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Industrial dynamism and the creation of a "virtuous cycle" between R&D, market growth and price reduction
The case of photovoltaic power generation (PV) development in Japan

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Abstract

In light of the global environmental consequences of CO_2 emissions resulting from energy use, systems options for the rational use of energy, particularly of energy efficiency improvement and renewable energy technology, have become crucial. Despite its leading efforts in developing extensive renewable energy, Japan has not necessarily achieved comparative advantage in this field owing to inherent resource constraints for renewable energy. One of the exceptions is photovoltaic power generation (PV).

PV is considered to be a "footloose" renewable energy which is expected to overcome Japan's own geographical disadvantages as a technology breakthrough. MITI (Japan's Ministry of International Trade and Industry) initiated PV development under its Sunshine Project (R&D Program on New Energy) aiming at maximizing these advantages 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.

This paper, on the basis of an empirical analysis of Japan's PV development, demonstrates the industrial dynamism of this "virtuous cycle" as a policy initiative.

Keywords: PV; Virtuous cycle; Technology spillover; Learning exercise; Technology stock

1. Introduction

Despite its geographical disadvantages, Japan has taken a leading role in world photovoltaic power generation (PV) development (Williams et al., 1996). This is due to (1) the "footloose" character of the technology which, like semiconductor technology, can maximize the benefit of learning effects and economies of scale, and also to (2) the interdisciplinary nature of its development, which can maximize the benefit of technology spillover (Watanabe, 1997). These are the reasons why PV is classified as a technology-driven clean energy technology (Watanabe, 1996).

In light of these advantages, Japan's Ministry for International Trade and Industry (MITI) initiated PV development under its Sunshine Project starting from 1974, with the aim of maximizing these advantages 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 (Watanabe, 1999). Supported by a PV R&D acceleration strategy in 1979 (Industrial Technology Council of MITI, 1979) and also the establishment of the research

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association for PV development in 1990, the technology knowledge stock of PV R&D increased dramatically. An increase in this technology knowledge stock contributed to a dramatic increase in solar cell production. This led to a dramatic decrease in solar cell production price, and induced a further increase in solar cell production. This increase in solar cell production induced further PV R&D, thus creating a "virtuous cycle" between R&D, market growth and price reduction (Watanabe 1995a, 1999). Although the achievement of a "virtuous cycle" has significant techno-economic implications (Watanabe and Clark, 1991; Watanabe and Honda, 1992; Watanabe et al., 1991; Watanabe, 1995c), limited research has been undertaken thus far to appropriately elucidate Japan's policy work in this area. In his recent publication Grubler (1998) analyzed this "virtuous cycle" by utilizing the author's data and noticed the function of a learning exercise (Arrow, 1962; Cohen and Levinthal, 1989; Romer, 1986) triggered by MITI's inducement. However, his analysis remains aggregate behavior without considering the impacts of inter-firm technology spillover.

This paper, on the basis of an empirical analysis of Japan's firm level PV development over the last two decades, demonstrates the industrial dynamism of a "virtuous cycle" as a policy initiative. Section 2 reviews the current state of the broad involvement of cross-sectoral industry in Japan's PV development. Section 3 analyzes the state of inter-firm technology spillover in Japan's leading PV firms. Section 4 assesses the "virtuous cycle" between R&D, market growth and price reduction. Section 5 briefly summarizes implications for techno-economics.

2. The broad involvement of cross-sectoral industry in PV development

2.1. Vigorous R&D by leading cross-sectoral firms

In line with its PV development strategy to encourage the broad involvement of leading cross-sectoral firms, MITI established an R&D consortium for PV development called the Photovoltaic Power Generation Technology Research Association (PVTEC) in 1990. Table 1 identifies firms participating in PV development under the Sunshine Project as members of PVTEC. Looking at the table we note that broad interdisciplinary firms from textiles, chemicals, petroleum and coal products, ceramics, iron and steel, non-ferrous metals, electrical machinery, and public institutes have participated in PV development in Japan. In addition to PVTEC, MITI entrusted PV development to broad sectors including the electric power industry, the housing industry and construction. The total number of firms participating in MITI's PV development in 1996 amounted to 65.

Fig. 1 illustrates trends in Japan's R&D expenditure for PV R&D by both MITI's Sunshine Project and industry over the period 1974–1995. Looking at Fig. 1 we note that R&D expenditure for PV R&D in Japan increased dramatically from 1980. This was in line with the recommendation by the Industrial Technology Council (one of MITI Minister's advisory bodies) to accelerate PV R&D as a priority project under the Sunshine Project (Industrial Technology Council of MITI, 1979).[1] Although this expenditure declined from 1987, during the period of Japan's "bubble economy", it changed to an increasing trend again from 1993. This can be attributed to MITI's new policy under the New Sunshine Program (R&D Program on Energy and Environmental Technologies) which started in 1993 and accelerated PV R&D activities as a priority project under the global environmental consequences of CO_2 discharge resulting from energy use. These trends demonstrate the significance of a policy initiative with respect to Japan's PV development (Watanabe, 1995b,d).

