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Behavior of technology in reducing prices of innovative goods—an analysis of the governing factors of variance of PV module prices

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Abstract

Classical growth accounting theory suggests that technological innovation leads to a price decrease. Technology diffusion theory states that technology diffuses into a market place in an epidemic manner and is incorporated into production factors and innovative goods. In addition, learning theory suggests that the learning exercise results in a price decrease. Even though these theories work with overlapping processes no significant work has yet to be undertaken to bridge these three theoretical frameworks. Consequently, the behavior of technology in reducing the prices of innovative goods remains a 'black box.'

This paper attempts to elucidate this black box by unraveling this mechanism. An empirical analysis across a distribution of 639 PV module prices in Japan's leading PV firms is introduced and the mechanism of technology contribution to decreasing these prices is identified.

Keywords: Technology incorporation; Technology spillover; Prices formation; PV module

1. Introduction

Not withstanding enormous academic and commercial investments in unraveling technological innovation, its behavior is still largely uncharacterized. In this regard many of the stylized facts are unknown. As a rational shift toward information and knowledge-based economic development, this process is a crucial issue. Similarly, as R&D investments decline, capturing technology spillover becomes an increasingly important part of this process (Watanabe et al., 2001).

Triggered by classical growth accounting theory initiated by Denison (1962) as well as Jorgenson and Griliches (1967) a number of studies have linked technology innovation and price decrease treating this behavior as a proxy for technology innovation.

Similarly, Rogers (1962) analyzed the diffusion process and mechanism of innovation. Following this work, a number of studies has traced the diffusion trajectory of technology in the market place chiefly based on the epidemic concept.

In addition, Arrow's (1962) monumental work on learning by doing explored new territory in linking price reduction and technological improvement through a learning exercise. In this context, a number of studies have compiled invaluable analyses for the identification of the effect of learning exercises on the reduction of prices for innovative goods.

A number of works endeavor to elucidate the behavior of technology primarily based on these three dimensions. However, no substantial studies have attempted to bridge these three theoretical frameworks. Consequently, this behavior in prices reduction for innovative goods remains a black box.

This paper attempts to elucidate this black box by analyzing Japan's photovoltaic power generation (PV) technology. The success story of Japan's technology in this field demonstrates the construction of a 'virtuous cycle' between technology development, production increase and price reduction.

Using this success story, an empirical analysis was undertaken using a distribution of 639 PV module prices in Japan's leading PV firms in 2000. Furthermore, on

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the basis of a numerical analysis, the mechanism of technology contribution to decreasing prices was characterized. Of particular interest was the role this mechanism played in the construction and support of this virtuous cycle.

Section 2 reviews the virtuous cycle between technology development, production increase and price reduction in Japan's PV development. Section 3 analyzes the distribution of 639 PV module prices. Section 4 explains the mechanism of a virtuous cycle between technology spillover, technology improvement and the learning exercise leading to price decrease. In Section 5, a numerical analysis is conducted for the identification of the governing factors for variance of PV module prices. Section 6 briefly summarizes concluding remarks and implications for a technology innovation strategy.

2. The 'Virtuous Cycle' between technology development, production increase and price reduction

Japan's PV technology is an exceptional example of achieving comparative advantage in the renewable energy field. Overall, Japan's pioneering efforts in developing renewable energy technology (RET) have not achieved the same results primarily because of inherent resource constraints for RETs. However, Japan has taken a leading role in world PV development. This is largely due to two main factors. First, PV technology, similar to semiconductor technology, maximizes the benefits of learning effects because it is central to a complex web of related technologies. Secondly, the interdisciplinary nature of its development also maximizes the benefits of technology spillovers (Watanabe and Griffy-Brown, 1999). These two critical success factors highlight the role of the endogenous technological innovation process at work, which induces technological change. In this context, Japan's Ministry of International Trade and Industry (MITI)[1] initiated PV development under its Sunshine Project (R&D program on New Energy)[2] in order to induce technological change by maximizing these endogenous factors. This was achieved by: (i) encouraging the broad cross sectoral industry involvement; (ii) stimulating inter-technology stimulation and cross sectoral technology spillover; and (iii) inducing a vigorous industry investment in PV R&D leading to an increase in industry's PV technology stock. An increase in this technology stock contributed to a significant increase in solar cell production. Figs. 1 and 2 illustrate trends in solar cell production in the world and the share of production by country. Looking at Fig. 1, we note that Japan's solar cell production significantly increased since 1997: 35.0 MW in 1997, 49.0 MW in 1998, 80.0 MW in 1999 and 128.6 MW in 2000. Consequently, its share in the world demonstrates conspicuously increased from 28% in 1997, 32% in 1998, 40% in 1999, and 45% in 2000 as illustrated in Fig. 2.

Figs. 3 and 4 illustrate trends in such dramatically increasing solar cell production in Japan and its share in Japan's total production. Looking at Fig. 4 we note that the shares of the top three firms (Sharp Corp., Kyocera Corp. and Sanyo Electric Co., Ltd) amounted to nearly 90% of solar cell production in Japan (91% in 1998, 92% in 1999 and 85% in 2000).

Greater solar cell production supported by an increase in technology stock and also induced by energy prices, provides both solar cell producers and customers with an opportunity for a learning exercise/experience curve in addition to the benefits of economies of scale. A higher level of production generally led to a decline in solar cell production prices as demonstrated in Table 1 and Fig. 5. The solar cell production price in 1974, the year the Sunshine Project was started, was 20,000 yen/W; it decreased to 5000 yen/W in 1980, 2000 yen/W in 1982, 1200 yen/W in 1985, 650 yen/W in 1990, and 595 yen/W in 1995, and 490 yen/W in 1999, respectively, at current prices. This process can be explained by two trajectories: (i) the inducement by technology stock coupled with the price of energy; and (ii) effects due to learning effects and economies of scale.

A significant decrease in solar cell production prices, induced a further increase in solar cell production. In addition, the subsequent increase in solar cell production induced further PV R&D and thus created a virtuous cycle between R&D, market growth and price reduction (Watanabe and Griffy-Brown, 1999, 2000).

Fig. 6 demonstrates a virtuous cycle between R&D triggered by the Sunshine Project, steady market growth and consequently significant price reduction in PV development in the Japanese industry over the period 1976–1995. Noteworthy is the 'double boost effect' to solar cell production coming from both increased technology stock of PV R&D and decreased solar cell production prices. Similarly a double boost effect can be observed in PV R&D, which is the source of technology stock, coming from increased solar cell production and MITIs PV R&D budget. This cycle suggests that there are certain meaningful mechanisms governing the interaction between technology increase and price reduction.

3. The distribution of PV module prices

This section will identify the mechanism of technology contribution to decreasing prices of innovative

[1] Due to Japanese Government structural reform in January 2001, MITI is now renamed METI (Ministry of Economy, Trade and Industry).

[2] This Project developed into the New Sunshine Program (R&D program on Energy and Environmental Technologies) in 1993.

