufacturing costs of $1.46/watt
- 10% pre-tax profit margin for wafer maker
- Cell/module manufacturing costs of $2.70/watt excluding equipment and excluding the price of the wafer
- Module price of $9.07/watt in 1994
- Annual module price decline of 20% per year
- Equipment lifetime of 5 years with no residual value or cost at end of lifetime
- 30% tax rate
- 5% corporate discount rate

It is important to emphasize that this positive NPV resulted despite 20% annual price decreases and a discount rate that was high by Japanese standards.

While the financial modeling suggested an attractive investment, the most important uncertainty in this investment was government support for end-customer incentives. Without strong end-customer incentives, the price of solar electricity would have been more than $1.2/kWh, compared to grid prices that were typically under $0.30/kWh.[104] Without incentives, unattractive end-customer economics would likely have led to competitive pressure that would have reduced module prices far below $9/watt in 1994, with the result being a negative NPV for solar power manufacturing capacity investments. Interviews with Sharp Solar, Kyocera Solar, Sanyo and Mitsubishi indicated that executives had conviction that the government incentives would be strong for at least five years.[105] In interviews, explanations of executives' rationales for believing that the government's incentive program was reliable included:

- Long-term government support for solar power and other renewable energy technologies since the mid-1970s;

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[104] Note: Professor Moniz raises the question, "What is the tax structure of grid electricity?"
[105] These interviews were conducted in 2003-2004 as part of research for Rogol (2004). At that time, interviewees said that they *had* believed that government incentives were highly likely to be maintained for several years after introduction in 1994-1996.

- Specific senior government officials making personal commitments to support long-term funding for the demand-side incentive program;
- The view that support for solar power was consistent with high-level government policies for environmental issues (e.g. Kyoto Protocol) and energy security policies (e.g. reducing energy imports); and
- Previous government experience in delivering multi-year funding for similar technologies (e.g. solar thermal).

That supply-side economics were deeply intertwined with demand-side economics that were driven by government incentives is a crucial (albeit perhaps obvious) point. This thesis will make the argument below that the coordination of grid-connection policies, demand-side policies and supply-side policies was a critical factor in the rapid growth of the Japanese solar power sector. The logic for this is partially visible here – supply-side executives made decisions about capacity expansions because of their belief that demand-side incentives would remain in place and would be well-managed. Without this expectation, module price expectations would have been much lower and the NPV of cell/module production investments would have been much less attractive. For example, if Japanese PV manufacturers assumed global module pricing ($4/watt) instead of local module pricing ($9/watt), the NPV of their investments would have been negative $182 million, even it global priced stayed flat at $4/watt for five years. As such, the lynchpin of their investment decision was faith that the government would continue strong demand-side incentives. Conversely, the lynchpin of the demand-side policy established by the government was that careful manipulation of the demand-side incentives could enable reductions in per-watt incentives that were more-than-offset by reductions in per-watt gross system prices which were, in turn, more-than-offset by per-watt reductions in system costs for suppliers.

This topic of intertwined and coordinated government policies will be a focus later in this thesis. For now, it is important to emphasize that, beyond expectations for continuing government support, executives and former executives from Japanese solar power companies expected that production costs would fall quickly with scale and that the price of solar power would reach parity with residential electricity prices within 10 to 20 years. The expectation for cost reductions was based, for example, on estimates of experience curves and progress ratios made by academics, consultants and business people. Publicly released estimates for progress ratios found in the literature range from 53% to 84%, with most in the range 78 to 82%.[106] (TABLE 17)

TABLE 17: Estimates of solar power progress ratios

Study	Progress ratio	# of observations	Years	Scope	Cost/price measure
Maycock and Wakefield (1975)	78%	16	1959-1974	U.S.	PV module sale price
Williams & Terzian (1993)	81.60%	17	1976-1992	Global	Factory module price
Cody & Tiedje (1997)	78%	13	1976-1988	Global	Factory module price
Williams (1998)	82%	19	1976-1994	Global	PV module price
Maycock (1998)	68%	18	1979-1996	Global	PV module price
IEA (2000)	65% to 84%	4 to 11	1976-1996	EU	Various

Source: Margolis (2002a)

Research on experience curves and cost reductions were supported by experience within the industry. For example, the price for modules decreased at a compound annual growth rate of 8% in Japan during the period 1994 to 2003.[107] Also, the efficiency of solar cells increased at a rapid pace during 1994 to 2003, with typical cell efficiencies increasing several percentage points from 1994 to 2003. Because an incremental increase in efficiency often enabled higher MW throughput without an increase in cost, a 1 percentage point increase in cell efficiency typically lowered the production cost of a cell/module by 5% or more.[108]

Executives at leading solar power companies expected significant cost reductions from learning and scale as their production volumes increased.[109] They anticipated that these cost reductions would lead to price reductions, and that the "gap" between solar power and grid price would continue to diminish in the coming years. While there were many scenarios for how the future might evolve, one "mental exercise" process that was used was:

- Doubling of volume every three years (i.e. 26% annual growth rate);
- 20% experience curve (i.e. 7% compound annual cost reduction); and

---

[106] Margolis (2002a) and Margolis (2002b). It is worth noting that the cost reduction achieved by specific companies and by the overall industry from 1994 to 2003 appear to be in line with a roughly 80% progress ratio. With the global industry growing at a 30% CAGR from 1994 to 2005, the sector doubled cumulative production roughly every 3 years. Research on the cost structure of specific solar power companies suggests that cost reductions of at least 6% annually (i.e. at least 20% for every doubling) have occurred in a wide cross-section of solar power companies.

[107] NEDO.

[108] Increase in cell efficiency from 14% to 15% typically led to an increase in cost of 7% minus any extra costs for the higher efficiency. The net increase in costs was typically 5% or higher per 1 percentage point increase in cell efficiency.

[109] Rogol (2004).

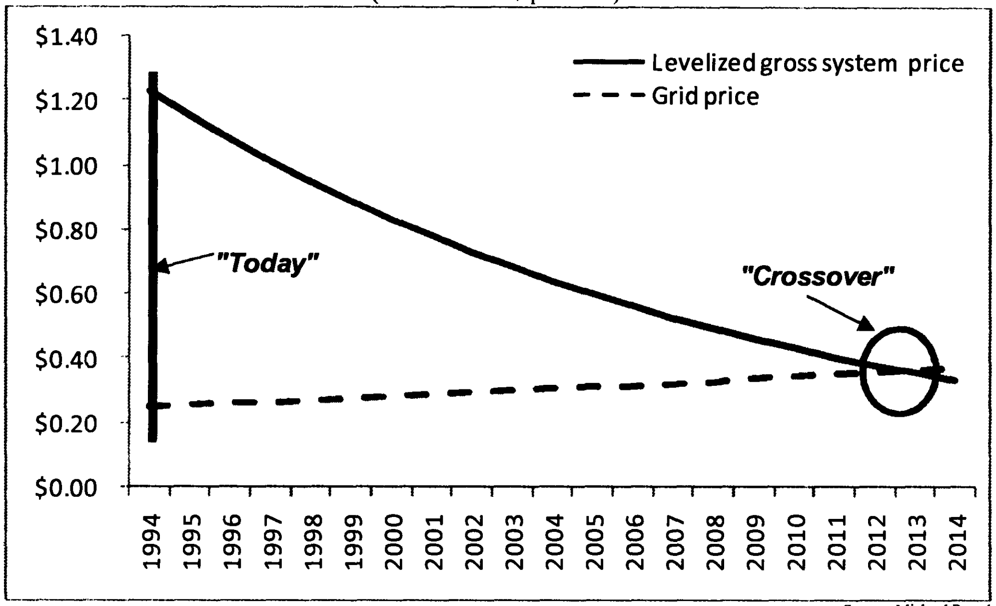
- 2% annual increase in nominal grid prices.

From the perspective of 1994, with other assumptions remaining the same, under this scenario expected levelized gross system price without any incentive would fall to parity with grid price by 2014 (+20 years). By the end of 1996, the "time to parity" appeared like it might be even shorter. With LGSP of $0.65/kWh at the start of 1997 and grid price of $0.23/kWh, it appeared that grid parity would be achieved in 2008 (+11 years), six years earlier than the same "mental exercise" conducted in 1994. By 2003, the "time to parity" had shortened considerably. With LGSP of $0.33/kWh in 2003 and grid price of $0.19/kWh, grid price appeared like it might be reached before 2010 (+7 years).[110] It is worth mentioning that this ongoing "mental exercise" did not account for the possibility of stronger growth enabling faster cost reductions and of higher residential grid prices enabling faster achievement of parity. Similar, this way of thinking ignores the distribution of grid prices, with above-average price customers reaching grid parity earlier. Each of these factors would reduce the "time to parity."

[110] For description of "cross-over" analysis, see methodologies in Section 2. Note: The date of cross-over from a 1997-perspective was 2006. The date of cross-over from a 2003-perspective was 2009. The decline in grid prices from 1996-1997 ($0.23/kWh in 1996 and $0.21/kWh in 1997) to 2002-2003 ($0.17/kWh in 2002 and $0.19/kWh in 2003) was the main reason that the date of cross-over moved from 2006 (1997-perspective) to 2009 (2003-perspective).

FIGURE 21: In 1994, LGSP vs residential grid parity under scenario of doubling cumulative production volume every 3 years, 80% progress ratio & 2% annual increase in grid price

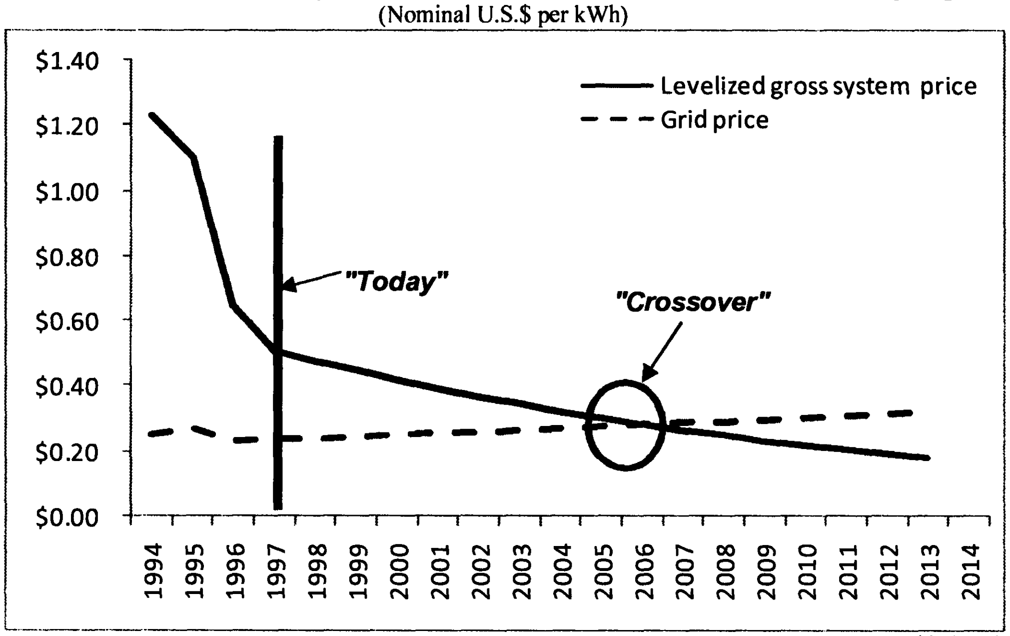
(Nominal U.S.$ per kWh)



Source: Michael Rogol calculation

FIGURE 22: In 1997, LGSP vs residential grid price parity under scenario of doubling cumulative production volume every 3 years, 80%progress ratio& 2% annual increase in grid price

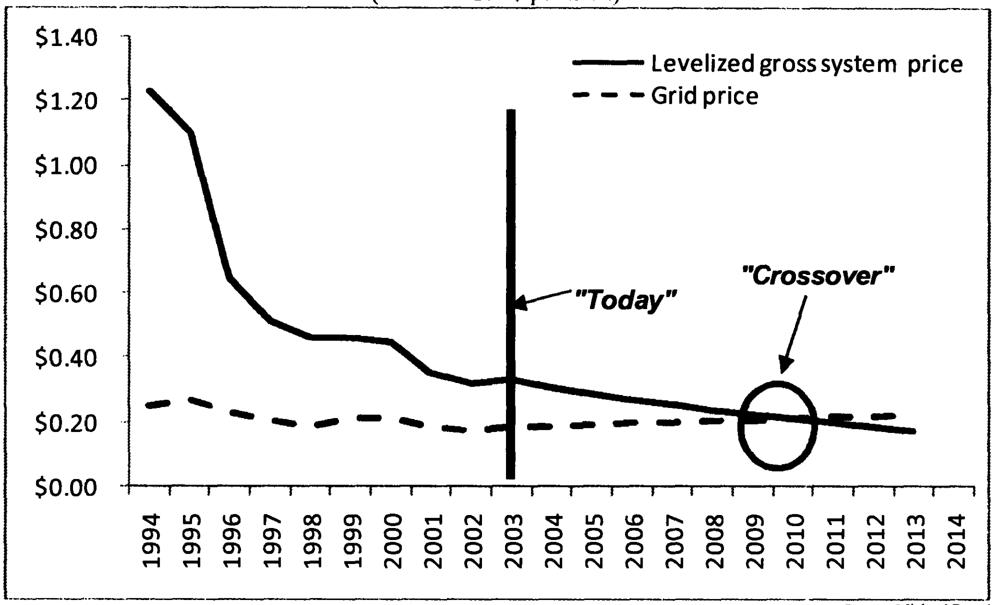
(Nominal U.S.$ per kWh)



Source: Michael Rogol calculation

FIGURE 23: In 2003, LGSP vs grid parity under scenario of doubling cumulative production volume growth every 3 years, 80% progress ratio and 2% annual increase in grid price

(Nominal U.S.$ per kWh)



Source: Michael Rogol calculation

The potential to reach grid parity within 20 years from the perspective of 1994, within 11 years from the perspective of 1997 and within 7 years from the perspective of 2003 gave solar executives the view that investing to increase the scale of their solar businesses would be rewarded by both cost reductions and, eventually, profit *without* the need for government demand-side incentives when price competition eased in the face of a rapidly rising demand due to substitution effects as solar power neared and fell below grid parity. To state this another way, solar executives in Japan expected demand elasticity to increase as the levelized system price approached and went below parity with grid price.[111] As this happened, solar demand would grow very quickly and costs would continue to come down, further expanding the market potential.[112]

This expectation was bolstered by real world evidence. As net prices for solar systems (gross price in yen/watt minus incentives) fell to around 600 yen/watt ($5.5/W), demand increased significantly. By 1996-1997, a "knee" in demand was apparent (yellow dots in FIGURE 24), indicating a significant increase in demand elasticity. Suppliers were able to see that the fully loaded cost of the entire supply chain was greater than this price point (blue dots to right of

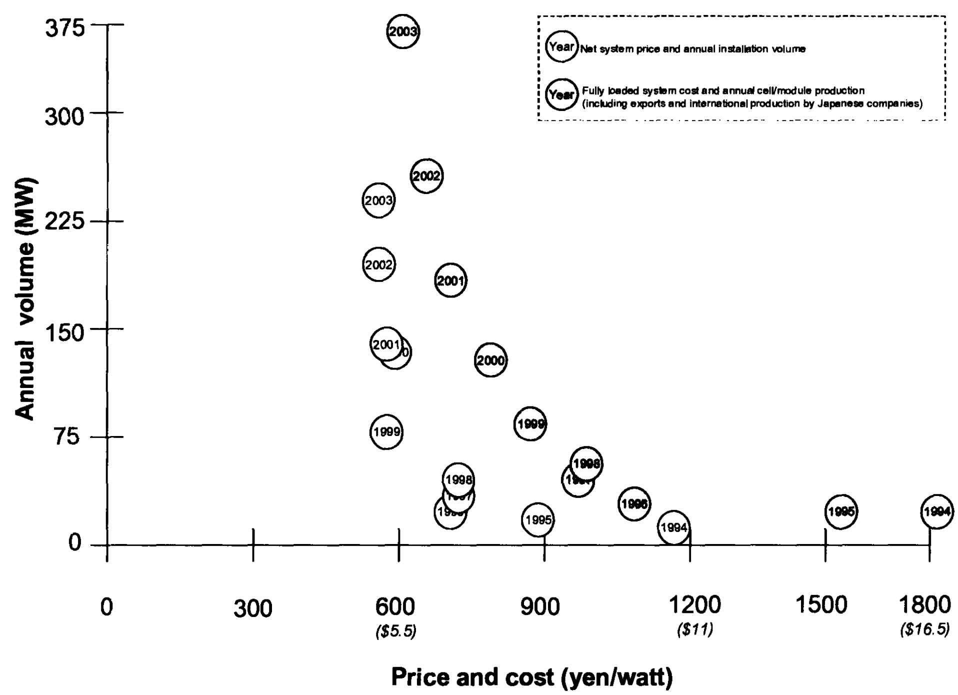
[111] Interviews for Rogol (2004).

[112] It is worth mentioning that there were no stranded cost payments required by small-scale solar power installation owners.

yellow dots in FIGURE 24). However, they could also see this difference decrease over time, falling from roughly $7/watt in 1994 to around $0.60/watt in 2003. (FIGURE 25) There was broad expectation that the existing progress ratio would continue and that the cost of solar power systems would decrease 5% or more annually. The result was that many Japanese executives expected to be able to deliver solar power systems with a fully loaded cost below 600 yen/watt within 5 years, if not sooner.[113]

FIGURE 24: Comparison of net system price and installation volume with fully loaded system cost and production volume 1994 to 2003

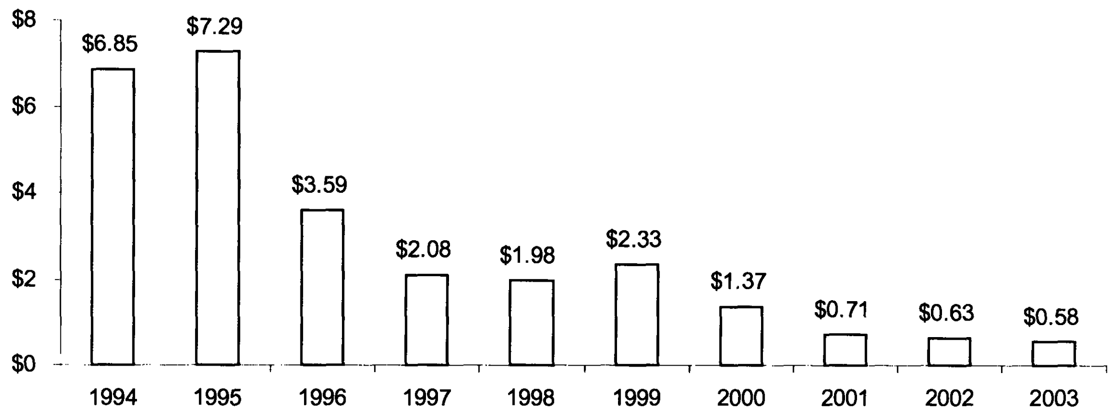
(Yen/watt and MW)



Source: Michael Rogol calculations and depiction based on IEA PVPS, NEDO and other data. Note: Rough estimates. Fully loaded cost estimate based on typical price excluding 10% profit margin. In later years, this assumption is likely too low, meaning that the upper blue dots might be more accurate if moved slightly to the left due to a higher margin.

[113] IEA PVPS (2004), Ikki et al (2004) and Rogol (2004).

FIGURE 25: Fully loaded system cost minus gross system price
($/watt above "break-even" without incentives)



Source: Michael Rogol calculation.. Note: Fully loaded cost estimate based on typical gross price excluding 10% profit margin.

In sum, it appears that the economics for solar suppliers in Japan were attractive *at the start of the period (i.e. in 1994)* because the incentive structures for end-customer installations helped ensure that solar power component and system prices in Japan stayed far above global price levels and were *attractive by the end of the period (i.e. by 2003)* because of expectations that cost reductions from learning and scale would drive solar power costs in Japan to levels that were below the price of residential grid-based electricity.

(iii) Expansion of the Japanese supply chain

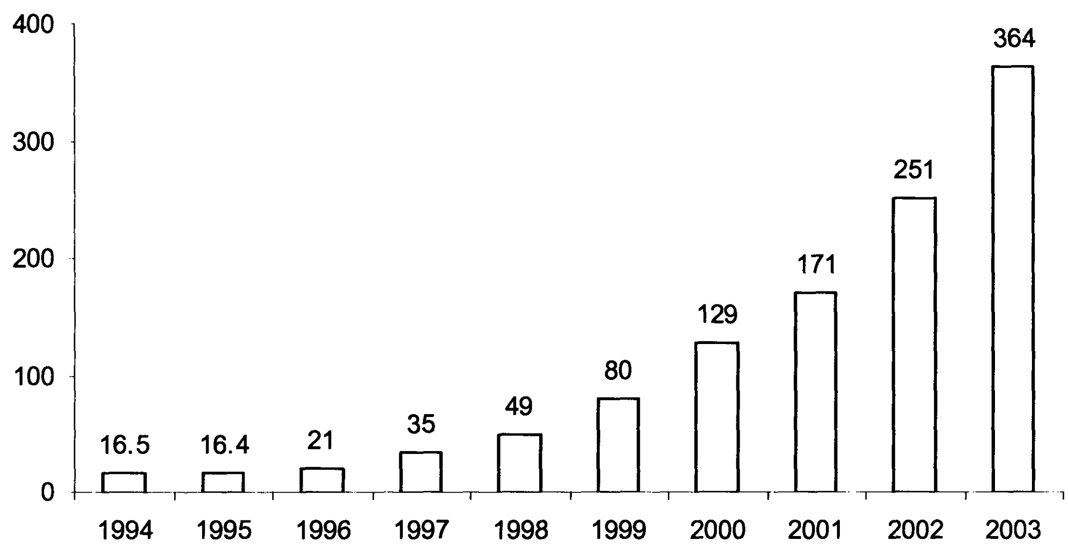
Given the attractive economics for suppliers throughout the period 1994 to 2003, it is not surprising that the companies pursued rapid expansion. This expansion and the cost reductions it achieved were based on a long history of knowledge building. Japanese companies had been involved in the solar power sector since the late 1960s. Before 1994, activities focusing largely on R&D, space applications such as satellites and small electronics products such as calculators. Although companies expressed interest in producing residential solar power systems, manufacturing and installation of this type of product was limited.[114]

During the period 1994 to 2003, solar power manufacturing increased rapidly in Japan. Production of the main system components (solar power cells and modules) increased 22-fold

[114] See, for example, http://sharp-world.com/solar/point/history.html.

from 17MW in 1994 to 364MW in 2003. (FIGURE 26) This equates to a 36% CAGR during this period, outpacing the rest of the world and enabling Japanese share of global cell/module production to increase from 24% in 1994 to 49% in 2003. (FIGURE 27) The main cell/module players in Japan included Sharp, Kyocera, Mitsubishi Electric and Sanyo. Each of these companies achieved significant global market share by 2003 and planned to further expand their capacity in the coming years.[115]

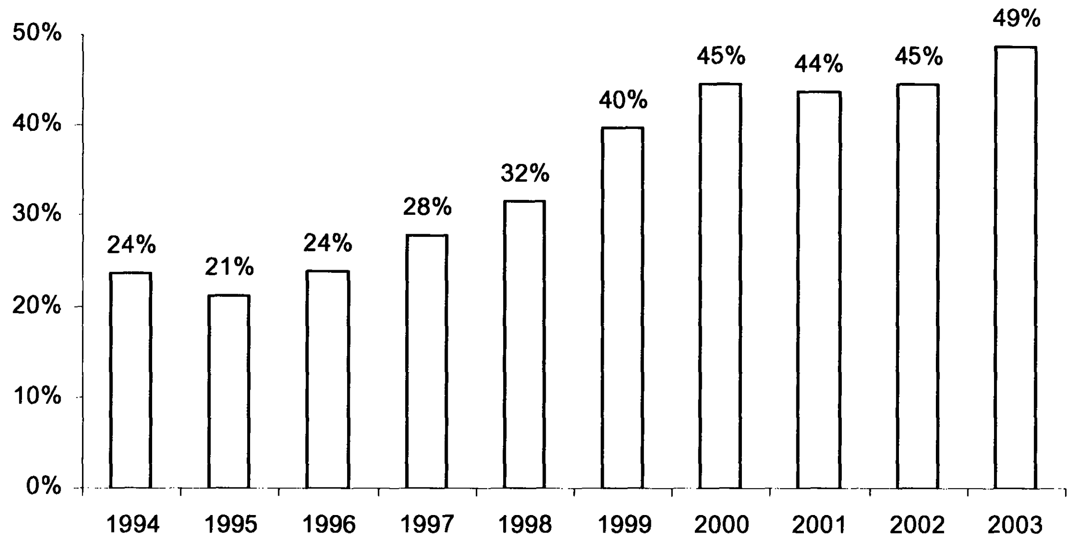
FIGURE 26: Production of solar power cells/modules by Japanese firms
(Megawatts per year)



Source: Maycock (2004)

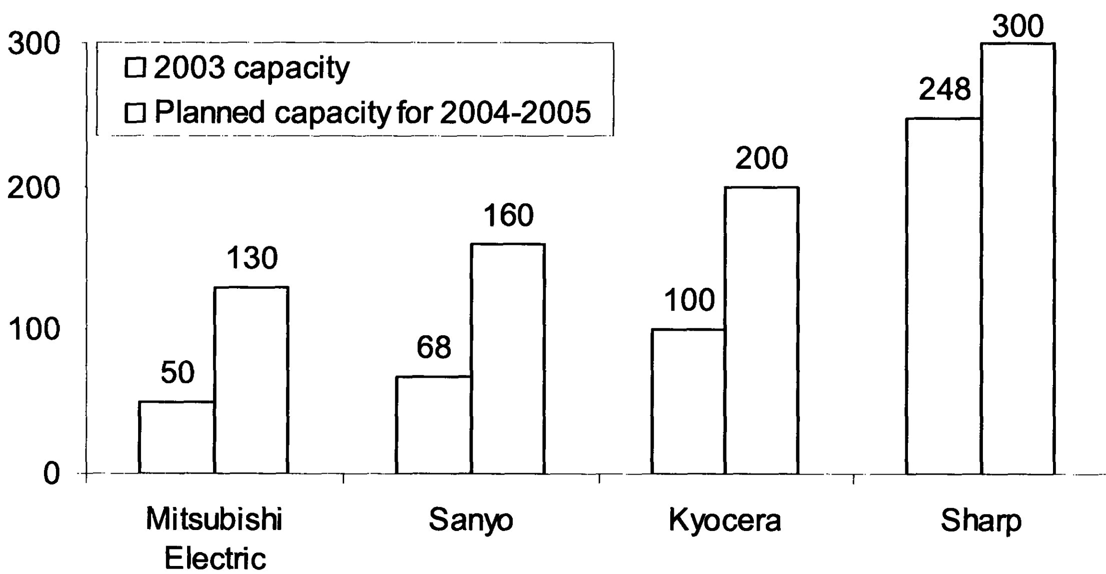
[115] Maycock (2004) and numerous articles (e.g. Photon International magazine).

FIGURE 27: Japan's share of global production of solar power cells/modules
(Percent)



Source: Maycock (2004)

FIGURE 28: Capacity & capacity plans by leading Japanese solar cell/module players
(Megawatts per year production capacity)



Source: Company press releases, corporate investor relations and press clippings.

The pace of this growth is understandable given the description of supplier economics in the preceding sub-section. Yet it is important to emphasize that the Japanese experience during 1994 to 2003 should be seen as exceptional. In other parts of the world, there were several examples of leading solar power companies making decisions that were quite different from the rapidly expanding Japanese suppliers. For example[116]:

- Siemens Solar, a subsidiary of a European conglomerate, was the world's largest solar power player in 1994 with 19% market share. In 2002, Siemens sold its solar business to Shell.

- Solarex, the largest producer of cells/modules in the U.S., had 11% market share in 1994. In 2001, Solarex sold itself to BP after losing market share for four consecutive years.

- Astropower, the second largest producer of cells/modules in the U.S., had 6% global market share in 2001 but lost market share in 2002 and went out of business in 2003. It was subsequently purchased by GE.

- Photowatt, the largest French producer of cells/modules, had 8% global market share in 1998, but then lost market share every year 1999 to 2003.

- Mobil, Texas Instruments, Enron and other "early-stage majors" exited the solar power sector at various times.

As a group, Japan's solar power companies were more aggressive in expanding their production than their international counterparts. The most notable increases in production occurred at Sharp, Kyocera and Sanyo. It is worth noting that all of these companies had significant production experience in similar production environments, such as televisions and electronics, raising the question of if and how Japanese solar industry growth was impacted by the industrial organization of the Japanese electronics sector.[117] It makes intuitive sense that the Japanese electronics companies had core competencies (in R&D, manufacturing, marketing, product development, product management and other areas) that were more directly applicable to the solar power sector than energy sector firms, though, as discussed below, further research on the impact of industrial organization is required.

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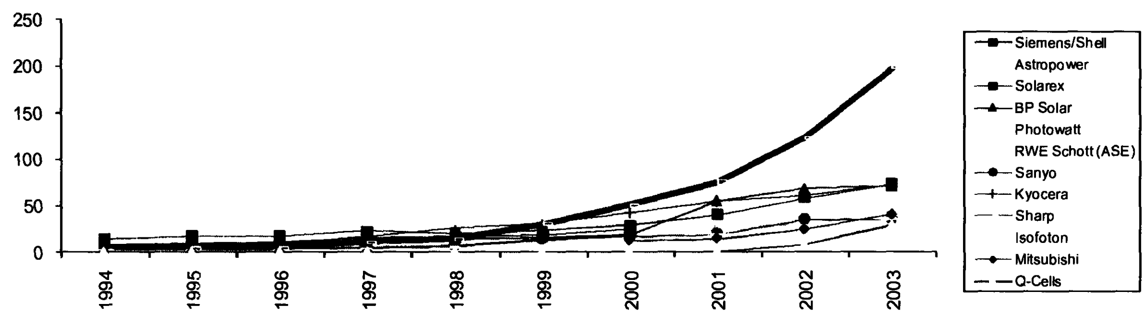
[116] Source: Maycock/PV News; Interviews with U.S. solar power industry executives.

[117] In previous draft, Professor Moniz raised the question, "Lobbying?" There is no evidence of significant lobbying efforts in the English language literature. In interviews, several Japanese executives expressed that it was the Japanese government putting pressure on Japanese businesses to expand solar power manufacturing (not the reverse of Japanese businesses putting pressure on the Japanese government) that was more common in the late-1980s thorough mid-1990s.

While several Japanese companies increased solar power production quickly, one company stands out for its growth: Sharp Solar. During this period, Sharp increased its production of solar cells/modules from 2MW in 1994 to nearly 200MW in 2003, equating to a 66% CAGR. This growth rate more than doubled the global industry average and significantly outpaced the second largest Japanese player, Kyocera, which had only a 33% CAGR during the same period.[118] One interesting question that deserves further research is, "Why did Sharp grow so much faster than the rest of the industry?"[119]

FIGURE 29: Solar cell/module production by company 1994 to 2003
(MW of production)



Source: PV News/Paul Maycock

(E) Industry coordination efforts

The rapid development of Japan's solar power sector appears to have been significantly impacted by a rigorous coordination effort that involved government, industry and academia. This sub-section attempts to describe and analyze this coordination effort. Specific information includes:

i. Coordination efforts in years leading up to 1994

ii. Coordination efforts from 1994 to 2003

[118] PV News/Paul Maycock

[119] Addressing this question requires additional research. One preliminary conjecture is that Sharp's movement toward larger scale production was earlier and/or faster than competitors because (a) it was based in Japan and was able to observe data on increasing demand elasticity in 1996-1997 as the "gap" between LNSP and grid price decreased, (b) had several years of experience in solar power from its integrated products (e.g. calculators) and (c) had significant experience in other industries with significant technical and/or manufacturing similarities (e.g. electronics, LCD TVs). Interestingly, a similar characterization could be made of Kyocera, and it appears that Kyocera also began to increase production significantly in the mid-1990s. However, interviews suggest that Kyocera was barred from sales of solar power systems in the Japan for misallocating government funds designated for a solar power R&D project. The details of this transgression, of the government punishment and of the rationale for not continuing to expand Kyocera Solar's capacity at a pace similar to Sharp Solar are unclear and require further research.

iii. Results and open questions

While coordination appears to have played an important role in the development of Japan's solar power sector, this is a preliminary conclusion based on limited information. Detailed descriptions of this coordination effort do not appear in the English-language literature and interviews to-date with Japanese solar power executives and policy makers have not explored this specific topic in details. As such, this sub-section seeks to contribute to the literature by laying out available information on Japan's coordination efforts. As a preliminary conclusion, it appears that coordination efforts played a central role in the rapid growth of Japan's solar power sector in the years 1994-2003. However, there is recognition that deeper information gathering and analysis will be necessary to further substantiate this preliminary conclusion.

i. Coordination efforts in years leading up to 1994

Coordinated efforts in Japan to build a solar power sector have a long history. As a response to the first oil crisis, the Japanese government launched the "Sunshine Program" in 1974 with a focus on both solar thermal and PV applications. The main objective for PV within this program was to support "dispersed-but-aggregated, utility-connected, residential rooftop systems."[120] Pursuing PV with this type of architecture was largely a new idea because most PV applications to that date were either non-grid-connected, remote applications (e.g. telecommunications, rural locations) or larger-scale applications.[121] Kurokowa and Ikki suggest this change of focus to the now-familiar small-scale, grid-connected architecture occurred in Japan because (a) Japan is mountainous making point of use/distributed energy useful, (b) the high price of land made multi-utilization attractive, and (c) the existing grid was geographically distributed to a large portion of the country, making it possible for it to serve as a backup to distributed, grid-connected PV systems.[122] Initial estimates made in the early 1970s suggested that there was realistic potential for 36GW of distributed, grid-connected rooftop installations in Japan. This would be roughly equivalent to 5% of Japan's electricity consumption, a level "considered significant for future energy options in Japan."[123] At this scale, solar power was seen as a viable option for contributing to both energy security (Japan is highly dependent on energy imports) and environmental protection (climate change and other environmental issues receive significant attention in Japan as demonstrated by Japan being the host nation for the Kyoto Protocol).

[120] Kurokawa and Ikki (2001).
[121] AGORES (1994).
[122] Kurokawa and Ikki (2001).
[123] Kurokawa and Ikki (2001).

It is worth highlighting that these early assessments of the market potential for residential rooftop grid-connected solar power systems were based on estimates not on experience because Japan had no residential rooftop PV systems during this period. It seems that these theoretical estimates of the market potential helped to focus Japanese policy on a specific type of PV specific application. Looking back in time, it is apparent today that residential rooftop applications were a logical starting point for solar power deployment due to the high price of residential electricity. In contrast to looking retrospectively, though, Japanese policy makers were forecasting the future. That they, in the 1970s and 1980s, saw the potential of grid-connected rooftop PV applications with such clarity is impressive.[124] [125] That they then turned this insight into sustained, coordinated action is even more so.

From its inception, the Sunshine Program explicitly attempted to coordinate and support the development of Japan's solar power sector. This support focused on supply-side incentives including R&D projects supported by government funding or government co-funding. According to Watanabe et al, the aim of these policies was to create a "virtuous cycle" for the supply-side:

> MITI (Japan's Ministry of International Trade and Industry) initiated PV development under its Sunshine Project (R&D Program on New Energy)... by: (1) encouraging the broad involvement of cross-sectoral industry, (2) stimulating inter-technology stimulation and cross-sectoral technology spillover, and (3) inducing vigorous industry investment in PV R&D, leading to an increase in industry's PV technology knowledge stock. An increase in this technology knowledge stock contributed to a dramatic increase in solar cell production. These increases led to a dramatic decrease in solar cell production price, and this decrease induced a further increase in solar cell production. An increase in solar cell production induced further PV R&D, thus creating a "virtuous cycle" between R&D, market growth and price reduction.[126]

From the start of the Sunshine Program, the government's goals explicitly involved coordination of a broad set of sectors and a broad set of technologies in order of support the development of the supply-side of the solar power sector. These goals were supported with the formation of the New Energy Development Organization (NEDO) under the auspices of the Ministry of

[124] In previous draft, Professor Moniz wrote, "Who pays?" in sidenote next to this paragraph. My current understanding is that the burden is placed on the gencos and grid operators to continue operations without any *explicit* compensation for stranded costs or extra operating costs. This may change in the future, but I believe that this was the case with solar at such a small scale during 1994-2003. Implicit compensation for stranded costs or extra operating costs may exist in that these costs may be included in the overall rate-base. Further research is required in this area.

[125] In contrast to later times, the primarily justification for the Sunshine Program at its inception was energy security.

[126] Watanabe et al (2000).

International Trade and Industry (MITI) in 1980, by the formation of the New Energy Foundation (NEF) in 1980 to promote adoption of renewable energy and by the formation of a consortium, named the Photovoltaic Power Generation Technology Research Association (PVTEC) in 1990. The PVTEC consortium focused on commercialization efforts including reducing solar cell production costs. The consortium included public institutes and companies, including many of Japan's largest companies, such as Asahi Glass, Fuji, Hitachi, Kawasaki Steel, Kyocera, Matsushita, Mitsubishi, Mitsui, Nippon Sheet Glass, Sanyo, Sharp, Shinetsu, Showa Shell, Sumitomo and Teijin, a group of companies with broad interdisciplinary backgrounds including textiles, chemicals, petroleum and coal products, ceramics, iron and steel, non-ferrous metals, electrical machinery.[127] Notably, utilities were not seen as part of the solar power supply chain and were not deeply involved in PVTEC activities.