2.2. The effect of MITI's inducement

Table 2 summarizes trends in PV R&D expenditure by eight leading Japanese PV firms and government financial support provided under MITI's Sunshine Project. Table 2 indicates that approximately 40% of MITI's PV R&D budget was appropriated to eight leading PV firms.[2] Table 3 summarizes the results of a correlation analysis of the PV R&D expenditure of these eight firms and MITI's financial support for PV R&D initiated by respective firms. Looking at the table we note that MITI's financial support significantly induced PV R&D expenditure based on a one-year time lag in all firms examined. This analysis demonstrates that the Sunshine Project functioned well in stimulating industry PV R&D by inducing vigorous R&D expenditure (Meyer-Krahmer, 1992).

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[1] Facing the second energy crisis in 1979, the Minister of MITI consulted the Industrial Technology Council about a priority policy menu. In response to this consultation, the Industrial Technology Council prepared a recommendation entitled "Strategy for Acceleration of the Sunshine Project" which identified certain R&D areas, including PV R&D, to be accelerated on a priority basis. In order to respond to this recommendation, MITI introduced new policies in 1980, including enactment of the "Law for the Promotion of the Development and Introduction of Oil Alternative Energy"; the creation of a new funding system by means of special accounts for energy security; and the establishment of NEDO (the New Energy Development Organization, MITI's affiliate responsible for energy R&D). Consequently, R&D activities of MITI's energy R&D projects, particularly priority R&D projects including PV R&D, were accelerated.

[2] The remaining 60%, of MITI's PV R&D budget was appropriated to national research institutes, universities for basic research, and other industries such as the electric power industry, the housing industry and construction for application-oriented research.

Table 1
Firms participating in the Photovoltaic Power Generation Technology Research Association (PVTEC)

Textiles (1)	Teijin Ltd
Chemicals (5)	Kanegafuchi Chemical Industry Co., Ltd, Shinetsu Chemical Co., Ltd, Diado-hoxan Co., Matsushita Battery Industrial Co., Ltd, Mitsui Toatsu Chemicals Inc.
Petroleum and coal products (3)	Showa Shell Sekiyu K.K., Tonen Co., Japan Energy Co.
Ceramics (3)	Asahi Glass Co., Ltd, Kyocera Co., Nippon Sheet Glass Co., Ltd
Iron and steel (1)	Kawasaki Steel Co.
Non-ferrous metals and products (3)	Osaka Titanium Co., Hitachi Cable, Ltd, Mitsubishi Materials Co.
Electrical machinery (8)	Oki Electric Industry Co., Ltd, Sanyo Electric Co., Ltd, Sharp Co., Sumitomo Electric Industries Ltd, Hitachi, Ltd, Fuji Electric Corporate Research and Development Ltd, Matsushita Electric Industrial Co., Ltd, Mitsubishi Electric Co.
Public institutes (2)	Japan Measurement and Inspection Institute, Central Research Institute of Electric Power Industry

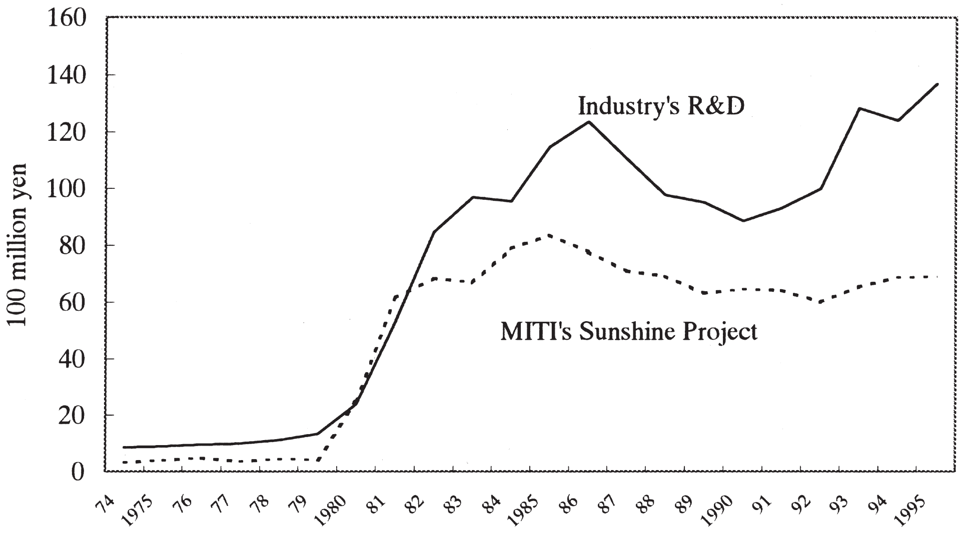

Fig. 1. Trends in R&D expenditure for PV R&D in Japan (1974–1995) — 1985 fixed prices.