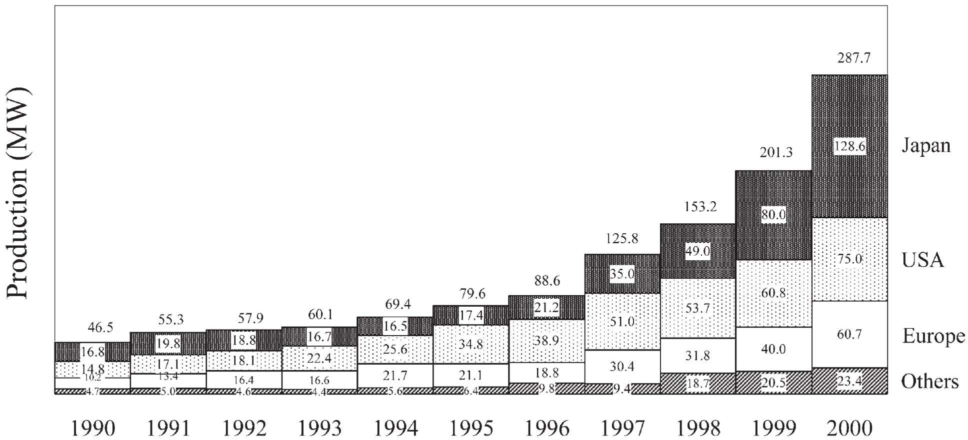

Fig. 1. Trends in solar cell production in the world (1990–2000): MW.

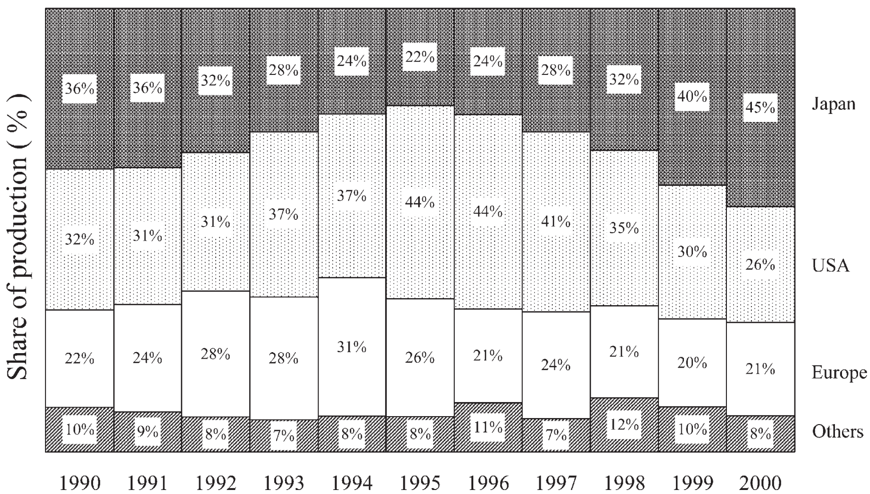

Fig. 2. Trends in solar cell production share in the world (1990–2000): %.

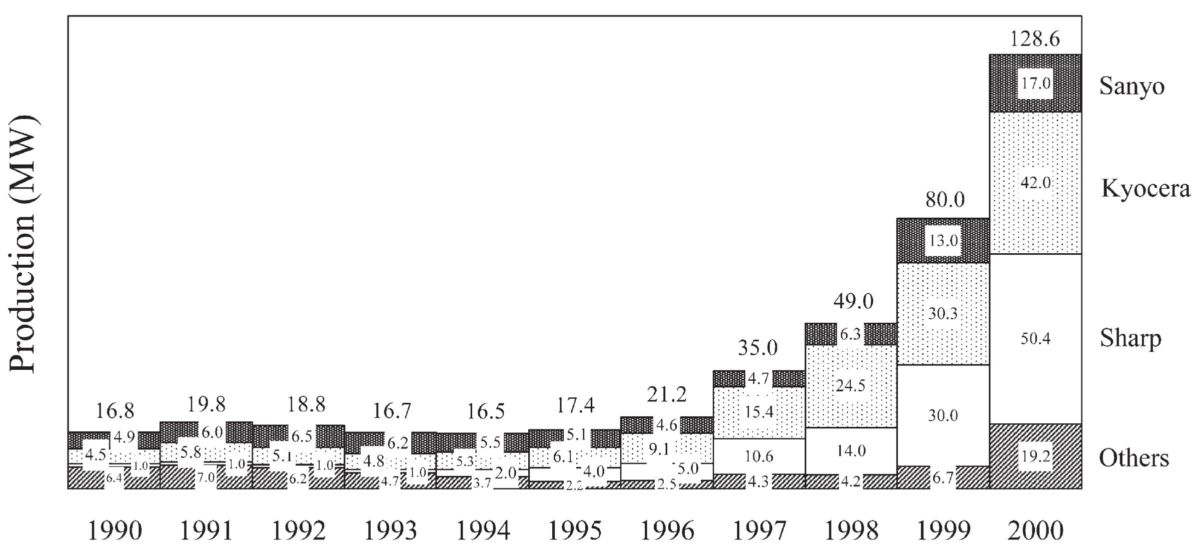

Fig. 3. Trends in solar cell production in Japan (1990–2000): MW.

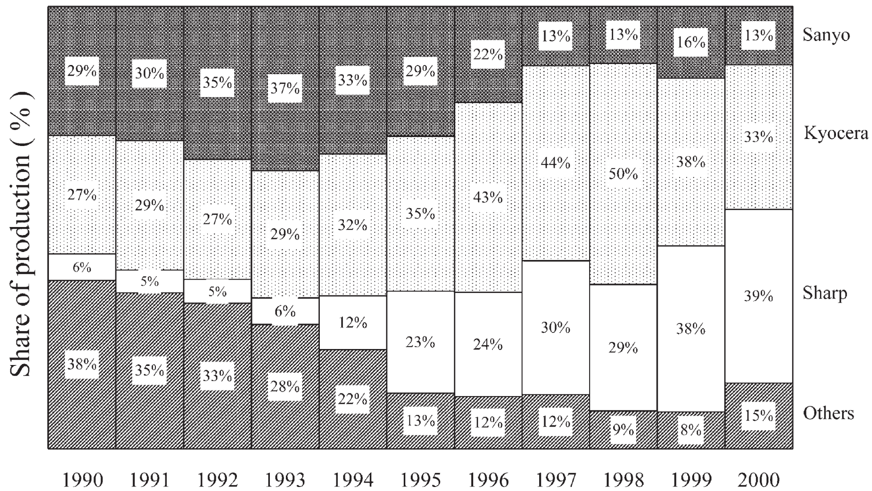

Fig. 4. Trends in solar cell production share in Japan (1990–2000): %.

Table 1
Trends in solar cell prices in Japan (1974–2000)—yen/W

	Current prices[a]	1985 fixed prices
1974	20000	26120
1975	16500	20960
1976	13500	16230
1977	10900	12790
1978	8600	10100
1979	6600	7390
1980	5000	4980
1981	3450	3400
1982	2000	1960
1983	1650	1630
1984	1400	1390
1985	1200	1200
1986	1030	1090
1987	900	980
1988	800	880
1989	720	780
1990	650	690
1991	635	675
1992	620	670
1993	615	680
1994	610	695
1995	595	690
1996	475	550
1997	520	610
1998	540	640
1999	490	590
2000	457[b] (297~592)[c]	

Sources: MITI/NEDO for prices in 1974–1999 and NEF for 2000 prices.