TABLE 18: Firms participating in PVTEC

Sector	Number of firms	Firm names
Textiles	1	Teijin
Chemicals	5	Kanegafuchi Chemical Industry Co., Shinetsu Chemical Co., Diado-hoxan Co., Matsushita Battery Industrial Co., Mitsui Toatsu Chemicals Inc.
Petroluem and coke products	3	Showa Shell Sekiyu K.K., Tonen Co., Japan Energy Co.
Ceramics	3	Asahi Glass Co., Kyocera Co., Nippon Sheet Glass Co.
Iron and steel	1	Kawasaki Steel Co.
Non-ferrous metals and products	3	Osaka Titanium Co., Kitachi Cable, Mitsubishi Materials Co.
Electrical machinery	8	Oki Electric Industry Co., Sanyo Electric Co., Sharp Co., Sumitomor Electric Industrial Co., Hitachi, Fuji Electric Corporate R&D, Matsushita Electric Industrial Co., Mitsubishi Electric Co.
Public institutes	2	Japan Measurement and Inspection Institute, Central Research Institute of Electic Power Industry

Source: Watanabe et al (2000)

PVTEC's mission was to help Japan stay ahead of other countries in the PV sector.[128] To pursue this mission, PVTEC sought to accelerate the development of the commercialization of solar power technologies by coordinating the R&D activities of member companies, organize projects assigned by NEDO and promote cooperation among universities, national research institutions,

[127] Watanabe et al (2000)
[128] www.pvtec.or.jp.

and overseas organization such as foreign research laboratories.[129] In addition to PVTEC, where the main focus was on R&D to support *manufacturing* of solar power system components, MITI also launched programs with "complementary" industries such as construction, housing and electric power that would have *applications* roles in the solar power supply chain. By the mid-1990s, MITI's coordination efforts for PV development involved at least 65 Japanese companies. [130] [131]

The coordination efforts involved significant financial support from MITI for R&D by private sector firms over this period, with the goal of stimulating private sector R&D. It appears that MITI's R&D funding efforts were made with the expectation that there would be significant spillover effects among firms.[132] From 1982 to 1993, the government spent $60 to $80 million annually on PV R&D. According to Watanabe, a researcher on Japan's solar power sector from Tokyo Institute of Technology, this spending "induced" private sector spending of an additional $70 to $120 million per year.[133] The private sector firms involved in significant PV R&D spending included Sanyo, Kyocera, Sharp, Fuji, Kaneka, Hitachi, Mitsubishi Electric and Sumitomo.[134] This spending appears to have significantly expanded the PV technology knowledge stock in Japan, with 6,337 PV patent applications from 1982 to 1993 (275 to 509 PV patent applications per year). These patent applications came from a wide variety of firms, with the top 8 companies accounting for roughly 60% of applications.[135]

It is worth highlighting that MITI's coordination efforts went beyond organization and funding. As one example among a multitude, MITI developed detailed models to project the pace, impact and timing of solar power R&D efforts. As part of this effort, in 1993 MITI surveyed 19 Japanese PV players to estimate the time lag and lifetime of solar power technologies. The results included:

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[129] http://www.pvtec.or.jp/englishindex.htm
[130] Watanabe et al (2000).
[131] Interviews with senior executives and policy makers within Japan's solar power sector provided modestly diverging views on the importance of PVTEC in the early 1990s. Some said that PVTEC was simply a mechanism to support NEDO priorities. Others said that PVTEC had a higher level of importance, and served as one of the solar sector's main forums for coordination, priority-setting and action. Regardless which view was correct (PVTEC as subservient to NEDO or PVTEC as a shaper of overall priorities), all interviewees agreed that the launch of PVTEC in 1990 and its subsequent efforts to coordinate solar sector industry-building activities were important to the rapid development of Japan's solar sector throughout the 1990s.
[132] Watanabe et al (2000).
[133] Watanabe et al (2000) citing Meyer-Krahmer
[134] Watanabe et al (2000). Note: Many of these companies emerged as leaders in the Japanese PV sector.
[135] Watanabe et al (2000)

> Out of the reliable responses, 57 valid samples for time lag and 28 for technology lifetime were obtained... Both samples are well balanced for firms and stages of technologies. Therefore, the time lag and the technology lifetime in leading Japanese PV firms over the last two decades were estimated by taking the average of the valid samples. The average time lag of PV R&D and its commercialization was 2.8 yr while the average lifetime of PV technology was 4.9 yr. Assuming that technology depreciates and becomes obsolete over time, the annual rate of PV technology obsolescence was estimated at 20.3% by taking the inverse of the lifetime of the technology.[136]

The point of sharing this example is to provide one anecdote of detail in which MITI was analyzing the potential for PV in the years leading up to 1994. This anecdote and others suggest that deep efforts were being made to formulate realistic technical and economic metrics for how the Japanese solar power sector would evolve.

This detailed analysis was used to develop roadmaps that included key technical, performance and economic milestones around which MITI's PV R&D efforts were then refocused.[137] FIGURE 30 provides an example from the early 1990s of the high-level technology deployment schedule for various solar technologies. FIGURE 31 provides an example from circa 1993 of the high-level expectations for perhaps the most important technical metric in solar sector R&D, solar cell efficiency.[138] FIGURE 32 provides an example from circa 1993 of economic targets that were included in the industry roadmaps. FIGURE 33 provides an example from circa 1993 of the market penetration potential expected as the result of technical improvements that would enable cost reductions that would in turn expand the addressable market for solar power. The point of sharing these examples is not to focus on the specifics, but instead to provide a broad overview of the types of metrics being forecasted, monitored and pursued with coordinated effort by Japanese government, corporate and academic institutions.

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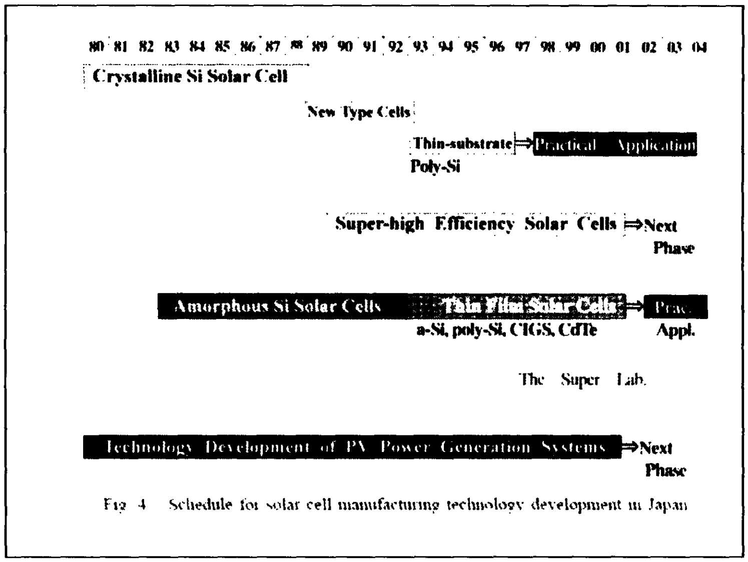
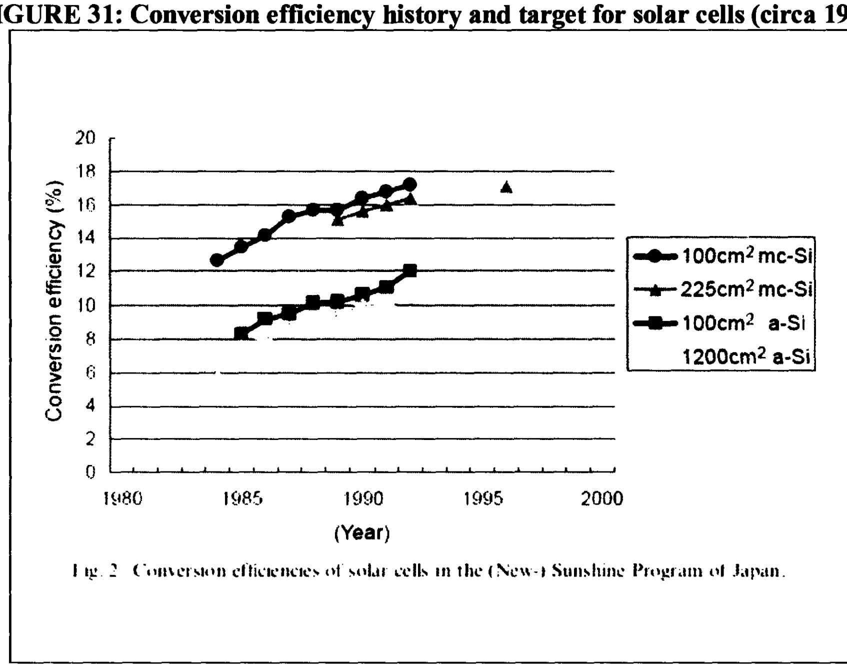
[136] Watanabe et al (2000).
[137] Note: Preliminary conjecture based on interviews. Requires further substantiation.
[138] Cell efficiency is perhaps the most important metric for solar power R&D because the costs of solar power systems and of solar electricity are highly leveraged to cell efficiency.

FIGURE 30: Schedule for solar cell technology deployment (circa 1993)



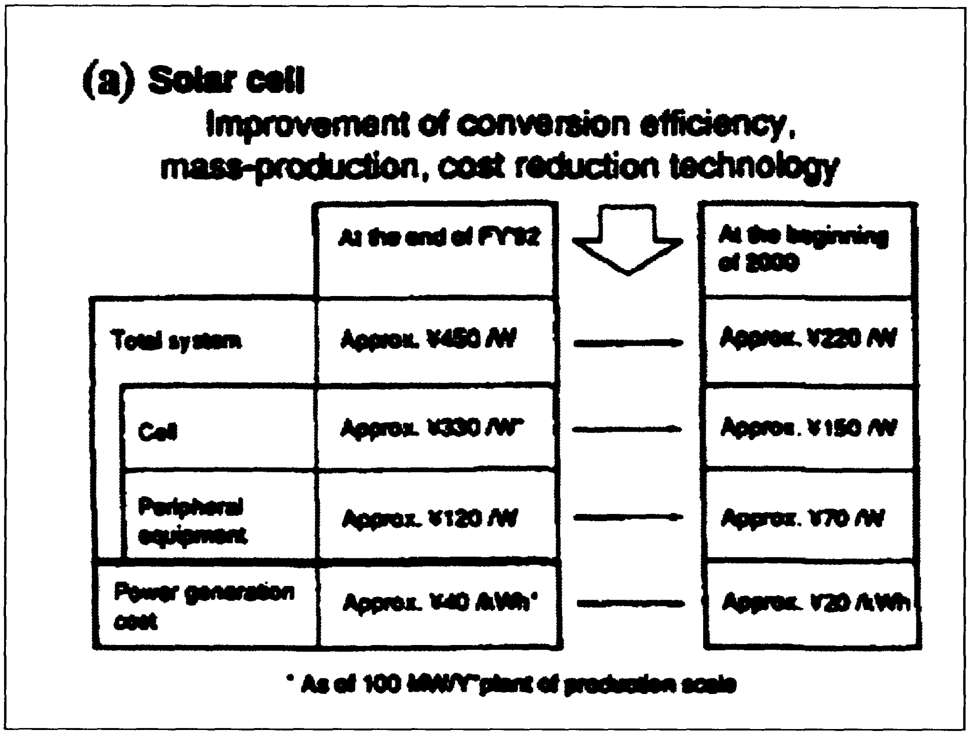
Source: Yamaguchi (2001). Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

FIGURE 31: Conversion efficiency history and target for solar cells (circa 1993)



Source: Endo and Tumura (2003). Note: In this graphic, "mc-Si" is short for mono-crystalline silicon and "a-Si" is short for amorphous silicon. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

FIGURE 32: Solar cell cost targets for 2000 (circa 1993)



Source: Chiba (1996) page 99. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

FIGURE 33: Positive cycle of cost reduction and demand increase (circa 1993)

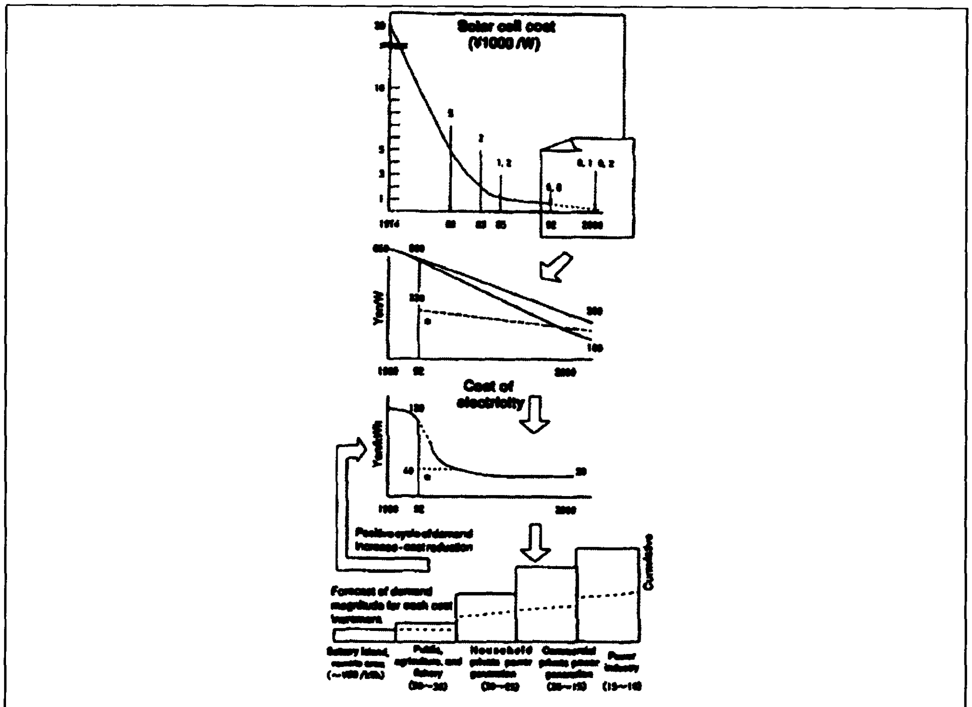


FIG. 4. Positive Cycle of Cost Reduction and Demand Increase

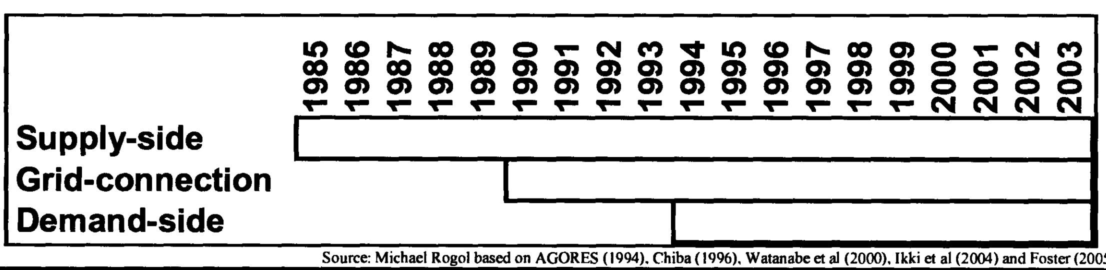
Source: Chiba (1996) page 98. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

Although difficult to read, FIGURE 33 includes information that helps to highlight the highly coordinated nature of Japan's solar power sector development. The bottom graphic within the four graphic stack represents "demand magnitude" as the cost for solar power decreases. In 1992, the cost of solar electricity was roughly $1.2/kWh. This was far above the cost range at which solar would be economic for "solitary island, remote area" (roughly $0.5/kWh), "public, agriculture and fishery" (roughly $0.3 to $0.5/kWh) or "household private power generation" (roughly $0.25 to $0.3/kWh). Yet the graphic identifies a "positive cycle of demand increase/cost reduction" as a key driver of increasing the addressable market size. According to interviewees, the *supply-side* cost reductions that came with scale were a key driver for MITI's pursuit of *demand-side* incentives policies in the years leading up to 1994. This view that demand-side incentive policies were an essential element of quickly driving down solar power costs was also interwoven with the understanding that demand-side incentives for residential grid-connected applications would be meaningless if grid-connection and net metering rules were not implemented prior to the demand-side incentives. This appears to have been the impetus for changes in grid connection and net metering rules in the years *before* demand-side incentives commenced in 1994.[139] While *proving* all of these complex interactions existed is not possible from the available data, the circumstances and timing of the supply-side policies, grid-connection/net meter policies and demand-side policies certainly suggest that coordination policies (i.e. policies that addressed the web of interdependencies between supply-side, demand-side and grid) must have already been significant prior to 1994.

ii. Coordination efforts from 1994 to 2003

Japan's solar power policies and its coordination efforts were significantly expanded from 1994 with the introduction of the New Sunshine Program's demand-side incentives. From 1994, strong incentives were put in place for end-customer installations that built upon existing grid connection policies and supply-side policies. (FIGURE 34) Most of the government funding supported small-scale residential solar power installations. These incentives provided per-watt reimbursement to customers for installing solar power systems on residential rooftops.[140] In addition to the residential rooftop incentive, there were also incentives for larger-scale installations that served as demonstrations. The strong government support for end-customer installations amounted to $1.3 billion in PV demonstration and deployment spending during the years 1994 to 2003. Most of this total was spent on the New Sunshine Program's cost-sharing program for residential rooftop installations that enabled more than 160,000 rooftop installations from 1994 to 2003.[141] (See FIGURE 35 for Japanese solar power RDD&D budgets during this period.)

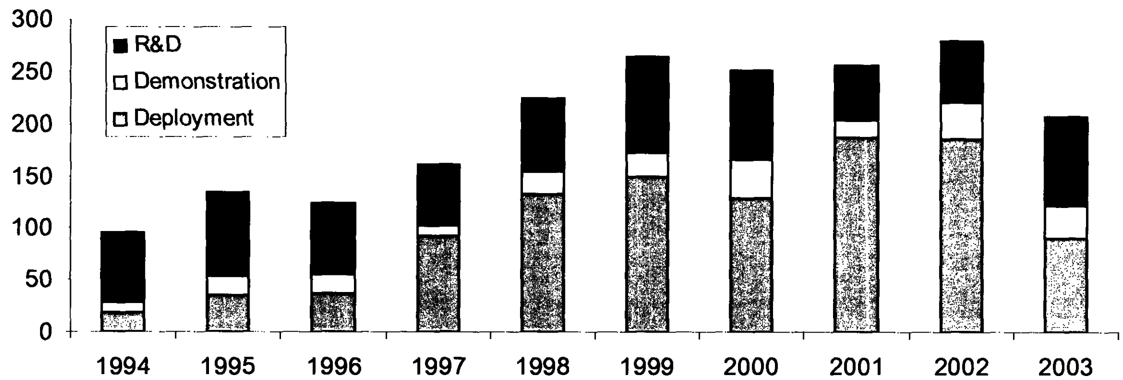
FIGURE 34: Timing of Japanese solar power policies



Source: Michael Rogol based on AGORES (1994), Chiba (1996), Watanabe et al (2000), Ikki et al (2004) and Foster (2005).

[139] Requires further substantiation based on additional research.
[140] See TABLE 3 for data on per-watt incentives.
[141] NEDO

FIGURE 35: Japan national government fund for solar power by category 1994 to 2003
($ million per year)

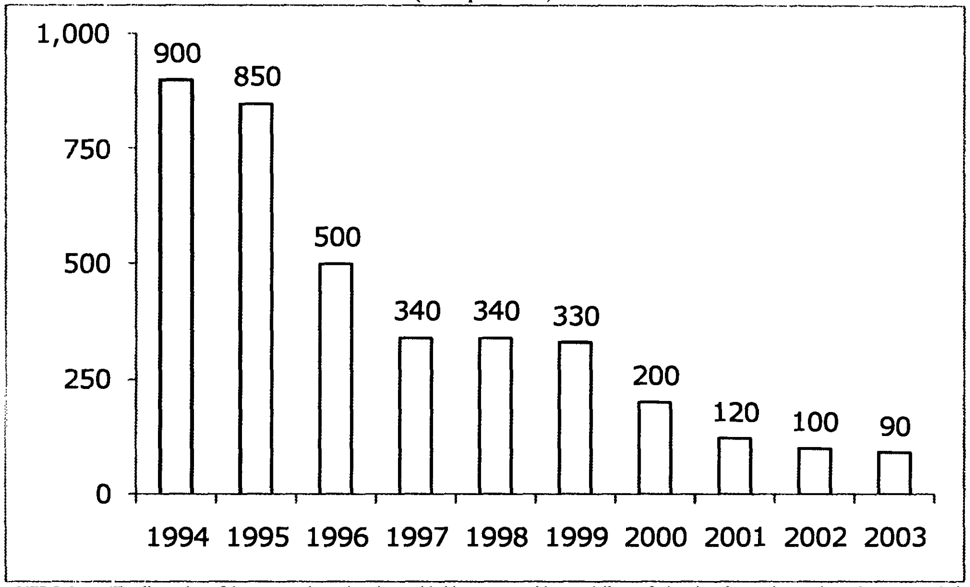


Source: IEA PVPS (1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004).

One important element of the demand-side incentives under the New Sunshine Program was that they declined over time in per-watt terms. As displayed in FIGURE 36, national-level incentives decreased from 900 yen/watt ($8.81/watt) in 1994 to 90 yen/watt ($0.08/watt) in 2003. Despite this 90% decrease in per-watt incentives, installations increased 32-fold over the same period. This expansion of demand occurred because gross system prices were decreasing even faster than incentives, so that net system prices (FIGURE 37) were decreasing at a 9% CAGR despite the diminished incentive.[142] The rapid decrease in gross system prices provided real-world confirmation for the theoretical expectation of the "positive cycle of demand increase/cost reduction" discussed by Watanabe et al (2000) and others.

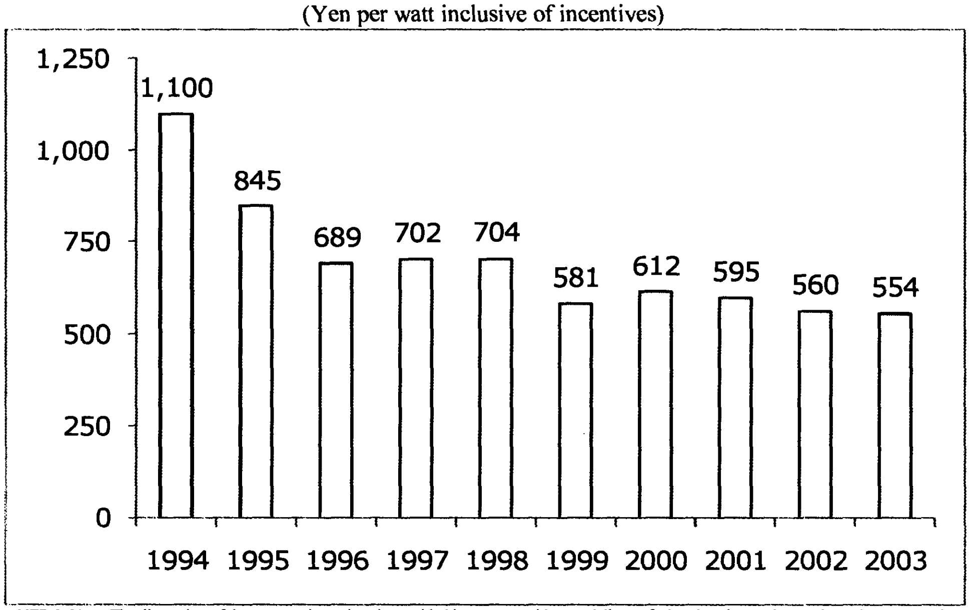
[142] In addition to decreases in gross system prices, small levels of local incentives also brought down net system prices.

FIGURE 36: Japanese national incentive for small-scale solar installations
(Yen per watt)



Source: NEDO. Note: The discussion of the per-watt incentives is provided in yen to avoid potentially confusion data due to changes in exchange rates during 1997-2001.

FIGURE 37: Net system price in Japan
(Yen per watt inclusive of incentives)



Source: NEDO Note: The discussion of the per-watt incentives is provided in yen to avoid potentially confusion data due to changes in exchange rates during 1997-2001.

It is important to emphasize that the decrease in incentives was *not* a random or pre-programmed occurrence. Instead, these per-watt incentives appear to have been manipulated with a high degree of precision by the team overseeing the incentive program within the New Energy Foundation (NEF) under MITI. While the literature does not have a detailed description of this process, interviews indicate that the incentive manipulation was based on careful monitoring of numerous factors that impacted the end-customer price of solar electricity (e.g. before-incentive solar power component and system prices as displayed in FIGURE 38). Changes in end-customer price for solar electricity were carefully compared to changes in demand to evaluate demand elasticity and estimate the potential demand impact of different changes in the per-watt incentive level.[143]

FIGURE 38: Example of economic benchmarks (circa 1998)

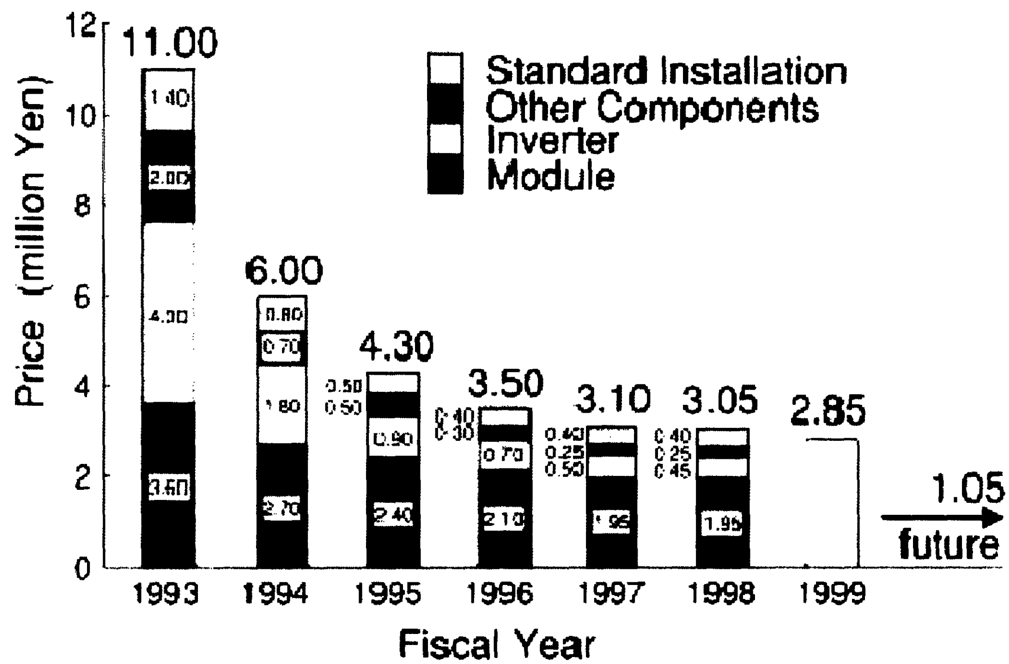


Fig. 3. Price trends of a 3 kW residential system

Source: Kurokawa and Ikki (2001) page 462.. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

It appears that the NEF team adjusted incentives based on careful monitoring and estimation of demand impact from changes in incentive levels. These adjustments were done following coordination with and communication among MITI, solar power manufacturers, solar power installers, generating companies and other players involved with the expansion of the solar power sector so that the precise level of adjustment and the exact timing of the adjustment were the result of complex inputs. Descriptions in interviews of this process are reminiscent of the U.S.

[143] Requires further substantiation and additional research.

Federal Reserve Board's deliberations, communications and actions surrounding changes in interest rates. One interviewee explained that the specific level and timing of incentive reductions was based on a "balance between trying to keep demand growing without overheating and trying to make sure that cost reductions of the suppliers were continuously passed on to consumers so that the incentives could eventually disappear."[144] [145]

Beyond the multifaceted interacts that took place among the NEF, NEDO, Japanese solar power manufacturers and other organizations involved in the Japanese solar power sector relating to demand-side incentives, there were also multifaceted interactions relating to supply-side incentives. On the supply-side, careful monitoring and analysis of key technical and performance criteria was taking place in order to evaluate the performance of solar power systems. This involved coordinated research efforts of NEF, NEDO, PVTEC, AIST, numerous private sector companies and other organizations. One example of this type of interwoven program involved collecting and analyzing the performance of a large number of installed PV systems to identify performance improvement potential (FIGURE 39). Many of these installations were supported by incentives administered by NEF, the system performance was monitored by AIST and data/analysis were utilized by MITI, NEDO, NEF and solar power companies. This monitoring activity enabled, among other things, the identification of losses from solar power system performance that was then used in the process of prioritizing PVTEC and AIST research programs. In this case, supply-side R&D efforts to address specific areas of performance losses after installation had potential to reduce costs, thereby potentially reducing price and thereby potentially increasing demand. This type of intricate interaction appears to have been a hallmark of Japan's solar power sector during the years 1994 to 2003.[146]

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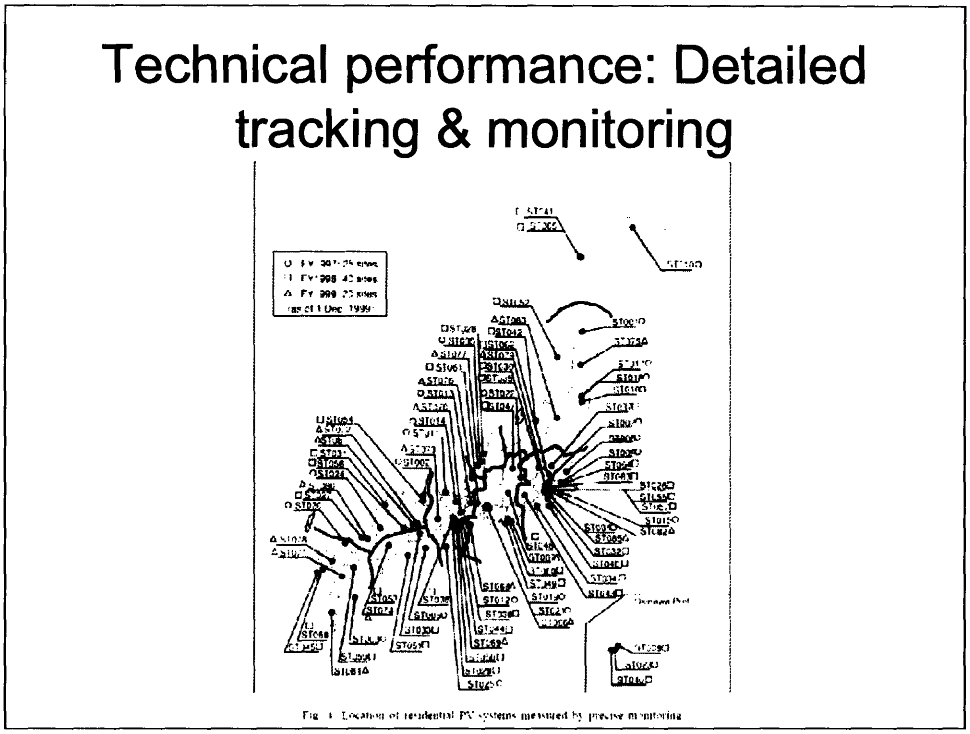
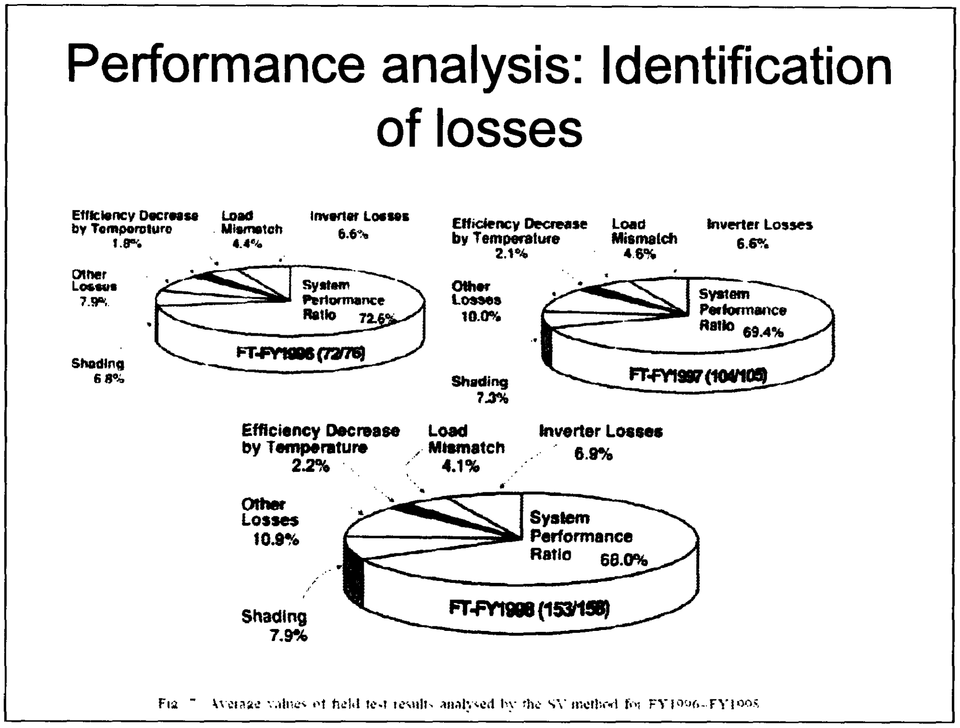
[144] Interview with New Energy Foundation June 2004.
[145] Again, requires further substantiation and additional research.
[146] Again, requires further substantiation and additional research.

FIGURE 39: Example of detailed monitoring of technical performance (circa 1998)



Source: Kurokawa and Ikki (2001) page 463. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

FIGURE 40: Example of problem identification and tracking (circa 1998)



Source: Kurokawa and Ikki (2001) page 463. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

iii. Results and open questions

One preliminary conclusion drawn from the above discussion is that coordinated industry-building efforts and reliable, responsive government support played an important role in the rapid growth of Japan's solar power sector from 1994 to 2003. The results from this industry-building exercise were impressive both in absolute terms and relative to the rest of the world:

- **Demand.** Installations of solar power in Japan increased more than 3000% during this period, from 7MW in 1994 to 223MW in 2003. As a result, cumulative installations grew from less than 2MW at the end of 1993 to 860MW at the end of 2003. During this period, Japan's share of annual OECD installations increased from virtually zero percent to 47% in 2003.[147]

- **Supply.** Production of solar power cells/modules in Japan increased more than 2000% during this period, from 17MW in 1993 to 364MW in 2003. In addition, production of feedstocks (e.g. silicon), production equipment and other system components (e.g.

[147] IEA PVPS (2004)

inverters) expanded quickly. During this period, Japan's share of global solar cell/module production increased from 24% in 1994 to 49% in 2003.[148]

- **Price.** Gross prices (without incentives) for solar power modules and non-module inputs decreased by 52%, and 80%, respectively, from 1994 to 2003. As a result, gross system prices decreased from $20/watt in 1994 to $6/watt in 2003 and levelized gross system prices decreased from $1.23/kWh in 1994 to $0.33/kWh in 2003.[149]

- **Incentives.** The Japanese national government provided more than $1 billion to support installation of solar power systems from 1994 to 2003. Impressively, the per-watt national incentives declined from nearly $9/watt at the start of the period to under $0.80/watt at the end of the period. Also impressive was the fact that the deployment budget peaked in 2001 at $188 million then declined in 2002 and again in 2003. Even with declining per-watt incentives and a declining deployment and demonstration budget, demand continued to grow in 2002 and 2003.[150]

- **Knowledge stock.** The technology knowledge stock for PV expanded significantly during the period 1994 to 2003. As a proxy of the expanding knowledge stock, more than 6,000 PV-related patent applications were filed during this period.[151] This level of PV patent activity appears to exceed any other country during the years 1994-2003.[152]

- **Technical performance.** The performance of solar power components and systems improved significantly over the period. Efficiencies of laboratory mono- and multi-crystalline silicon solar cells increased from roughly 21% and 16%, respectively, in 1994 to 25% and 20%, respectively, in 2003.[153]

- **Revenue.** The total revenue generated by Japan's solar power sector increased from Japanese solar power companies increased from roughly $135 million in 1994 to more than $1.3 billion in 2003.[154] During this period, Japan's share of the global solar revenue pool expanded quickly.

- **Jobs.** By 2003, Japan was home to the world's largest number of solar power employees. More than 11,000 Japanese worked in the solar power industry in 2003, up from under 1,000 in 1994.[155]

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[148] Maycock (2004)
[149] NEDO.
[150] NEDO, IEA PVPS (2004).
[151] Watanabe et al (2000).
[152] This claim was made by an interviewee in Japan who has spent considerable time working with patent statistics, but I do not yet have the data to verify it.
[153] Personal correspondence with member of U.S. National Renewable Energy Laboratory in 03/2007.
[154] Rough estimate assuming average gross installation price per watt in Japan multiplied by the number of MW installed in Japan in each year. In reality, this significantly understates the revenue generated by Japanese solar power companies in 2003. For example, this ignores revenue generated from exports.
[155] 2003 estimate from IEA PVPS (2004). 1994 estimate based on interviews.

The success of Japan's industry-building efforts went beyond the quantitative. Qualitative results were also clear, including insights about how Japan's solar power sector might evolve. These insights included:

- **Small-scale grid-connected systems.** In 1993, nearly all of the world's solar power production was "off grid" in applications such as signaling towers, remote houses, water pumping, remote village power and consumer electronics. In many cases, these applications required expensive batteries. One important insight that was first understood and then executed upon in Japan was the ability for small-scale, grid-connected systems to effectively use the existing electricity grid for storage/back-up, thereby eliminating the need for batteries. This insight led to the change of the grid connection and net metering laws in Japan in 1990-1993, before the start of the New Sunshine Program.

- **Spillover, learning and scale effects.** The price of a solar power system was prohibitively high for most end-customers in 1994 due to the high cost of manufacturing and installing these systems. Architects of the Japanese roadmap and New Sunshine program emphasized the importance of knowledge spillovers, learning curves and scale economics in how they evaluated potential cost reductions. This led to a decade (1980-1990) during which government and private sector expenditures were focused largely on building a technology knowledge base through R&D activities, followed by more aggressive demonstration and deployment efforts to capture cost decreases that come from learning as cumulative production increased and scale as the size of the production facilities/companies/industry increased.

- **Focus on grid parity.** Even before the New Sunshine Program commenced, there appears to have been agreement that cost reductions would be necessary in order to reach parity with grid price. Once this occurred, much larger-scale adoption would be feasible, and would enable realistic achievement of the Cabinet's target of 4.6GW in cumulative installations by 2010.