2.3. Creation of technology knowledge stock

The vigorous industry R&D expenditure induced by the Sunshine Project has created PV R&D technology knowledge stock. In line with previous approaches (Watanabe, 1992), the technology knowledge stock of PV R&D can be measured by the following equation:

$$T_t=R_{t-m}+(1-\rho)T_{t-1}, \qquad (1)$$

where T_t is the technology knowledge stock of PV R&D in time t; R_{t-m} is the PV R&D expenditure in time $t-m$; m is the lead time of PV R&D and its commercialization; and ρ is the rate of obsolescence of PV technology.

In order to identify the lead time for PV R&D and its commercialization (m) and the rate of obsolescence of PV technology (ρ), with the support of the AIST (Agency of Industrial Science & Technology) of MITI, 19 leading PV firms (including the eight firms examined in the previous sub-section) were surveyed in 1993 concerning the time lag and lifetime of PV technology. Reliable responses were received from 15 firms (including the eight firms examined, and the received response ratio with respect to number of firms was 79%). Out of the reliable responses, 57 valid samples for time lag and 28 for technology lifetime were obtained as illustrated in Appendix A. 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. Fig. 2 illustrates trends in Japanese industry's technology knowledge stock of PV R&D. Table 4 summarizes the same trends in eight leading PV firms. Fig. 2 and Table 4 demonstrate that the technology knowledge stock of PV R&D increased dramatically from 1983/1984 in Japanese industry while PV R&D expenditure rose sharply from 1980/1981. This time lag corresponds to a 2.8 yr time lag between PV R&D and its commercialization.

Table 2
Trends in industry's PV R&D expenditure and government support in Japan (1981–1995): billion yen at 1985 fixed prices[a,b]

	A	B	C	D	E	F	G	H	Other firms	Total
1981	6.3	3.4	14.5	0.6	5.1	10.7	3.7	1.5	7.3	53.1
	(4.6)	(0.4)	(5.9)	(0.2)	(1.9)	(9.1)	(1.4)	(1.3)	[36.6]	[61.4]
1982	6.2	3.6	10.4	2.8	5.3	17.0	3.6	2.1	33.6	84.6
	(4.6)	(0.5)	(4.8)	(0.4)	(1.9)	(11.5)	(1.5)	(1.4)	[41.7]	[68.3]
1983	8.2	4.3	7.9	4.6	7.6	14.0	4.1	2.1	43.9	96.9
	(5.1)	(1.0)	(2.4)	(0.6)	(4.3)	(5.7)	(2.6)	(1.7)	[43.5]	[66.9]
1984	10.2	5.6	8.1	4.1	6.9	15.0	6.5	2.3	36.8	95.5
	(5.7)	(1.6)	(2.4)	(0.5)	(4.3)	(7.3)	(4.3)	(1.7)	[51.1]	[78.9]
1985	11.0	9.7	8.3	45	7.8	12.6	5.4	1.7	53.6	114.6
	(6.0)	(5.4)	(2.2)	(0.6)	(5.0)	(4.3)	(3.1)	(1.1)	[55.9]	[83.6]
1986	14.5	8.2	7.0	5.1	8.9	5.7	5.7	1.8	66.6	123.5
	(7.3)	(3.8)	(3.4)	(0.6)	(5.8)	(3.2)	(3.3)	(1.1)	[48.2]	[76.7]
1987	14.9	8.6	6.4	6.9	7.8	5.8	5.4	1.9	52.7	110.4
	(7.4)	(3.7)	(3.0)	(0.8)	(5.0)	(4.1)	(2.2)	(1.2)	[43.6]	[71.0]
1988	15.2	8.1	4.7	9.7	6.8	5.6	6.6	1.5	39.4	97.6
	(7.6)	(2.6)	(1.9)	(3.4)	(4.0)	(3.9)	(2.8)	(0.9)	[42.1]	[69.2]
1989	14.9	8.0	4.9	8.1	5.5	5.5	6.3	0.5	41.4	95.1
	(7.3)	(3.1)	(2.1)	(2.9)	(3.6)	(4.2)	(2.1)	(0.3)	[37.6]	[63.2]
1990	15.0	7.9	6.4	8.3	5.5	6.4	4.6	0.4	34.2	88.7
	(7.2)	(3.5)	(2.8)	(2.7)	(3.2)	(4.9)	(2.0)	(0.2)	[38.0]	[64.5]
1991	16.7	6.5	6.3	8.8	5.6	5.1	4.7	0.5	39.9	94.1
	(7.2)	(3.2)	(2.8)	(3.1)	(3.3)	(3.7)	(1.9)	(0.3)	[39.2]	[64.7]
1992	17.7	9.8	7.9	9.3	6.1	5.6	4.7	0.4	39.9	101.4
	(7.3)	(3.7)	(3.7)	(3.3)	(3.7)	(4.2)	(1.9)	(0.2)	[32.8]	[60.8]
1993	20.7	9.5	8.5	12.3	7.1	7.1	3.3	0.6	62.1	131.2
	(7.7)	(3.8)	(4.2)	(3.8)	(4.0)	(5.2)	(1.4)	(0.4)	[36.2]	[66.7]
1994	19.7	10.8	7.1	15.0	8.4	6.6	3.8	0.4	54.8	126.6
	(7.6)	(4.6)	(3.3)	(4.0)	(4.6)	(4.7)	(1.6)	(0.3)	[39.6]	[70.3]
1995	18.5	12.9	6.8	15.7	9.3	6.9	4.0	0.4	65.5	140.0
	(7.4)	(5.2)	(2.9)	(4.3)	(5.1)	(5.2)	(1.6)	(0.3)	[38.7]	[70.7]