[a] Prices in 1974–1999 indicate the Government purchase prices.

[b] The figure indicates average of prices of 639 PV modules supported by NEF subsidy program in three firms examined.

[c] Figures in parenthesis indicate distribution of the above prices.

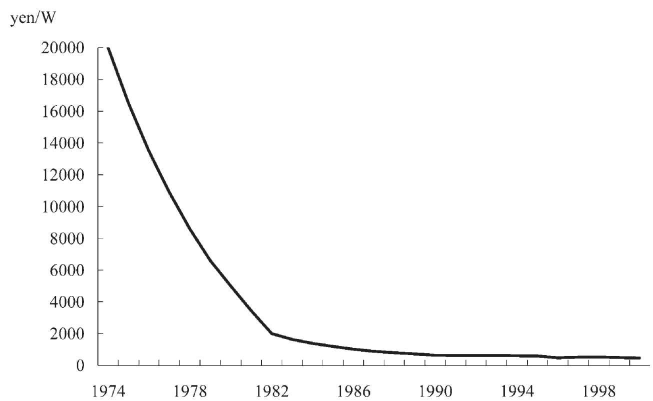

Fig. 5. Trends in solar cell prices in Japan (1974–2000): current prices (yen/W).

goods. Building on the findings obtained in the previous section with respect to a virtuous cycle between R&D, market growth and price reduction in Japan's PV development, an empirical analysis of the interaction between technology increase and price reduction in the forefront of Japan's PV development was undertaken.

Fig. 7 demonstrates the distribution of PV module prices in Japan's leading PV firms (a questionnaire in April 2001). The top three PV firms (Sharp Corp., Kyocera Corp. and Sanyo Electric Co., Ltd) which share nearly 90% of Japan's solar cell production were chosen and 675 PV module prices under the New Energy Foundation's (NEF) subsidy program for residential PV systems in 2000 were examined.

The New Energy Foundation was established in 1980 as one of MITIs affiliate with a special mission to secure a stable energy supply, particularly to promote the development and utilization of new and renewable energy resources.

Among NEFs responsibilities is the Subsidy Program for residential PV systems. This program started in 1994

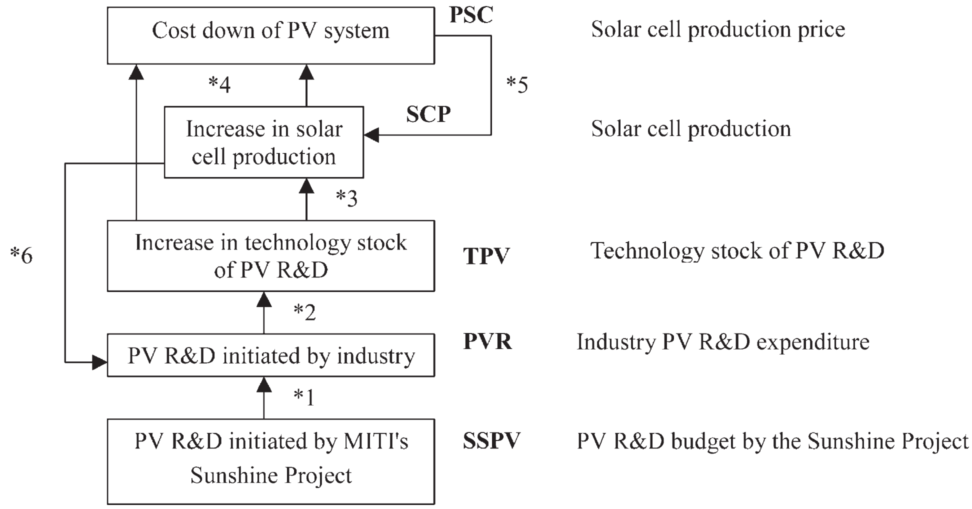

Fig. 6. Virtuous cycle for PV development in Japan (1976–1995) ((fixed price); PVPAT: number of PV patent application; and PVRr: industry PV R&D expenditure in fixed prices.).

		$adj.R^2$	DW	
*1	$\log(PVR) = 1.37 + 0.77\log(SSPV\text{-}1)$	0.979	1.31	
	(29.35)			
*2	$TPVt = PVR_{t-m} + (1-\rho)TPV_{t-1}$ m=2.8 years, ρ=20% p. a.			
*3	$\log(SCP) = -8.26 + 2.19\log(TPV) + 5.94\log(Pey)$	0.977	1.36	
	(35.48.) (13.60)			
*4	$\log(PSC) = 11.97 - 0.973\log(TPV) - 1.04\log(Pey)$	0.988	1.53	Inducement by technology and energy prices.
	(-39.51) (-5.59)			
	$\log(PSC) = 130.87 - 0.06\,Year - 0.31\log(SCP)$	0.995	1.38	Effects due to economies and learning scale of effects.
	(-9.32) (-18.87)			
*5	$\log(SCP) = 16.97 - 2.02\log(PSC\text{-}1) + 2.98\log(Pey\text{-}1)$	0.995	1.25	
	(-58.73) (13.61)			
*6	$\log(PVR) = 3.59 + 0.43\log(SCP)$	0.973	1.03	
	(25.96)			
	$\log(PVPAT) = 66.43 - 0.02\,Year + 0.55\log(PVRr) + 0.10\log(TPV)$	0.982	2.31	
	(-2.09) (16.19) (1.89)			

where *PVR:* industry PV R&D expenditure; *SSPV:* PV R&D budget by the Sunshine Project; *TPV:* technology stock of PV R&D; *m*: time lag of PV R&D to commercialization; ρ: rate of obsolescence fo PV technology; *SCP*: solar cell production; *Pey*: relative energy prices; *PSC*: solar cell production price (fixed price); *PVPAT*: number of PV patent application; and *PVRr*: industry PV R&D expenditure in fixed prices.

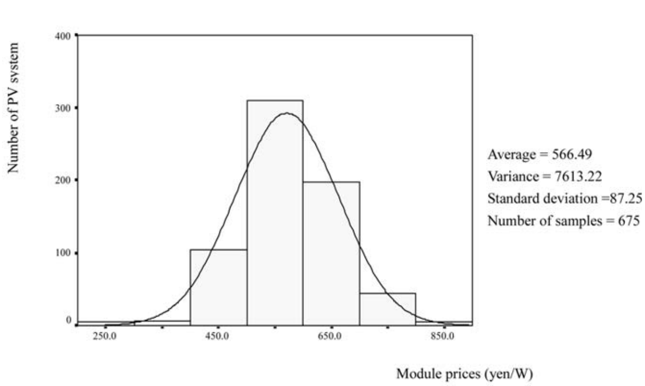

Fig. 7. Distribution of module prices in Japan's leading PV firms (2000): gross samples.

and aims to induce PV development by reducing PV prices and, thereby, stimulating the PV market.

Table 2 summarizes trends in this subsidy demonstrating that the ratio of the subsidy has been decreasing as PV development continues and currently the level of the subsidy is 120.0 yen/W. MITIs policy is to expand the number of 'adopters' or subsidy recipients within a certain limit of the Government budget by decreasing the level of the subsidy.