- **More potential for c-Si than thin films.** The Japanese government and companies recognized by the late-1990s that traditional crystalline silicon technologies provided strong-than-expected growth potential, especially in comparison with thin films that faced significant challenges in achieving large economies of scale. While this was not a unanimous view, it appears to have been a dominant view, leading to both a continuing focus on incremental innovation (in the Arrow sense) within government R&D budgets and to a much faster ramp-up of c-Si production by Japanese firms, including Sharp.[156] It also led the Japanese to evaluate and act on the need for lower cost, higher volume solar-grade silicon production in a time-frame that would surprise many.[157]

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[156] According to one interviewee, the point of inflection when Sharp decided to aggressively pull away from the pack was tied to a technical conclusion that thin films would not quickly displace c-Si so that investments in c-Si would not be quickly obsolete. This view is supported by interviews with other executives with some pointing out that the information necessary to draw this technical conclusion came significantly from government-backed R&D efforts for which significant information was disclosed.

[157] In hindsight, the Japanese focus on c-Si appears to have been a good decision. Today, c-Si accounts for more than 90% of global solar cell/module production. While thin films and alternative technologies have potential for market share gains in future, c-Si appears likely to continue as the industry leading technology for several years to come. In contrast to decisions made by the largest

- **BIPV.** There was early recognition of the benefits of integrating solar power into building design (building integrated photovoltaics or BIPV). The focus on BIPV led to coordinated research between homebuilders, module makers and research laboratories. Perhaps the most striking example of this collaboration involved Sharp, Sekisui Chemical and NEDO in order to integrate Sharp's solar power modules into Sekisui Chemical's prefabricated homes. By 2003, Sekisui Chemical alone was responsible for roughly 36MW of annual solar power installations.[158]

- **Demand dynamics.** By the mid-1990s, an understanding of the demand curve was emerging in Japan. One basic insight was that demand increased significantly driven by substitution for grid price at net system prices below 600 yen/watt ($5.5/watt), equal to roughly $0.40/kWh.

Interviewees shared numerous examples of these types of insights leading to concrete actions by a variety of players in government and industry. As one anecdote, ongoing analysis of technical data in the early 1990s led to changes in the focus of R&D projects. Academic reviews of the effectiveness of Japan's solar R&D spending indicated (unexpectedly, according to interviewees) that the cost-effectiveness of R&D for traditional crystalline silicon (c-Si) technologies was noticeably higher than for alternative technologies such as amorphous silicon (a-Si) starting from circa 1996. (FIGURE 41) This, combined with analysis that there would be increasing need for solar-grade silicon material in the future if c-Si technologies proved to have higher-than-expected market potential (FIGURE 42), led to increasing funding for solar-grade silicon R&D.[159] (FIGURE 43) Basically, Japanese researchers correctly predicted that silicon usage by the solar power sector would grow very quickly, creating a *potential* long-term for new sources of silicon. This *potential* need led to *actual* funding for solar-grade silicon R&D.[160]

Japanese solar power companies such as Sharp, Kyocera and Sanyo to focus on c-Si technologies, some of the largest international competitors (e.g. BP, Shell) instead expanded their focus on alternative technologies during this period. The results of investments in alternative PV technologies for BP and Shell ended with plant closures within a few years.

[158] Rogol (2004).

[159] Endo and Tamura (2003); Interviews with NEDO.

[160] It turns out that the analysis of the solar power sector requiring significant new sources of silicon was prescient. By the end of 2004, the silicon market became tight with demand in the solar sector far outstripping production capacity. At time of writing this thesis, the silicon market remains tight, with prices well above their historical levels.

FIGURE 41: Cost-efficiency of solar cell R&D in Japan 1992 to 2002
(% efficiency improvement/billion yen)

Table 1
Cost-efficiencies of R&D on solar cells from the viewpoint of manufacturing cost reduction rate in the FY1992

(% billion yen)	mc-Si	a-Si
By conversion efficiency improvement	2.6-3.0[a]	1.3-1.7[b]
By net-cost reduction	2.0	5.2

[a] $100cm^2$-$225cm^2$ for multicrystalline silicon (mc-Si).
[b] $100cm^2$-$1200cm^2$ for amorphous silicon (a-Si).

Table 2
Cost-efficiencies of R&D on solar cells from the viewpoint of manufacturing cost reduction rate in the FY1996

(% billion yen)	mc-Si	a-Si
By conversion efficiency improvement	1.9-2.3[a]	1.3-2.9[b]
By net-cost reduction	0.6	2.8

[a] $100cm^2$-$225cm^2$ for multicrystalline silicon (mc-Si).
[b] Initial stabilized conversion efficiency for $1200cm^2$ amorphous silicon (a-Si).

Table 3
Cost-efficiencies of R&D on solar cells from the viewpoint of manufacturing cost reduction rate after FY1996

(% billion yen)	mc-Si[a]	a-Si[b]
By conversion efficiency improvement	10.3	2.8
By net-cost reduction	5.5	1.2

[a] FYs1997-2002, includes the NEDO's SOG-Si project for multicrystalline silicon (mc-Si).
[b] FYs1997-2000 for amorphous silicon (a-Si).

Source: Endo and Tamura (2003).

FIGURE 42: Forecast of silicon usage through 2010 made in mid-1990s

(Tons of high purity silicon production)

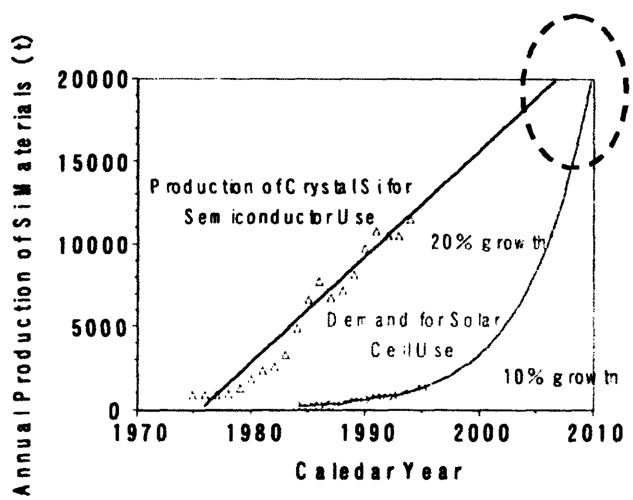


Fig 14 Changes in Si material demands for solar cell use in comparison with the production of crystal-line Si for IC use

Source: Yamaguchi (2001) page 129. Note: Dotted circle added.

FIGURE 43: Solar power R&D for PV under the Sunshine and New Sunshine Programs
(Million yen/year)

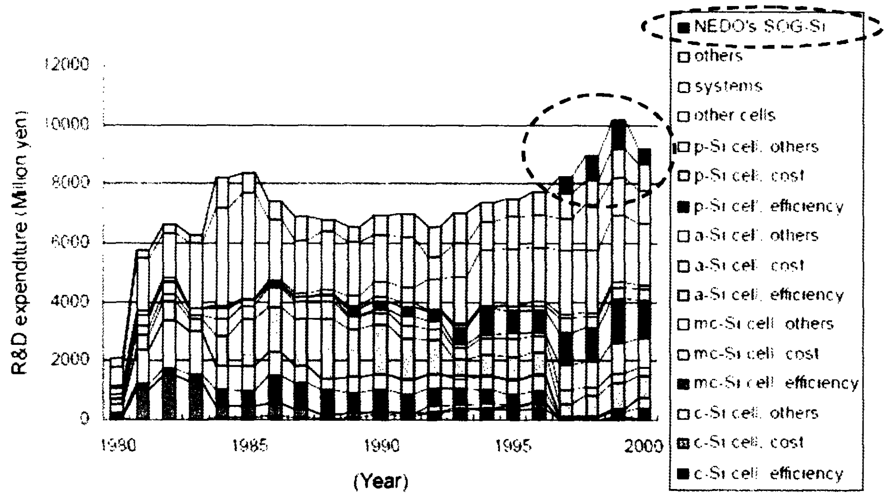


Fig. 1. R&D expenditure for photovoltaics in the (New-) Sunshine Program of Japan

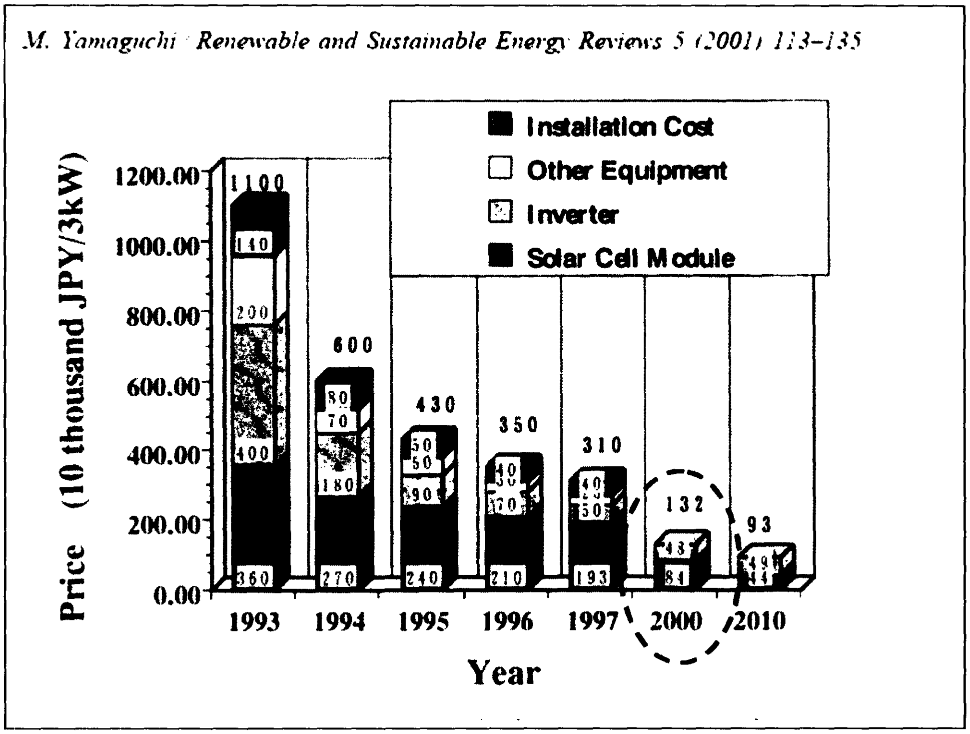
Source: Endo and Tamura (2003) page 753. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

While the results of Japan's industry-building efforts were impressive and had impact, they were not without mistakes. For example, tracking of data on the various components that made up gross installed system prices indicated an installed system price in 1997 of 1060 yen/W ("310 10 thousand yen/3kW system" in FIGURE 44) or about $9/W. There was an expectation, based on historical price reductions from 1994 to 1997 as the New Sunshine Program was ramping up, that the gross installed system price had realistic potential to decrease by 50+% over the three years 1998 through 2000.[161] This expectation proved unrealistic, with the gross installed system price

[161] Yamaguchi (2001).

decreasing only 20% from 1998 to 2000.[162] Similarly, there was an expectation that the cost of producing thin film modules would decrease after year 2000 and, as a result, their price would also fall rapidly and production would rise rapidly.[163] (FIGURE 45) However, the cost of thin film production did not fall as rapidly as expected, and, as result, neither thin film prices nor volumes performed as expected.[164]

FIGURE 44: Example of forecast that was not achieved (circa 1997)



Source: Yamaguchi (2001). Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

[162] NEDO.
[163] Yamaguchi (2001).
[164] Maycock (2004) for volumes in 2003. Interviews with Kaneka and Sharp for prices/costs.

FIGURE 45: Example of forecast that was not achieved

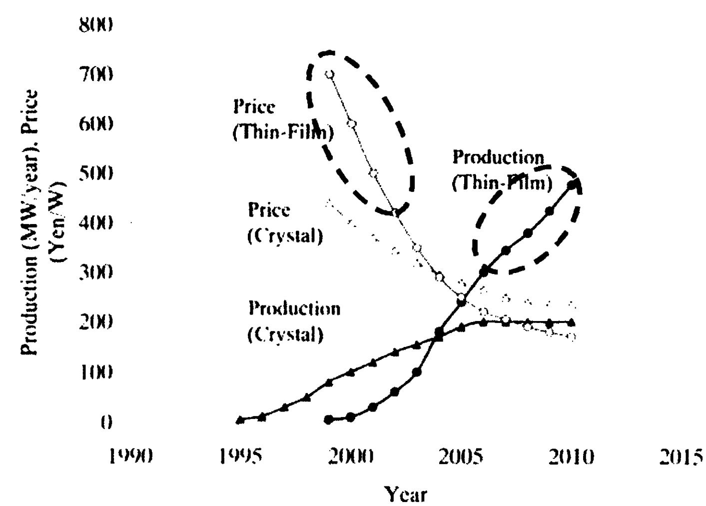


Fig 16 Production scenario of thin-film solar cells and bulk crystal Si cells in Japan

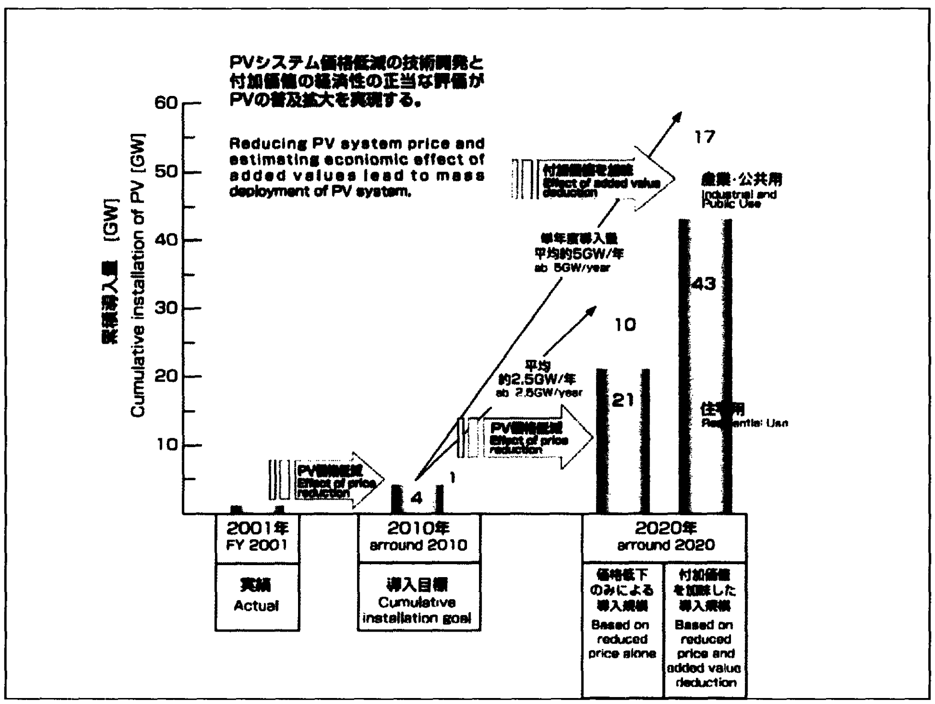
Source: Yamaguchi (2001). Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image. Note: Dashed-circles added to highlight specific area.

Despite these examples, overall, the industry-building effort succeeded and Japan's solar power sector grew quickly during the period 1994 to 2003. By 2003, the industry had established a solid foundation for future growth with a gap between solar LNSP and grid prices that appeared likely to be overcome in the next few years, fully loaded cost of solar power systems quickly approaching "cross-over" with the net price many customers were willing to pay, a truly nationwide distributed network of small solar power installations and expectations that export markets offered significant sales potential. As a result, many companies had announced expansion plans. For example, Mitsubishi, Sanyo and Kyocera each planned capacity increases of 100% or more, and Sharp, the largest player in the world, planned to increase capacity by at least 21%.[165]

[165] Maycock (2004).

From the perspective of 2003, there were expectations that the sector would continue to thrive, and planning was taking place for much larger-scale expansion of the sector.[166] Updated government policies indicated a collective belief that the Japan would achieve 5GW of cumulative installations by 2010, up to 30-60GW by 2020 and 83GW by 2030. By 2030, this would be roughly equivalent to 50% of total residential electricity consumption and more than 10% of total Japanese electricity consumption. These high level goals were accompanied by updated technical, economic and operational plans for improving efficiencies, reducing costs and expanding markets.[167] (FIGURE 46, FIGURE 47 and FIGURE 48).

FIGURE 46: Example of ongoing roadmapping efforts (circa 2002)



Source: PVTEC (2006). Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

[166] Rogol (2004).
[167] PVTEC (2006).

FIGURE 47: Example of ongoing roadmapping efforts (circa 2002)

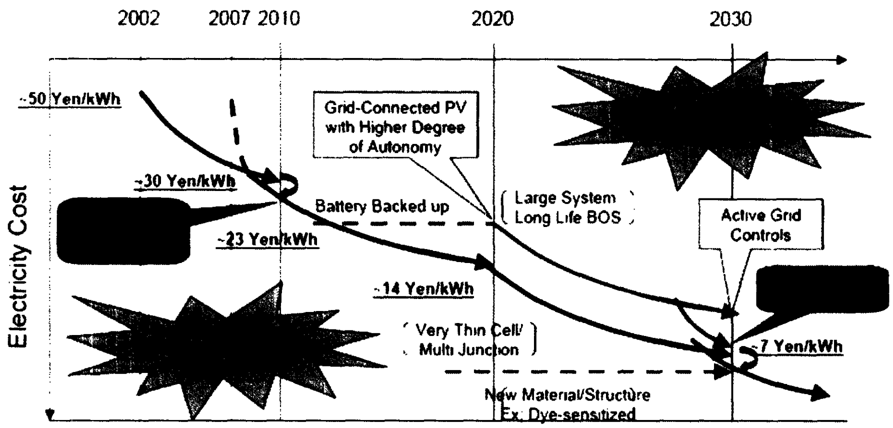
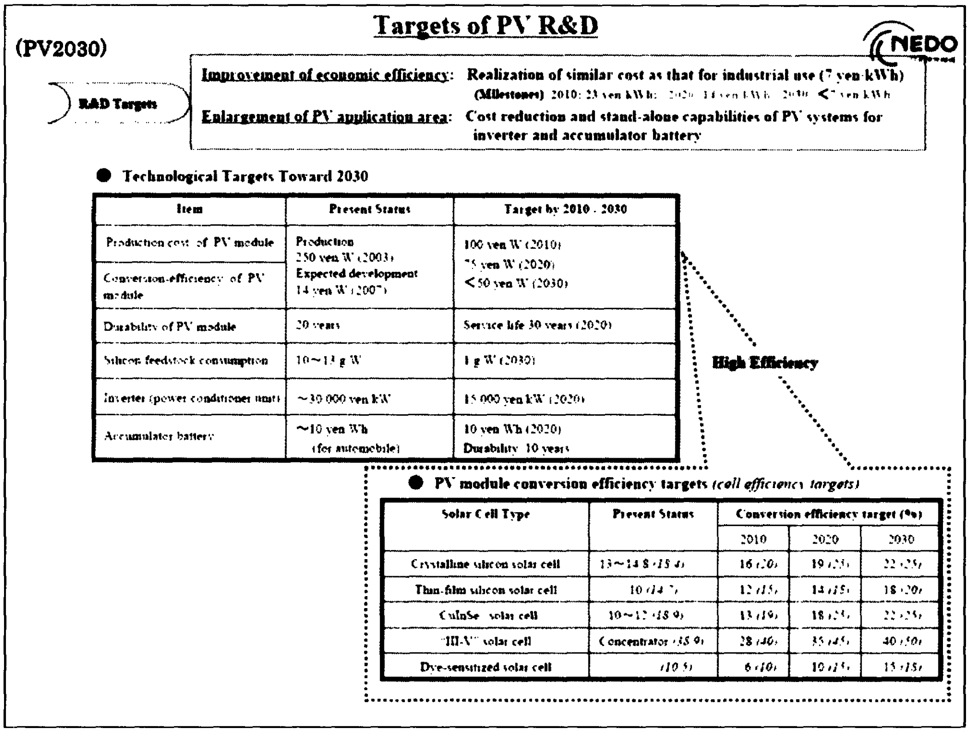


Fig. 27. Japan's PV roadmap and system price goals to 2030. The goal is for 4.8 GW PV installed by 2010 and 83 GW by 2030.

Source: Foster (2005). Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

FIGURE 48: Example of ongoing roadmapping efforts (circa 2005)



Item	Present Status	Target by 2010 - 2030
Production cost of PV module Conversion-efficiency of PV module	Production 250 yen W (2003) Expected development 14 yen W (2007)	100 yen W (2010) 75 yen W (2020) <50 yen W (2030)
Durability of PV module	20 years	Service life 30 years (2020)
Silicon feedstock consumption	10~13 g W	1 g W (2030)
Inverter (power conditioner unit)	~30 000 yen kW	15 000 yen kW (2020)
Accumulator battery	~10 yen Wh (for automobile)	10 yen Wh (2020) Durability 10 years

Solar Cell Type	Present Status	Conversion efficiency target (%)		
		2010	2020	2030
Crystalline silicon solar cell	13~14.8 (15.4)	16 (20)	19 (25)	22 (25)
Thin-film silicon solar cell	10 (14.7)	12 (15)	14 (15)	18 (20)
CuInSe solar cell	10~12 (18.9)	13 (19)	18 (25)	22 (25)
"III-V" solar cell	Concentrator (35.9)	28 (40)	35 (45)	40 (50)
Dye-sensitized solar cell	(10.5)	6 (10)	10 (15)	15 (15)

Source: NEDO. Note: This graphic has been copied directly from the source in order to provide the reader of this thesis with a direct replica of how this type of information is presented by Japanese authors in the literature. Similar charts appear in Japanese in both the literature and in confidential corporate documents obtained during interview/research process. The blurriness of the graphic is due to replication. Please see source for clearer image.

While this section has highlighted some of the impressive achievements of Japan's solar power sector during the period 1994 to 2003, it certainly falls short of detailing *exactly* what the Japanese did to enable the rapid growth of their solar power sector. One of the preliminary conclusions drawn from analysis of available information is that the role of coordination and roadmapping was particularly important to the rapid expansion of Japan's solar power sector. Further research should focus on more detailed descriptions of the organizations, people and processes involved in coordinating/roadmapping Japan's solar power sector. This is perhaps the most important area for further research. In addition, several other open questions remain, including:

- What influence did the industrial structure of Japan's utilities and electronics sector have on the evolution of its solar power sector?
- What are more precise measures of demand elasticity for solar power?

- Why did Sharp expand solar power manufacturing capacity so much faster than other companies in Japan's solar power sector?

In conclusion, Japan's solar power sector grew rapidly from 1994 to 2003. On the demand-side, installations increased 32-fold during the period. On the supply-side, production expanded 22-fold during the period. In terms of prices, gross system prices declined by 70% despite decreasing per-watt incentives during the period. The rapid expansion of installations (+47% CAGR), rapid expansion of production (+22% CAGR) and rapid decrease in gross system prices (-12% CAGR) appears to have been enabled by a combination of Japanese government policies that included grid connection policies, demand-side policies, supply-side policies and coordination policies.

- SECTION 4 -

CASE STUDY: U.S. SOLAR POWER SECTOR 1994-2003

Section 4

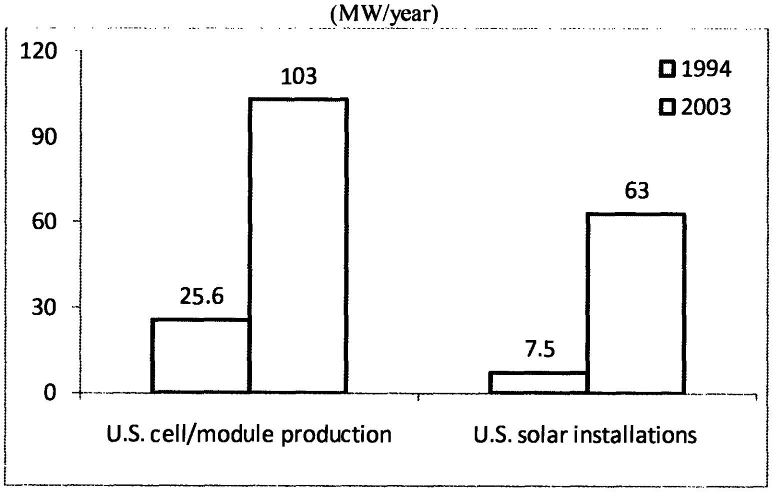
Case study: U.S. solar power sector 1994-2003

(A) Introduction

During the years 1994 to 2003, the development path of the U.S. solar power was both similar to and dissimilar from the development of Japan's solar power sector in the same period. On the surface, the solar power sector exhibited strong growth in production, strong growth in installations and strong price declines in both countries. From a supply-perspective, U.S. solar/cell module production increased 4-fold, from 26MW in 1994 to 103MW in 2003.[168] From a demand-perspective, U.S. solar power installations increased 8-fold, from 8MW in 1994 to 63MW in 2003.[169] This equates to 17% compound annual growth in U.S. production, 27% compound annual growth in U.S. installations. In terms of price, the gross price of solar power systems declined by 40%, from $12/watt in 1994 to $7/watt in 2003.[170] This equates to a 5% compound annual decrease in price. The patterns observed in the U.S. and presented in FIGURE 49 (U.S. solar cell/module production and U.S. solar power installations) and FIGURE 50 (gross system price in the U.S. over this period) are similar in direction to those observed in Japan (i.e. production up, installations up, price down).

FIGURE 49: U.S. solar cell/module production and U.S. solar power installations

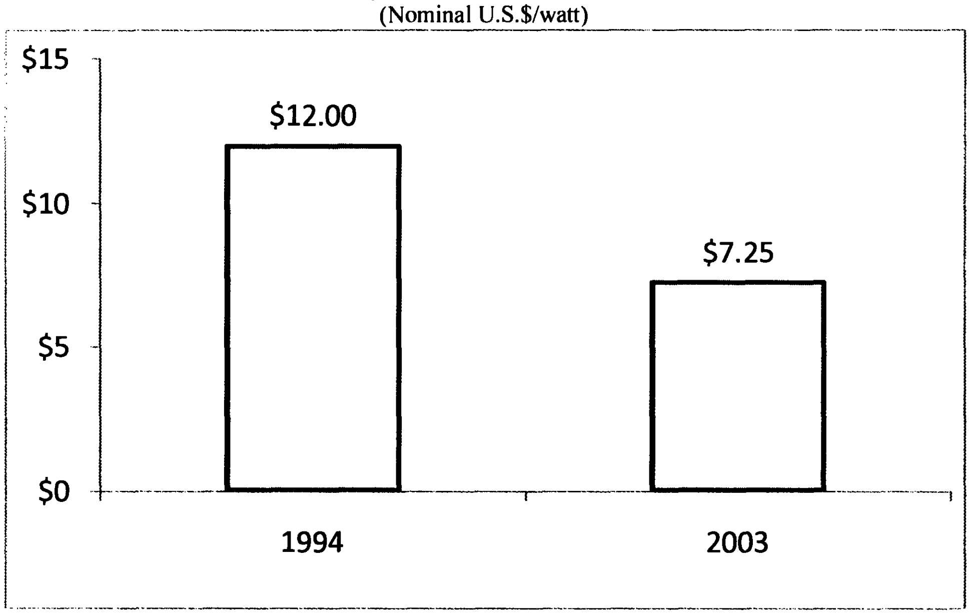
(MW/year)



Source: Maycock (2004) for production, IEA PVPS (2004) for installations

168 Maycock (2004)
169 IEA PVPS (2004)
170 IEA PVPS (2004)

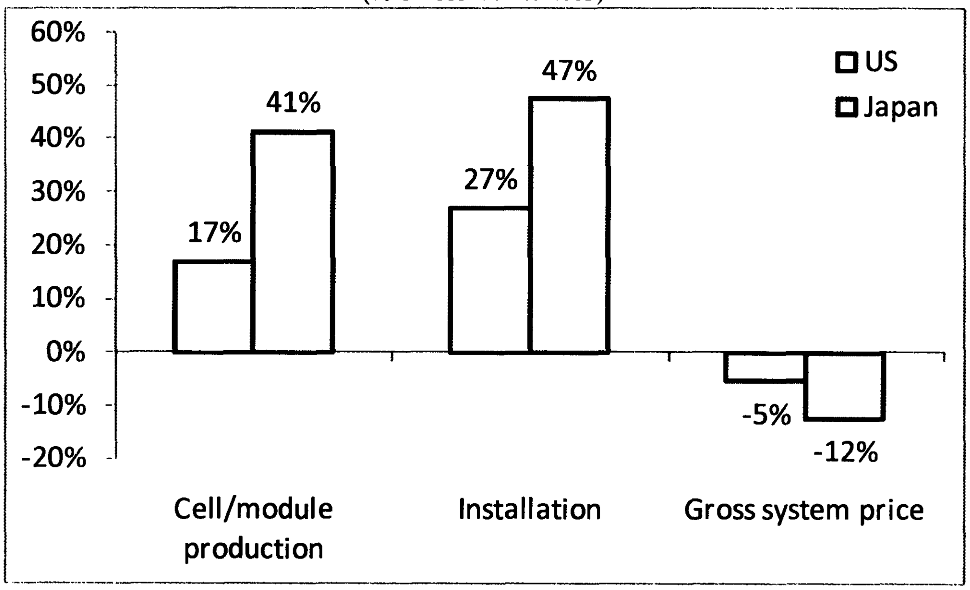
FIGURE 50: Typical U.S. solar system gross price
(Nominal U.S.$/watt)



Source: IEA PVPS (2004)

Yet, despite the directional similarity, the pace of change in the U.S. was significantly slower than in Japan in terms of production growth rate, installation growth rate and price decrease. Whereas Japanese solar cell/module production grew at a 41% CAGR from 1994 to 2003, the U.S. only grew at a 17% CAGR. Whereas Japanese solar power installations grew at a 47% CAGR, the U.S. only grew at a 27% CAGR. Whereas Japanese gross solar power system prices declined at a 12% CAGR, prices in the U.S. declined at only a 5% CAGR (albeit from a lower starting point). FIGURE 51 presents the compound annual growth rates for production, installations and prices in the U.S. and Japan during the years 1994 to 2003.

FIGURE 51: Compound annual growth rates for production, installations and price
(% CAGR 1994 to 2003)

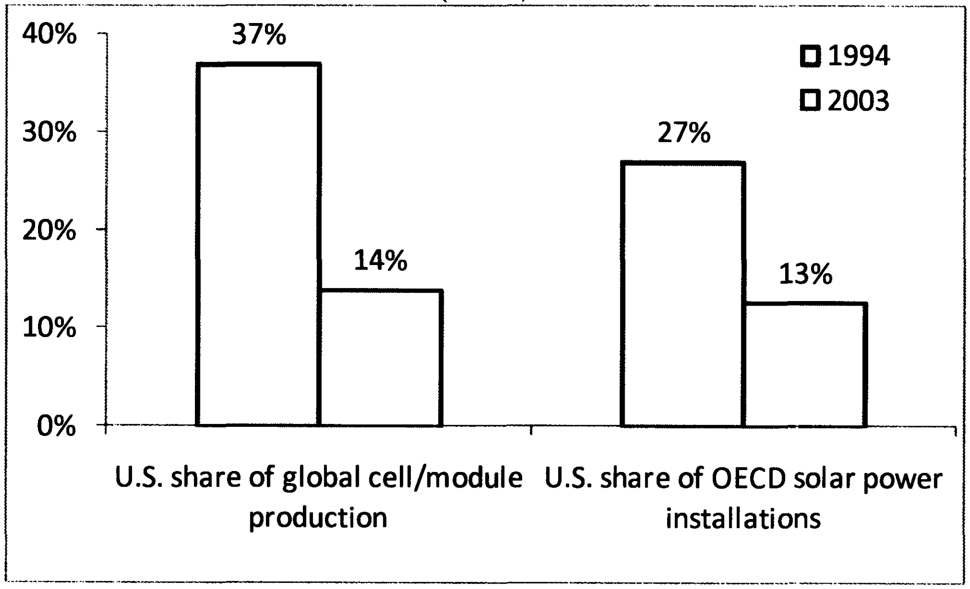


Source: Maycock (2004). IEA PVPS

From a global perspective, during this period Japan overtook the U.S. as the world's largest solar power producer and solar power market. U.S. cell/module manufacturers had 37% global market share in 1994 and U.S. end-customers accounted for 27% of OECD annual installations. By 2003, the picture had changed, with the U.S. share of annual OECD installations was down to 13% (half its 1994 level), the U.S. share of global cell/module production was down to 14% (less than half its 1994 level) and the U.S. was no longer the world leading producer of solar power components or installer of solar power systems. In contrast, Japan increased global share of cell/module production (24% in 1993 to 49% in 2003), increased share of OECD installations (20% in 1994 to 45% in 2003) and saw price declines that were much stronger than in the U.S. (12% compound annual decrease in Japan compared to 5% in the U.S.).[171]

[171] Production estimates based on Maycock (2004). Installation estimates based on IEA PVPS (2004)

FIGURE 52: U.S. share of global solar cell/module production & of OECD solar power installations
(Percent)



Source: Maycock (2004), IEA PVPS (2004)

This contrast between, on one hand, strong solar power production growth installation growth and price decreases and, on the other hand, the strong decline in U.S. share of global supply and demand raises the questions, "What enabled such strong growth of the U.S. solar power sector from 1994 to 2003?" and also "What constrained growth of the U.S. solar power sector from 1994 to 2003?" This section attempts to provide a description of and explanation for the ambiguous growth of the U.S. solar power sector during the years 1994 to 2003. Throughout the section, there is attempt to highlight the role of policy within the U.S. solar power sector.

(B) Grid connection

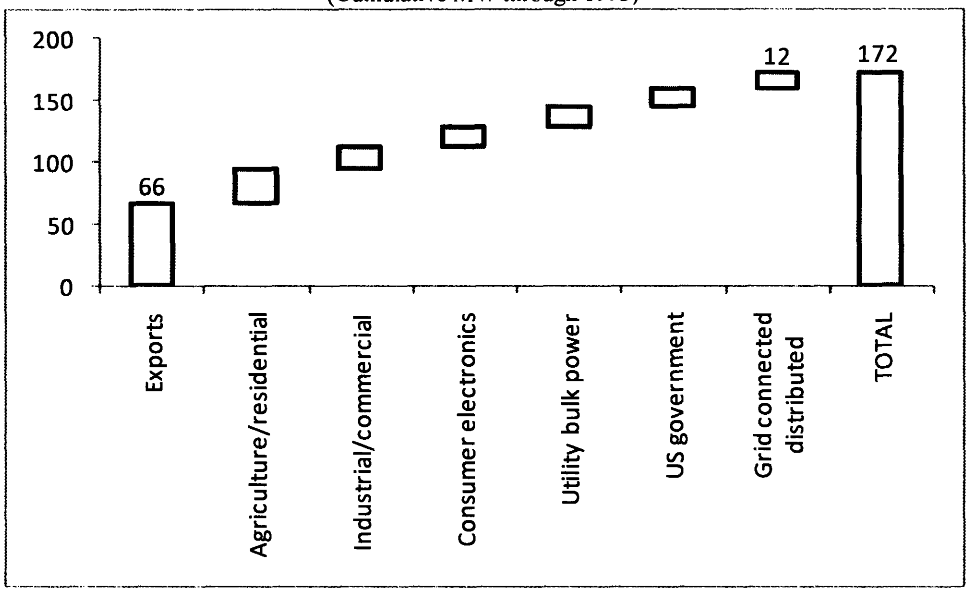
In the years leading up to 1994, the U.S. was the largest producer, installer and exporter of solar power systems. According to data from DOE, the cumulative U.S. solar power "market" through 1993 equaled 172 MW. Of this, about 38% of the market[172] was exports, with 66MW of cumulative exports through 1993. Within the domestic market, there were several small segments including agriculture/residential (16% of cumulative installations), industrial/commercial (10%), consumer electronics (9%), utilities (9%) U.S. government (9%) and grid-connected distributed (7%).[173] Overall, this was similar to Japan in that the market for

[172] Definition of "market" from DOE includes exports.