[a] A–H include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd, Mitsubishi Electric Corp., Sumitomo Electric Industries, Ltd.

[b] Figures in parentheses indicate the amount of government (MITI's) financial support. Figures in square brackets include support to non-industry sectors (universities and national research institutes).

Table 3
Impacts of government PV R&D in inducing industry PV R&D in Japan (1976–1995)[a]

	α	(t-value)	Adj. R^2	DW	
Industry total	0.768	(29.35)	0.979	1.31	
PV firm[b]					
A	0.905	(8.60)	0.900	1.41	1980–1995
B	0.455	(12.50)	0.917	2.18	1981–1995
C	0.634	(13.89)	0.932	2.09	
D	0.433	(12.57)	0.943	2.82	1982–1995
E	0.181	(4.51)	0.805	1.50	1981–1995
F	1.159	(33.14)	0.984	2.13	
G	0.427	(6.23)	0.844	1.70	1981–1995
H	0.614	(5.98)	0.818	1.76	1981–1995

[a] Model:

$PVR=A\cdot SSPV_{-1}^{\alpha}$,

where $SSPV$ — PV R&D budget by the Sunshine Project; and PVR — industry's PV R&D expenditure.

[b] A–H include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd, Mitsubishi Electric Corp., Sumitomo Electric Industries, Ltd.

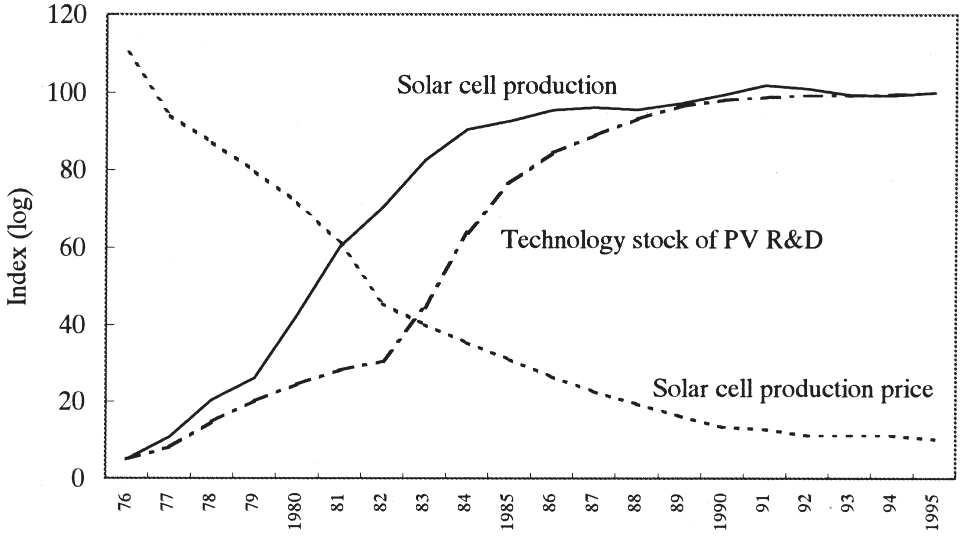

Fig. 2. Trends in PV development in Japan (1976–1995) — index.