Since the distribution in Fig. 7 contains those data which do not necessarily reflect the price formation by market mechanism such as price dumping, Fig. 8 demonstrates an elaborated distribution within 2σ which encompasses 639 samples covering 95.4% of the entire sample.

Table 2
Trends in subsidy program for residential PV systems by new energy foundation (1994–2001)

FY	Total subsidy (100 million yen)	Term	Subsidy per W (yen)	Limit
1994	20.00		900.0	
1995	32.70		850.0	
1996	40.60		500.0	
1997	11.11		340.0	
1998	14.70		340.0	
1999	16.04		329.2	
2000	14.50	First	270.0	
		Second	180.0	Under 720 thousands yen
		Third	150.0	Under 600 thousands yen
2001	23.60		120.0	Under 10.kW

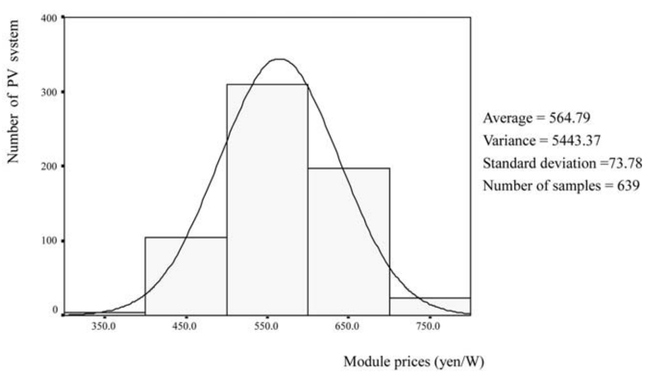

Fig. 8. Distribution of module prices in Japan's leading PV firms (2000): samples within 2σ distribution.

Six hundred and thirty-nine samples within 2σ consisting of 350 samples from Sharp Corp., 234 from Kyocera Corp. and 55 from Sanyo Electric Co., Ltd were used.

Fig. 9 demonstrates the distribution of the module prices[3] in these samples in three leading PV firms at the end of 2000.

Looking at Fig. 9 we note that:

(i) distribution of module prices in three firms can be approximated to normal distribution;
(ii) average prices and standard deviation (SD) in Sharp Corp., Kyocera Corp. and Sanyo Co., Ltd are 466.8 yen/W (SD: 95.6 yen/W), 414.6 yen/W (SD: 68.2) and 474.5 yen/W (SD: 66.8), respectively.

[3] Prices expected to be reduced by the NEF subsidy are reducted.

4. Technology contribution to price decrease

Classical postulates suggesting that technological progress incorporates into production factors as well as innovative goods, and also stimulates learning effect, all lead to a price reduction as reviewed in Section 1. Following these postulates and also the key findings in Section 2 with respect to the interaction between technology increase and price reduction, this section reviews a mechanism of technology contribution to price decrease.

Fig. 6 in Section 2 demonstrates that, corresponding to the postulates of Arrow (1962), we observe in learning exercise the significant contribution to price decrease in Japan's PV development. In addition, active inter-technology and cross-firm technology spillover lead to technological improvement also in Japan's PV development (Watanabe and Griffy-Brown, 1999, 2000). Therefore, in order to elucidate a mechanism of technology contribution to price reduction, analyses of both technology formation process and also a system function between technology formation, incorporation and learning effect are indispensable.

4.1. Technology stock formation in PV module

Technology formation process can generally be identified by tracing technology stock formation process.

Total technology stock of PV module i can be depicted as follows (Watanabe et al., 2001):[4]

$$T = T_i + Z{\cdot}T_s, \tag{1}$$

where T_i is the indigenous technology stock in module i, Z the assimilation capacity of spillover technology ($0 \le Z \le 1$), and T_s the potential spillover pool.

Provided that PV firms make every effort in fully utilizing all possible technology spillover, the potential spillover pool T_s can be depicted as follows:[5]

[4] See also Cohen and Levinthal (1989).

[5] In general,

$$T_s = \sum_{\substack{h=1 \\ h \neq i}}^{n} (T_h)_j + \sum_{\substack{h=1 \\ h \neq i}}^{n} \sum_{\substack{k=1 \\ k \neq j}}^{m} Z_{hk}(T)_k,$$

where Z_{hk} is a module h's capacity to assimilate technology in module k. When PV firms make every effort in fully utilizing all possible spillover technology, all potential spillover technology pool would be treated homogeneously leading to the following equilibrium (see Scherer, 1982; Jaffe, 1986):

$$Z_{is}T_s = Z_{is} \sum_{\substack{h=1 \\ h \neq i}}^{n} (T_h)_i + \sum_{\substack{h=1 \\ h \neq i}}^{n} \sum_{\substack{k=1 \\ k \neq j}}^{m} Z_{is}Z_{hk}(T)_k \approx Z_{is}\left(\sum_{\substack{h=1 \\ h \neq i}}^{n} (T_h)_i + \sum_{\substack{k=1 \\ k \neq j}}^{m} (T)_k \right),$$

where $Z_{is}T_s$ is the assimilated spillover technology of module i; and Z_{is} the module i's capacity to assimilate technology in potential spillover pool.

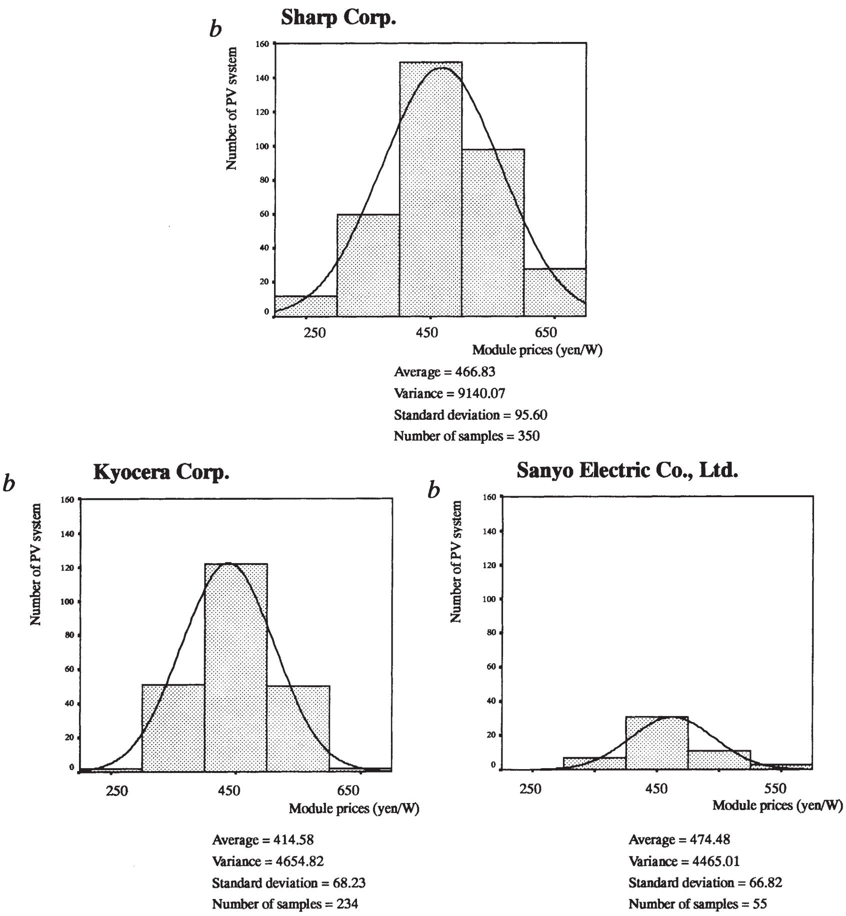

Fig. 9. Distribution of module prices in Japan's leading PV firms (2000): reduced prices by subsidy. (a) Module prices are at current prices. (b) Number of PV system indicates system installed or to be installed in 2000.

$$T_s = \sum_{\substack{h=1 \\ h \neq i}}^{n} (T_h)_j + \sum_{\substack{k=1 \\ k \neq j}}^{m} (T)_k, \tag{2}$$

where $(T_h)_j$ is the technology stock in module h in firm j, and $(T)_k$ the total technology stock in firm k.