[173] Data from IEA PVPS shows slightly different volumes of cumulative installations by segment, but the overall point that grid-connected distributed solar power in the U.S. were small through 1993 is clear from the IEA PVPS data as well. According to the IEA PVPS data, grid-cumulative connected distributed systems amounted to 7MW by 1993, compared to 12MW reported in the DOE data.

small-scale grid-connected systems was very small and the bulk of the cumulative solar power installations were driven by test programs, small-scale non-grid connected systems and/or government installations.[174]

FIGURE 53: Cumulative solar power market applications in U.S. as of end-1993
(Cumulative MW through 1993)



Source: DOE; AGORES

However, there were two important differences. First, the U.S. industry viewed the market globally and saw *exports* as a key part of its market by 1994. This can be seen in the large size of exports relative to domestic market applications above in FIGURE 53. Second, this was different from Japan in that there was more significant experience with small-scale grid-connected systems in the U.S. prior to 1994. Through 1993, there were roughly 12MW of small-scale grid-connected systems in the U.S. This included 2MW of installations in 1990, 2MW in 1991 and 2MW in 1992.[175] In 1993, there were no reported small-scale installations.[176] Detailed information on these small-scale systems is not available in the literature, however interviews

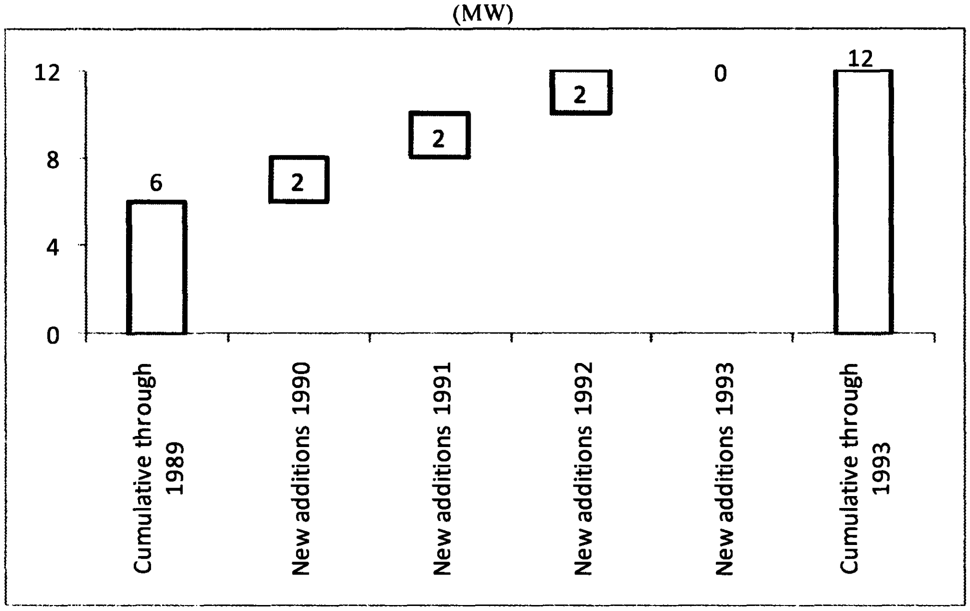
[174] DOE. Also, a more detailed description is provided by Ramakumar and Bigger (1993): "In 1988, there were 219-PV systems identified with a total installed capacity of 11 MW connected to utility systems [12]. Their size distribution is shown in Fig. 5, in which the largest plants appear according to segment size rather than total plant size. All these had been installed in the 1978-1988 period. Most installations over 5 kW are associated with federal, state, or utility demonstration projects. There are two significant exceptions, both privately financed: the 1 .O-MW (rated) Hesperia-Lugo project installed in 1982 and the 6.5-MW (rated) Carrisa Plains project installed in 1984; both in California. The operating performance and experience with most of the larger installations have been documented well in the literature [13]-[23]. Hesperia-Lugo: In 1982, a 1 MW single crystal silicon PV plant was installed in the Mojave desert area of Southern California near the town of Hesperia, 160 km east of Los Angeles. This system was privately financed and built by ARCO Solar Inc. The flat-plate modules are mounted on 108 two-axis trackers and have a total may area of 10 275."

[175] Phone and email interviews January-February 2007. One interviewee indicated, "The decade 1984 to 1994 was the golden era of grid connection in the U.S. Most of what we know now has its roots in that decade."

[176] Estimates of installations from AGORES

with solar power industry executives suggest that the there was a noteworthy base of experience with two types of customers: (1) individual homeowners with strong passion for environmental issues/solar power who received one-off approvals from their local electricity provider to connect their system; (2) test cases of small-scale solar power installations organized by existing utilities for residential/commercial installations.[177]

FIGURE 54: Small-scale grid-connected distributed applications in US
(MW)



Source: DOE; AGORES

Prior to 1994, these small-scale grid-connected systems were largely one-off installations or small test programs for which systematic grid connection and net metering rules did not exist in a format similar to Japan. In the U.S., electricity policy was largely seen as a state's jurisdiction. Rules to allow net metering at a retail price would have been set at the state-level. Net metering would have been a departure from the "avoided cost" rate (typically closer to the wholesale rate) that would otherwise be paid to such generators under interconnection rules for qualifying facilities dictated under the original federal PURPA law in 1978 that mandated local utility interconnections for non-utility generators.[178] Unlike Japan, where a systematic, nationwide approach was taken to system connection and net-metering rules, these rules were much more of a local-level patchwork that evolved in different ways at different paces for different geographies.[179]

[177] Phone and email interviews January-February 2007.
[178] http://en.wikipedia.org/wiki/Public_Utility_Regulatory_Policies_Act
[179] Phone interviews January-February 2007.

In 1996, the state of California became the first large area in the U.S. to allow net metering for solar power systems at the same rate electricity was purchased from the utility (i.e. not at "avoided cost").[180] The California net metering rule took effect under California Public Utility Code §2827 in 1996. This required all utilities to allow connections of up to 1 MW for solar power systems, and capped each utility's cumulative net metering requirement at 0.25% of the utility's aggregate peak customer demand.[181] Other states, including New York and PJM[182] moved in a manner similar to California, but the U.S. remained a patchwork of net metering rules even today.

In addition to net metering rules, the State of California also initiated in the late 1990s a process to simplify grid connection of distributed energy systems, including solar power. In 1999, the state rulemaking process formally commenced and in 2000 the California Public Utilities Commission (CPUC) developed "Rule 21." This created streamlined rules and interconnection processes for installations of systems under 10kW, and automatically qualified these systems for both net metering as well as "simplified interconnection" standards. Systems from 10 kW to 1 MW were subject to varying degrees of interconnection scrutiny, dependent upon their passage through an initial set of screens and reviews with the local utility. If a formal interconnection study were required as the outcome of this process, then these costs were determined by the utility and borne by the system owner. This and subsequent rules significantly streamlined the grid-connection process.[183] FIGURE 55 provides an overview of the application approval process.

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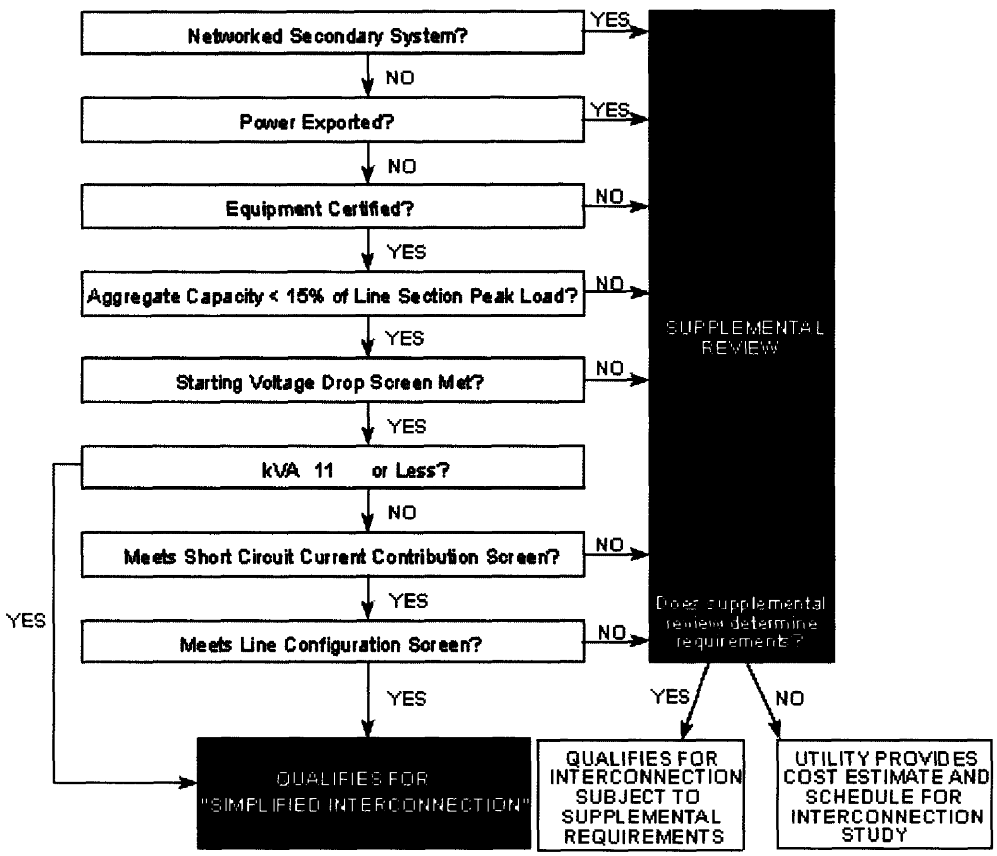
[180] Phone interview with NREL. Note: Regions in the Northeast were also pursuing standards at this time, including New York and PJM (Pennsylvania, New Jersey, Maryland).

[181] California Public Utility Code §2827

[182] Pennsylvania, New Jersey, Maryland.

[183] California Distributed Energy Resource Guide (updated regularly) from the California Energy Commission (www.energy.ca.gov/distgen/interconnection/application.html). California Distributed Energy Resource Guide for Rule 21: www.energy.ca.gov/distgen/interconnection/california_requirements.html. California interconnection standards: www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=CA21R&state=CA&CurrentPageID=1&RE=1&EE=1.

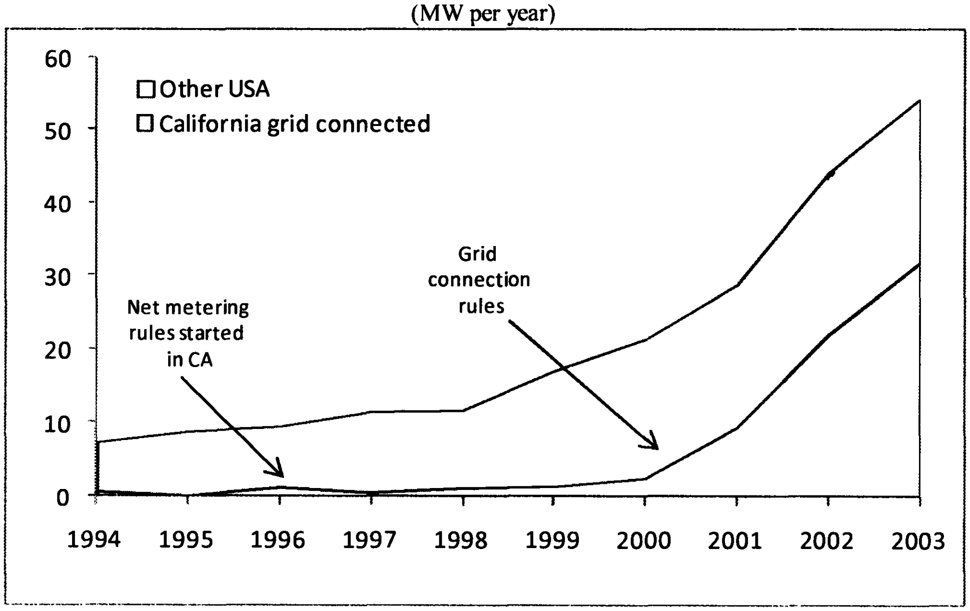
FIGURE 55: California's initial review process for applications to interconnect DER devices



Source: http://www.energy.ca.gov/distgen/interconnection/application.html

The Japan case in the previous section highlighted that grid connection and net metering rules may be a necessary but not sufficient condition for rapid growth of solar power installations. This appears to be confirmed by the California experience. California was the first market within the U.S. to establish simplified grid connection and net metering rules for solar power. With formal adoption of "Rule 21" in December 2000, the state had both net metering and grid connection rules for solar power systems. From 2001, solar power installations expanded very quickly in California. As seen in FIGURE 56, from 2001, the Californian market was the key driver of growth for the overall U.S. market in 2001, 2002 and 2003. While there were other factors (e.g. increasing California's per-watt buy-back incentive) that likely influenced the rapid expansion of installations in California, it appears that grid connection and net metering rules were a pre-condition for rapid expansion of installations in California as they appeared to have been in Japan.

FIGURE 56: U.S. solar power installations 1994 to 2003
(MW per year)



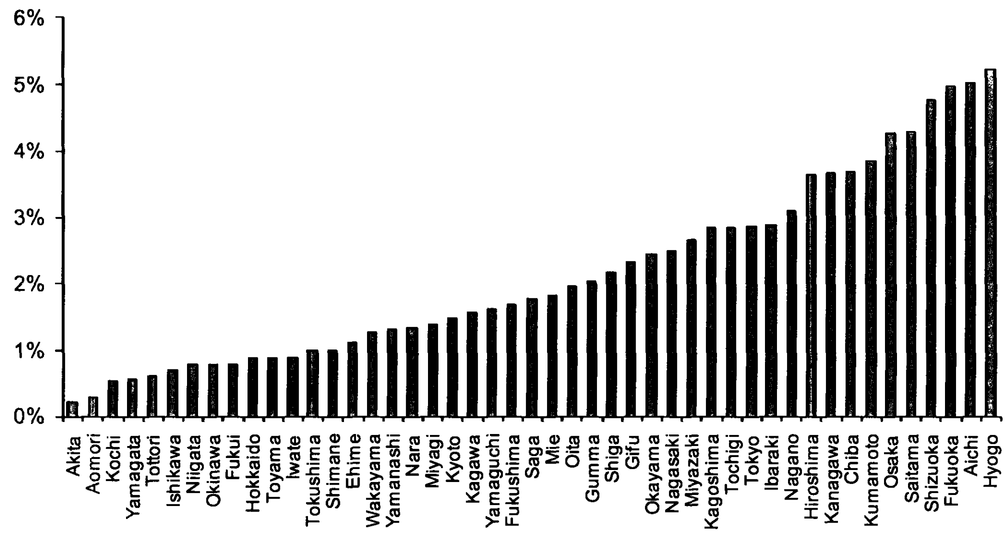
Source: IEA PVPS: http://www.energy.ca.gov/renewables/emerging_renewables/GRID-CONNECTED_PV.XLS;
Note: Assumes 80% DC to AC conversion efficiency.

In the period 2001 to 2003, several other states adopted grid-connection and net metering rules. These include New York, Texas, New Jersey, Pennsylvania and Maryland.[184] By the end of the period, the patchwork of grid connection and net metering policies in various states was a strong contrast to the consistent policies in place in Japan. This is one example of a potentially important difference between Japan and the U.S. In the case of grid connection and net metering policies, Japan was largely organized at a national level then adjusted or augmented at the local/regional level, but the U.S. was organized largely at the state or even local level. The homogeneity of Japanese grid connection/net metering policy may have been a factor that enabled a much broader geographic distribution of solar power installations. For example, by FY2004, installations in Japan were spread fairly evenly across the country (see FIGURE 57), with the largest prefectures having less than 6% of total Japanese installations.[185] In contrast,

[184] Phone interview with NREL.
[185] NEF

California dominated with the U.S. market by 2003, accounting for 51% of U.S. installations in 2003 (FIGURE 57).[186] The different pattern of grid connection rules (more homogeneous in Japan, more diverse in U.S.) and the different pattern of geographic installations (geographically diverse in Japan, geographically homogeneous in the U.S.) may be driven by dissimilar industry structures for the electric power industry in Japan and the U.S. This raises the question for additional research, "What impact did the structure of the electric power industry have on the evolution of the solar power sector in Japan and the U.S.?"

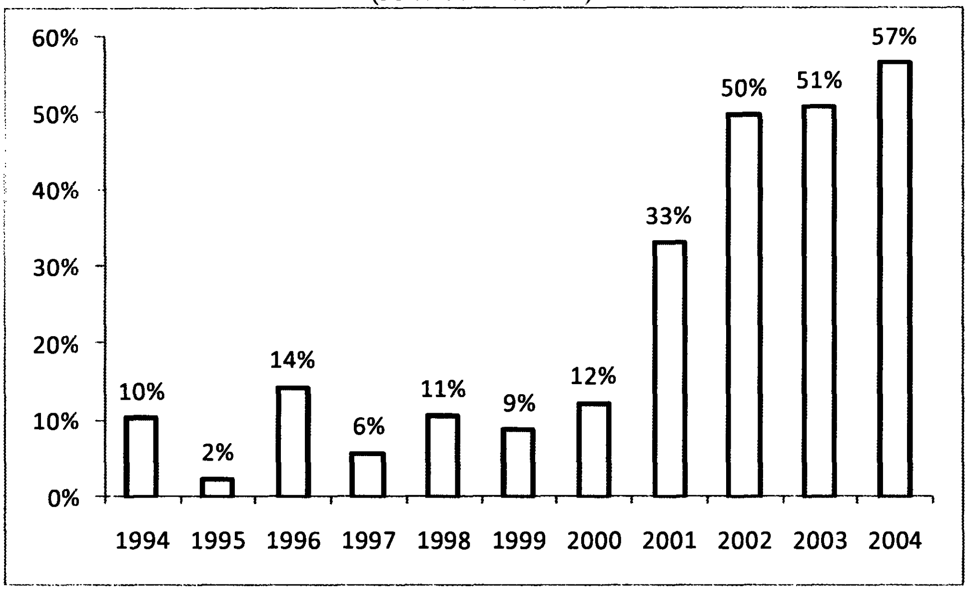
FIGURE 57: Japan solar power installations by prefecture
(MW installed in FY2004)



Source: NEF

[186] IEA PVPS (2004), Maycock (2004).

FIGURE 58: California as percentage of total U.S. installations
(Percent 1994 to 2003)



Source: IEA PVPS. Paul Maycock

(C) Demand

Installations of solar power in the U.S. during the period 1994 to 2003 can be divided into two categories: (1) grid-connected systems in California and (2) other. Breaking out grid-connected systems in California from other solar power segments in the U.S. is useful for several reasons, including:

- **Scale.** Grid-connected systems in California were the key driver of growth in the U.S. market during the period 1994 to 2003. Over this period, California account for 32% of all U.S. solar power installations and for 56% of the growth in solar power installations. As mentioned above, by 2003, California accounted for 51% of annual U.S. installations.[187]

- **Grid connected systems.** Growth of installations in California was driven by grid-connected systems. This was similar to the pattern in Japan, making it useful for comparison.

- **Data.** The non-Californian segments of U.S. demand were each small and only limited data are available on these segments. As a result, detailed analysis is more difficult.

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[187] CEC, IEA PVPS

- **Incentives.** The incentives established in California were similar to the per-watt buy-down program instituted in Japan under the New Sunshine Program. As a result, California is a useful comparison to better understand similarities and differences with Japan.

For these reasons, this sub-section focuses largely on grid-connected solar power installations in the California market.

Using the same process described in the Japan case (previous section), we estimated the end customer economics for grid-connected solar power systems in the California during the years 1994 to 2003. At the start of this period, gross system price in the California was roughly $12/watt, of which $4/watt was the module price and $8/watt was the non-module input price. By 2003, the gross system price declined by 40% to $7.25/watt as the result of a 25% decrease in module price and 47% decrease in non-module input price.[188] Over the same period, total incentives increased from no incentive in 1994 to $3.75/watt in 2003.[189] The result was that net system price decreased by 73%, from $12/watt in 1994 to $3.50/watt in 2003. This decrease in net system price equates to a negative 13% CAGR.

There were several differences in system prices between California and Japan during the years 1994 to 2003. (TABLE 19, TABLE 20, FIGURE 59). These differences include:

- **Module price:** The price for modules in Japan was higher than California for the entire period, with prices for modules in the U.S. of $4/watt in 1994 and $3/watt in 2003 compared to module prices in Japan of $9/watt in 1994 and $3.85/watt in 2003.[190]

- **Non-module input price:** The price for non-module inputs was much higher in Japan than in California at the start of the period, but declined to be lower than California by 2003. In 1994, the price of non-module inputs was $10.50/watt in Japan, 31% above the U.S. price of $8.00/watt. By 2003, the price in Japan had decreased to $2.10/watt, 50% lower than the California price of $4.25/watt.[191]

- **Incentives:** Japanese incentives for solar power were much higher than California incentives at the start of the period, but decreased to a level below California by 2003. In 1994, Japanese incentives were approximately $9/watt, while the California had no

[188] IEA PVPS (2004)
[189] Wiser et al (2006).
[190] IEA PVPS (2004), NEDO, Maycock (2004)
[191] IEA PVPS (2004), NEDO, Maycock (2004)

incentive. By 2003, Japanese incentives had declined to $1.18/watt, while the California incentives had increased to $3.75/watt.[192]

TABLE 19

California and Japan solar power system prices 1994 to 2003

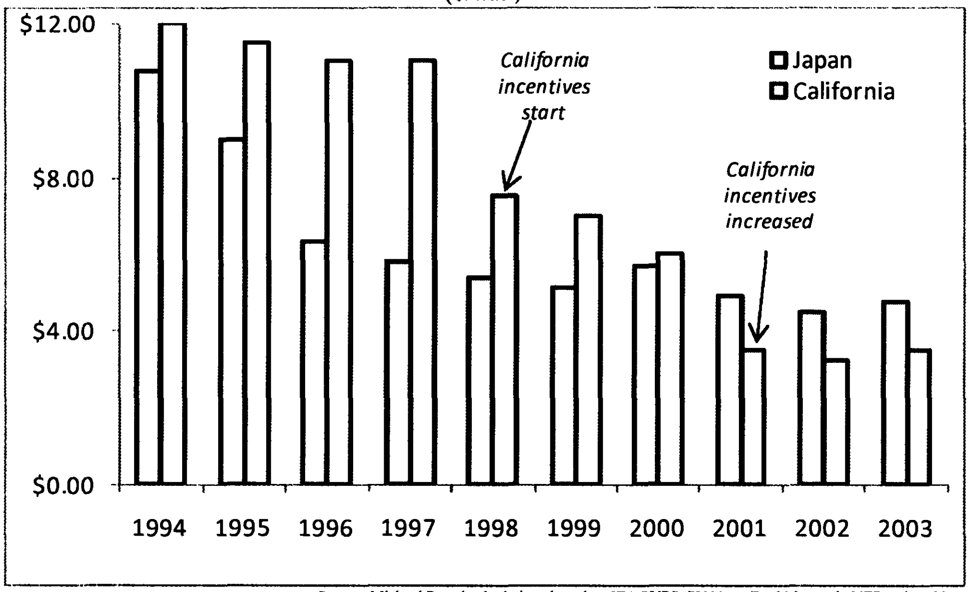
JAPAN	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Exchange rate (yen/US$)	102	94	109	121	131	114	108	122	125	116
Residential electricity price ($/kWh)	$0.25	$0.27	$0.23	$0.21	$0.19	$0.21	$0.21	$0.19	$0.17	$0.19
Residential electricity price (yen/kWh)	25.5	25.4	25.0	25.1	24.4	24.2	23.1	22.8	21.8	21.5
Gross system price ($/watt)	$19.57	$18.09	$11.03	$8.76	$8.17	$8.26	$7.83	$6.24	$5.67	$5.95
Gross system price (yen/watt)	2000	1700	1200	1060	1070	939	844	758	710	690
LGSP ($/kWh)	$1.23	$1.10	$0.65	$0.51	$0.46	$0.46	$0.45	$0.35	$0.32	$0.33
LGSP (yen/kWh)	126	103	71	62	60	52	49	43	40	38
Module price ($/watt)	$9.07	$8.37	$5.94	$5.42	$5.11	$5.28	$5.08	$3.98	$3.70	$3.83
Module price (yen/watt)	927	764	646	656	670	600	548	484	463	446
Non-module price ($/watt)	$10.50	$9.96	$5.09	$3.34	$3.05	$2.98	$2.75	$2.25	$1.97	$2.10
Non-module price (yen/watt)	1073	936	554	404	400	339	296	274	247	244
National incentives ($/watt)	$8.81	$9.05	$4.60	$2.81	$2.60	$2.90	$1.86	$0.99	$0.80	$0.78
National incentives (yen/watt)	900	850	500	340	340	330	200	120	100	90
Local incentives ($/watt)	$0.00	$0.05	$0.10	$0.15	$0.20	$0.25	$0.30	$0.35	$0.40	$0.40
Local incentives (yen/watt)	0	5	11	18	26	28	32	43	50	46
Total incentives ($/watt)	$8.81	$9.10	$4.70	$2.96	$2.80	$3.15	$2.16	$1.34	$1.20	$1.18
Total incentives (yen/watt)	900	855	511	358	366	358	232	163	150	136
Net system price ($/watt)	$10.77	$9.00	$6.34	$5.80	$5.37	$5.10	$5.67	$4.90	$4.47	$4.77
Net system price (yen/watt)	1,100	845	689	702	704	581	612	595	560	554
LNSP ($/kWh)	$0.70	$0.57	$0.39	$0.36	$0.32	$0.30	$0.34	$0.29	$0.26	$0.27
LNSP (yen/kWh)	72	54	42	44	42	34	37	35	33	31

CALIFORNIA	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Residential electricity price ($/kWh)	$0.117	$0.116	$0.119	$0.119	$0.110	$0.109	$0.113	$0.123	$0.126	$0.128
Gross system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$10.50	$10.00	$9.00	$8.00	$7.75	$7.25
LGSP ($/kWh)	$0.85	$0.84	$0.79	$0.79	$0.71	$0.69	$0.65	$0.54	$0.50	$0.44
Module price ($/watt)	$4.00	$4.00	$4.00	$4.15	$4.00	$3.50	$3.75	$3.50	$3.25	$3.00
Non-module price ($/watt)	$8.00	$7.50	$7.00	$6.85	$6.50	$6.50	$5.25	$4.50	$4.50	$4.25
National incentives ($/watt)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Local incentives ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Total incentives ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Net system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$7.50	$7.00	$6.00	$3.50	$3.25	$3.50
LNSP ($/kWh)	$0.85	$0.84	$0.79	$0.79	$0.52	$0.49	$0.44	$0.25	$0.23	$0.23

Source: Michael Rogol calculations based on IEA PVPS, PV News/Paul Maycock, NEDO data. Note: Preliminary.

[192] NEDO, IEA PVPS (2004), Wiser et al (2006).

FIGURE 59: California and Japan net system prices 1994 to 2003
($/watt)



Source: Michael Rogol calculations based on IEA PVPS, PV News/Paul Maycock, NEDO data. Note: Preliminary.

TABLE 20: Price change and CAGR in Japan and U.S. 1994 to 2003
(%)

CALIFORNIA	Change 1994-2003	CAGR 1994-2003
Module price	-25%	-3%
Non-module price	-47%	-7%
Gross system price	-40%	-5%
Total incentive	N/A	N/A
Net system price	-71%	-13%
JAPAN	**Change 1994-2003**	**CAGR 1994-2003**
Module price	-58%	-9%
Non-module price	-52%	-8%
Gross system price	-70%	-12%
Total incentive	-87%	-20%
Net system price	-56%	-9%

Source: Michael Rogol calculations based on IEA PVPS, PV News/Paul Maycock, NEDO data. Note: Preliminary.

To estimate the levelized system price for solar power systems in the California, the model assumptions were adjusted to represent the California market. (TABLE 21) In comparison, there were two important macro-level differences between California and Japan. First, long-term residential interest rates in the U.S. were higher than interest rates in Japan. In Japan, interest rates ranged from 2.3% to 4% over the period 1994 to 2003. In comparison, interest rates in the

U.S. ranged from 5.8% to 7.9%, 3.5 to 5.2 percentage points higher than in Japan.[193] The higher interest rates increase levelized system price. Second, the solar resource (measured in watts/m^2/day) is typically 25% higher in the California, with 5.25 W/m^2/day in the U.S. compared to 4.25 W/m^2/day in Japan.[194] The higher solar resource effectively decreases the levelized system price.

TABLE 21: Assumptions used to estimate LSP for California 1994-2003

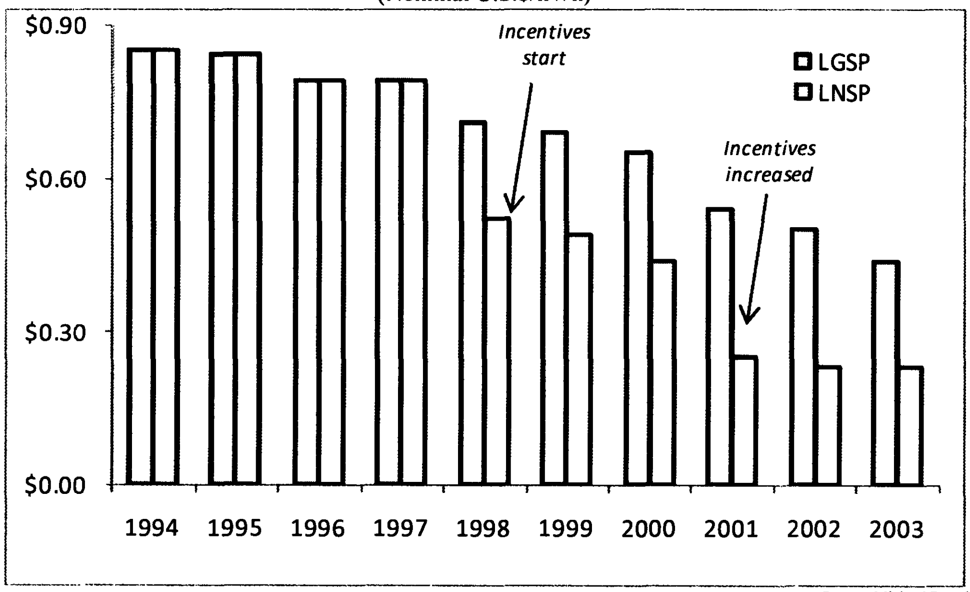
KEY ASSUMPTIONS	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Installation size (kW DC)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Gross system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$10.50	$10.00	$9.00	$8.00	$7.75	$7.25
National incentive ($/watt)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Local incentive ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Total incentive ($/watt)	$0.00	$0.00	$0.00	$0.00	$3.00	$3.00	$3.00	$4.50	$4.50	$3.75
Net system price ($/watt)	$12.00	$11.50	$11.00	$11.00	$7.50	$7.00	$6.00	$3.50	$3.25	$3.50
System lifetime (years)	25	25	25	25	25	25	25	25	25	25
Inverter replacement price ($/watt)	$0.50	$0.48	$0.45	$0.43	$0.41	$0.39	$0.37	$0.35	$0.33	$0.32
Inverter replacement frequency (years)	6.0	6.4	6.7	7.1	7.6	8.0	8.5	9.0	9.6	10.1
Annual O&M (% installed price)	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
Solar resource (kW/m^2/day)	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
AC conversion factor (%)	71%	72%	73%	74%	75%	76%	77%	78%	79%	80%
Annual output degradation (%)	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Residential electricity price ($/watt)	$0.12	$0.12	$0.12	$0.12	$0.11	$0.11	$0.11	$0.12	$0.13	$0.13
Electricity price inflation for DCF forecast (%)	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Nominal interest rate (%)	7.5%	7.8%	7.7%	7.7%	7.1%	7.3%	7.9%	7.0%	6.5%	5.8%
LEVELIZED SYSTEM PRICE	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Levelized gross system price ($/kWh)	$0.85	$0.84	$0.79	$0.79	$0.71	$0.69	$0.65	$0.54	$0.50	$0.44
Levelized net system price ($/kWh)	$0.85	$0.84	$0.79	$0.79	$0.52	$0.49	$0.44	$0.25	$0.23	$0.23

Note: Preliminary.

The levelized system price in California decreased significantly during this period. The levelized gross system price declined from $0.85/kWh in 1994 to $0.44/kWh in 2003, equating to a negative 7% CAGR. The levelized net system price decline even faster, decreasing from $0.85/kWh in 1994 to $0.23/kWh in 2003. This equated to a negative 14% CAGR. In comparison, the LNSP was lower in Japan for the years 1994 to 2000, but was higher in Japan for the years 2001 to 2003. This change of California's LNSP below Japan's LNSP was driven largely by the rising level of per-watt incentives in California during a period when per-watt incentives in Japan were declining.

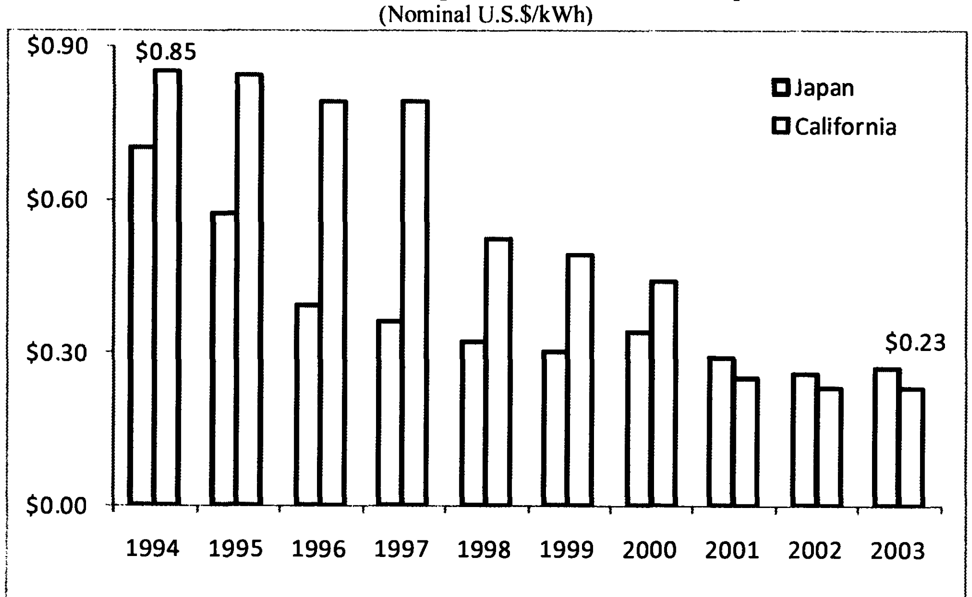
193 CLSA
194 PVWatts

FIGURE 60: Levelized gross and net system price in California 1994 to 2003
(Nominal U.S.$/kWh)



Source: Michael Rogol calculations.

FIGURE 61: Levelized net system price in California and Japan 1994 to 2003
(Nominal U.S.$/kWh)



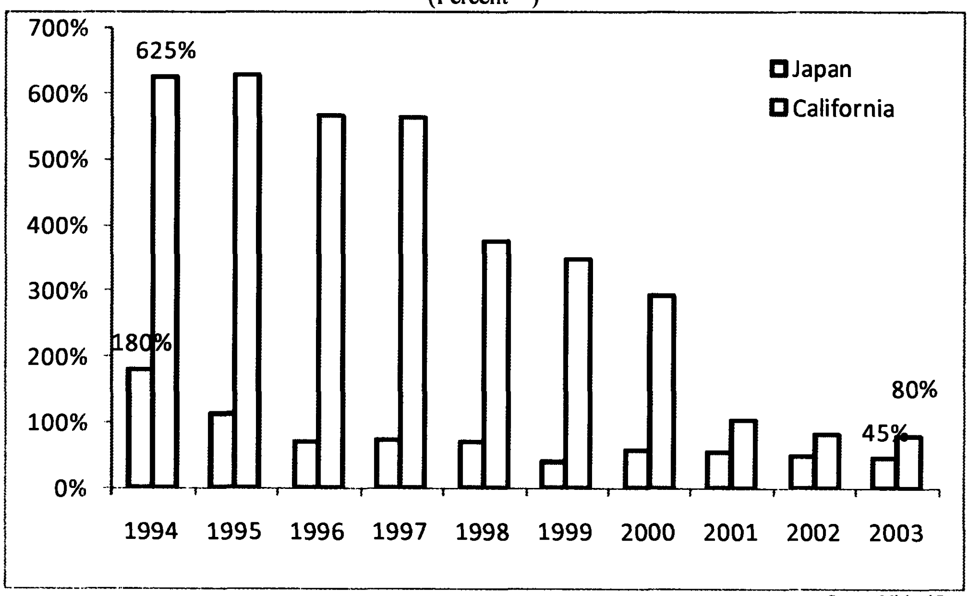
Source: Michael Rogol calculations.

In California, both the "solar premium" and the "solar gap" decreased significantly during the years 1994 to 2003.[195] The "solar premium" declined from 625% in 1994 to 80% in 2003 and the "solar gap" decreased from $0.73/kWh in 1994 to $0.10/kWh in 2003. In comparison, the "solar

[195] Again, "solar premium" is (LNSP/grid price -1) and "solar gap" is (LNSP – grid price).

premium" in Japan was lower throughout the entire period, with a premium of 180% in 1994 declining to 45% in 2003. It is worth noting that while the "solar premium" decreased in both countries, it fell much faster in the California than in Japan during this period, especially in 2001. It is also important to mention that one driver of declining California "solar gap" and "solar premium" was rising average residential grid prices in California. From 1994 to 2003, average residential grid prices increased roughly 9%, from $0.117/kWh to $0.128/kWh.[196] Finally, it is worth noting that the "solar gap" remained much wider in the California than in Japan from 1994 to 2000, but then was roughly equivalent in the two markets from 2001 to 2003.

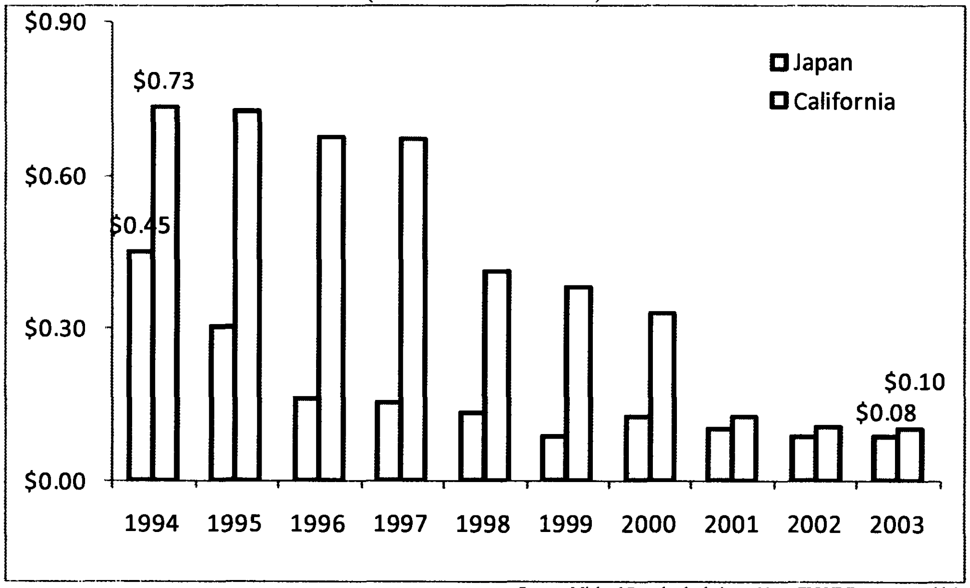
FIGURE 62: "Solar premium" in California and Japan 1994 to 2003
(Percent[197])



Source: Michael Rogol calculation.