2.4. Solar cell production

Table 5 summarizes trends in solar cell production in Japanese industry. Japan's solar cell production in 1995 amounted to 17.4 MW, which shared 21.9% of world total production.[3] Table 5 also indicates trends in solar cell production by eight leading Japanese PV firms which indicates that the share of the top four firms amounted to nearly 90% of solar cell production in Japan.

Contrary to Table 5, Table 2 indicates that a broader cross-section of firms has been involved in PV R&D rather than solar cell production. Stimulated by this observation, comparing Tables 4 and 5 we note the following structure:

1. while the production levels of firms A and B are similar, the technology knowledge stock of firm A is much greater than that of firm B;
2. while there is no substantial differences between the technology stocks of firms B, C, D, E, F and G, their production levels can be classified into three groups: firm B (its production level is much higher than those of the other firms compared), firms C and D (their production levels are similar and they belong to the top four firms), and firms E, F and G (their production levels are much lower than those of the other firms compared).

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[3] World solar cell production in 1995 was 79.6 MW, consisting of USA 34.8 MW (43.7%), Japan 17.4 MW (21.9%), Europe 21.1 MW (26.4%) and other countries 6.3 MW (8.0%).

Table 4
Trends in the technology knowledge stock of PV R&D in Japan's industry (1981–1995): billion yen at 1985 fixed prices[a]

	A	B	C	D	E	F	G	H	Other firms	Total
1981	5.9	11.5	5.2	1.1	9.2	2.0	4.1	1.0	1.2	41.2
1982	6.9	12.4	7.2	1.3	10.9	2.0	5.4	1.1	1.2	48.4
1983	9.8	13.1	10.5	1.4	13.1	4.5	7.7	1.4	7.0	68.5
1984	14.2	13.8	14.0	1.7	15.5	14.3	9.8	2.6	28.2	114.1
1985	17.5	14.8	18.6	4.1	17.7	30.9	11.5	4.1	59.2	178.4
1986	22.1	16.3	22.7	8.1	21.7	38.8	13.8	5.3	90.6	239.4
1987	27.9	19.5	26.3	10.6	24.2	47.0	17.3	6.6	111.4	290.8
1988	33.3	24.9	29.3	12.9	27.2	50.1	19.3	6.9	145.1	349.0
1989	41.2	28.2	30.4	15.4	30.6	45.7	21.0	7.3	180.2	400.0
1990	47.8	31.0	30.7	19.2	32.3	42.4	22.4	7.7	194.3	427.8
1991	53.3	32.6	29.3	24.9	32.6	39.5	24.3	7.5	195.1	439.3
1992	57.5	34.2	28.2	28.0	31.6	37.0	26.2	6.5	196.1	445.3
1993	61.0	34.9	28.9	30.7	30.7	36.0	26.0	5.6	192.0	445.8
1994	65.4	35.0	29.4	33.4	30.2	33.9	25.9	4.9	193.1	451.2
1995	70.0	37.5	31.3	36.0	30.2	32.7	25.7	4.3	198.8	466.5

[a] A–H include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd, Mitsubishi Electric Corp., Sumitomo Electric Industries, Ltd.

Table 5
Trends in solar cell production in Japanese industry (1981–1995): MW[a]

	A	B	C	D	E	F	G	H	Other firms	Total
1981	0.1	0.1	0.4	0.3	0.2	tr	tr	tr	0.1	1.2
1982	0.9	0.2	0.5	0.3	0.7	tr	tr	tr	0.1	2.7
1983	2.1	0.4	0.5	0.6	1.7	tr	tr	tr	0.2	5.5
1984	3.0	1.0	0.6	0.9	2.1	0.1	tr	tr	1.2	8.9
1985	3.0	0.8	0.6	1.1	2.6	0.1	tr	tr	2.1	10.3
1986	3.4	0.9	0.6	1.2	2.5	0.1	tr	tr	3.9	12.6
1987	3.3	1.3	0.3	2.0	1.0	0.1	tr	tr	5.2	13.2
1988	3.1	1.7	0.3	2.4	0.5	0.1	tr	tr	4.7	12.8
1989	3.6	3.2	0.4	1.9	0.1	0.1	tr	tr	4.9	14.2
1990	4.4	4.6	0.3	1.8	0.1	0.1	tr	tr	5.2	16.8
1991	6.0	5.8	0.7	3.1	0.1	0.1	tr	tr	4.0	19.8
1992	6.5	5.1	1.0	3.0	tr	tr	tr	tr	3.2	18.8
1993	6.2	4.8	1.0	1.7	tr	tr	tr	tr	3.0	16.7
1994	5.5	5.3	2.0	1.8	tr	tr	tr	tr	1.9	16.5
1995	5.1	6.1	4.0	0.2	tr	tr	tr	tr	2.0	17.4

[a] A–H include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd, Mitsubishi Electric Corp., Sumitomo Electric Industries, Ltd.