Thus, given that PV firms make every effort to fully utilize all possible technology spillover, the total technology stock of PV module i can be depicted as follows:

$$T = T_i + Z\left(\sum_{\substack{h=1 \\ h \neq i}}^{n} (T_h)_j + \sum_{\substack{k=1 \\ k \neq j}}^{m} (T)_k\right). \tag{3}$$

The general concept of this technology stock formation in PV module i can be illustrated in Fig. 10.

4.2. Correlation between technology spillover, technology improvement and learning effects

Correlation between technology spillover, technology improvement and learning effects leading to price

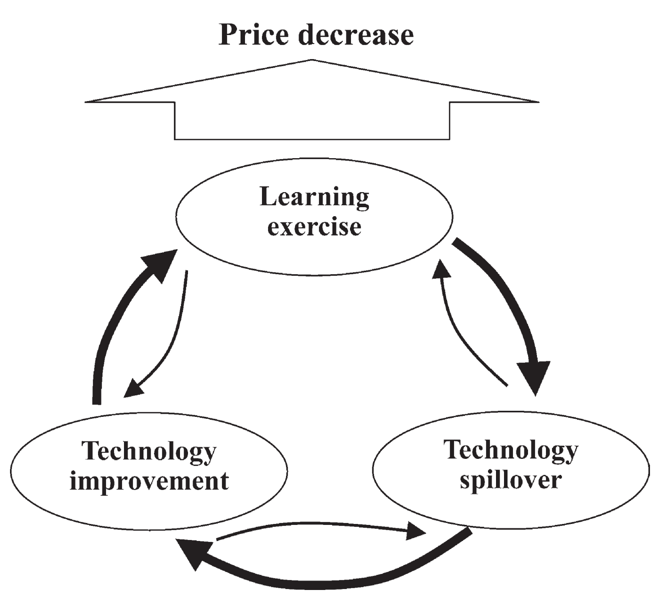

Fig. 10. Correlation between technology spillover, technology improvement and learning exercise.

decrease can be analyzed as follows (Watanabe and Griffy-Brown, 1999).

4.2.1. Technological improvement and learning effects

Newly generating technology $[T]$ can be seen in the following equation as a function of the current technological level T and R&D investment R for the generation of $[T]$:

$$[T] = \omega(T,R). \tag{4}$$

Eq. (4) can be developed to Eq. (5) by using a learning function φ (Thomson, 1993).

$$[T] = \phi(T)R. \tag{5}$$

Learning function $\varphi(T)$ has generally following characteristics:

$$\phi(T) > 0,\ \phi'(T) > 0,\ \phi''(T) < 0. \tag{6}$$

The technological level after generating $[T]$ will improve to T_2 which can be seen in Eq. (7).

$$T_2 = T + [T] > T. \tag{7}$$

Since $\phi(T) > 0$, $\phi(T_2) > \phi(T)$ which simply demonstrates that learning effects increase as technological level increases.

4.2.2. Learning effects and technology spillover

According to Jaffe (1986)[6], provided that technology Td spillover from the donor (D) to host (H), assimilating technology in the host $[Td]h$ can be expressed in the following way by using the assimilation capacity function θ:

$$[Td]h = \theta(Th)\cdot f(\alpha)\cdot Td \tag{8}$$

Eq. (8) can be developed as follows:

$$[Td]h = \phi(Th)\cdot f(\alpha)\cdot Td \tag{9}$$

Eq. (9) demonstrates that assimilating technology depends on learning capacity.

The technology newly generated in the host by assimilating technology spillover can be expressed in the following equation:

$$[Th_2] = \phi(Th)Rh + [Td]h = \phi(Th)Rh + \phi(Th)f(\alpha)Td = \phi(Th)[Rh + f(\alpha)Td]. \tag{10}$$

Since the technology level of the host at this stage Th_2 is $Th_2 = Th + [Th_2] > Th$, $\phi(Th_2) > \phi(Th)$ which demonstrates that learning capacity increases as technology spillover increases.

The learning capacity increase leads to a price decrease as postulated by Arrow (1962). This is also demonstrated in the previous analysis of Japan's PV development.

[6] See also Griliches (1979).

On the basis of this characterization we note a potential virtuous cycle between technology spillover, technology improvement and a learning exercise leading to a price decrease generated through the interactions illustrated in Fig. 11. This concept is the basis of our analysis.

5. Governing factors of variance of PV module prices

Since variance of PV module prices are generally subject to the level of incorporated technology stock (T), capacity (size: CP) and performance (conversion efficiency: PF) of the module, given the average module prices Mp_0, module prices Mp can be depicted as follows:[7]

$$\mathrm{Mp} = F(T,\mathrm{CP},\mathrm{PF},\mathrm{Mp}_0,\varepsilon), \tag{11}$$

where ϵ indicates error term.

Tables 3 and 4 summarize trends in technology stock of PV R&D in three firms examined, and the performance of PV modules examined, respectively.

From Eq. (11), the variance ratio of module prices in comparison to their average can be depicted as follows:

$$\frac{\mathrm{Mp}}{\mathrm{Mp}_0} = G(T,\mathrm{CP},\mathrm{PF},\varepsilon'). \tag{12}$$

The Taylor expansion to the secondary term is as follows:

$$\ln\left(\frac{\mathrm{Mp}}{\mathrm{Mp}_0}\right) = A + \alpha_1 \ln T + \alpha_2 \ln \mathrm{CP} + \alpha_3 \ln \mathrm{PF}$$

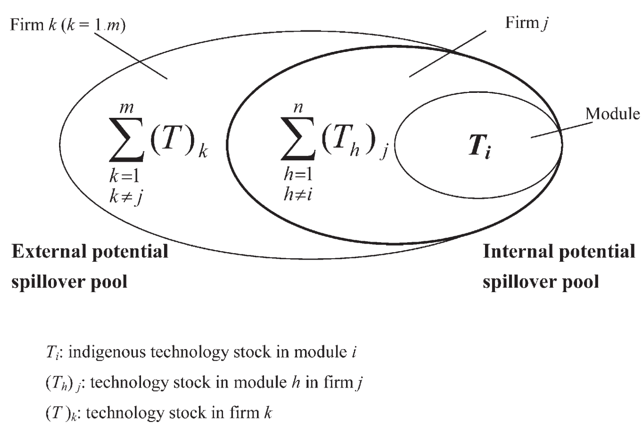

Fig. 11. General concept of technology stock formation in PV module.