[196] U.S. EIA
[197] LNSP/grid price - 1

FIGURE 63: "Solar gap" in California and Japan 1994 to 2003
(Nominal U.S.$/kWh[198])

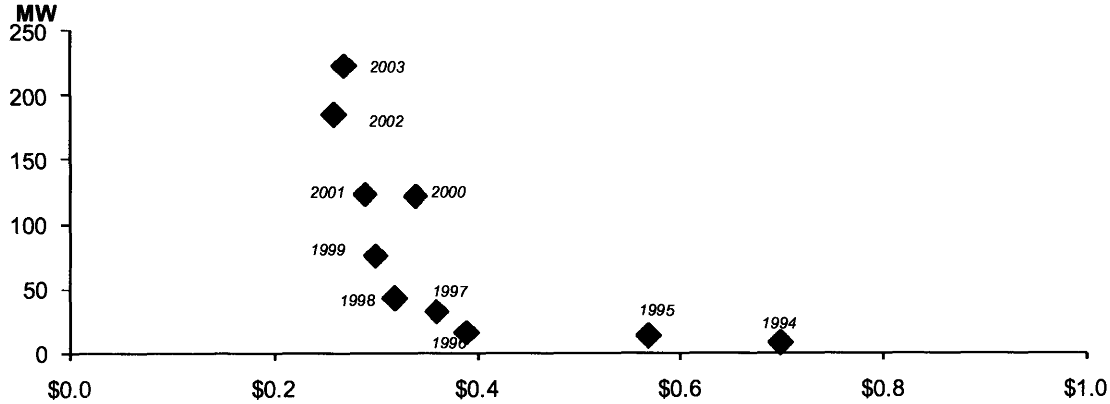


Source: Michael Rogol calculations.. Note: FIGUREs may not add due to rounding.

There are several similarities between the economics of solar power for end-customers in the U.S. and Japan. These similarities include a significant reduction in solar module price, solar system prices, LGSP, LNSP and "gap" in both markets over the years 1994 to 2003. Perhaps the most striking similarity is the pattern of adoption observed in FIGURE 64 and FIGURE 65, which present annual installations of solar power (y-axis) compared to levelized net system price (x-axis) for the years 1994 to 2003. In FIGURE 64, installations in Japan "tip" from around 1997, with a significant increase in elasticity of demand (i.e. change in volume/change in price) increasing significantly after the LNSP drops below ~$0.35/kWh. In FIGURE 65, installations in California "tip" from 2001, with a significant increase in elasticity of demand after LNSP drops below $0.25/kWh.

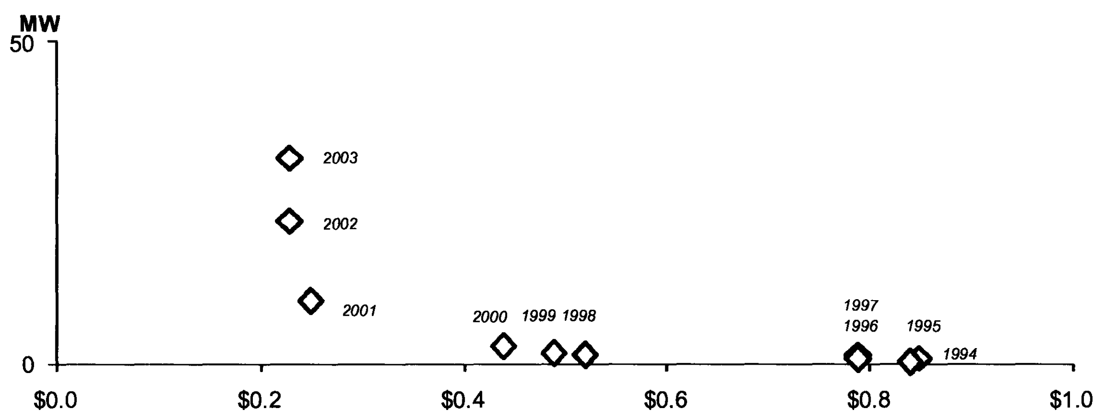
[198] LNSP minus grid price

FIGURE 64: Installations and LNSP in Japan 1994 to 2003
(MW per year of installations (y-axis) and nominal U.S.$/kWh LNSP[199] (x-axis))



Source: Michael Rogol calculations.

FIGURE 65: Installations and LNSP in California 1994 to 2003
(MW per year of installations (y-axis) and nominal U.S.$/kWh LNSP[200] (x-axis))



Source: Michael Rogol calculations.

That both markets exhibit this "tip" makes intuitive sense because the price of solar power for the end customer (as represented by the LNSP) was approaching parity with *average* grid price in both markets. As LNSP approached *average* grid price, solar power became economically competitive with grid prices. All other things equal (i.e. same sunlight, same interest rate), the economic competitiveness of solar power occurred for customers with *higher than average* grid prices in each markets, which is likely why the "tip" occurred prior to LNSP reaching *average*

[199] LNSP minus grid price
[200] LNSP minus grid price

grid price.[201] That both markets exhibit this "tip" at different price points also makes intuitive sense because the substitute price for solar power (i.e. the price of grid based electricity) was different in Japan and California. As a result, it makes sense that the "tip" in Japan occurred at an LNSP that was higher than California because grid prices in Japan were higher than grid prices in California. But even using *average* grid prices provides strong preliminary evidence that in Japan and in California followed a similar pattern. In addition to the clear similarities in FIGURE 64 and FIGURE 65 above, the installation growth rates of the two markets were quite similar during the period 1994 to 2003 (47% CAGR in Japan compared to 51% CAGR in California) and the elasticities of demand were also quite similar (-2.8 "gap" elasticity in Japan compared to -2.6 in California).

TABLE 22: Estimate of demand elasticity in Japan and California 1994 to 2003

	Price change 1994-2003 (CAGR %)	Installation growth 1994-2003 (CARG %)	Elasticity (Change in installation/ change in price)
Japan gross system price	-12%	47%	-3.8
Japan net system price	-9%	47%	-5.5
Japan levelized net system price	-10%	47%	-4.7
Japan "gap" of LNSP minus grid price	-17%	47%	-2.8
	Price change 1994-2003 (CAGR %)	**Installation growth 1994-2003 (CARG %)**	**Elasticity (Change in installation/ change in price)**
California gross system price	-5%	51%	-9.4
California net system price	-13%	51%	-4.0
California levelized net system price	-14%	51%	-3.8
California "gap" of LNSP minus grid price	-20%	51%	-2.6

Source: Michael Rogol calculations.

In terms of policies, there were also several similarities between California demand-side policies and those in Japan. For example: both California and Japan used per-watt "buy-down" incentives that reduced the net system price for end-customers; both California and Japan demonstrated multi-year funding of their respective buy-down programs; and managers of both the California and Japan incentive program management teams oversaw significant data collection, organized significant data dissemination and made small adjustments of per-watt incentives (i.e. fairly precise manipulation of the per-watt incentives). While there are striking similarities between the

[201] An area for further research would be to investigate the relationship between the distribution of grid prices (i.e. location, price and volume of electricity consumption) and the adoption of solar power. For the purpose of this thesis, average grid prices were used as a simplifying assumption.

demand-side in Japan and the demand-side in California for solar power during the years 1994 to 2003, there were also several clear differences. These differences include:

- **Regional not national.** As highlighted above, the growth of solar power installations in Japan was distributed nation-wide, while U.S. installation growth was largely contained to California.

- **Scale.** During the decade 1994 to 2003, Japan installed a total of 835MW of solar power systems, while California installed only 72MW.[202] As a result, the Japanese market was an order-of-magnitude larger than the California market during the period of this case study.

- **Timing.** For the Japanese market, 1997 was the most noteworthy growth year with installations doubling from 16MW in 1996 to 32MW in 1997. For California, the most noteworthy growth was recorded in 2001, with the market more than tripling from 3MW in 2000 to 10MW in 2001.[203] Also, strong demand-side incentives were instituted in Japan from 1994, while they started in California in 1998. As such, the California market appears to have lagged the Japanese market by approximately 4 years.[204]

One other important difference between Japan and the U.S. was the role of exports. As highlighted earlier in this sub-section, exports had a much larger role in the U.S. solar power sector. The topic of exports is addressed in the next sub-section on supply.

(D) Supply

The preceding sub-section focused on solar power from a demand (end-customer) perspective. This sub-section focuses on the economics of solar power from a supply (manufacturer) perspective, and provides a comparison between the supply-side economics for solar power manufacturers in the U.S. compared to Japan. This sub-section includes:

(i) Economics of the U.S. solar power supply chain
(ii) Expansion of the U.S. supply chain 1994 to 2003

Whereas the previous sub-section on demand highlighted many similarities (albeit with some differences) in the dynamics of the demand-side in the U.S. (specifically California) and Japan,

202 IEA PVPS (2004)
203 IEA PVPS (2004), CEC.
204 Taking "scale" and "timing" together points to the view that California was quite similar to Japan but with a lag of 4 years.

one key point from this sub-section is that the supply-side dynamics were quite different (albeit with some similarities) in Japan and the U.S. during the years 1994 to 2003.

(i) Economics of the U.S. solar power supply chain[205]

During the years 1994 to 2003, the economics of solar power manufacturing in the U.S. quite different than in Japan. In particular, lower grid prices, lower module prices in the U.S. and higher interest rates in the U.S. made expansion of solar power manufacturing using traditional crystalline silicon technology for sale to U.S. end-customers economically unattractive (negative NPV and long time to reach parity with grid price). This led to (a) a stronger focus on exports to higher price module markets and (b) pursuit of alternative technologies with potential for "radical innovation" in the sense suggested by Arrow.[206]

By 1994, solar power manufacturers in the United States were familiar with the cost reductions achieved through learning and scale. During the period 1975 to 1993, U.S. solar cell/module manufacturing increased from 0.3MW to 22.4, equal to a 28% compound annual growth rate.[207] Over the same time period, the typical price of modules decreased from roughly $35/watt to roughly $3.00/watt, equal to roughly negative 8% compound annual rate.[208] Similar to Japan, estimates by academics, consultants and businesses in the U.S. suggested an experience curve with prices declining by 20% for every cumulative doubling of output.[209]

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[205] Note: This section focuses on U.S. solar power supply at a national level. In the previous subsection on demand, California had been the focus because solar installations in California were the dominant driver of growth for the overall U.S. market from 1994 to 2003. On the supply-side (this subsection), no similar geographic concentration existed. The solar power supply chain in the U.S. involved producers from a broad number of geographic regions. As a result, this subsection focus on the overall U.S. solar power supply picture, not on California.

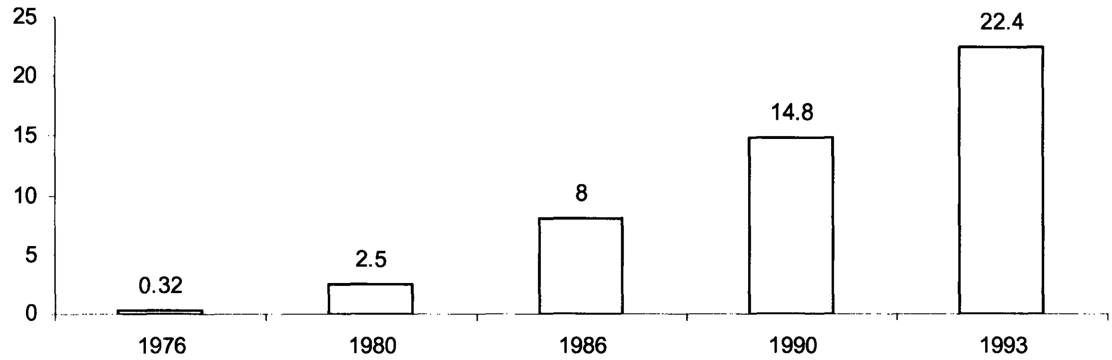
[206] See Henderson (1993) for description of difference between innovations that are incremental versus radical in an economic sense.

[207] Maycock (2004)

[208] Maycock (2004)

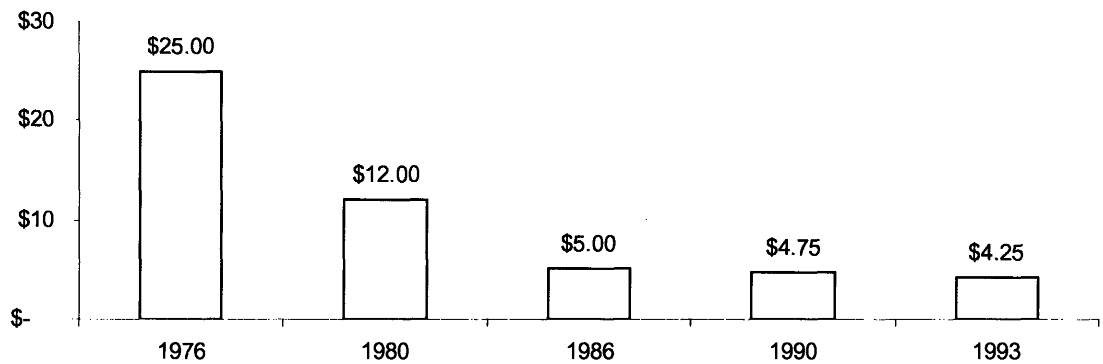
[209] Margolis (2002a)

FIGURE 66: U.S. cell/module production
(Megawatt/year)



Source: Paul Maycock; PV News

FIGURE 67: Typical module price in U.S.
(Nominal U.S.$ per watt)



Source: Paul Maycock; PV News.

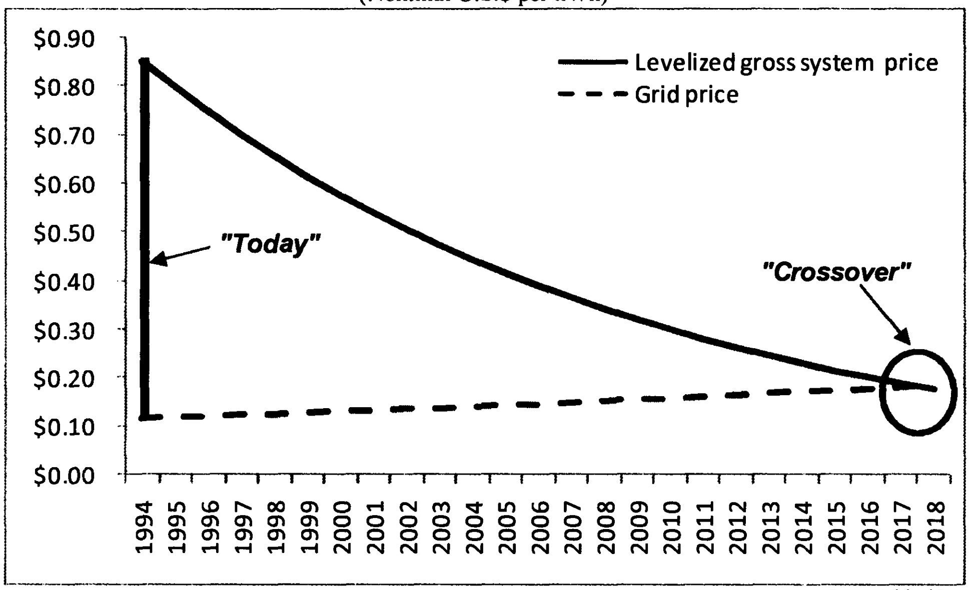
While the trends of higher production volume and lower prices were similar to Japan, one important difference between the economics facing solar power manufacturers in Japan and the U.S.: grid prices were substantially lower in the U.S. than in Japan. As a result, the "solar gap" was higher and the time to grid parity longer.[210] From the perspective of the start of 1994, grid parity would not occur for 24 years (2018), assuming cumulative doubling every 2 years, a 20% learning curve and 2% annual grid price increases. By the start of 1997, grid parity had moved a

[210] For purposes of this mental exercise, average residential grid prices in California were used because California was the largest solar power installation market in the U.S. from 1994 to 2003. However, California's grid prices were significantly above the national average, meaning that a true apples-to-apples comparison of Japanese LGSP versus Japanese average residential grid price with U.S. LGSP versus U.S. average residential grid price would have put "time to parity" even further into the future for the U.S.

three years further into the future (2021), a strong contrast to the situation in Japan, where grid parity had moved closer from the start of 1994 (+19 years) to the start of 1997 (+9 years). By the start of 2004, grid parity in the U.S. still appeared far off, with expected parity 14 years in the future (2018). For U.S. manufactures, this was 14 years in the future, compared to 6 years in the future in Japan. In short, grid parity looked further off at the start, middle and end of the period than it did in Japan.[211]

FIGURE 68: In 1994, LGSP vs grid parity under scenario of doubling cumulative production volume every three years, 20% experience curve and 2% annual increase in grid price

(Nominal U.S.$ per kWh)

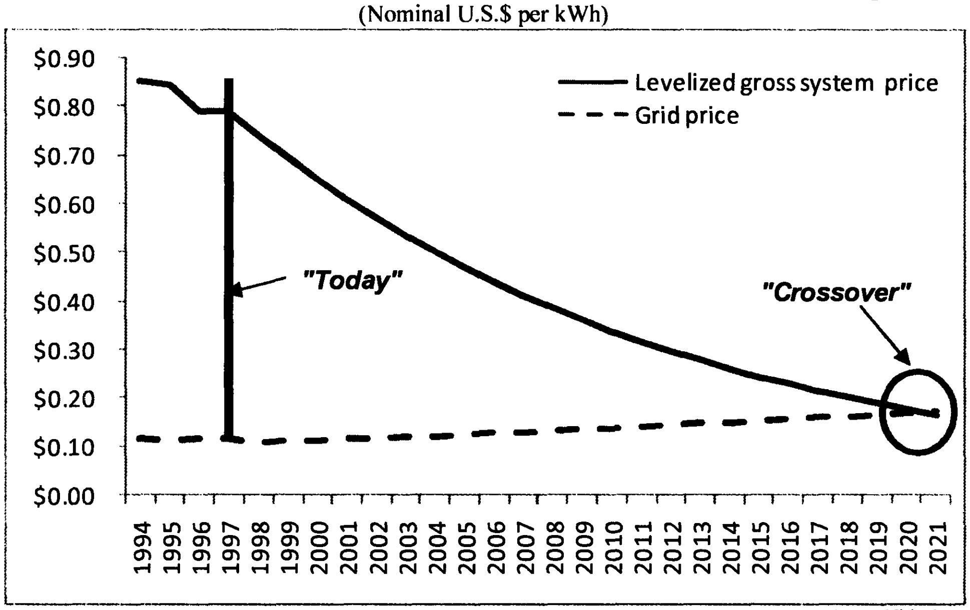


Source: Michael Rogol calculation.

[211] In a previous draft, Professor Henderson commented, "Implies (a) no spillovers from Japan and (b) don't understand learning curve." In response, the key difference between the U.S. and the Japanese perspective on grid parity was (i) lower grid price in U.S. and (b) higher interest rate in U.S. The combination of these two factors account for most of the difference in perceived time-to-parity between U.S. and Japan.

FIGURE 69: In 1997, LGSP vs grid parity under scenario of doubling cumulative production volume every three years, 20% experience curve and 2% annual increase in grid price

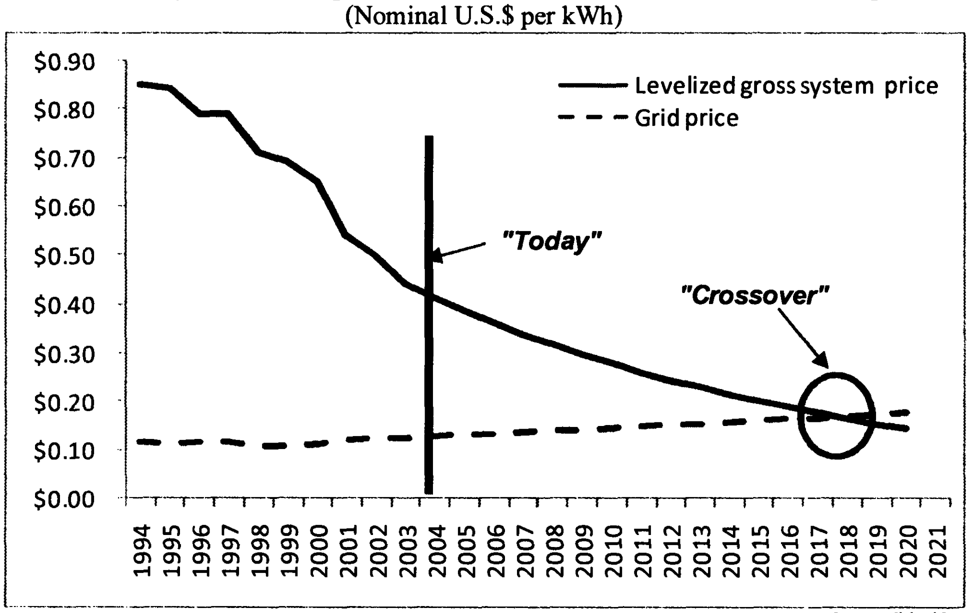
(Nominal U.S.$ per kWh)



Source: Michael Rogol calculation

FIGURE 70: In 2003, LGSP vs grid parity under scenario of doubling cumulative production volume every three years, 20% experience curve and 2% annual increase in grid price

(Nominal U.S.$ per kWh)



Source: Michael Rogol calculation

The economics facing solar power companies in the U.S. trying to sell to U.S. customers were also unattractive when evaluated using a net present value framework. As a rough estimate, the net present value of a $72mn investment in a combined 100MW cell/module facility in 1994 with operations starting in 1994 would have had a NPV of roughly negative $122mn under the following assumptions:

- Capex of $0.72/watt all expended at beginning of 1994
- No production in 1994
- Full production 1995 through 1999
- Manufacturing debottlenecking and creep of 2% per year from 1996
- Silicon usage of 18 grams/watt
- Silicon price of $40/kg
- Fully loaded ingot/wafer manufacturing cost of $1.17/watt
- 10% pre-tax profit margin for wafer maker
- Cell/module manufacturing costs of $2.16/watt excluding equipment and excluding the price of the wafer
- Module price of $4.00 per watt in 1994
- Annual module price decline of 5% per year
- Equipment lifetime of 5 years with no residual value or cost at end of lifetime
- 30% tax rate
- 5% corporate discount rate

It is important to emphasize that this negative NPV resulted despite a cost structure for the solar supply chain in the U.S. that was more than 20% lower than in Japan[212], expectations of module price reductions of only 5% annually compared to an 8% CAGR historically and a discount rate of 5% that would likely have been too low for many U.S. solar power companies because they were smaller firms that likely had higher costs of capital.[213]

(ii) Expansion of the U.S. supply chain 1994 to 2003

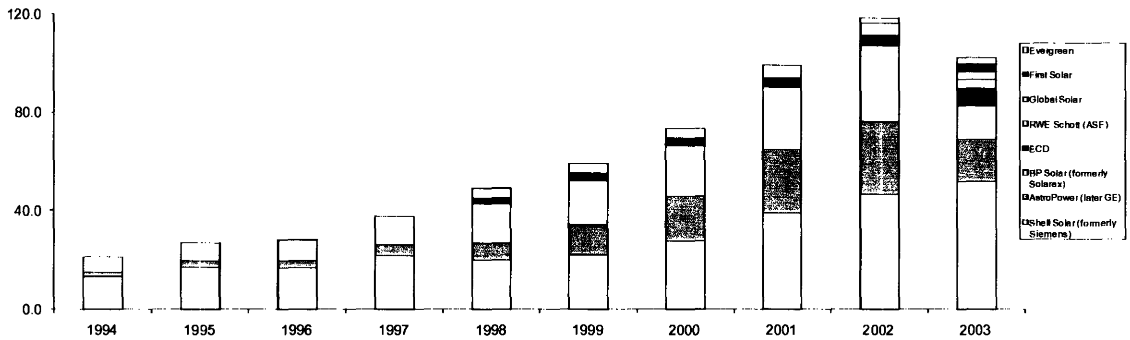
There were four main implications of the less attractive economics in the U.S. First, U.S. production growth was significantly slower than in Japan because the perceived economic payoff was lower for U.S. firms selling to U.S. customers. From 1994 to 2003, U.S. production increased from 26MW to 103MW, equaling a 17% CAGR, a growth rate that was less than half

[212] U.S. had lower cost structure due to larger manufacturing scale and larger volume cumulative experience.

[213] This NPV estimate does not take into account the opportunity for U.S. solar manufacturers to export. With higher prices in many international markets such as Japan and Germany, the economics of production in the U.S. for sale to non-U.S. markets was more attractive than the NPV estimate made in this subsection. The reason for not including exports within the NPV calculation is that there is no consistent data on the price of solar power exports from the U.S. Interviews suggested a broad range of prices for exports. As a result, including exports in the NPV estimate would require a guess without deep justification on the average price of exports.

Japan's growth rate.[214] At a corporate level, expansion plans were a strong contrast to the consistent, rapid growth in Japan. For example, a significant portion of corporate-level production growth was driven by acquisitions. For example, BP Solar acquired Solarex in 1995 and Shell acquired Siemens Solar in 2002.[215] These acquisitions enabled the acquiring companies to be among the largest U.S. solar power players. In contrast, the growth of the largest Japanese players was almost completely organic through internal expansion of production capacity. The topic of industry structure in the U.S. (small firms and energy companies) compared to Japan (larger firms from the electronics sector) is an area for additional research.

FIGURE 71: U.S. solar cell/module production by company
(MW per year)



Source: Maycock/PV News.

Second, because the "time to parity" was much longer and the NPV of traditional crystalline silicon technologies for domestic sales was negative, companies in the U.S. tended to have a much stronger focus on radical innovation, in the sense suggested by Arrow.[216] This pursuit of innovations that had potential to significantly lower costs was a contrast with Japan, where the strong focus was on incremental innovation. The difference was seen in Japanese companies scaling-up the more reliable crystalline silicon technologies, whereas many U.S. companies pursued alternative technologies such as amorphous silicon (e.g. Energy Conversion Devices), CdTe (e.g. First Solar) and CIS/CIGS (e.g. Shell Solar).[217] This difference had significant implications: interviewees stressed that the failure of thin film technologies to meet expectations was a core reason for Arco/Siemens Solar and Amoco Solar/Enron Solar to exit the solar business.

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[214] Maycock (2004)
[215] Maycock (1995) and Maycock (2002)
[216] Henderson, R. "Underinvestment and Incompetence as responses to radical innovation: evidence from the photolithographic alignment industry", RAND Journal of Economics opg 248-270 Vol 24 Summer 1993.
[217] Press clippings, Maycock, PV News.

The focus on radical innovation in the U.S. was supported by government policy. Whereas total solar power spending (RDD&D) by the Japanese national government exceeded that of the U.S. federal government every year 1994 to 2002, the U.S. spent more on R&D than Japan in 1994, 1995, 1996 and 1997, and also spent a higher proportion of its R&D budget on radical technologies than the Japanese.[218] More details on U.S. government priorities and spending are provided later in this section.

The U.S. focus on radical innovation came through clearly during interviews with U.S. solar power executives, technologists and policy makers. During interviews in the U.S., there were often comments on potential for "breakthroughs," "big wins," "homeruns," and "game changing technologies."[219] Interviewees often focused their comments on companies pursuing non-crystalline silicon technologies (e.g. Konarka, First Solar, Energy Conversion Devices), and downplayed the long-term potential of crystalline silicon players like BP, Shell, Evergreen and AstroPower (later GE). In contrast, Japanese interviewees tended to focus their comments on companies such as Kyocera and Sharp whose main solar activities were crystalline silicon.

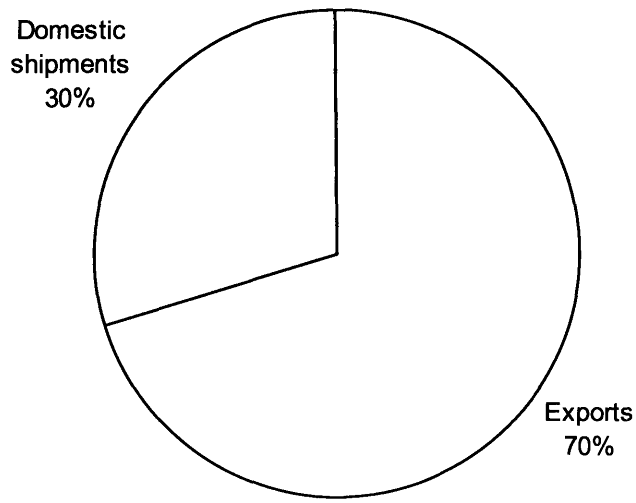
Third, as discussed in more detail in subsequent sections, it should be noted in trying to explain the slower growth rate of solar power manufacturing in the U.S. compared to Japan that the U.S. was a less predictable, more inconsistent environment for solar power companies. For example, the level of R&D funding was less consistent in the U.S. than in Japan during this period, with a higher standard deviation in federal R&D funding in Japan compared the U.S.[220]

Given the long "time to parity" in the U.S. and lack of policy support to reduce the "gap" between LGSP and grid price, it is somewhat surprising that U.S. manufacturers grew as fast as they did. This growth was driven largely by a fourth factor: exports to international markets. Prices for cells/modules in international markets tended to be higher than in the U.S., driven by a combination of higher incentives and lower interest rates. As a result, during the years 1994 to 1999, exports accounted for roughly 70% of total U.S. cell/module production. (FIGURE 72)

[218] IEA PVPS, NEDO, NREL, Interviews.
[219] Interviews.
[220] Calculation based on IEA PVPS data.

Following the introduction of California's incentive program, however, the role of domestic shipments increased from 30% of U.S. production during 1994-1999 to 45% in 2003.[221]

FIGURE 72: Shipments of U.S. cell/module production 1994 to 1999
(Percent)



Source: U.S. EIA

Overall, there was a strong contrast between Japanese and U.S. solar power supply in the period 1994 to 2003. This contrast includes:

- Lower gross prices for solar power modules and systems in the U.S.;
- Lower grid prices in the U.S.;
- Higher interest rates in the U.S.;
- Longer "time to parity" in the U.S.;
- Lower (apparently negative) NPV for expanding solar power manufacturing in the U.S.;
- Stronger focus on exports among U.S. producers;
- Stronger focus on "radical" technology focus among U.S. producers;
- More acquisitions and failures in the U.S.;

[221] U.S. EIA

- Bigger role for traditional energy companies and start-ups (instead of electronics sector players) in the U.S; and
- Less stable government supply-side policies.

Beyond the description provided in this sub-section, there are areas for future research into the supply-side development of the solar power sector in the U.S. and how this compared to Japan. These areas includes further evaluating the importance of industry structure (including presence of leading big energy companies in U.S. versus big electronics companies in Japan and the presence of small, specialized solar distributors in the U.S. versus larger homebuilders/integrators in Japan), the role of foreign versus domestic players in the development of the solar power sector (i.e. foreign firms BP, RWE Schott and Shell played a significant role within the U.S. solar power sector) and the role of spillovers across companies (including between Japanese and U.S. firms).

(E) Coordination

The previous case study on Japan's solar power sector from 1994 to 2003 emphasized that coordination appears to have played an important role in the rapid development of the sector. In contrast, the U.S. lacked consistent coordination efforts both in the years leading up to 1994 and also during the years 1994 to 2003. This subsection provides:

(i) A brief overview of the U.S. coordination activities in the 1980s
(ii) An overview of U.S. coordination activities in the 1990s and early 2000s
(iii) Open questions

The key point made in this subsection is that U.S. coordination activities were on a smaller scale, and were less consistent than the coordination activities in Japan. This difference appears to have been important in enabling much faster growth of Japan's solar power sector compared to the U.S. solar power sector during the years 1994 to 2003.

(i) A brief overview of the U.S. coordination activities in the 1980s

At the start of the 1980s, the solar power sector in the U.S. was heavily influenced by government policies. These policies included: federal government purchases that accounted for roughly 25% of global solar power volume, more than $140 million per year in R&D spending including approximately 250 industry and university contracts in fiscal year 1980[222], federal tax credits for end-customer installations, and federal tax credits for manufacturing capacity expansions. At that time, U.S. government support for solar power far exceeded government support in Japan. For example, in 1981, the U.S. government spent roughly $140mn on solar power R&D compared to only $20mn in Japan. Also, the U.S. had demand-side incentives in the form of tax credits for installations of solar power systems whereas Japan did not have any significant demand-side programs.

However, during the mid- and late-1980s, the U.S. solar power sector had a choppy experience driven by changes in U.S. government policies. These changes included:

- A rapid decrease in federal government purchases starting in 1981;
- Expiration of consumer tax credits for installation of solar power systems in 1985; and
- Expiration of business tax credits for solar manufacturing capacity additions and R&D in 1985.

Margolis (2002) provides a summary of this period: "The National Photovoltaic Program budget was cut from $150 million in 1980, to $50 million in 1984, and $35 million in 1988. In constant dollars this was an 80% decline in the program's budget during the Reagan years. The impact of these cut-backs on the program was severe: entire sub-programs were terminated, research teams at industrial and national laboratories were disbanded or reduced to skeletal staffs, and experienced program managers at DOE were removed and replaced by people with limited qualifications and little experience to run the program effectively (Frankel 1986, 81). The Reagan Administration was particularly hostile towards applied R&D and D&C activities. Thus by the mid-1980s, roughly 80% of the program's budget was being allocated to advanced R&D on material properties of thin film and concentrator PV cells."[223] The decreasing government budgets and an increasing focus on longer-term R&D coincided with disruption in the growth of solar power manufacturing. For example, cells/modules production, which had increased steadily from 1974 to 1982, experienced a sharp decline in 1983, recovered slightly in 1984-85 and then dipped again in 1985-86.[224] In contrast to the declining supply-side spending in the U.S., government support for solar power R&D in Japan increased significantly over the same period.

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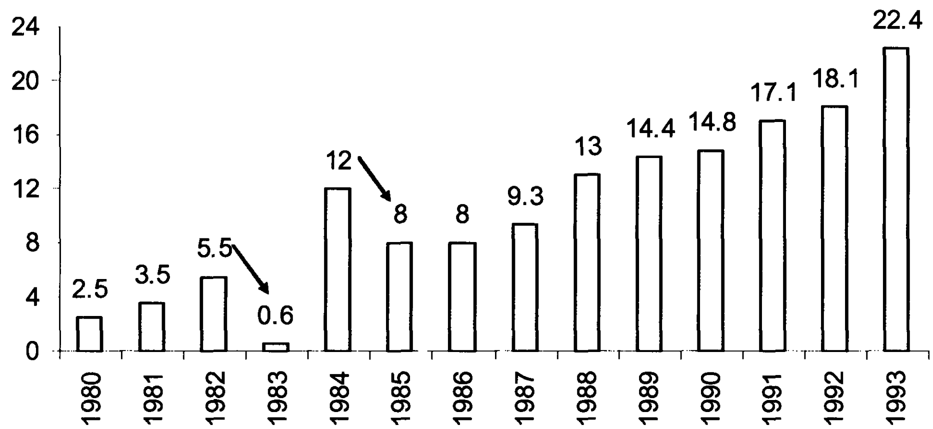
[222] Margolis (2002b)
[223] Margolis (2002b)
[224] Chiba (1996), Watanabe et al (2000), NEDO, IEA PVPS, US EIA.

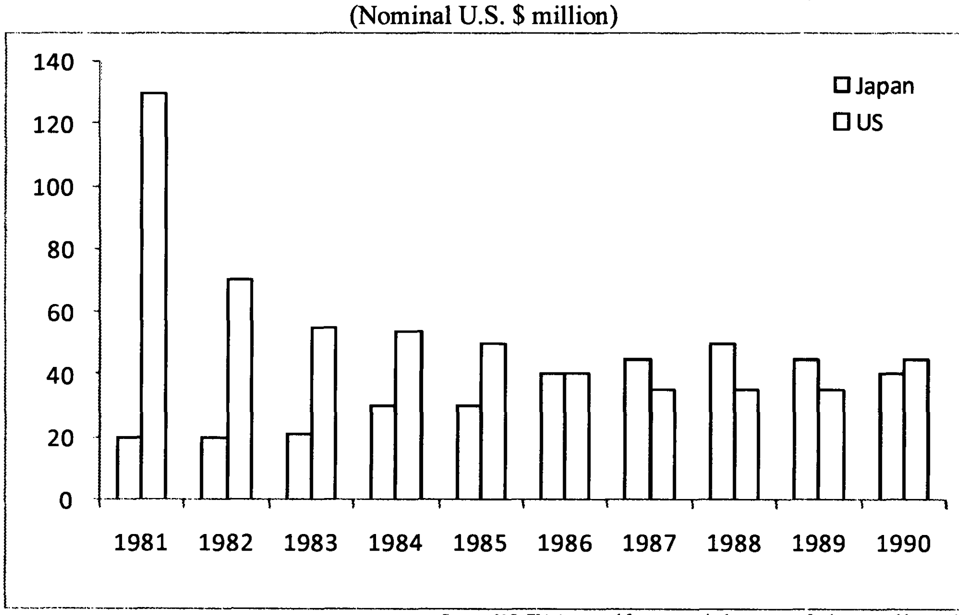
From 1981 to 1988, Japanese government R&D spending increased in nominal terms from roughly $20mn to roughly $50mn, with a lower portion of funding allocated to advanced R&D on material properties of novel photovoltaic technologies.[225]

FIGURE 73: Solar cell/module production U.S. 1980 to 1993
(MW/year production)



Source: PV News/ Paul Maycock

FIGURE 74: Government PV R&D budget in U.S., Japan and Germany 1981 to 1999
(Nominal U.S. $ million)

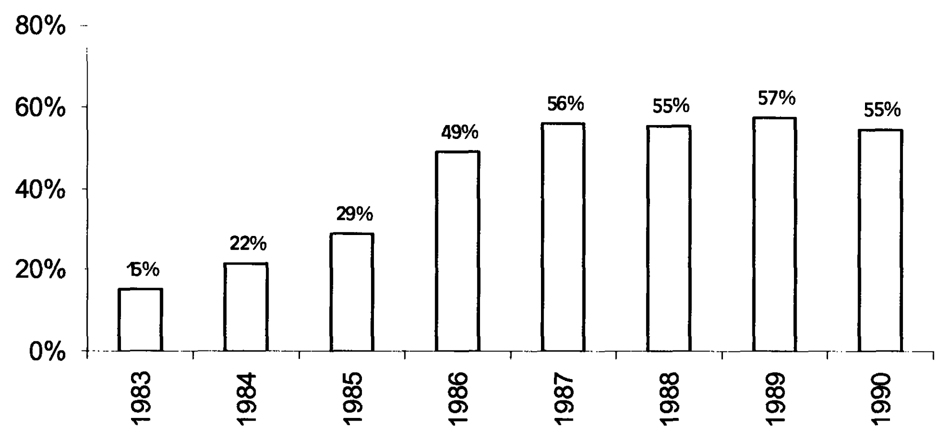


Source: U.S. EIA (recreated from www.eia.doe.gov/cneaf/solar.renewables/rea_isses/fig8s.html

[225] Chiba (1996), Watanabe et al (2000), NEDO, IEA PVPS, US EIA.