These observations suggest that broad inter-firm or cross-sectoral technology spillovers have prevailed in the structure of this industry in Japan. The following section attempts to demonstrate this hypothetical view.

3. Inter-firm technology spillover

3.1. Impact of inter-firm technology spillover on PV innovation

Vigorous PV R&D expenditure and the resulting technology knowledge stock are the sources of innnovation considered as technology-driven energy. Consequently, such R&D expenditure and subsequent technology stock are expected to generate a number of patent applications in the field of PV R&D. Table 6 and Fig. 3 summarize trends in the number of PV patent applications in Japanese industry, including applications submitted by the eight leading PV firms. In line with previous approaches (e.g., Griliches, 1984), provided that the generation of PV patents is governed by the flow and stock of PV R&D and they are represented by PV R&D expenditure and technology knowledge stock of PV R&D, respectively, the number of PV patent applications (*PVPA*) can be represented by the following equation:

$$PVPA=F_1(PVRr, TPV), \tag{2}$$

where *PVRr* is PV R&D expenditure in fixed prices and *TPV* is technology knowledge stock of PV R&D. Given

Table 6
Trends in the number of patent applications in the field of PV R&D in Japan's industry (1981–1995)[a]

	A	B	C	D	E	F	G	H	Other firms	Total
1981	23	4	14	0	48	6	26	8	146	275
1982	28	11	16	7	14	20	35	15	214	360
1983	39	4	28	16	5	20	33	9	256	410
1984	61	14	45	9	19	51	40	14	249	502
1985	73	17	47	17	11	48	40	10	202	465
1986	116	21	78	23	52	29	54	18	97	488
1987	82	59	111	20	46	23	53	20	72	486
1988	134	47	63	26	27	29	74	15	82	497
1989	96	20	45	17	40	16	73	6	68	381
1990	73	15	41	18	26	11	62	3	88	337
1991	128	4	34	11	10	12	45	8	49	301
1992	108	12	42	5	13	15	35	1	171	402
1993	85	10	47	21	12	14	19	2	210	420
1994	71	11	34	25	20	7	12	1	328	509
1995	87	17	29	7	30	15	9	1	309	504

[a] A–H include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd, Mitsubishi Electric Corp., Sumitomo Electric Industries, Ltd.

Fig. 3. Trends in the number of PV patent applications in Japanese industry (1974–1995).

that the essential requirement of a patent application is the novelty of a new idea and such a novel idea generally is depleted as time passes (Freeman, 1982), a third factor t which represents the time trend should be incorporated into the equation for PV patent applications as follows:

$$PVPA=F_2(t, PVRr, TPV). \quad (3)$$

Furthermore, considering the interdisciplinary nature of PV R&D, MITI's PV R&D policy aimed at stimulating cross-sectoral technology spillovers, and subsequently broad inter-firm technology spillovers as observed in Section 2.4, TPV should represent technology stock consisting of proprietary PV R&D and assimilated spillover technology generated by other firms (Jaffe, 1986; Bernstein, 1998). Provided that a firm makes every effort to maximize the contribution of assimilated spillover technology by embodying it into the production processes, TPV can be decomposed as follows:

$$TPV=TPV_i+Z\left(\sum TPV_j-TPV_i\right), \quad (4)$$

where TPV_i is the technology knowledge stock of PV R&D in firm i; ΣTPV_j is thw technology knowledge stock of PV R&D in all industry; and Z $(0<Z<1)$ is the assimilation capacity.

On the basis of the foregoing, Eq. (2) can be estimated by the following simple Cobb–Douglas type function for Japanese industry PV patent applications over the period 1976–1995:

Table 7
Factors contributing to a change in the number of PV patent applications in Japanese industry (1976–1995)[a]