[7] Since solar cell production prices in aggregate level are subject to the technology stock of PV R&D of the respective firm and relative energy prices in Japan's PV development (see Fig. 6 in Section 2), levels of technology stock of each respective modules are estimated by ranking the technology stock level of the firm in accordance with the distribution of module prices in the firm illustrated in Fig. 9.

Table 3
Trends in the technology stock of PV R&D in Japan's leading PV firms (1979–2000): billion yen at 1985 fixed prices

	Sharp Corp.	Kyocera Corp.	Sanyo Electric Co., Ltd
1979	3.9	9.7	4.4
1980	4.5	11.0	5.2
1981	5.3	11.9	6.1
1982	7.7	12.4	6.9
1983	10.5	13.1	9.8
1984	14.0	13.8	14.2
1985	18.6	14.8	17.5
1986	22.7	16.3	22.1
1987	26.3	19.5	27.9
1988	29.3	24.9	33.3
1989	30.4	28.2	41.2
1990	30.7	31.0	47.8
1991	29.3	32.8	53.3
1992	28.2	34.2	57.5
1993	28.9	34.9	61.0
1994	29.4	35.0	65.4
1995	31.3	37.5	70.0
1996	33.0	39.5	76.1
1997	33.2	42.6	79.9
1998	33.1	47.0	82.5
1999	33.7	51.4	86.9
2000	33.3	55.7	93.2

Technology stock of PV R&D is measured by the following equation: $T_t = R_{t-m} + (1-\rho)T_{t-1}$, where T_t is the technology stock of PV R&D in time t; R_{t-m} the PV R&D expenditure in time t-m; m the lead time of of PV R&D and its commercialization; and ρ the rate of obsolescence of PV technology. On the basis of the survey of Japan's 19 leading firms in 1993 m is estimated 2.8 years while ρ is estimated at 20.3% (Watanabe and Griffy-Brown, 1999).

$$+ \beta_1 \ln T \ln \mathrm{CP} + \beta_2 \ln T \ln \mathrm{PF} + \gamma_1 \ln \mathrm{CP} \ln \mathrm{PF}. \tag{13}$$

Provided that assimilation capacity Z is small enough, using Eq. (1), $\ln T$ can be depicted as follows:

$$\ln T = \ln(T_i + ZT_s) = \ln T_i\left(1 + Z\frac{T_s}{T_i}\right) = \ln T_i + \ln\left(1 + Z\frac{T_s}{T_i}\right) \approx \ln T_i + Z\frac{T_s}{T_i}, \tag{14}$$

where α_1, α_2, α_3, β_1, β_2 and γ_1 are coefficients.

Substituting $\ln T$ in Eq. (13) by Eq. (14) following equation can be obtained:

$$\ln\left(\frac{\mathrm{Mp}}{\mathrm{Mp}_0}\right) = A + \alpha_1 \ln T_i + \alpha_1 Z\frac{T_s}{T_i} + \alpha_2 \ln \mathrm{CP} + \alpha_3 \ln \mathrm{PF} + \beta_1 \ln T_i \ln \mathrm{CP} + \beta_1 Z\frac{T_s}{T_i}\ln \mathrm{CP} + \beta_2 \ln T_i \ln \mathrm{PF} + \beta_2 Z\frac{T_s}{T_i}\ln \mathrm{PF} + \gamma_1 \ln \mathrm{CP} \ln \mathrm{PF} + \varepsilon''. \tag{15}$$

Table 4
Performance by conversion efficiency of PV modules in Japan's leading PV firms (2000)

Product	Type	W/m^2	(Conversion efficiency %)
Sharp Corp.			
NT-K140A	Single-crystalline silicon	145.47	(14.55)
NT-J128B	Single-crystalline silicon	133.00	(13.30)
Average		139.24	(13.92)
NE-K136A	Multi-crystalline silicon	141.31	(14.13)
NE-J130A	Multi-crystalline silicon	135.08	(13.51)
NE-K125A	Multi-crystalline silicon	129.88	(12.99)
NE-J130T	Multi-crystalline silicon	129.86	(12.99)
Average		134.03	(13.40)
Kyocera Corp.			
G421	Multi-crystalline silicon	133.33	(13.33)
R421	Multi-crystalline silicon	129.85	(12.99)
Average		131.59	(13.16))
Sanyo Electric Co., Ltd			
HIP-J54B1	Hybrid solar cells[a]	152.36	(15.24)
HIP-H552B1	Hybrid solar cells	148.13	(14.81)
HIP-G751B1	Hybrid solar cells	141.36	(14.14)
HIP-J50B	Hybrid solar cells	152.36	(15.24)
HIP-G748B1	Hybrid solar cells	141.36	(14.14)
Average		147.11	(14.71)

[a] The hybrid solar cells are made by combining amorphous silicon and crystalline silicon.

Taking the regression of Eq. (15) coefficients with statistical significance in each of the respective firms can be identified and are summarized in Table 5.

Looking at Table 5, we note that technology stock and spillover technology contribute significantly to a decrease in module prices. In addition, the combined effect of technology stock and performance of the module (conversion efficiency) also contributes to a decrease in module prices.

Unlike technology stock and the performance of the module, the impact of the capacity (size) of the module is negligible. The combined effect with technology spillover on the module prices of Sanyo Electric Co., Ltd is only an exceptional case. In this case, the impact increases module prices. This is due to the expensiveness of large size amorphous film.

In order to identify the governing factors for the vari-

Table 5
Coefficients of factors governing module prices in Japan's leading PV firms (2000)

	α_1	$\alpha_1 Z$	$\beta_1 Z$	β_2	Adj. R^2
Sharp Corp.	−0.29 (−2.81)	−0.00 (−9.47)		−0.14 (−2.60)	0.565
Kyocera Corp.	−0.31 (−2.36)	−0.00 (−4.11)		−0.09 (−1.36)	0.530
Sanyo Electric Co., Ltd	−0.49 (−2.21)	−0.00 (−4.43)	0.00 (2.96)	−0.11 (−1.07)	0.593

ance of module prices, a decomposition of the variance of module prices is attempted.