With only a small market for solar power products in the U.S, a rising portion of U.S. production was exported. From 1983 to 1990, the volume of U.S. solar power exports rose at a 22% CAGR from 1.9MW in 1983 to 7.5MW in 1990. Over the same period, the share of exports in total U.S. solar power shipments increased from 15% to 55%.[226] (FIGURE 75) It is worth noting that the small volume of solar power products that were purchased by customers in the U.S. was predominantly for applications such as telecommunications towers and remote non-grid-connected location, not for grid-connected rooftop systems.[227] Overall, the 1980s were a period of inconsistent policy with inconsistent production growth and limited expansion of the grid-connected domestic market. This was a contrast to Japan's solar power sector during the 1980s, during which policies appear to have been more consistent while production and installation growth were limited.

FIGURE 75: Exports as percent of total U.S. shipments 1983 to 1990
(Percent)



Source: U.S. EIA

(ii) An overview of U.S. coordination activities in the 1990s and early 2000s

In the early 1990s, U.S. government spending on solar power R&D increased. From 1988 to 1992, budgets for the National Photovoltaic Program under the Bush administration increased from $35 million to $51 million, with the focus of spending on applied R&D.[228] The higher level of government spending coincided with higher U.S. production, with output increasing by 72%

[226] US EIA.
[227] Maycock/PV News, U.S. EIA, Margolis (2002b)
[228] Maycock/PV News, U.S. EIA, Margolis (2002b)

from 1988 to 1993. Despite the increasing budgets and rising production, interviewees described the period before 1994 as "choppy," "inconsistent," "unreliable," and "always changing in unexpected ways."[229] The lack of clear direction and focus was dissimilar to Japan which, in the years before 1994, adopted high-level goals for solar power (400MW of cumulative installations by 2000, 4.6GW by 2010), instituted clear grid connection and net metering rules, and had fairly consistent government budgets for PV despite a slow domestic economy.

With the U.S. solar power sector losing global market share, many in the industry expressed frustration about inconsistent policy direction.[230] In the build-up to the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, U.S. government funding for solar power increased and a permanent 10% PV investment tax credit for businesses was instituted. Higher funding levels for solar power continued, with the federal budget for PV R&D increasing steadily from roughly $36mn in 1990 to roughly $84mn in 1997.[231]

The government support for solar power included coordinated industry-building efforts to identify both R&D priorities and potential roadblocks to the U.S. solar sector's growth. This detailed research to identify priorities and roadblocks was part of the Department of Energy's new Photovoltaic Manufacturing Technology (PVMaT) project. Initiated in 1991, PVMaT was intended to be a five-year cost-share project between industry and government that would enable the U.S. solar sector to get "back on its feet."[232] At its inception, the project's goal was "to ensure that the U.S. industry retains and extends its world leadership role in the manufacture and commercial development of PV components and systems."[233] The project prioritized four main areas for its activities:

1. Improving manufacturing processes and equipment;
2. Accelerating manufacturing cost reductions for PV modules, balance-of-systems components, and integrated systems;
3. Improving commercial product performance and reliability; and

[229] Intereviews with U.S. industry executives and former solar power policy managers.
[230] Interviews
[231] Maycock/PV News, U.S. EIA, Margolis (2002b)
[232] Margolis (2002b)
[233] Witt in Margolis (2002b)

4. Laying the groundwork for substantial scale up of U.S. based PV manufacturing plant capacities.[234]

This focus on process and industrial engineering R&D was a significant departure from the historical focus on materials R&D. The first phase of PVMaT focused on problem identification and was completed in early 1991. This phase involved 22 subcontracts awards worth up to $50,000 each.[235] (TABLE 23) This phase was designed to identify and prioritize areas of PV module manufacturing processes where R&D could help achieve cost significant reductions.

TABLE 23: Companies participating in PVMaT Phase 1

Alpha Solarco	Mobil Solar
AstroPower	Photon Energy
Boeing	Siemens Solar
Chronar	Solar Cells, Inc.
Crystal Systems	Solar Engineering Applications Corp.
Energy Conversion Devices	Solarex
Entech	Solar Kinetics
Glasstech Solar	Spectrolab
Global Photovoltaic Specialists	Spire
Iowa Thin Film Technologies	Utility Power Group
Kopin Corp.	Westhinghouse

Source: Margolis (2002b).

Over the next four years, PVMaT pursued many of these cost reductions with more than $65 million in DOE funds and $48 million in industry cost-sharing.[236] (TABLE 24) These efforts contributed to a 30% cost reduction in direct module manufacturing costs over from 1992 to 1996.[237] (FIGURE 76) According to executives, these projects had noticeable impact on actual manufacturing costs (i.e. not just theoretical gains) and were an important reason that manufacturing output of cells/modules increased significantly from 1992 to 1997.[238]

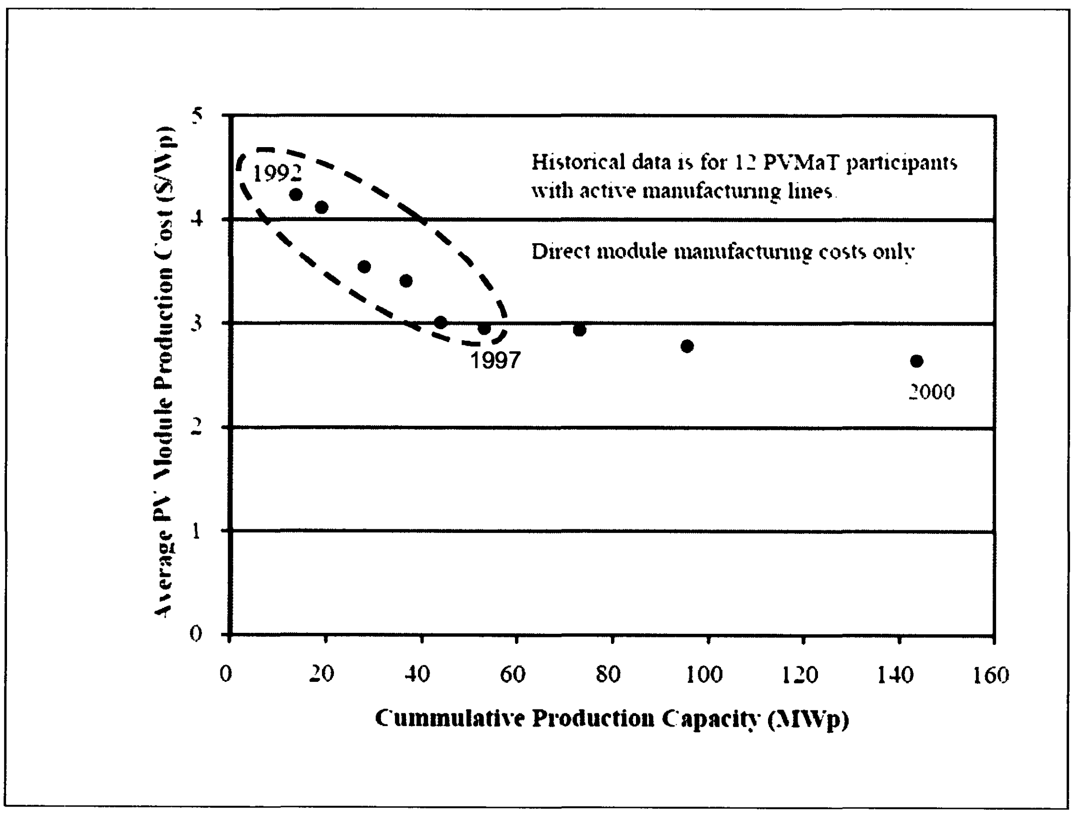
[234] Witt in Margolis (2002b)
[235] Margolis (2002b)
[236] Margolis (2002b)
[237] Margolis (2002b)
[238] Margolis (2002b)

TABLE 24: PVMaT funding and cost share 1992 to 1995

Year	Phase	DOE funding ($mn)	Private funding ($mn)	Private cost share (%)
1992	Process specific manufacturing	$30.7	$21.3	41%
1992	Generic/teamed research	$2.2	$0.8	25%
1993	Process specific manufacturing	$13.4	$14.6	52%
1995	Product-driven systems & components	$5.4	$1.8	25%
1995	Product-driven module manufacturing	$14.3	$10.1	42%

Source: Margolis (2002b)

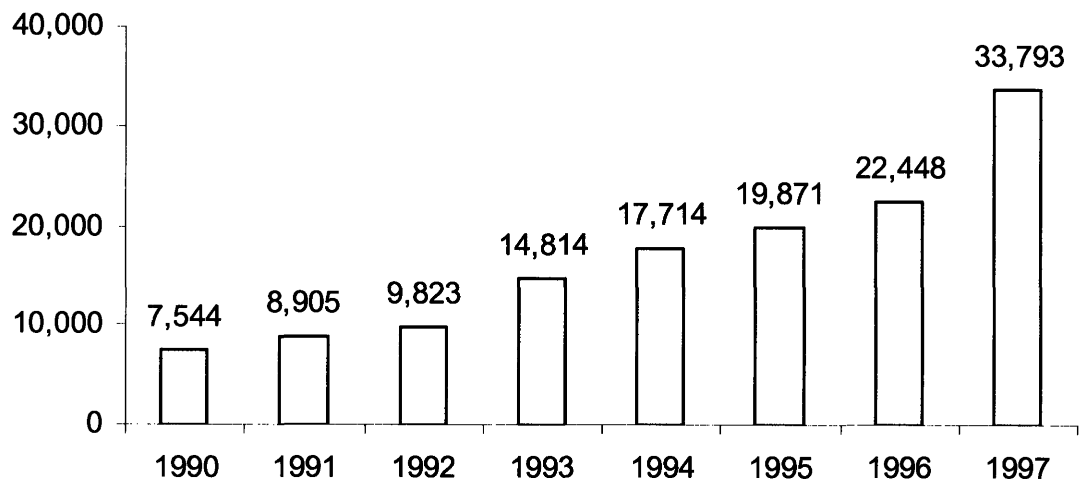
FIGURE 76: Module production cost based on PVMaT data 1992-2000



Source: Margolis (2002b)

Several interviewees pointed to the combination of cost reductions and attractive export markets to explain the 19% CAGR in U.S. production from 1990 to 1997. According to one executive, "Without both manufacturing cost reductions and hungry customers in Germany and Japan, we would not have been able to expand as quickly."[239] From 1990 to 1997, exports expanded nearly five-fold from 7.5MW to 33.8MW. By 1997, exports accounted for 73% of U.S. PV shipments with a quarter of exports going to Japan and a third going to Germany.[240]

FIGURE 77: U.S. solar cell/module exports 1990 to 1997
(Watts)



Source: EIA. Note: 1990 to 1997 timeframe used for this graphic because this is period in which PVMaT supply-side R&D activities were gearing up and operating but before the California demand-side incentive was implemented.

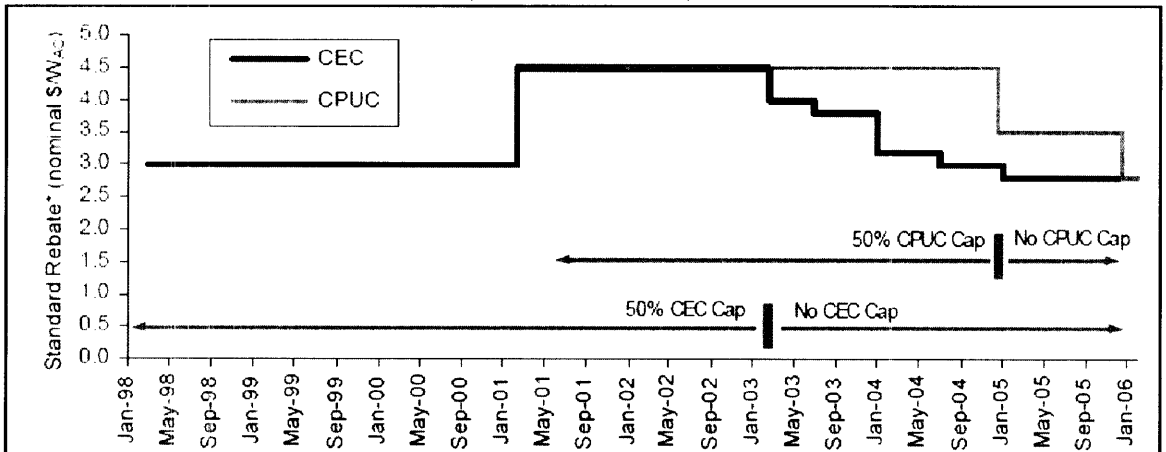
In summary, U.S. production expanded quickly during the years 1990 to 1997 at a time when the U.S. federal government initiated coordination and industry-building efforts. These efforts focused on the supply-side and did not include any significant demand-side coordination efforts. This was a contrast to Japan in that Japan's industry coordination efforts included both supply-side and demand-side elements. Expanding production was supported by higher levels of government R&D funding and more aggressive industry building (i.e. roadmapping) activities within PVMaT that enabled cost reductions. While U.S. purchases of solar power products increased, the increase was in niche segments such as telecommunications and remote off-grid applications. Because the pace of U.S. installation growth was lower than production growth, the bulk of U.S. shipments were exported to other markets, including Japan and Germany.

Two significant changes occurred starting in 1998. First, as presented above, the state of

239 Interview November 2006.
240 U.S. EIA

California instituted significant incentives for end-customers to install solar power systems. These incentives provided end-customers with up to $3.00/watt-AC[241], with a maximum of up to 50% of the total installed system cost. In 2001, these incentives were expanded both in size (incentive raised to $4.50/watt-AC) and scope (incentive applicable to systems grid-connected) (FIGURE 78) These incentives, combined with easier grid-connection rules, helped drive a rapid expansion of the California grid-connected market and also much of the growth of the overall U.S. market.[242] (FIGURE 79)

FIGURE 78: Evolution of the Standard Rebates for the CEC and CPUC Programs
(Nominal $/watt-AC)

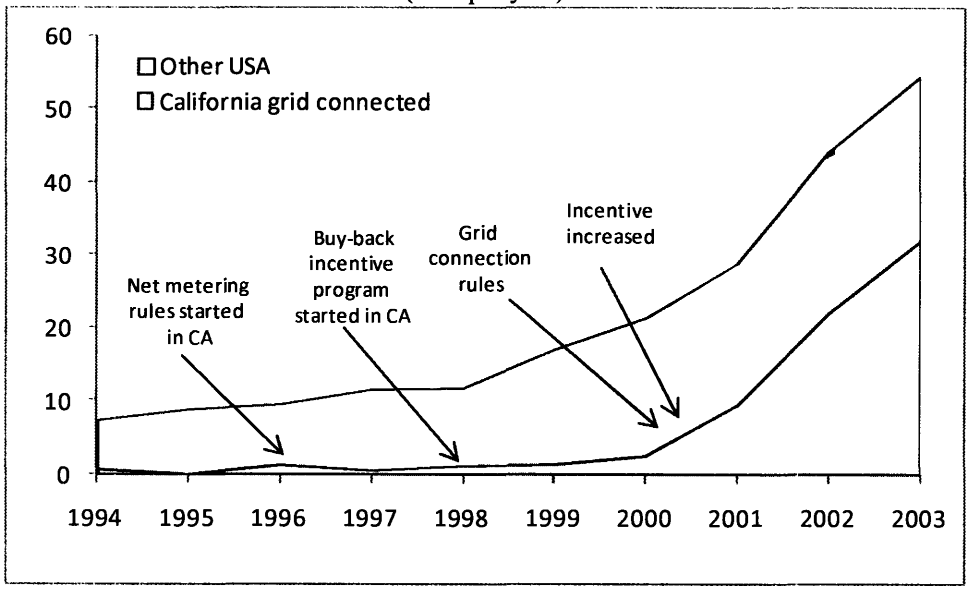


* Within the CEC's program, systems installed on affordable housing and schools have, at times, received higher incentives; owner-installed systems have, at times, received lower incentives; systems >30 kW_{AC} were eligible for rebates from program inception to February 2003; and systems >10 kW_{AC} received $2.5/$W_{AC}$ (capped at 40%) from March 1999 to February 2001.

Source: Wiser, Bolinger, Cappers., Margolis (2006)

[241] Note: Most prices and incentives in this thesis are reported in watts-DC not watts-AC.
[242] Margolis et al

FIGURE 79: U.S. solar power installations 1994 to 2003
(MW per year)



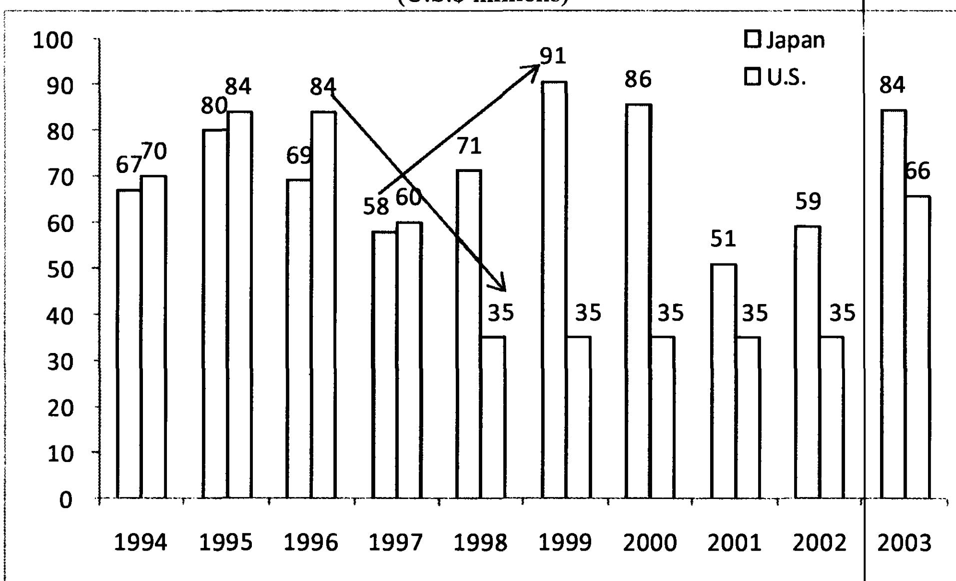
Source: IEA PVPS; http://www.energy.ca.gov/renewables/emerging_renewables/GRID-CONNECTED_PV.XLS;
Note: Assumes 80% DC to AC conversion efficiency.

Second, at the same time that California was implementing grid-connection rules and demand-side incentives, U.S. federal-level coordination activities and supply-side programs were significantly curtailed. The trend of rising government PV R&D funding that started in 1990 reversed in 1997-1998 with federal spending decreasing from a high of $84 million in 1996 to $60 million in 1997 and $35 million in 1998. This decrease is funding derailed the supply-side oriented industry-building efforts started by PVMaT and significantly reduced the ability of the federal government to support cost-sharing R&D programs with U.S. PV companies. This was particularly challenging for earlier stage U.S. PV companies pursuing non-traditional technologies, including ASE (ribbon silicon), AstroPower (silicon film), Energy Conversion Devices (amorphous silicon), Evergreen Solar (ribbon silicon), Solar Cells (CdTe), Solarex (amorphous silicon) and SunPower (concentrators). Each of these companies turned to new sources of funding soon after the decrease in the PV R&D budget at DOE, including public equity markets (AstroPower), private equity (Evergreen, Solar Cells) and larger multinational corporations (ASE, Solarex, SunPower).[243] The sharp decrease in solar R&D funding and industry coordination activities in 1997-1998 was a contrast to Japan because (a) U.S. federal

[243] Press clippings.

R&D funding decreased at a time when Japanese PV R&D funding was increasing and (b) U.S. coordination activities were curtailed at a time when coordination activities appear to have been increasing in Japan.

FIGURE 80: National government spending on solar power R&D 1994 to 2003
(U.S.$ millions)



Source: IEA PVPS

The decreasing supply-side incentives and coordination efforts was followed by companies pursing new funding sources. For example, AstroPower launched an IPO and then used the funds to expand monocrystalline silicon production from 6MW in 1998 to 17MW in 2003, Shell acquired Siemens Solar then expanded production from 20MW in 1998 to 52MW in 2003, First Solar used private equity funding investors to reach 3MW of production, Evergreen used private equity funding to reach 3MW of production, and Cypress acquired, refocused and started SunPower's back-contact monocrystalline silicon production. Collectively, U.S. cell production expanded at a 13% CAGR from 51MW in 1997 to 103MW in 2003. This compares to a 48% CAGR in Japanese cell/module production from 1997 to 2003.[244]

The net result was a significant reshaping of the U.S. solar power sector. By 2003, nearly all of the companies producing solar cells in the U.S. were either start-ups that had little or no production prior to 1998 (Amonix, ECD, Evergreen Solar, First Solar, Global Solar, Iowa Thin

[244] Press clippings, IEA PVPS, Maycock/PV News.

Film, SunPower) or were large international players who had acquired U.S. production facilities (BP, RWE Schott, Shell).[245] (TABLE 25) The rapid change in companies involved in solar power cell/module production in the U.S. was quite different than Japan, where the companies who began manufacturing in the mid-1990s continued to grow and become among the largest global players by the mid-2000s. The key point is that significant turnover among suppliers in the U.S. solar power sector (e.g. Arco → Siemens Solar → Shell Solar → subsequently SolarWorld, Amoco Solar → Amoco Solar/Enron Solar → BP Solar, exit of Exxon, Mobil, Texas Instruments, Motorola, Ontario Hydro) was a strong contrast to the more stable base of companies within the Japanese solar power sector.

TABLE 25: U.S. and Japan cell production by technology type and volume 1998 and 2003

1998 UNITED STATES				2003 UNITED STATES		
Company	**Technology**	**Production (MW)**		**Company**	**Technology**	**Production (MW)**
ASE	Ribbon Si	4	→	RWE Schott	Ribbon Si	4
AstroPower	monocrystalline Si	6.1	→	AstroPower(GE in 2004)	monocrystalline Si	17
AstroPower	Si film	1	→	AstroPower(GE in 2004)	Si film	0
Siemens	monocrystalline Si	20	→	Shell Solar	monocrystalline Si	49
Siemens	CIS		→	Shell Solar	CIS	3
Solarex	multicrystalline	14	→	BP Solar	multicrystalline	13.42
Solarex	amorphous Si	2	→	BP Solar	amorphous Si	0
Solec	monocrystalline Si	4	→	??		??
ECD	amorphous Si	2.2	→	ECD	amorphous Si	7
SunPower	Concentrator		→	SunPower	Back contact mono Si	0.6
Other		0.7		Evergreen Solar	Ribbon Si	2.8
				First Solar	CdTe	3
				Iowa Thin Film	amorphous Si	0.1
				Global Solar	CIS	2
				Amonix	Concentrator	0
				Other		19.08
TOTAL		**54**		**TOTAL**		**121**

1998 JAPAN				2003 JAPAN		
Company	**Technology**	**Production (MW)**		**Company**	**Technology**	**Production (MW)**
Canon	amorphous Si	2	→	Canon	a-Si/microcrystalline-Si	0
Daido Hoxan	monocrystalline Si	1	→	??	??	??
Kyocera	multicrystalline	24.5	→	Kyocera	mulitcrystalline Si	72
Mitsubishi Electric	multicrystalline	1.1	→	Mitsubishi Electric	mulitcrystalline Si	42
Sanyo	amorphous Si	1	→	Sanyo	amorphous Si	5
Sanyo	amorphous Si/monocrystalline Si	2.5	→	Sanyo	amorphous Si/monocrystalline Si	30
Sharp	monocrystalline Si	6.15	→	Sharp	monocrystalline Si	42.6
Sharp	multicrystalline	7.8	→	Sharp	mulitcrystalline Si	155.2
Sharp	amorphous Si	0.5	→	Sharp	amorphous Si	0.1
Showa Shell		0		Showa Shell	monocrystalline Si	0
Other		2		Hitachi	monocrystalline Si	0.02
				Kaneka	amorphous Si	13.5
				Matsushita	monocrystalline Si	0.6
				Mitsubishi Heavy	amorphous Si	4
				Kobe Steel	mulitcrystalline Si	0.4
				Adjustment		2
TOTAL		**49**		**TOTAL**		**364**

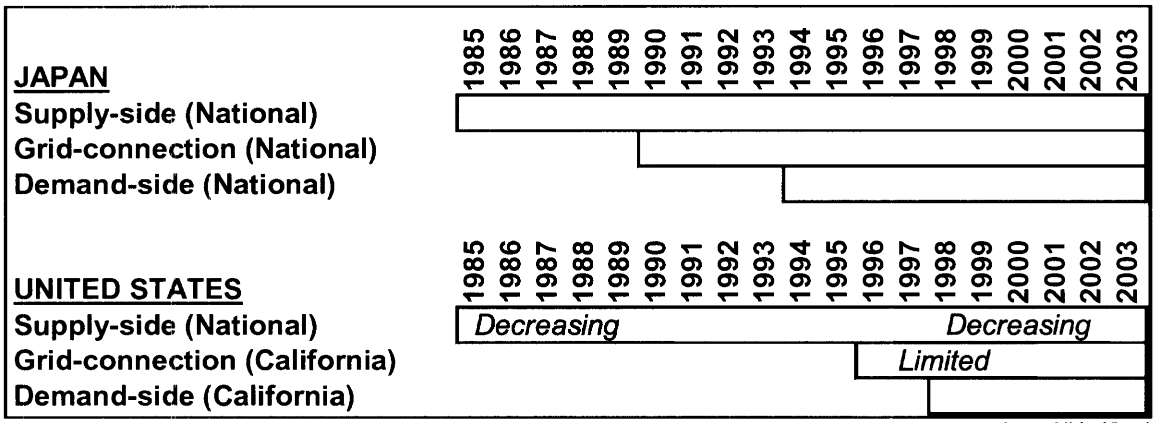
Source: Compiled by Michael Rogol based on IEA PVPS data. Note: Further research required to confirm the activities of Daido Hoxan and Solec in 2003.

It important to emphasize that the diminishment of U.S. supply-side incentives occurred precisely at the time when the largest U.S. state instituted strong demand-side incentives. This is important

245 Press clippings. One exception was AstroPower, which grew from organically from 6MW of production in 1998 (11% U.S. production market share) to 17MW in 2003 (14% market share).

because it demonstrates that the U.S. was not pursuing a Japanese-esque coordination effort to create a “virtuous cycle” for PV sector expansion. As shown in FIGURE 81, a break in coordination and supply-side incentives occurred in the late 1990s in the U.S., which contrasts with the more consistent picture presented of Japan in the previous section.

FIGURE 81: Timing of government policies supporting solar power (schematic overview)



Source: Michael Rogol

In summary, the U.S. solar power sector continued expanding during the years 1998 to 2003. On the demand side, new incentives in California were the key driver of increasing U.S. demand and higher growth rates. On the supply side, decreasing funding from the federal government led companies to seek new sources of funding that enabled production to expand, albeit at a slower pace. Coordination was pursued by the U.S. federal government for a portion of the period then curtailed despite PVMaT contributing to strong cost reductions. This curtailment and the more limited nature of U.S. coordination efforts (focus on supply-side not supply- and demand-sides) was a contrast to Japan, where strong government coordination efforts at the national level throughout the period helped drive production growth *and* strong installation growth that was both stronger and more consistent than in the U.S.

(iii) Results and open questions

In many respects, this case on the U.S. solar power sector during the years 1994 to 2003 raises questions that require additional research. Within the area of coordinated efforts to build the U.S. solar power sector, open questions include:

- How did the structure of the U.S. electronics and computer sectors, the U.S. electricity sector and the broader U.S. energy sector limit or enable efforts to pursue coordinated industry building for the solar power sector?

- What are the opportunities for and limits of applying lessons from the apparently successful though short-lived efforts of PVMaT?

- What are the opportunities for and limits of applying lessons from the California solar power sector (specifically demand-side incentives and grid connection/net metering rules) to other geographic locations in the U.S.?

- What prevented stronger coordination of supply-side, demand–side and grid-connection/net metering policies in the U.S. during the years 1994 to 2003?

- What lessons from U.S. efforts to coordinate solar power industry building are applicable to other efforts to support industry building for other energy technologies?

- How did the traditional strong state/weak federal role in electricity regulation, pricing, net metering, demand, supply and planning hinder the growth of national-level solar power policies?

Research to address these questions may be the focus of future efforts.

- SECTION 5 -

COMPARATIVE ANALYSIS OF CASE STUDIES

Section 5

Comparative analysis of case studies

(A) Introduction

The preceding sections have presented case studies of the development of the solar power sectors in Japan and the U.S. from 1994 to 2003. Overall, both countries' solar power sectors grew in terms of production and installations during this period and both countries experienced price reductions for solar power systems. Yet the pace of installation growth, the pace of production growth and the pace of price reductions were significantly faster in Japan than in the U.S. Why did the solar power sector develop more quickly in Japan than in the U.S.? This result is surprising for several reasons, including:

- The U.S. was much larger than Japan in terms of solar power production and installations in the years leading up to 1994;
- Solar resource (i.e. watt-hours/watt/day) was significantly higher in many parts of the U.S. than Japan;
- Prior to 1994, the U.S. was a global leader in solar power technology in terms of innovation and private sector R&D; and
- Japan's economy was in a period of slow growth during the years 1994 to 2003, while the U.S. economy was expanding more quickly throughout this period.[246]

This section provides a comparative analysis of the Japanese and U.S. cases in order to identify factors that enabled faster growth of Japan's solar power sector. This section concludes by highlighting questions for additional research.

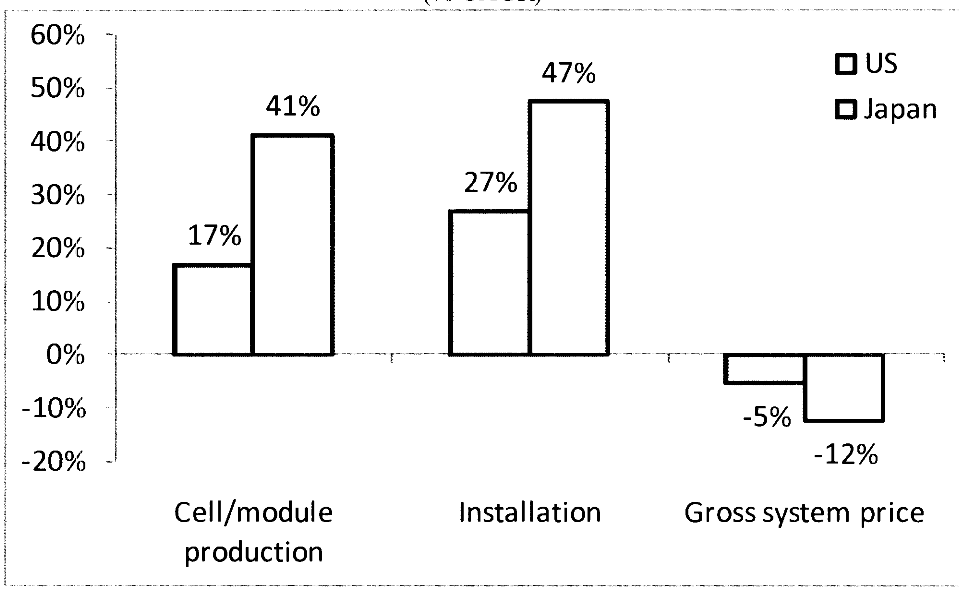
(B) Comparative analysis of the case studies

The case studies on the Japanese and U.S. solar power sectors from 1994 to 2003 provide the basis for comparative analysis. As a starting point of comparison, it is clear that the solar power sector in Japan grew faster than the solar power sector in the U.S.: Installations in Japan grew at

[246] World Bank

a 47% CAGR from 1994 to 2003 while installations in the U.S. grew at only a 27% CAGR. FIGURE 82 provides an overview of the Japanese and U.S. CAGRs for installations, cell/module production and gross system prices from 1994 to 2003.

FIGURE 82: Growth rate of installation, production & gross system price in Japan & U.S. 1994-2003
(% CAGR)



Source: IEA PVPS; Maycock/PV News; NEDO

Faster decreases in gross system prices in Japan than in the U.S. provide an intuitive explanation for the faster growth rate in Japanese installations compared to the U.S., with gross system prices decreasing at a 12% CAGR in Japan compared to only 5% in the U.S. The faster price decrease in Japan can itself be intuitively explained by the faster growth in production (41% CAGR in Japan compared to 17% CAGR in U.S.), which enabled stronger cost decreases in Japan compared to the U.S. This first-order explanation suggests *interplay among factors* is a key aspect of why the Japanese solar power sector grew faster than the U.S. More specifically, this explanation suggests interplay among four factors: (a) decreasing gross system prices price, (b) increasing installations, (c) increasing production and (d) decreasing costs.

This raises the second-order question, "What factors led to (a) decreasing prices, (b) increasing installations, (c) increasing production and (d) decreasing costs?" To begin addressing this question, FIGURE 83 presents numerous factors influencing the growth of solar power. The color-coding in this FIGURE attempts to highlight factors that made California and the U.S. overall more- or less-attractive location for solar power sector growth compared to Japan. The high proportion of red-colored cells ("less attractive than Japan") and the limited number of green-colored cells ("more attractive than Japan") is a stylized starting point for explaining why Japan's solar power sector grew faster from 1994 to 2003: With more attractive extrinsic factors, industrial organization, end-customer economics and manufacturer economics, it is not surprising that Japan's solar sector grew more quickly than the U.S. solar power sector.

FIGURE 83: Comparison of Japan and U.S. solar power sectors during period 1994 to 2003

EXTRINSIC FACTORS	JAPAN	CALIFORNIA	U.S. (incl CA)
Solar resource (watt-hours/watt/day)	3 to 4.5		
Interest rates	2% to 4%		
Average grid price	\$0.19 to \$0.25/kWh		
INDUSTRIAL ORGANIZATION FACTORS	**JAPAN**	**CALIFORNIA**	**U.S. (incl CA)**
Electricity industry structure	~12 main players	~3 main players	
Experience of leading cell/module players	Largely electronics		
Commitment of leading solar players	Consistent		
END-CUSTOMER ECONOMIC FACTORS	**JAPAN**	**CALIFORNIA**	**U.S. (incl CA)**
Levelized gross system price in 1994	\$1.23/kWh		
Levelized gross system price in 2003	\$0.33/kWh		
Levelized net system price in 1994	\$0.70/kWh		
Levelized net system price in 2003	\$0.27/kWh		
"Gap" with grid price in 1994	\$0.45/kWh		
"Gap" with grid price in 2003	\$0.08/kWh	\$0.10/kWh	
"Gap" elasticity 1994 to 2003	-2.8	-2.6	N/A
Price at which demand "tips"	\$0.35/kWh		
MANUFACTURER ECONOMIC FACTORS	**JAPAN**	**CALIFORNIA**	**U.S. (incl CA)**
Module price in 1994	\$9/watt		
Module price in 1998	\$5/watt		
Module price in 2003	\$4/watt		
NPV of 100MW cell/module investment in 1993*	NPV > \$0		
POLICY FACTORS	**JAPAN**	**CALIFORNIA**	**U.S. (incl CA)**
Grid-connection policies	Throughout 1994-2003		
Demand-side policies	Throughout 1994-2003		
Supply-side policies	Throughout 1994-2003		
Coordination policies/roadmapping	Throughout 1994-2003		
Total policy spending 1994-2003 (nominal US\$)	\$2 billion		
	Color coding:	*More attractive than Japan*	
		Similar to Japan	
		Less attractive than Japan	

Source: Michael Rogol *Note: This is an estimate of the net present value for a 100MW cell/module plant in 1993 and 2003 with the output of the plant being sold at expected domestic market prices. This does not take into account potential for exports to higher priced markets. The simple points being conveyed here are that (1) the economics of a solar power manufacturing capacity were less attractive in the U.S./California than in Japan at the start of the period 1994 to 2003.

Yet, because interplay among first-order factors is important, it is not surprising that isolating independent and dependent second-order factors is difficult. A more precise explanation for the faster growth observed in the Japanese solar power sector requires a detailed description that goes beyond the stylized overview in FIGURE 83. The remainder of this sub-section discusses aspects of the Japanese solar power sector that help to more thoroughly explain the faster growth observed in Japan:

1. Extrinsic factors;
2. Industrial organization factors;
3. End-customer economic factors;
4. Manufacturing economic factors; and
5. Policy factors.