	λ	(t-value)	α	(t-value)	β	(t-value)	γ	(t-value)	Adj. R^2	*DW*
Industry total	−0.02	(−2.09)	0.55	(16.19)	0.10	(1.89)			0.982	2.31
PV firm[b]										
A	−0.16	(−1.97)	1.38	(10.52)	0.75	(1.64)	0.03	(0.57)	0.982	2.50
B	−0.22	(−2.48)	2.67	(4.00)	1.37	(2.28)	0.05	(1.11)	0.927	1.73
C	−0.14	(−3.03)	0.11	(0.45)	0.87	(4.86)	0.10	(2.28)	0.812	1.56
D (1981–1995)	−0.46	(−6.89)	1.52	(7.73)	0.98	(3.73)	0.01	(0.87)	0.908	1.77
E	−0.32	(−3.42)	1.73	(3.11)	1.82	(2.64)	0.33	(2.49)	0.875	2.56
F (1980–1995)	−0.14	(−3.05)	1.41	(8.24)	1.10	(3.26)	0.04	(0.83)	0.937	2.65
G	−0.18	(−1.39)	1.49	(2.09)	1.40	(1.44)	0.03	(1.03)	0.942	2.00
H (1980–1995)	−0.18	(−1.37)	1.13	(4.64)	1.06	(3.12)	0.01	(0.76)	0.941	2.56

[a] Model:

$$PVPA=A\,e^{\lambda t}PVRr^{\alpha}[TPV_i+Z_j(\textstyle\sum TPV_j-TPV_i)]^{\beta}$$

$$\ln PVPA\approx\ln A+\lambda+\alpha\ln PVRr+\beta\ln TPV_i+\gamma\left(\frac{\sum TPV_j}{TPV_i}-1\right),$$

$$\gamma\equiv Z\beta$$

where *PVPA* — number of PV patent applications; *PVRr* — PV R&D expenditure (real); TPV_i — technology knowledge stock of PV R&D in firm i; and ΣTPV_j — technology knowledge stock of PV R&D in whole industry.

[b] A–H include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd, Mitsubishi Electric Corp., Sumitomo Electric Industries, Ltd.

$$PVPA=A\,e^{\lambda t}PVRr^{\alpha}\left[TPV_i+Z\left(\sum_j TPV_j-TPV_i\right)\right]^{\beta}, \qquad (5)$$

where A is a scale factor; λ, α and β are elasticities.

In the case of leading PV firms which share a reasonable share of their own technology knowledge stock created through proprietary PV R&D out of the technology knowledge stock of PV R&D in all industry, considering that generally $Z\ll 1$, the ratio of assimilated spillover technology and proprietary technology knowledge stock is smaller enough than 1 $[Z(\Sigma TPV_j-TPV_i)/TPV_i\ll 1]$. Therefore, Eq. (5) can be approximated by the following equation:

$$\ln PVPA=\ln A+\lambda t+\alpha\ln PVRr+\beta\ln TPV_i\left(1+Z\frac{\sum TPV_j-TPV_i}{TPV_i}\right)\approx\ln A+\lambda t+\alpha\ln PVRr+\beta\ln TPV_i+\gamma\left(\frac{\sum TPV_j}{TPV_i}-1\right), \qquad (6)$$

where $\gamma\equiv Z\beta$.

By utilizing Eq. (6), Table 7 identifies factors governing leading PV firm PV patent applications over the period 1976–1995. Looking at the table we note that PV R&D expenditure proves statistically to make the most significant contribution to PV patent applications (except for firm C, which is insignificant) followed by technology knowledge stock. In many firms not only technology knowledge stock of proprietary R&D but also assimilated spillover technology displays a statistically significant contribution to PV patent applications.[4] The elasticity of the time trend λ was negative with statistical significance in all the firms examined. These findings provide the following implications with respect to the governing factors of PV patent applications in Japanese industry over the last two decades:

1. as an essential requirement of a patent applications, R&D expenditure representing the forefront R&D activities demonstrates the most significant contribution;[5]
2. not only R&D expenditure flow but also its stock (technology knowledge stock of proprietary R&D) demonstrates a reasonable contribution. In many firms, assimilated technology knowledge stock demonstrates a significant contribution; and

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[4] 2.5% significance for two firms, 15% significance for two firms, and 20–25% significance for three firms. Insignificant for firm A technology stock of proprietary R&D, which is much greater than other firms'.

[5] Only one exception is the case of firm C which was statistically insignificant. Looking at Tables 2 and 5 we note that, contrary to its recent increase in solar cell production, firm C's PV R&D expenditure share has decreased. This suggests that firm C depends on its proprietary technology knowledge stock based on its previous R&D and the assimilation of spillover technology rather than forefront proprietary R&D for PV patent applications. Table 7 supports this view by demonstrating the significance of both the technology stock of proprietary R&D and assimilated spillover technology.

3. coinciding with the general trend of the depletion of novel ideas worthy of patent applications, a general trend of successive dimunition of the number of patents was observed in all firms examined.