Applying Euler's theorem to Eq. (12), the variance ratio of module prices Mp/Mp_0 can be developed as follows:

$$\frac{Mp}{Mp_0} = \frac{1}{Mp_0}\left(\frac{\partial Mp}{\partial T}T + \frac{\partial Mp}{\partial CP}CP + \frac{\partial Mp}{\partial PF}PF + \varepsilon''\right). \quad (16)$$

Taking the partial differentiation of Eq. (13) by the respective governing factors, the elasticities of the respective factors can be obtained as follows:

$$\frac{\partial \ln (Mp/Mp_0)}{\partial \ln T} = \frac{\partial \ln Mp}{\partial \ln T} = \frac{\partial Mp}{\partial T}\frac{T}{Mp} = \alpha_1 + \beta_1 \ln CP + \beta_2 \ln PF \therefore \frac{\partial Mp}{\partial T} = \frac{\partial \ln Mp}{\partial \ln T}\frac{Mp}{T} = \frac{Mp}{T}(\alpha_1 + \beta_1 \ln CP + \beta_2 \ln PF), \quad (17)$$

$$\frac{\partial Mp}{\partial CP} = \frac{Mp}{CP}(\alpha_2 + \beta_1 \ln T + \gamma_1 \ln PF), \quad (18)$$

$$\frac{\partial Mp}{\partial PF} = \frac{Mp}{PF}(\alpha_3 + \beta_2 \ln T + \gamma_1 \ln CP). \quad (19)$$

Therefore, the variance ratio of PV module prices is decomposed in the following equation:

$$\frac{Mp}{Mp_0} = (\alpha_1 + \beta_1 \ln CP + \beta_2 \ln PF)\frac{Mp}{Mp_0} + (\alpha_2 + \beta_1 \ln T + \gamma_1 \ln PF)\frac{Mp}{Mp_0} + (\alpha_{32} + \beta_2 \ln T + \gamma_1 \ln CP)\frac{Mp}{Mp_0} = (\alpha_1 + \beta_1 \ln CP + \beta_2 \ln PF)\frac{Mp}{Mp_0} + (\alpha_2 + \beta_1 \ln T_i + \beta_1 Z\frac{T_s}{T_i} + \gamma_1 \ln PF)\frac{Mp}{Mp_0} + (\alpha_2 + \beta_2 \ln T + \beta_2 Z\frac{T_s}{T_i} + \gamma_1 \ln CP)\frac{Mp}{Mp_0}. \quad (20)$$

The first term of Eq. (20) indicates the impacts of technology (both indigenous technology stock and assimilated technology spillover) on the variance ratio. Similarly, the second and third terms indicate impacts of capacity (size) and performance of the module, respectively.

Using the coefficients in Table 5, and combining these in Eq (20), the factors governing the distribution of module prices in Japan's leading PV firms in 2000 are estimated.

Table 6 and Fig. 12 summarize the results of the analysis by demonstrating the share of the variance ratio of respective modules in accordance with their distribution by prices.

Looking at Table 6 and Fig. 12 we note that technology (both indigenous and assimilated spillover technology) contributes to reduce the prices of PV modules. Furthermore, this contribution functions uniformly in all PV modules examined thereby minimizing the variance of PV module prices. This significant and uniform spillover demonstrates our hypothetical view with respect to the technology stock formation postulates in Section 4.1.

Fig. 13 analyzes the correlation between the degree of technology contribution to reduce the prices of PV modules and the standard deviation of the prices of the modules in the three firms examined. This demonstrates that the technology contribution reduces the standard deviation of the prices. Fig. 13 also demonstrates that this technology contribution can be attributed to the level of technology stock in the firm.

Therefore, this empirical analysis supports the theoretical framework demonstrated in Section 4.2. This framework, based on classical theories including growth accounting theory and learning theory, describes the mechanism of a virtuous cycle between technology spillover, technology improvement and learning exercise leads to price decreases.

Finally, the impacts of the performance of the respective modules (conversion efficiency) on the distribution of module prices were analyzed.

Table 7 summarizes the results of the analysis on the correlation between distribution of module prices and the contribution by performance in the three firms examined. Table 7 indicates the significant correlation which demonstrates that the performance of the respective modules affects the variance of module prices.

6. Conclusion

This paper analyzed and characterized the mechanism of technology contribution to the decreasing prices of innovative goods. Understanding this behavior is increasingly relevant in terms of identifying specific mechanisms for achieving policy objectives through the marketplace. This is particularly important in policy area such as sustainable techno-economics development and the promotion of clean energy technology.

In this regard, Japan as a national must continually respond to environmental and economic pressures. Currently, Japan is transitioning from an industrial, manufacturing-based economy to an information-based economy. Furthermore, it is also suffering from a reduction in R&D investment, increasing the need to capture technology spillover in order to stimulate innovation.

Table 6
Distribution of module prices and factors governing the distribution of module prices in Japan's leading PV firms (2000)

Sharp Corp.															
Distribution of module prices	0.002	0.002	0.003	0.003	0.003	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.002	0.001
Contribution of technology stock	−0.014	−0.014	−0.018	−0.009	−0.013	−0.013	−0.013	−0.009	−0.009	−0.014	−0.013	−0.009	−0.013	−0.018	−0.012
Contribution of performance	0.846	0.846	0.843	0.778	0.756	0.750	0.743	0.737	**0.736**	0.737	0.741	0.747	0.801	0.823	0.860
Others	0.168	0.168	0.175	0.230	0.257	0.263	0.271	0.272	0.272	0.277	0.272	0.262	0.212	0.195	0.152
Variance ratio	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.009	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Kyocera Corp.															
Distribution of module prices	0.002	0.003	0.004	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.003	0.003	0.002	0.001
Contribution of technology stock	−0.133	−0.133	−0.133	−0.133	-0.133	−0.133	−0.133	−0.133	−0.133	−0.133	−0.133	−0.133	−0.133	−0.133	−0.133
Contribution of performance	0.570	0.537	0.520	0.486	**0.484**	0.491	0.492	0.496	0.501	0.509	0.517	0.525	0.537	0.553	0.597
Others	0.562	0.595	0.613	0.647	0.648	0.642	0.641	0.636	0.631	0.624	0.616	0.608	0.596	0.579	0.536
Variance ratio	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Sanyo Electric Co., Ltd															
Distribution of module prices	0.002	0.003	0.004	0.004	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.005	0.004	0.003
Contribution of technology stock	−0.270	−0.275	−0.279	−0.279	−0.279	−0.275	−0.275	−0.279	−0.270	−0.275	−0.279	−0.279	−0.275	−0.275	−0.279
Contribution of performance	0.601	0.592	0.580	0.567	0.564	0.555	0.553	0.545	0.543	0.543	**0.540**	0.541	0.553	0.570	0.599
Others	0.669	0.683	0.699	0.712	0.715	0.720	0.722	0.734	0.727	0.732	0.739	0.738	0.722	0.705	0.680
Variance ratio	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