(1) Extrinsic factors

Extrinsic factors (i.e. factors originating outside the solar power sector) made end-customer economics in Japan more attractive than in the U.S. The combination of modest solar resource, low interest rates and high grid prices made Japanese end-customer economics more attractive than in California. Results are summarized in TABLE 26. Negative numbers in this TABLE indicate that a specific extrinsic factor (left column) made end-customer economics in Japan relatively more attractive (i.e. lower "gap") compared to California (middle column) and the U.S. overall (right column), all other factors being equal. For example, lower interest rates made the levelized price of solar in Japan roughly \$0.21/kWh lower than in California and the U.S. overall, and higher grid prices made the "gap" between solar power and average residential grid price in Japan roughly \$0.13/kWh lower in than in California and \$0.16/kWh lower than in the U.S. overall. Similarly, within this TABLE, positive numbers indicate that an extrinsic factor (left column) makes end-customer economics in Japan relatively less attractive (i.e. higher "gap") compared to California (middle column) and the U.S. overall (right column), all other factors being equal. For example, the lower level of solar resource in Japan made the levelized price of solar in Japan roughly \$0.23/kWh higher than California and \$0.15/kWh higher than the U.S. overall. Together, the combination of extrinsic factors made Japanese end-customer economics in 1994 roughly \$0.13/kWh more attractive than in California and \$0.23/kWh more attractive than in the U.S. overall.[247]

[247] This is a single example, but there is a broad range of estimates based on varying assumptions. The estimates provided in this table and in this section are intended as rough rules-of-thumb. Assumptions used for the basis of this example are: 3kW system; 4.25 watt-hours/watt/day in Japan, 5 watt-hours/watt/day in California and 5.5 watt-hours/watt/day in U.S.; \$12/watt-DC gross system price (the gross system price in California in 1994; gross solar system price in Japan was roughly \$20/kWh in 1994, but the U.S. price is used to enable an apples-to-apples comparison of the impact of extrinsic factors); no incentive; 4% discount rate for Japan and 7.5% discount rate (roughly equal to the nominal long-term interest rate in 1994) for California and the U.S.; inverter replacement every 10 years;

TABLE 26: Comparative analysis: Relative impact of extrinsic factors on Japanese end-customer economics for solar power in 1994
($/kWh impact)

Extrinsic factors	Japan compared to California	Japan compared to U.S. overall
Solar resource	$0.23	$0.15
Interest rates	-$0.21	-$0.21
Grid prices	-$0.13	-$0.16
TOTAL*	**-$0.13**	**-$0.23**

Source: Michael Rogol. Note: For more complete explanation see comments in body of document and in footnotes. *"TOTAL" is not the sum of rows above. TOTAL is calculation of the difference in "gap" for Japan compared to California and the U.S. overall, taking into account the combination of extrinsic factors. This calculation is not equal to the sum of impacts from the individual extrinsic factors (solar resource, interest rate, grid prices).

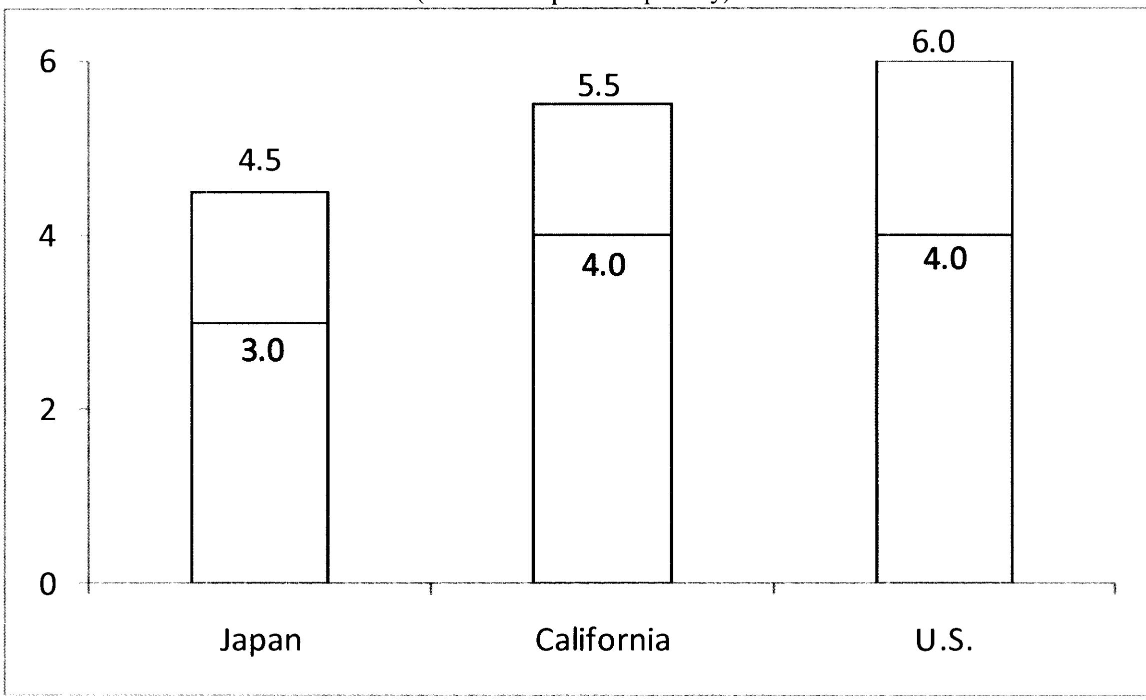
The simple point made by TABLE 26 is that, all else being equal, extrinsic factors make the "gap" between levelized solar power price and grid price lower than in California and the U.S. overall. This point may appear counter-intuitive because the level of solar resource is significantly higher in many areas of the U.S. than in Japan. As shown in FIGURE 84, Japan's typical solar resource is 3 to 4.5 watt-hours/watt/day compared to a range of 3 to 6.5 watt-hours/watt/day in most of the U.S. and 4 to 6 watt-hours/watt/day in most of California.[248] In other words, the solar resource in the U.S. is often 30 to 40% higher than in Japan, making it appear that the U.S. is a more logical location for solar power installations. As an example, assuming (a) all other factors aside from solar resource being equal and (b) solar resource of 4.25 watt-hours/watt/day in Japan compared to 5.5 watt-hours/watt/day for a typical California location and 5 watt-hours/watt/day for a typical U.S. location, the levelized price of solar electricity for end-customers in Japan was roughly $0.23/kWh higher than in California and $0.13/kWh higher than in the U.S. overall.[249]

0.25% annual output degradation; 25 year system life; 75% system conversion factor accounting for inversion and system losses; average residential grid prices of $0.25/kWh in Japan, $0.117/kWh in California and $0.09/kWh for U.S. overall.

[248] RETScreen, PVWatts, Sunbird.jrc.it

[249] This is a single example, but there is a fairly broad range based on varying assumptions. Assumptions used for the basis of this example are: 3kW system; 4.25 watt-hours/watt/day in Japan, 5.5 watt-hours/watt/day in California and 5.5 watt-hours/watt/day in U.S.; $12/watt-DC gross system price (the gross system price in California in 1994); no incentive; 7.5% discount rate (roughly equal to the nominal long-term interest rate in the U.S. in 1994) for Japan, California and the U.S.; inverter replacement every 10 years; 0.25% annual output degradation; 25 year system life; 75% system conversion factor accounting for inversion and system losses. Result is roughly $1.02/kWh in Japan, $0.78/kWh in California and $0.86/kWh in U.S., which equates to a difference of $0.24/kWh between Japan and California and $0.15/kWh between Japan and the U.S. Note: Numbers may not add due to rounding.

FIGURE 84: Range of typical solar resource
(Watt-hours per watt per day)

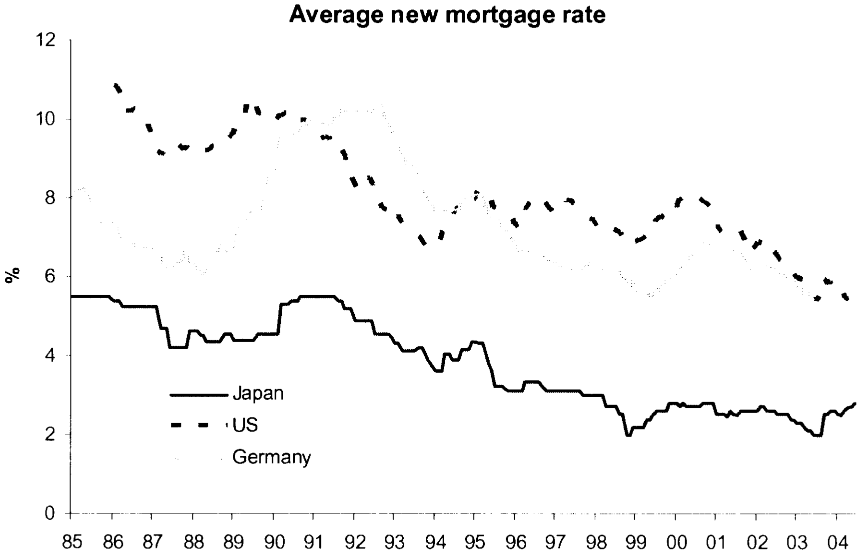


Source: RETScreen, PVWatts, Sunbird.jrc.it

Yet other extrinsic factors beyond solar resource are involved in solar power end-customer economics. Specifically, interest rates are an important factor in end-customer economics, with a 1-percentage point increase (decrease) in interest rate equating to roughly 7% increase (decrease) in the levelized price of solar electricity assuming all other factors remain constant.[250] Long-term consumer interest rates in Japan were roughly 2% to 4% during the years 1994 to 2003, compared to roughly 6% to 9% in the U.S. This equates to a "spread" of roughly 3.5- to 5-percentage points between the interest rates for end-customer installations in Japan versus the U.S. (See FIGURE 85) As a result, all other factors (including solar resource) being equal and assuming a 3.5-percentage point "spread" (e.g. 4.0% in Japan in 1994 compared to 7.5% in California and 7.5% in the U.S.), the levelized price of solar electricity for end-customers in Japan was roughly $0.21/kWh lower than in Japan than both California and the U.S.[251] This means that, typically, the higher solar resource in the U.S. was offset by the lower interest rate in Japan.

[250] This estimate of 7% is intended as a rough rule-of-thumb. Precise estimates of the impact of interest rate changes on levelized prices vary depending upon assumptions. In this case, for a $12/W installed price, a 1-percentage point decrease in interest rate from 8% to 7% results in a decrease in levelized system price of roughly $0.09/kWh. For additional details, see Conkling and Rogol (2006)
[251] This is a single example, but there is a fairly broad range based on varying assumptions. Assumptions used for the basis of this example are: 3kW system; 5.5 watt-hours/watt/day in both Japan and U.S (a typical rate for California); $12/watt-DC gross system price (a typical price in the U.S. in 1994); no incentive; 4% discount rate for Japan and 7.5% discount rate based for U.S.; inverter

FIGURE 85: Average new mortgage rates in largest lending markets
(Interest rate %)



Source: CLSA

In addition to solar resource and interest rates, grid-based electricity prices are another important extrinsic factor. In Japan, average residential grid prices ranged from \$0.19 to \$0.25/kWh during the years 1994 to 2003. In contrast, average U.S. residential grid prices ranged from \$0.08 to \$0.09/kWh from 1994 to 2003, with California in a range of \$0.11 to \$0.13/kWh.[252] As shown in FIGURE 86, Japan's residential electricity prices were among the highest in the world, while U.S. prices were among the lowest. This meant that the substitute price for solar power was "easier" to reach in Japan than in California (Japan \$0.13/kWh lower in 1994) and the U.S. overall (Japan \$0.16/kWh lower in 1994).

Taken together, differences in solar resource (e.g. 4.25 watt-hours/watt/day in Japan, 5.5 watt-hours/watt/day in California and 5.0 in the U.S), differences in interest rates (e.g. 4% in Japan, 7.5% in California and 7.5% in the U.S.) and differences in grid prices (e.g. \$0.25/kWh in Japan,

replacement every 10 years; 0.25% annual output degradation; 25 year system life; 75% system conversion factor accounting for inversion and system losses. Result is roughly \$0.58/kWh in Japan and \$0.78/kWh in California and the U.S. This equates to Japan being roughly \$0.20/kWh lower than the U.S. and California. Note: Similar results occur if using real instead of nominal discount rates and prices.

[252] Japan and U.S. averages from U.S. EIA. California averages from www.energy.ca.gov/electricity/statewide_weightavg_sector.html

$0.12/kWh in California and $0.09/kWh in the U.S.), but the same installation price[253] (e.g. $12/watt), the difference between solar power price and grid price was much lower in Japan than in the U.S., in general, and much lower than even a sunny, high electricity price state such as California. As shown in FIGURE 87, the levelized gross system price without incentives of a $12/W installation was $0.54/kWh above average residential grid price in Japan compared to $0.67/kWh in California and $0.78/kWh in the U.S. overall. In other words, assuming the same installation price and no incentives, California was roughly 24% further from grid parity (i.e. from average residential grid prices) than Japan in 1994 and the U.S. overall was roughly 43% further from grid parity than Japan. In short, lower interest rates and higher grid prices in Japan more than made up for Japan's lower solar resource. Together, these extrinsic factors made end-customer economics in Japan more attractive than in the U.S.[254]

In addition, other extrinsic factors may have further favored Japan's solar power sector compared to California and the U.S. overall. These factors include (a) energy security concerns due to high degree of energy imports in Japan and (b) environmental protection concerns due to rising activism around environmental issues such as climate change. Quantifying the impact of these extrinsic factors that may have contributed to the growth of Japan's solar power sector is an area for potential further research.[255]

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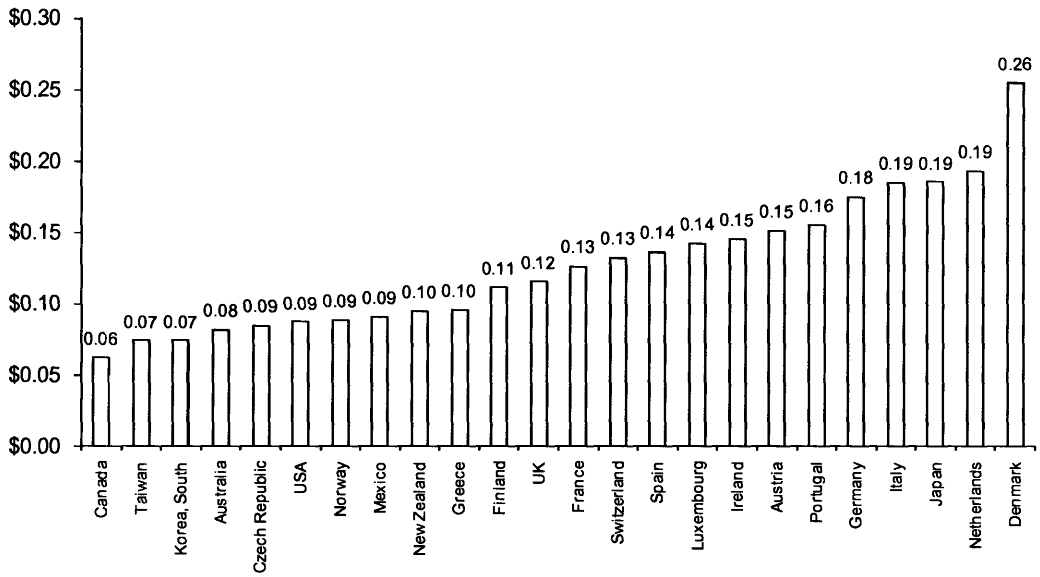
[253] This assumption is being made to enable an apples-to-apples comparison of extrinsic factors. Installed system prices were significantly higher in Japan than in the U.S. in 1994, but there was expectation among Japanese that the price would rapidly decrease as the scale of Japanese installations increased. This expectation was based on data showing that U.S. installed system prices were much lower than Japanese in 1993. This expectation turned out to be fulfilled, with gross system prices declining rapidly in 1994-1996. Later in this section, actual installation prices (as opposed to $12/W assumption) are incorporated into both the analysis and the discussion.

[254] While the extrinsic factors made end-customer economics more attractive in Japan than in the U.S., the economics were still unattractive relative to average residential grid prices. As noted in previous sections, analysis presented in this thesis is based on typical interest rates and average residential grid prices. Additional research on customer-specific interest rates and grid-prices is necessary to better evaluate the specific economic choice facing specific customers.

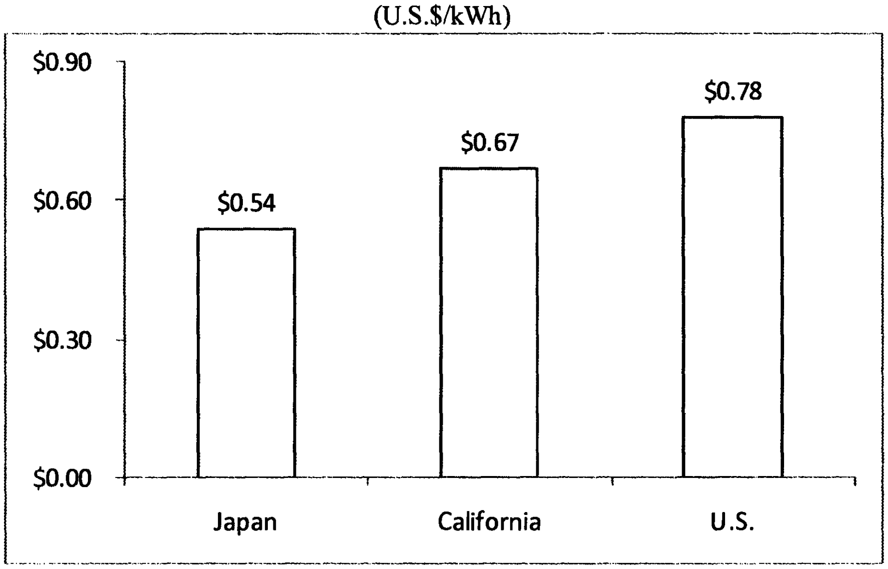
[255] One potential research path is to compare a time series of public opinion on energy security and environmental issues to the adoption of solar power systems in various geographies in Japan and the U.S. in order to identify potential correlations.

FIGURE 86: Average residential electricity price in 2003
(U.S.$/kWh)



Source: Energy Information Administration

FIGURE 87: LGSP of $12/W system minus average residential grid price in 1994
(U.S.$/kWh)



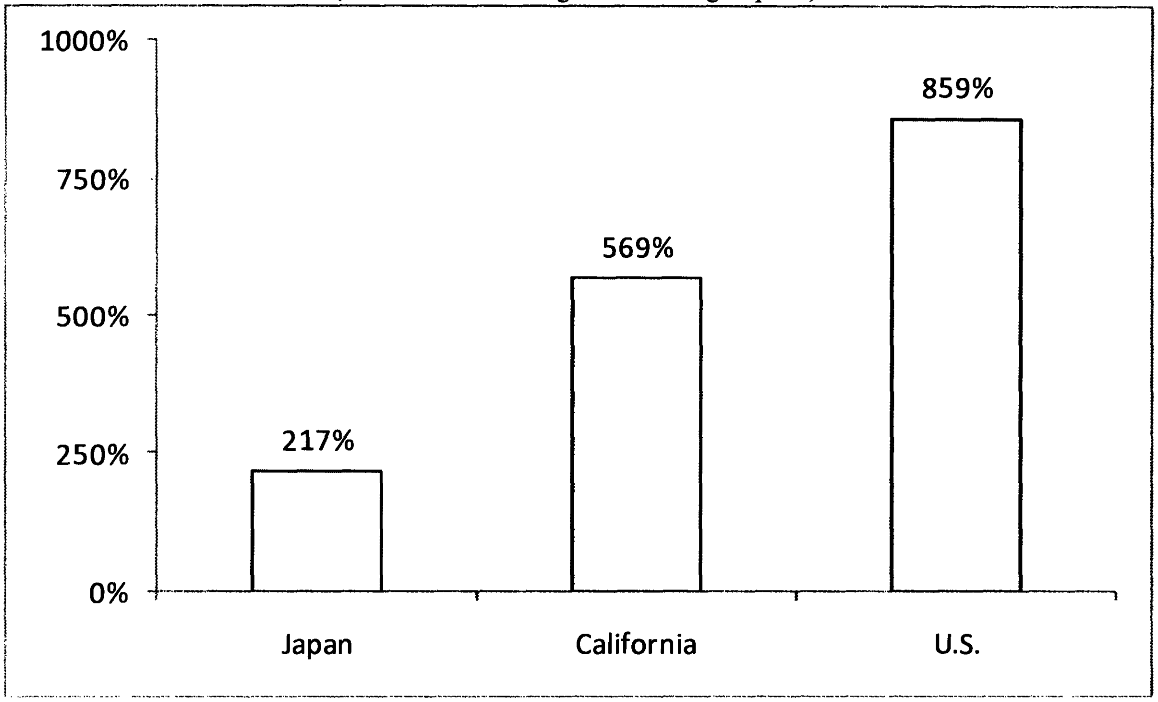
Source: Michael Rogol calculation. Note: Estimates in this figure represent a mental exercise using a $12/watt system price in order to compare on an apples-to-apples basis among Japan, California and the U.S. Gross installed system prices in Japan in 1994 were roughly $20/W not $12/W.

The more favorable extrinsic setting in Japan raises the question, "How much of the superior growth exhibited by Japan's solar power sector during the years 1994 to 2003 is attributable to extrinsic factors?" The answer to this question appears on the surface to be, "None of Japan's superior growth rate can be attributed to extrinsic factors." This is because differences in extrinsic factors in the Japan versus the U.S. were similar prior to 1994, so that these were not new factors that drove the growth of Japan's solar power sector from 1994 to 2003. In other words, Japanese solar resource was poorer than U.S. solar resource prior to and after 1994, Japanese interest rates were lower than U.S. interest rates prior to and after 1994 and Japanese grid prices were higher than U.S. grid prices prior to and after 1994, so that these extrinsic factors *by themselves* do not provide a compelling explanation for why the Japanese solar power sector grew faster than the U.S. during the years 1994 to 2003, something that it had not done prior to 1994.

Yet this answer requires more nuance. In 1994, solar power was not economic for end customers in Japan, California or the U.S. overall. The levelized gross price of a $12/watt solar power system was well above average residential grid prices in Japan, California and the U.S. overall. Specifically, the levelized price of a $12/watt system would have been 217% above grid price in Japan, 569% in California and 859% in the U.S. overall. (See FIGURE 88) While $12/watt solar power systems were well above grid prices, the extrinsic factors in Japan meant that the premium was significantly lower than in California or the U.S. overall. This lower premium in Japan than in California or the U.S. may have increased cognitive recognition among executives and policy makers that solar power had realistic potential of reaching grid parity. While this *alone* may not have triggered action by executives and policy makers, the extrinsic factors *in combination with other factors* may have led to action by executives and policy makers. At minimum, it makes intuitive sense that extrinsic factors contributed to a modestly more attractive setting in which Japanese executives and policy makers recognized that a profitable, fast-growth industry could be built in Japan. Attempting to quantify the extent to which extrinsic factors alone played a positive role in enabling the rapid growth of the solar power sector is a topic for further research.[256]

[256] Some initial thoughts on process for further research: First, collect local-level data on neighborhood-specific residential grid prices from specific generation/distribution companies, on neighborhood-specific long-term interest rates from specific bank branches and on neighborhood-specific gross system prices from NEDO and CEC. Second, run analysis of levelized system price using this new data. Third, conduct comparative assessment of levelized system price analysis of different locations.

FIGURE 88: Levelized price of a $12/W solar power system relative to average residential grid price
(Percent above average residential grid price)



Source: Michael Rogol calculation. Note: Estimates in this figure represent a mental exercise using a $12/watt system price in order to compare on an apples-to-apples basis among Japan, California and the U.S. Gross installed system prices in in Japan in 1994 were roughly $20/W not $12/W.

(2) Industrial organization factors

In the years leading up to 1994, the U.S. solar power sector had established itself as the world leader in terms of technology, production and installations. Yet during the years 1994 to 2003, this leadership quickly transitioned to the Japanese. Extrinsic factors alone do not explain the pace and scale of this leadership transition. In addition to extrinsic factors, it appears that several factors related to industrial organization likely fostered rapid growth in Japan's solar power sector beyond the growth achieved in the U.S.

These factors include a more stable, less complex electric power industry structure in Japan. The Japanese electric power industry in the period 1994 to 2003 was characterized by relative consistency and a lower level of institutional complexity compared to the U.S. electric power sector. Japan had a dozen large generating companies throughout the period 1994 to 2003.[257]

[257] According to Nishimura (1999), nine electric power companies (EPCO's) "are vertically integrated, investor-owned utility companies that dominate Japan's electric power sector." In addition to these EPCOs, other major players include a small number of government-financed wholesale companies generating electricity.

The largest electric power utilities were the dominant suppliers of electricity, with an 88% share of production and consumption in 1994 (TABLE 27), and retained a similar share of production through 2003.[258] In contrast, the U.S. had hundreds of large electric power generators and a more complex regulatory structure.[259] Not only was the U.S. electric power sector more complex, it was also changing more quickly, with the pace of deregulation, mergers and acquisitions and capacity additions moving significantly faster in the U.S. than in Japan during this period.[260] Further, as detailed in Section 3B, the Japanese protocols for connecting solar power systems to the existing electricity networks were consistent and straightforward from the early-1990s. This was a contrast to the grid connection rules in the U.S, which were non-existent in most U.S. geographies. Grid connection rules were determined by state, not federal, regulation, and, even within states, rules varied from utility to utility. For U.S. geographies in which grid connection rules existed, the rules were inconsistent across geographies.[261]

TABLE 27: 1994 Japanese electric power production by supplier
(TWh and percent)

	Production
12 electric power utilities (TWh)	849
Portion (%)	*88%*
Other suppliers (TWh)	115
TOTAL (TWh)	964

Source: JEPIC (2003).

The less complex industrial organization of the Japanese electric power industry and the easier nationwide grid connection rules had positive economic consequences for the solar power sector. Specifically, grid connection enabled solar power systems to operate without expensive storage and backup devices. This reduced the gross system price by roughly $2/watt, equivalent to a levelized price reduction in Japan of roughly $0.12/kWh.[262] (FIGURE 89) Because the industrial

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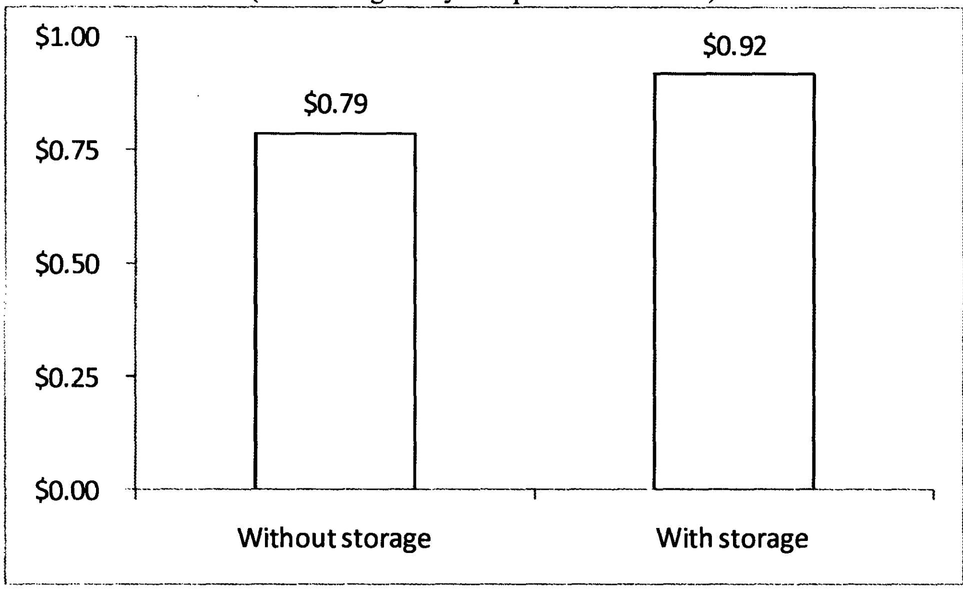
[258] JEPIC (2003)
[259] Note: The California electric power industry, with 4 utilities controlling roughly 90% of electricity generation, was more concentrated than the overall U.S. electric power industry. In the mid- and late-1990s, these utilities were, according to one interviewee, "in turmoil" due to the changing regulatory and competitive landscape.
[260] For example, see EIA (2000) "The Changing Structure of the Electric Power Industry" including Chapter 9 on "Mergers, Acquisitions, and Power Plant Divestitures of Investor-Owned Electric Utilities".
[261] Phone interview with U.S. NREL May 2007.
[262] Estimating the cost per watt or cost per kWh of storage in 1994 is difficult for two reasons. First, there is little available data in the literature. Second, costs for storage systems have a wide range depending on the characteristics of the storage. Cost reduction of roughly $2/watt for cost of storage in 1994 estimated based on interviews with Japanese executives in 2003-2004 as part of research for Rogol (2004). For more recent estimates of storage costs, see "Energy Storage: Role in Building Based PV Systems" by TIAX (2007). Assumptions used for the basis of this example are: 3kW system; 5 watt-hours/watt/day in Japan; $12/watt-DC gross system price (a typical price in the Japan in 1994) without storage and $14/watt-DC with storage; no incentive; 4% discount rate for Japan; inverter replacement every 10 years; 0.25% annual output degradation; 25 year system life; 75% system conversion factor accounting for inversion and system losses. Result is roughly $0.79/kWh in Japan without storage and $0.92/kWh with storage. The difference equates to roughly $0.12- $0.13/kWh.

organization of the U.S. electric power sector was more complex and simplified, consistent grid connection rules were more difficult to implement and, therefore, this potential savings was not accessible in most of the U.S. Even in California, the implementation of grid connection rules took place later than in Japan. The key point is that the industrial organization of the U.S. electric power sector was a less conducive environment for growth of the solar power sector.

FIGURE 89: Levelized price of a solar power system with ($12/watt) and without ($14/watt) storage
(Levelized gross system price in US$/kWh)



Source: Michael Rogol calculation. Note: The storage price of $2/watt is a rough estimate. Assumptions used for the basis of this example are: 3kW system; 5 watt-hours/watt/day in Japan; $12/watt-DC gross system price (a typical price in the Japan in 1994) without storage and $14/watt-DC with storage; no incentive; 4% discount rate for Japan; inverter replacement every 10 years; 0.25% annual output degradation; 25 year system life; 75% system conversion factor accounting for inversion and system losses. Result is roughly $0.79/kWh in Japan without storage and $0.92/kWh with storage. The difference equates to roughly $0.12- $0.13/kWh.

A second factor relating to industrial organization that may have contributed to the strong growth of Japan's solar power sector was the role of established players from the electronics sector. The composition of companies in the Japanese industry was much more heavily weighted toward electronics companies than was the case in the U.S. Collectively, Sharp, Sanyo and Kyocera accounted for 79% of Japanese cell/module production and 19% of global cell/module production in 1994.[263] These three electronics players were not only the leaders of Japan's solar sector in 1994, but they remained the backbone of Japan's solar sector through 2003, accounting for 86% of Japan's cumulative cell/module production (976MW out of 1132MW) during the period 1994 to 2003. Similarly, at other stages of the supply chain, a small number of larger companies with complementary skills from other industries were involved (for example, specialty chemical

[263] Other companies (e.g. Tokuyama, Mitsubishi Materials) were suppliers to both the electronics and solar power sectors.

companies in silicon production and homebuilders in system integration). The scale of these players, their experiences in other industries, their commitment to the solar power sector and their familiarity working with government institutions appears to have contributed to an environment in which a robust roadmapping effort helped to support the growth of Japan's solar power sector.[264]

The fact that these companies had experience in a similar industry (electronics), had similar scale (all are multi-billion dollar revenue companies) and had similar perspectives about the solar power sector (by the mid-1990s, each company believed that solar power would become a much larger sector and would achieve grid parity[265]) may have contributed to their similar decisions to expand solar cell/module manufacturing quickly. The collective actions of these three players may have reduced risk by attracting more attention from feedstock providers, equipment vendors, standards setting groups and policy makers than if any of these companies had acted in isolation. As a result, it seems logical that the common traits among key players within Japan's solar power sector enabled more rapid expansion of the Japanese than if these common traits had not existed.

In contrast to the Japanese experience, the largest U.S. solar energy players were not electronics sector players, but were a mixture of oil companies, power companies, start-ups and companies with other backgrounds. Perhaps the most obvious theme among the companies was the presence of international energy companies such as BP, Shell, Mobil, Arco, Amoco, Enron and RWE. Yet international energy companies in the U.S. solar power sector were much less consistent than Sharp/Kyocera/Sanyo in terms of their growth, had lower share of U.S. cell/module production than the Japanese electronics companies and, unlike the Japanese solar power players, underwent significant ownership changes during the years 1994 to 2003 (e.g. BP acquiring Amoco Solar/Solarex/Enron Solar which itself had previously been owned by Amoco and was later sold to SolarWorld; Shell acquiring Siemens Solar which itself had been acquired from Arco; notable "exits" from the solar sector including Exxon, Mobil, Texas Instruments, Motorola, Ontario Hydro and RWE).[266] In addition to these energy companies, there were numerous start-ups in the U.S. solar power sector, including Amonix, AstroPower, Energy Conversion Devices, Entech,

[264] As mentioned previously, the details of *exactly* what this roadmapping effort involved is the subject for futher research.
[265] Interviews as part of Rogol (2004)
[266] Note: Most though not all of these corporate moves occurred during the period 1994 to 2003. Sources: Maycock/PV News. Also details on mergers and acquisitions in U.S. solar power sector from press clippings such as query.nytimes.com/gst/fullpage.html?res=9D04E7D91638F934A35757C0A96F958260 and www.solarexpert.com/grid-tie/press4.html.

Evergreen Solar, First Solar, GT, Spire and others. A similar grouping of solar start-ups does not appear to have existed in Japan. Overall, the industrial organization of the Japanese solar power sector was more stable and consistent than the U.S. solar power sector, which may have reduced risk and enabled faster growth of the Japanese solar power sector. (TABLE 28 presents cell/module production by the largest Japanese and U.S. solar cell/module players.)

TABLE 28: Japanese and U.S. cell/module production 1994 to 2003

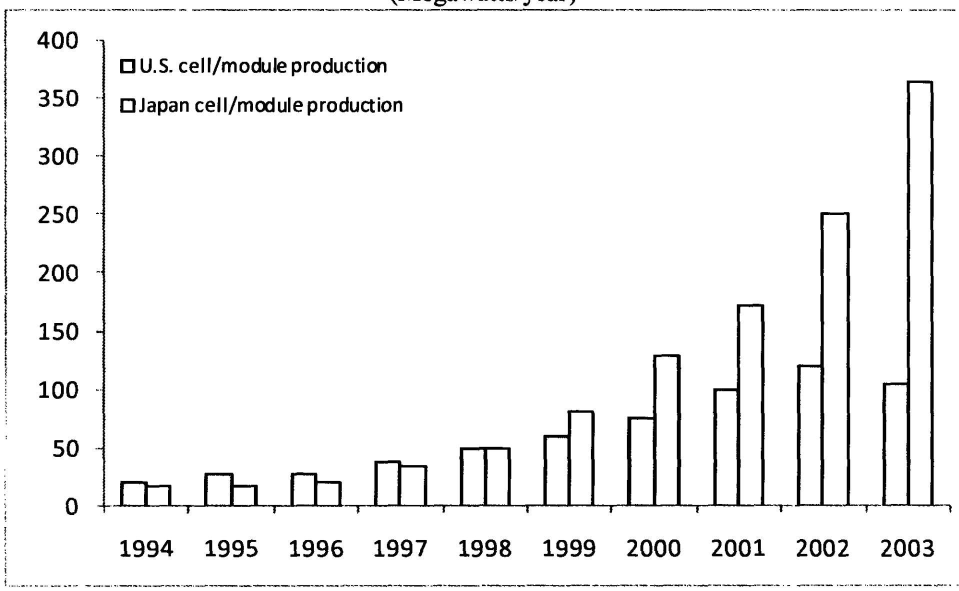
(MW per year and percent)

JAPANESE PRODUCTION	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Sharp	2.0	4.0	5.0	10.6	13.9	30.0	50.4	75.0	123.1	197.9
Kyocera	5.5	6.1	9.1	15.3	24.5	30.3	42.0	54.0	60.0	72.0
Sanyo	5.5	5.1	4.6	4.7	6.4	13.1	17.0	19.0	35.0	35.0
% Japanese production by electronics players	79%	93%	88%	87%	91%	92%	85%	86%	87%	84%
Mitsubishi	0.0	0.0	0.0	0.0	0.0	0.0	12.0	14.0	24.0	40.0
Other	3.5	1.1	2.5	4.4	4.2	6.6	7.2	9.2	9.0	19.0
JAPAN TOTAL	16.5	16.4	21.2	35.0	49.0	80.0	128.6	171.2	251.1	363.9
% Japan share of global production	24%	21%	24%	28%	32%	40%	45%	44%	45%	49%
US PRODUCTION	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Shell Solar (formerly Siemens)	13.5	17.2	17.0	22.0	20.0	22.2	28.0	39.0	46.5	52.0
BP Solar (formerly Solarex/Amoco/Enron Solar)	6.1	7.2	8.4	11.3	15.9	18.0	20.5	25.2	31.0	13.4
RWE Schott (formerly ASE, Mobil)	0.0	0.0	0.0	0.0	4.0	4.0	4.0	5.0	5.0	4.0
AstroPower (later GE)	1.7	2.5	2.8	4.3	7.0	12.0	18.0	26.0	29.7	17.0
ECD	0.0	0.0	0.0	0.0	2.2	3.0	3.0	3.8	4.0	7.0
Global Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
First Solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
Evergreen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	2.8
Other	0.0	0.0	0.0	0.0	0.6	1.0	1.5	1.3	2.5	2.0
U.S. TOTAL	21.2	26.9	28.3	37.6	49.7	60.2	75.0	100.3	120.6	104.2
% U.S. share of global production	31%	35%	32%	30%	32%	30%	26%	26%	21%	14%

Source: Maycock PVNews.

While the impact of a more homogeneous group of industry players is difficult to isolate and quantify, it is clear that the solar sector players in Japan (specifically the electronics companies with solar divisions) made stronger commitments to corporate-level expansions and to industry-level coordination (e.g. roadmapping) than their U.S. counterparts. As displayed in FIGURE 90, Japanese cell/module production grew much faster than U.S. cell/module production starting in 1995. The economic rationale for corporate-level expansion decisions was provided in Section 3 (Japan) and Section 4 (U.S.) using NPV analysis. In addition to this microeconomic explanation for expansion of solar power manufacturing by Japanese companies, there seems to be a broader set of factors that lined-up to enable the rapid expansion of Japan's solar power sector. This broader set of factors includes industrial organization factors (e.g. less complex electricity industry and players in the solar power sector with a more homogeneous history, outlook, size and commitment) that almost certainly enabled Japan's solar power supply-side to expand faster than the U.S. with its more complex electricity industry and more heterogeneous solar power players.[267]

FIGURE 90: Annual cell/module production in Japan and U.S. 1994 to 2003
(Megawatts/year)



Source: Maycock/PV News.