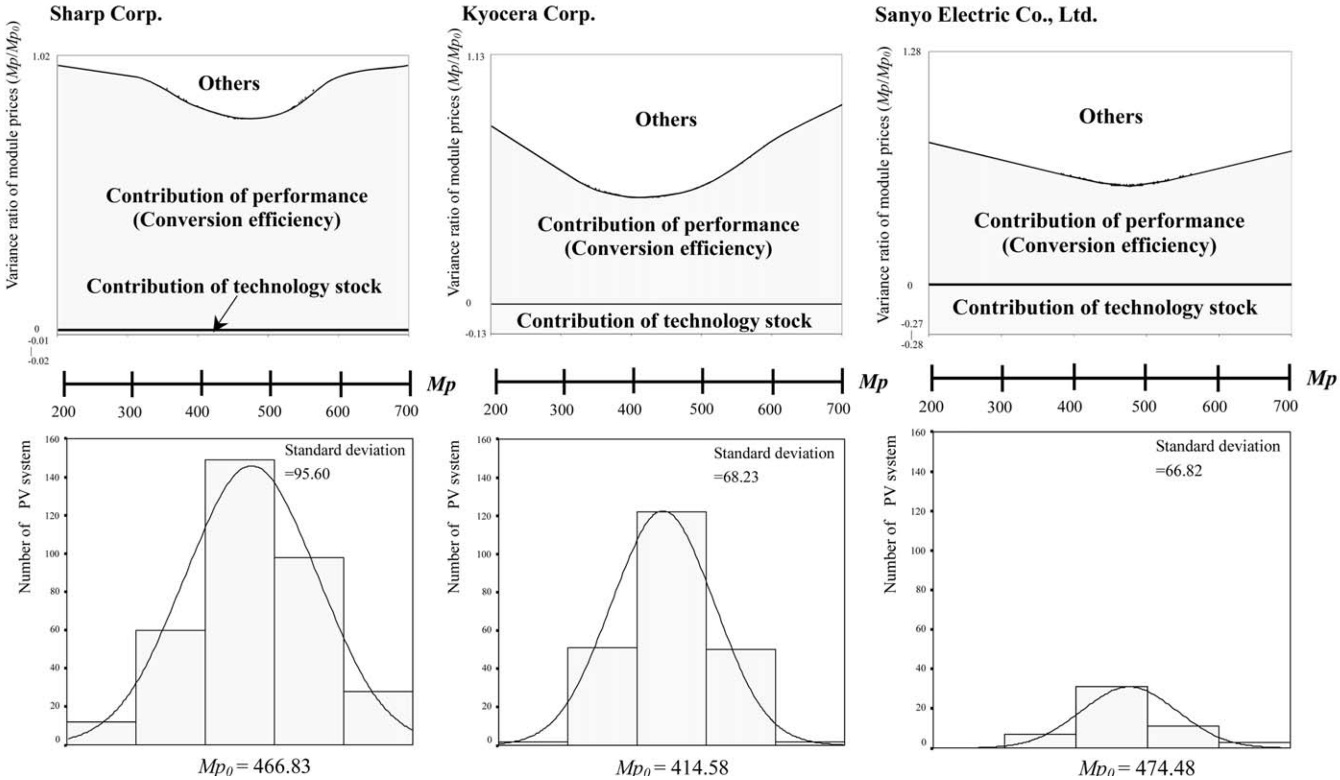

Fig. 12. Distribution of module prices and their factors in PV modules (2000).

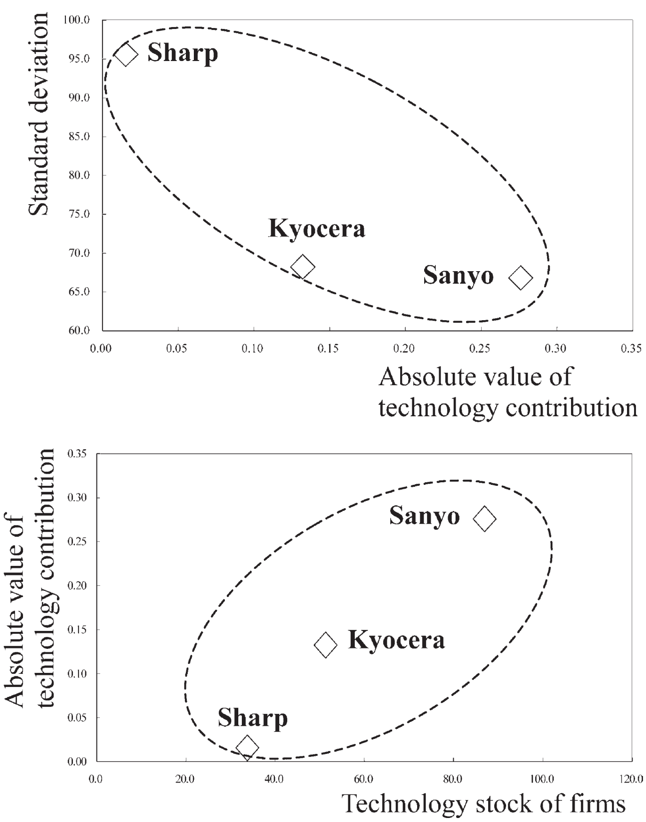

Fig. 13. Correlation between technology contribution, standard deviation and technology stock in Japan's leading PV firms.[8]

Table 7
Correlation between distribution of module prices and contribution by performance in Japan's leading PV firms (2000)

	a	b	Adj. R^2
Sharp Corp.	−7.29 (−237.30)	−6.41 (−48.81)	0.921
Kyocera Corp.	−11.31 (−238.68)	−8.66 (−120.91)	0.985
Sanyo Electric Co., Ltd	−6.13 (−14.21)	−1.30 (−1.76)	0.768

$\ln \mathrm{DMp} = a{+}b \ln \mathrm{CPF}$where DMp is the distribution of module prices; CPF the contribution of performance and a, b the parameters. DMp is approximated by normal distribution.

Japan's outstanding achievement in PV development is a very good example because a virtuous cycle between technology development, production increase and price reduction, as well as technology incorporation was created.

In this context, an empirical and numerical analysis of 639 PV module prices in Japan's PV firms was undertaken. In this analysis, the governing factors of PV modules prices were analyzed and the behavior of technology

[8] Technology contribution: technology contribution to decrease standard deviation of PV module prices; Standard deviation: standard deviation of PV module prices; and technology stock: whole technology stock in each respective PV firms.

in reducing the prices of the innovative goods was identified.

Based on this analysis, important findings include:

(i) Technology both indigenous and assimilated spillover technology contributes significantly to reduce the prices of PV modules.
(ii) This contribution functions uniformly to all PV modules examined thereby minimizing the variance of PV module prices.
(iii) This suggests that technology is incorporated into innovative goods through a dynamic game between internal indigenous technology stock and the external potential spillover pool as well as the internal potential spillover pool and indigenous technology stock. Ultimately, this dynamic game leads to equilibrium.
(iv) The magnitude of technology contribution to price reduction as well as minimization of the variance of prices is subject to the level of the technology stock of the firm.
(v) A virtuous cycle between technology spillover, technology improvement and learning exercise seems to be the structural source leading to price decreases.
(vi) Unlike the uniformed contribution of technology to all PV modules, the performance of the respective modules (conversion efficiency) affects the variance of module prices while the size of the module provides no significant effects on price distribution.

PV development is one of the Japanese Government's priority projects and under the strong initiative of METI (Ministry of Economy and International Trade: Former MITI), its affiliates NEDO (New Energy and Industrial Technology Development Organization) and NEF extensive stimulation and inducement of firm's PV development has occurred. Among these groups, NEFs subsidy program for the residential PV system, together with NEDOs R&D stimulation, provides an effective inducement in constructing a virtuous circle between price reduction and production (demand) increase. NEF first published in 2001 the details of prices and their components for the PV system for which the organization provided subsidies.

This decision, though risky, was highly successful in stimulating constructive competition between producers and customers.

Furthermore, this constructive competition could play a significant role in further price reduction, because of the existing virtuous cycle between price reduction and production (demand) increase.

In addition, NEFs decision to reveal price information significantly contributed to academic research in elucidating this black box of technology and price reduction, providing a mechanism for evaluating such programs. This paper would not have been possible without this bold decision. Provided this data are available in subsequent years, the further elucidation of this ongoing dynamic process is possible.

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