The impact of increasing scale and learning was that solar power costs in Japan decreased significantly during the years 1994 to 2003. The 22-fold growth in annual production in Japan equates to roughly 22-fold growth in cumulative production, which in turn equates to between four- and five-doublings during the period 1994 to 2003. Assuming a progress ratio of roughly 80% for the solar supply-chain, this equates to a predicted reduction in the cost (not price but cost) of a solar power system of roughly 60% to 70%. In contrast, the U.S. solar power supply-side increased annual and cumulative production by only 4-fold from 1994 to 2003. This equates to two-doublings, compared to nearly five-doublings in Japan. Assuming a progress ratio of 80%, this equates to a predicted reduction of cost for the U.S. supply-side of roughly 36%. The implication is that cost reductions from scale and learning of the Japanese solar power sector should have been roughly twice as fast as in the U.S.

The much stronger volume growth achieved from 1994 to 2003 by the Japanese solar power supply-side compared to the U.S. is not attributable to any one factor. However, several extrinsic

[267] Note: A similar case can be made for the downstream portion (integration/installation) of the solar power sector in which Japan's larger homebuilders and electrical contractors can be compared to much smaller independent integrator/installers in the U.S.

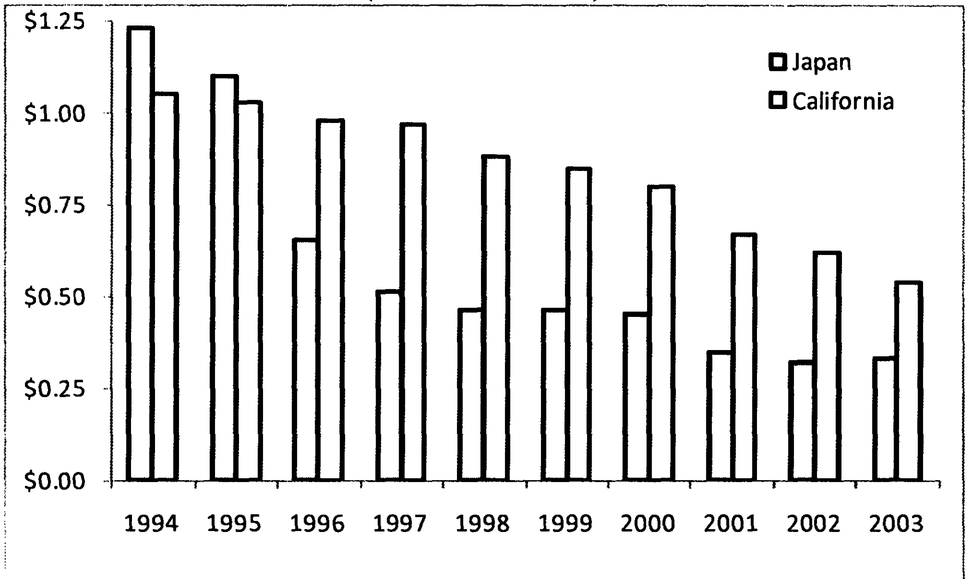
factors and aspects of industrial organization appear likely to have lined-up in a manner that helped enable rapid growth of Japan's solar power sector. Both the extrinsic and the industrial organization factors are potential areas for further research in order to better evaluate the relative impact of each factor. Within this thesis, additional details on the supply-side are provided below in "(4) Manufacturer economic factors."

(3) End-customer economic factors (i.e. Factors that reduced the "gap")

In addition to extrinsic factors and industrial organization factors, other factors influenced end-customer economics by reducing the "gap" between levelized net system price and average residential grid price in Japan earlier and faster than in the U.S. The earlier and faster reduction in the "gap" in Japan resulted from a combination of (a) fast solar power system price decreases and (b) the government's end-customer incentive program. As shown in FIGURE 91, levelized gross system prices (i.e. without incentives) in Japan were higher in Japan than the U.S. in 1994-1995, but went below the LGSP in the 1996 and remained lower through 2003.[268] This reduction in the LGSP was driven primarily by decreases in module prices (-9% CAGR) and non-module prices (-16% CAGR) in Japan that far exceed decreases in module prices (-3% CAGR) and non-module prices (-7% CAGR) in the California and overall U.S. market. (FIGURE 92).

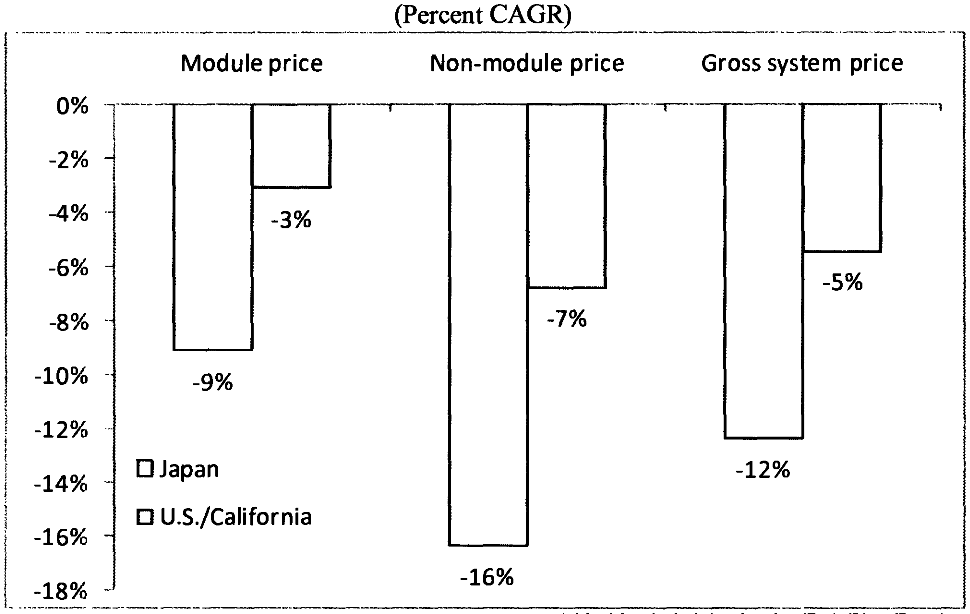
[268] As described in Section 3, the main drivers of LGSP decreases in Japan were reduction in the price of non-module system inputs (installation, wiring, inverter, etc.) and in the price of modules.

FIGURE 91: Levelized gross system price in California and Japan 1994 to 2003
(Nominal U.S.$/kWh)



Source: Michael Rogol calculations.

FIGURE 92: Compound annual price changes in module, non-module and system prices in California and Japan 1994 to 2003
(Percent CAGR)



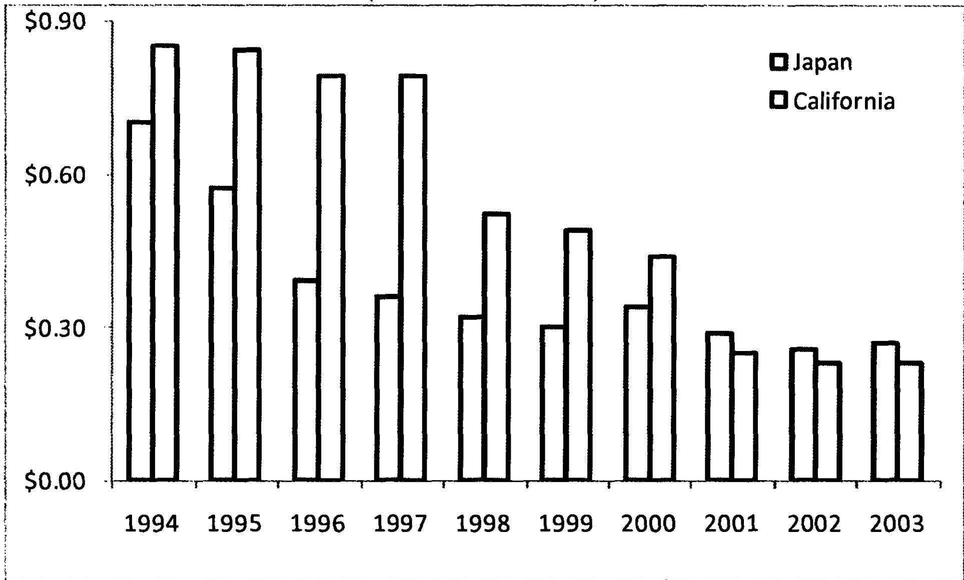
Source: Michael Rogol calculations based on IEA PVPS. NEDO. Maycock/PVNews.

Interestingly, the overall gross system price reductions in both Japan and the U.S./California were similar in magnitude to the cost reductions suggested by applying an 80% progress ratio to the expansion of the supply side. Specifically, gross system price in Japan decreased by a factor of 70% in US$-terms and 66% in yen-terms from 1994 to 2003, almost precisely in line with the 60% to 70% cost reduction range estimated on page 160. Similarly, the gross system price in the U.S./California decreased by a factor of 40% from 1994 to 2003, in line with the 36% reduction in cost estimated on page 160. The key point is that increasing scale on the supply-side appears to be closely related to decreasing costs which in turn appears to be closely related to decreasing prices. The apparent linkages are supply-side volume increase → cost reduction → price reduction.

While 'production growth that drove cost reductions that drove price reductions' is an important pattern in both Japan and the U.S., interviewees in both Japan and the U.S. repeatedly mention incentive programs as being an "important fuse", "a trigger" and "the starting point for real end-customer demand."[269] This makes sense in that the early years of the incentive program in Japan had very high per-watt incentives (roughly $10/watt in 1994 and 1994) that drove down the "gap" between levelized net system price and average residential grid price. As shown in FIGURE 93, the levelized net system price in Japan was lower than in California in 1994 and 1995 as the result of the high level of Japanese demand-side incentives (roughly $9/watt). From 1996, the demand-side incentive was reduced significantly (to roughly $4.6/watt in 1996) but (as seen in FIGURE 93) the LNSP continued to decrease in Japan *despite* the declining incentive as the result of strong decreases in non-module and module prices. With implementation of a similar buy-down incentive in California in 1998 and an increase in the per-watt incentive in 2001, the LNSP in California decreased significantly in 1998 and again in 2001. As shown in FIGURE 94, the "gap" between LNSP and average residential grid prices in Japan fell faster and earlier than the "gap" in the U.S. This was the result of a combination of large per-watt incentives in 1994-1995 and significant gross system price reductions from 1996 to 1998. In 1998 and again in 2001, the "gap" in California decreased as the result largely of higher per-watt incentives.

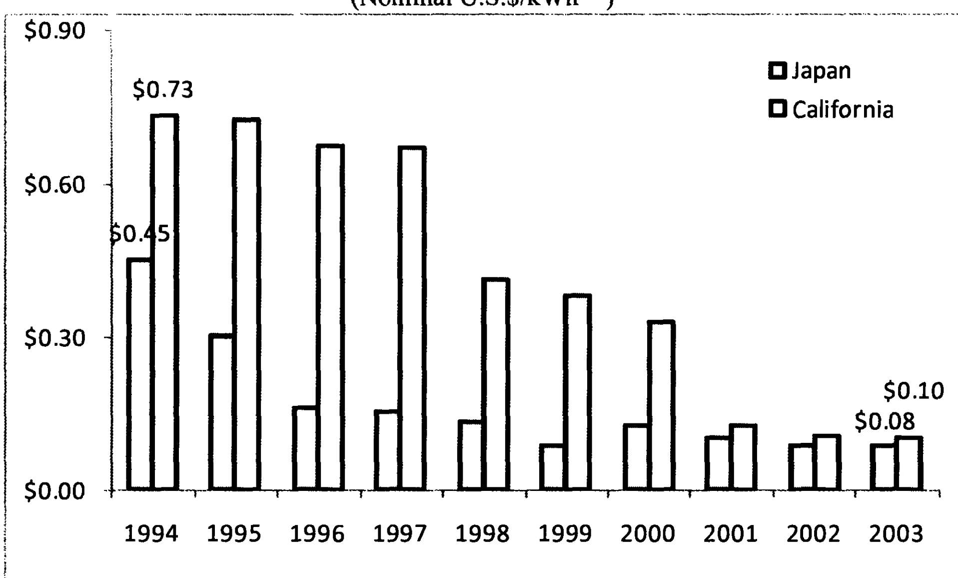
[269] Interviews as part of research for Rogol (2004).

FIGURE 93: Levelized net system price in California and Japan 1994 to 2003
(Nominal U.S.$/kWh)



Source: Michael Rogol calculations.

FIGURE 94: "Solar gap" in California and Japan 1994 to 2003
(Nominal U.S.$/kWh[270])



Source: Michael Rogol calculations.

One key point is that the "gap" decreased quickly in Japan in the early years of the period 1994-2003 as the result of a combination of government incentives and gross solar system price

[270] LNSP minus grid price

reductions. The result of the declining "gap" was a significant increase in installations. Another key point is that the demand-side pattern in California was quite similar to the pattern in Japan. Following incentives being put in place in California in 1998-2001, installations grew quickly as the "gap" declined. The pattern of "gap" reduction and installations was strikingly similar in both markets, with similar compound annual growth rates (47% in Japan and 51% in California) and similar elasticities of demand (-2.8 in Japan and -2.6 in California) for 1994 to 2003. The most noticeable differences between the demand pattern in Japan and in California were that California's demand "tipped" (a) later than Japan (1996 versus 2001) and (b) at a lower LNSP than Japan (i.e. from LNSP of roughly $0.35/kWh in Japan versus roughly $0.25/kWh in California).

It is also worth noting that the "gap" was *positive* in both Japan and California throughout the period 1994 to 2003. This raises the question, "Why did customers adopt solar power if the 'gap' was positive?" There are several possible explanations for this. For example, some customer may have been willing to pay a premium for solar power due to its "green" image.[271] Perhaps more likely, the problem may be one of data – using typical interest rates and average residential grid prices for analysis may overstate the "gap" for many customers. Further research should be conducted on *actual* interest rates and grid prices for specific customers in order to more accurately assess end-customer economics and adoption patterns.

Yet even using *average* data for interest rates and grid prices, it is clear that there was a multifaceted interaction between demand-side incentives/supply-side scale expansions/cost reductions/price reductions/demand increases. It appears that demand-side incentives were a "trigger" for rapid growth in installations in both the U.S. and Japan, with rapid expansion of installations occurring only after incentives were instituted. These incentives reduced the "gap", thereby improving end-customer economics and driving demand for installations.

(4) Manufacturer economic factors

On the supply-side, a mosaic of factors led to attractive economics – and hence rapid expansion – for companies along the supply chain within Japan's solar power sector. A simplistic representation of the attractive supplier economics, as discussed in Section 4, is the net present

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[271] According to one interviewee, "10% of the population will pay a 2% premium; 2% will pay a 10% premium. A classic demand curve."

value of an investment in a 100MW cell/module manufacturing plant in Japan in 1994 to supply the domestic market. From the perspective of 1994, the NPV of this $90 million investment was *positive* $114 million. That the NPV was positive is surprising because the fully-loaded cost of manufacturing in Japan at the start of the period (1994-1995) were higher than in the U.S. Costs in Japan were higher due to smaller scale, less experience, etc. compared to U.S. counterparts at that time. Yet the NPV was positive due to (1) the high price of modules in Japan ($9/watt, well above module prices of $4/watt in the U.S./California) and (2) expectations that the price of modules would decrease but not quickly collapse to global prices.[272]

This second expectation (no quick collapse of module price in Japan to global price levels) was based on belief that the Japanese federal government incentive program would provide significant, reliable price support for several years. As discussed in Section 3, faith in the Japanese government's *demand-side* incentive program was central to *supply-side* decisions to expand capacity. This is yet another example of interplay among factors that makes isolation of variables difficult. Through the period 1994 to 2003, prices for solar modules (-9% CAGR) and non-module inputs (-16% CARG) decreased rapidly. These price decreases occurred at the same time that national per-watt incentives were being reduced. The level and pace of these incentive reductions served to both push down prices *and* maintain prices that were above global levels. (FIGURE 95) It appears that this careful manipulation of the per-watt incentive enabled not only improving end-customer economics (driven by incentive system price reductions outpacing incentive reductions) but also attractive manufacturer economics (i.e. cost reductions that outpaced – or at least kept pace with – price reductions) and module prices that remained above U.S. levels throughout the period 1994 to 2003.

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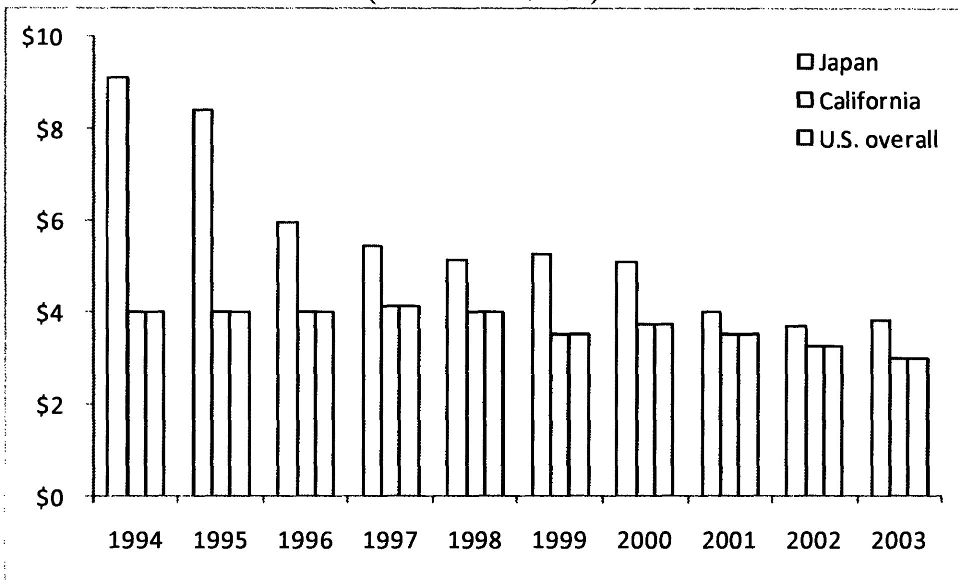
[272] An area for further research is the downstream portion of the Japanese supply chain. Conducting a similar assessment of the NPV of investments made by, for example, Sekisui Chemical and Panahome, would extend this analysis beyond the cell/module level and confirm that the description provided here is applicable to the broader supply chain instead of the cell/module level alone.

FIGURE 95: Module price in Japan, California and U.S. overall 1994 to 2003
(Nominal U.S.$/watt)

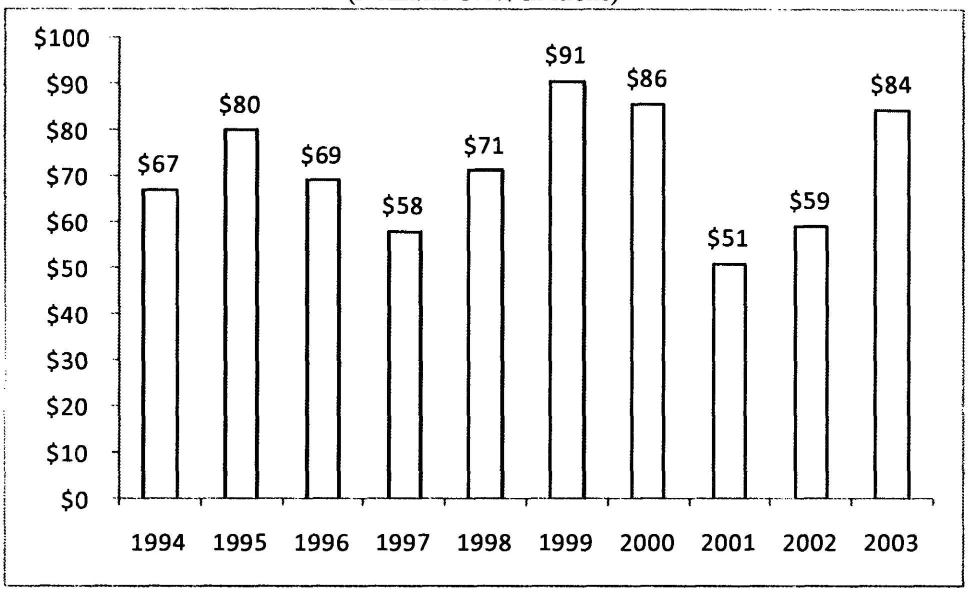


Source: Maycock/PV News; NEDO; IEA PVPS.

The overarching point is that manufacturing investment decisions were influenced by a mosaic of factors – high grid prices, low interest rates, easy grid-connection rules, reliable demand-side incentives, consistent supply-side programs, more conducive industrial organization and other factors – that provided a strong environment for supply-side growth in Japan. These factors lined-up in a manner that enabled attractive manufacturer economics (i.e. positive NPV estimates) and led to the most important result: significant investments to scale-up Japan's solar power sector. This is the most important result because these investments brought not only supply, but also cost reductions which were passed along to customers as price reductions, which in turn "opened-up" more demand even while per-watt demand-side incentives were declining and, eventually, being eliminated.

In Japan, the $716 million spent by the government on supply-side R&D from 1994 to 2003 (FIGURE 96) was an *additional* factor (i.e. in addition to the extrinsic, industrial organization and demand-side factors discussed above). The scale (tens of millions of dollars per year) and consistency (program funding was considered reliable) were cited by interviewees as being important for establishing a knowledge base for the sector. However, the supply-side incentives were only part of a mosaic that created an attractive investment picture for Japanese solar power companies.

FIGURE 96: Japanese government solar power R&D 1994-2003
(Nominal U.S.$ millions)



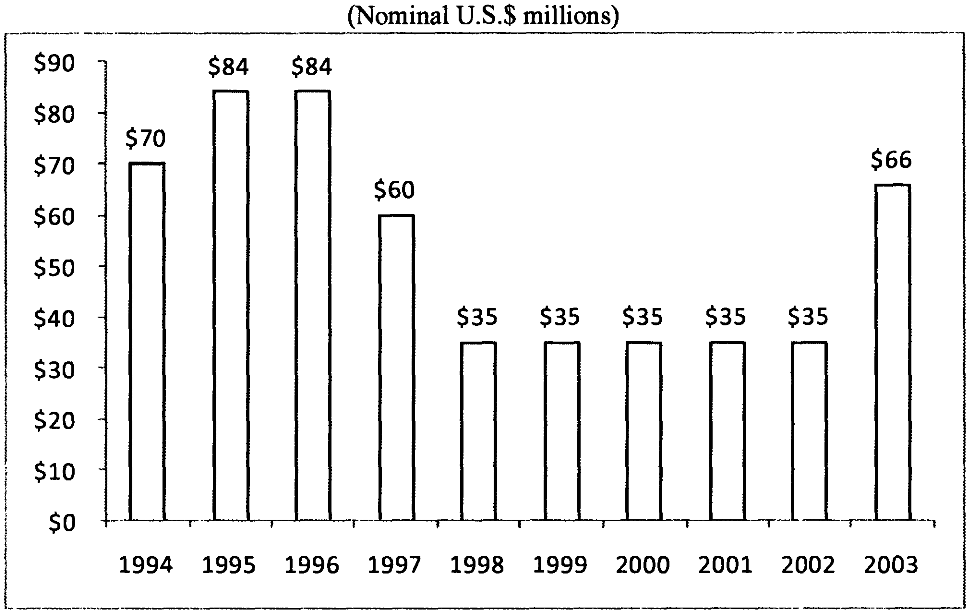
Source: IEA PVPS.

The remarkable line-up of factors that supported the rapid growth of Japan's solar power supply-side appears to have occurred, at least partially, as the result of a rigorous coordination effort.[273] This coordination effort involved a multifaceted group of participants from government, solar power companies, housing companies, electric power companies, chemical companies and other sectors. Given the central importance of supply-side cost reductions, it is not surprising that many interviewees pointed to the PVTEC's efforts to roadmap and coordinate as an important element in the success of Japan's solar power sector. Yet given the complexity of the mosaic, it is also not surprising that there appear to have been numerous other institutions (including NEF, NEDO and AIST) involved in various coordination activities. Currently, there is no detailed information in the English language literature on these coordination efforts, highlighting an important focus for future research.

[273] Of course, some of these factors (especially the extrinsic factors such as solar resource and interest rate) were beyond the scope of any coordination effort. But many (e.g. demand-side incentive manipulation, supply-side research prioritization, grid connection rules) appear likely to have been significantly influenced by coordination efforts.

In contrast to the attractive supply-side mosaic in Japan, the picture in the U.S. was much less compelling. As discussed in Section 4, the NPV of a 100MW cell/module plant in 1994 the U.S. to supply the domestic market had an NPV of roughly *negative* $122 million. This was a contrast to the positive NPV estimated for Japan in 1994. The major difference between the two NPV estimates was that price for modules were much lower in the U.S. Yet beyond lower prices that drove a negative NPV in the U.S., there were numerous other factors – rapid decline in government supply-side programs, no national and inconsistent state demand-side incentives, a less cohesive industrial organization, inconsistent or non-existent grid-connection rules, lower grid prices, higher interest rates and other factors – that created a less attractive environment for supply-side expansions. In the U.S., government R&D spending (FIGURE 97) was both 25% lower than in Japan and also significantly more volatile. This was an *additional* factor (i.e. in addition to the extrinsic, industrial organization and demand-side factors discussed above) that made the expansion of the supply-side in the U.S. less attractive than in Japan. The supply-side incentives were part of a mosaic that created a less attractive investment picture for U.S. solar power companies.

FIGURE 97: U.S. government solar power R&D 1994-2003
(Nominal U.S.$ millions)



Source: IEA PVPS.

The net impact was that the Japanese supply-side expanded at a much faster rate than the U.S. From 1994 to 2003, Japanese cell/module production increased at a 41% CAGR, more than twice the rate of the U.S. (17% CAGR). This drove down costs faster in Japan than in the U.S., which in turn drove faster price reductions, which in turn enabled reduction in the per-watt incentives without disrupting rapid expansion of Japan's solar sector. The short point to this long description is that there were numerous, overlapping factors that enabled faster growth of the supply-side in Japan.

(5) Policy factors

The above descriptions of intrinsic, industrial organization, demand and supply related factors shows clear interplay among factors and has already touched upon the role of government policies in enabling the rapid growth of Japan's solar power sector. This subsection focuses on these policy factors. Specifically, the rapid growth of Japan's solar sector was supported by a combination of policies, including:

- **Grid connection rules.** Policies to enable solar power systems to connect to existing power networks and to enable customers to "net meter"[274] appear to have been necessary but not sufficient conditions for the rapid expansion of solar power manufacturing and consumption in Japan. These policies reduced the cost of solar power by roughly $2/watt (roughly $0.13/kWh)[275] and, as a result, enabled suppliers to consider pursuing a new market segment (small-scale grid-connected systems) without the need for expensive storage equipment. Grid connection policies were established at an earlier time and more consistently (nationally versus at state level) in Japan than in the U.S.

- **Demand-side incentives.** Government incentives reduced the "gap" between the levelized net price of solar power and residential grid prices appear to have been an important "trigger" in the rapid increase in solar power consumption by Japanese end-customers. In addition, the consistency of these policies appears to have been important because it provided an additional positive signal to suppliers assessing investments in solar power manufacturing capacity.

- **Supply-side incentives.** Rapid expansion of production that reduced the cost of solar power was a lynchpin of Japan's "virtuous cycle." Supply-side policies (specifically R&D cost-sharing) appear to have been an important element in establishing a foundation for the rapid growth of solar power manufacturing. The consistency, scale (tens of millions of dollars per year) and predictability of Japan's supply-side incentives helped create a knowledge base that in turn enabled manufacturers to quickly move down the learning/experience curve. In contrast, inconsistent funding in the U.S. (especially at precisely the time that California instituted significant demand-side incentives) was a factor that likely diminished the pace at

[274] "Net meter" rules enable the customer to sell any excess solar electricity back to their traditional electricity supplier at full retail price and also to use electricity from the traditional electricity supplier during times (e.g. night or cloudy day) when their electricity use exceeds the supply from the solar power system.
[275] Rough estimate based on interviews not on actual data. Cost reduction of roughly $2/watt for cost of storage in 1994.

which U.S. solar power companies expended, thereby limiting cost reduction potential and the potential impact of a "virtuous cycle."

- **Coordination policies.** It appears that coordination/roadmapping efforts were important to the growth of Japan's solar power sector. These coordination efforts included: (a) identification of target segments/markets and barriers to growth in specific segments; (b) data/information/feedback on customer adoption (price, volume, etc.); (c) data/information/feedback on in-field problems that led to the adaptation of supply-side R&D incentives; and (d) precise manipulation of demand-side incentives. The U.S. also undertook industry roadmapping and coordination efforts, though these efforts were more limited than the Japanese efforts in terms of both scope (supply-side focus in U.S. compared to broader industry focus in Japan), scale (more industry stakeholders involved in Japanese roadmapping/coordination efforts than in U.S.) and duration (Japan's effort lasted throughout 1994 to 2003 whereas the U.S. effort under PVMaT was significantly diminished from 1998).

The combination of policies in Japan lined-up with other factors to help stimulate fast growth of solar power installations in Japan *and* fast growth of solar power manufacturing in Japan *and* fast decreases in solar power prices in Japan. In contrast, the combination of U.S. policies lined up with a less attractive extrinsic setting (i.e. lower grid prices and higher interest rates) and a less conducive industrial organization to deliver installation growth, production growth and price reductions that were slower than Japan.

It is important to emphasize that preliminary interviews point to coordination/roadmapping policies as having a shaping influence that was of central importance to the growth of Japan's solar sector. This is not to say that coordination/roadmapping activities were solely responsible for the rapid growth of the sector, but that they played an important role. Emphasizing this point is important because the current English literature lacks a description of *exactly* what was involved in the Japanese coordination/roadmapping efforts. Additional research is necessary to be able to better evaluate how the coordination/roadmapping helped shape not only many of the factors (e.g. manipulation of demand-side incentives, focus of supply-side R&D budgets) but also how coordination/roadmapping shaped *interplay* among factors.

(C) Key lessons learned and implications for the U.S.

The central question for this thesis is, "Why did the solar power sector develop quickly in Japan?" The first-order response to this question, based on a comparative analysis of the

Japanese and U.S. solar power sectors from 1994 to 2003, is that the rapid growth of Japan's solar power sector was enabled by *interplay* among (a) decreasing gross system prices price, (b) increasing installations, (c) increasing production and (d) decreasing costs.

The second-order explanation for this interplay is that *a mosaic of factors* led to (a) decreasing prices, (b) increasing installations, (c) increasing production and (d) decreasing costs. This mosaic included the extrinsic setting (solar resource, interest rate, grid price), industrial organization (including the structure of the electric power sector and the structure within the solar power sector), demand-side incentives that drove down the "gap" with and provided a "trigger" for supply-side growth, and supply-side expansion that enabled significant cost reductions and price reductions that more than offset the decline in demand-side incentives. Within this complex interplay of numerous factors, roadmapping and industry coordination efforts played an important role by shaping the direction of Japan's solar power sector. This shaping influence (discussed in Section 3) included: focusing on small-scale grid-connected systems; enabling learning spillovers; supporting supply-side and demand-side policies that pursued grid parity; recognizing the stronger-than-expected growth potential from crystalline silicon technologies; and focusing on BIPV applications that had stronger economic benefits than non-building integrated applications.

In contrast, the U.S. during the years 1994 to 2003 had slower growth in installations, slower growth in solar power manufacturing and slower decreases in solar power prices compared to Japan. The comparative case studies suggest that these differences (slower demand side growth, slower supply side growth and slower price reductions in the U.S.) resulted from a mosaic of factors, including: less attractive extrinsic environment (e.g. lower grid prices and higher interest rates); less conducive industrial organization (e.g. inconsistent and/or non-existent grid-connection rules in many geographies); less compelling end-customer economics (e.g. slower reduction in "gap"); unattractive supply-side economics (e.g. negative NPV for many investments); lower funding for and less consistency in supply-side incentives; later and less geographically consistent funding for demand-side incentives; and less consistent policies and less robust coordination policies in the U.S.

One key implication from this analysis for U.S. policies is that an integrated approach to solar power policies that takes into account grid-connection policies, demand-side policies, supply-side policies and coordination policies may have benefits. In addition to this high-level conclusion, there are also more specific lessons-learned from the Japanese experience that may be applicable in a U.S. setting. For example, U.S. policy makers might attempt to:

- Focus supply-side and demand-side policies in areas where parity with the substitute price is most likely to be achieved (e.g. higher price electricity markets, regions with the strongest solar resource);
- Establish federal grid-connection and net metering rules that are simple for solar power system integrators to implement;
- Set demand-side incentives that are commensurate with the "gap" between levelized solar power prices and grid prices;
- Institute demand-side incentives that decline over time so that supply-side cost reductions enable end-customer prices to decline at the same time that government incentives also decline;
- Establish a reliable budget for demand-side incentives that increases confidence among suppliers and customers;
- Consider that careful manipulation of demand-side incentive levels may be necessary to effectively drive down solar power prices;
- Consider programs to reduce the interest rate for long-term loans to pay for solar power systems because interest rates have a significant impact on the levelized price of solar power;[276]
- Collect, analyze and react to data on demand elasticity and, more specifically, changes in demand elasticity as the levelized net system price of solar power approaches the price of its substitute (i.e. approaches parity with grid price);
- Establish a reliable budget for supply-side incentives that increases confidence among suppliers and enables the development of a deep knowledge base that can be tapped to reduce costs;
- Pursue programs that are commensurate with the stage of technological understanding. And, more specifically, do not pursue *deployment* programs for technologies that are not well understood;
- Focus on cell-level efficiency gains and other production cost metrics (e.g. grams/watt, yield) in order to drive down the cost of the total system;
- Focus on cost reduction efforts in non-module system inputs (including hardware and non-hardware inputs) that have significant potential for cost compression;

[276] This specific potential policy lever is highlighted because interviewees consistently overlook it as a potentially high-impact lever for policy intervention to support solar power installations.

- Consider establishing a systematic coordination effort for supply-side research, development and demonstration projects similar to Japan's PVTEC with a consortium of industry, academic and government participants; and

- Because cognition is necessary from a diverse set of actors (industry, customers, policy makers), make reliable data collection, analysis and dissemination a priority.

The above list is *preliminary* and further research is required to provide more concrete and better substantiated implications for the U.S. solar power sector. In particular, two areas in which neither the English-language literature nor this thesis provide sufficiently detailed descriptions or analysis are (a) Japan's roadmapping/industry coordination efforts and (b) analysis of the impact of industrial organization on the solar power sector's growth. These two areas are mentioned in particular because they are important for generalizing lessons from the solar power sector and assessing the applicability of these lessons to other technology sectors.

(D) Questions for further research

While the case studies presented in this thesis suggest that there are insights to be gained from a comparative analysis of the U.S. and Japanese solar power sectors that may be applicable for U.S. policy makers, these results are based on a limited analysis. This work has led to an additional set of research questions:

- Provide detailed description and analysis of the Japanese PVTEC consortium's industry roadmapping and roadmapping activities and their impact: How *exactly* did this consortium come into existence, operate and influence the growth of Japan's solar power sector?

- Refine the case studies to include more focus on industrial organization: Why was production growth largely the focus of electronics companies in Japan and of smaller companies/energy companies (i.e. not large electronics manufacturers) in the U.S.? Does this manufacturing expertise explain the difference in the faster growth of manufacturing in Japan? Was the emergence of electronics sector players as leading solar power players a result of Japanese policy? Are there lessons for U.S. roadmapping/coordination efforts on the supply-side?[277]

- Extend the case studies to include more focus on downstream. Is there a parallel downstream story (i.e. were the larger Japanese homebuilders better positioned in terms

[277] As Professor Moniz pointed out during discussion (March 2007), "Another issue is the role of industrial organization. It seems to me that the focus of building off the semiconductor/microelectronics industry provided a different industry organization, one that was much more amenable than the U.S. industry organization. How would you roadmap an industry that has behemoths and little start-ups? If you want to go from the case studies to focus on industry roadmaps, then you much incorporate the industrial organization in Japan. The industrial organization may have been the key in Japan. If so, roadmapping was a much easier tool to apply…"

of cost reductions, product development, market, sales, government relations, etc.) than the smaller, specialized solar distributors in the U.S.? What role did the homebuilders and electrical contractors have in lowering cost, raising awareness and boosting market acceptance faster than manufacturing cost reductions alone would have permitted? How does the case of the Japanese homebuilders compare with the specialized solar distributors in the U.S. and with the farmers cooperatives in Germany?

- Build-up comparative case studies of the development of the solar power sector in additional geographies: In terms of further research, Germany is a top priority. This is (a) because Germany became the world's largest solar power market from 2004 as the result of introduction of a significant demand-side incentive and (b) because the German policy was a feed-in tariff not a buy-down incentive program. Evaluating the similarities and differences among Japan, the U.S. and Germany will almost certainly yield deeper insights to address questions such as, "Why did the solar power sector develop quickly in Japan?"[278]

- Compare the Japanese experience in roadmapping the solar power sector with experience in other sectors. How, for example, did industry coordination efforts occur in a non-commodity sector such as biotech?

- Build-up comparative case studies of the development of other, similar industries: What are the similarities, differences and lessons learned by comparing the development of the solar power sector to the development of the semiconductor industry in U.S. and Japan and/or coalbed methane in U.S.? What was the role of roadmapping and industry coordination efforts in these other cases?

- Develop a theoretical framework for a system dynamics model of the development of the solar power sector: What are the key parameters for this model? How can research begin to estimate these parameters?

In conclusion, this thesis used a comparative case study methodology to address the question, "Why did the solar power sector develop quickly in Japan?" The comparative analysis suggests that the rapid growth of Japan's solar power sector resulted from a mosaic of reinforcing factors including a combination of policies, including grid connection rules, supply-side incentives, demand-side incentives and coordination policies. This research has also identified a set of research questions for further research.

[278] One peer reviewer commented: "I think the structure of the incentive was third-order. Other factors that made Germany interesting: (1) Like Japan, lower sunlight but higher grid prices that allows another evaluation of how important overall "gap" is versus "gap factors"; (2) largely federally driven policy (like Japan, unlike U.S.); (3) distinctive downstream organization; (4) emergence of a financially-driven ground-mounted segment (unlike Japan or U.S.) that allows 2-significant digit, statistically significant correlation of LNSP with demand."

Appendix: References

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