3.2. Impacts of inter-firm technology spillover on solar cell production

Since PV is a technology-driven clean energy technology, a solar cell is really a product of PV technology and trends in its production depend on the technology knowledge stock of PV R&D. The observation indicated in Section 2.4 suggests that this stock consists of technology knowledge stock of proprietary PV R&D and assimilated spillover technology generated by other firms. Furthermore, a firm strategy regarding solar cell production is a strategy to be forwarded in the context of the development of oil-substituting technology and governed by trends in energy prices.

On the basis of these observations, an equation describing the governing factors of solar cell production in Japanese industry over the last two decades can be estimated by the following simple Cobb–Douglas type function:

$$SCP = APey^{\alpha}\left[TPV_i + Z\left(\sum_j TPV_j - TPV_i\right)\right]^{\beta}, \tag{7}$$

where *SCP* is solar cell production; and *Pey* is relative energy prices.

Similar to Eq. (6), Eq. (7) can be approximated by the following equation:

$$\begin{aligned} \ln SCP &= \ln A + \alpha \ln Pey + \beta \ln TPV_i\left(1 + Z\frac{\sum TPV_j - TPV_i}{TPV_i}\right) \approx \ln A + \ln Pey + \beta \ln TPV_i \\ &\quad + \gamma\left(\frac{\sum TPV_j}{TPV_i} - 1\right), \end{aligned} \tag{8}$$

where $\gamma \equiv Z\beta$.

By utilizing Eq. (8), Table 8 identifies factors governing leading PV firm solar cell production over the last two decades. Looking at the table we note that technology knowledge stock of both proprietary PV R&D and assimilated spillover technology provides a significant contribution to increasing solar cell production. In addition, an increase in relative energy prices provides a significant contribution to a production increase (except for firm D, which is insignificant). Comparing Tables 7 and 8 we note that the impact of inter-firm technology spillover is more significant on solar cell production than patent applications. This suggests that technology spillover provides a direct contribution to solar cell production rather than through the stimulation of PV innovation.

3.3. Impact of inter-firm technology spillover on change in solar cell production prices

Greater solar cell production supported by an increase in technology knowledge stock and also induced by energy prices provides both solar cell producers and customers with an opportunity for a learning exercise in addition to the benefits of economies of scale. A higher level of production has generally led to a decline in solar cell production prices as demonstrated in Table 9 and Fig. 2. 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 1983, 1200 yen/w in 1985, 650 yen/w in 1990, and 600 yen/w in 1994, respectively, at current prices. This process can be explained by two trajectories: (1) inducement by technology knowledge stock and prices of energy, and (2) effects due to learning effects and economies of scale.

On the basis of the above observations, equations describing the trajectories of solar cell production prices in Japanese industry over the last two decades can be estimated by the following simple Cobb–Douglas type functions.

1. Inducement by technology knowledge stock and prices of energy:

$$PSC = A\cdot Pey^{\alpha}\left[TPV_i + Z\left(\sum_j TPV_j - TPV_i\right)\right]^{\beta}, \tag{9}$$

where *PSC* is solar cell production price (fixed price). Similar to the foregoing, Eq. (9) can be approximated by the following equation:

$$\begin{aligned} \ln PSC &= \ln A + \alpha \ln Pey + \beta \ln TPV_i\left(1 + Z\frac{\sum TPV_j - TPV_i}{TPV_i}\right) \approx \ln A + \alpha \ln Pey \\ &\quad + \beta \ln TPV_i + \gamma\left(\frac{\sum TPV_j}{TPV_i} - 1\right), \end{aligned} \tag{10}$$

where $\gamma \equiv Z\beta$.

2. Effects due to learning effects and economies of scale:

$$PSC = A\,\mathrm{e}^{\lambda t} SCP^{\alpha}. \tag{11}$$

By utilizing Eqs. (10) and (11), Table 10 identifies factors governing leading firm solar cell production

Table 8
Factors contributing to a change in solar cell production in Japanese industry (1976–1995)[a]

	α	(t-value)	β	(t-value)	γ	(t-value)	Adj. R^2	*DW*	
Industry total	5.94	(13.50)	2.19	(35.48)			0.985	1.75	
PV firm[b]									
A	12.40	(7.45)	3.53	(10.35)	0.32	(3.80)	0.935	1.92	1980–1995
B	6.82	(13.41)	5.05	(18.06)	0.14	(4.93)	0.985	1.98	1978–1995
C	2.94	(2.92)	1.01	(9.07)	0.11	(1.91)	0.893	1.19	
D	0.10	(0.08)	0.77	(3.76)	0.02	(2.77)	0.902	1.64	1991–1995
E	14.52	(7.85)	2.19	(1.97)	0.25	(1.49)	0.877	1.77	1980–1990
F	6.20	(13.05)	0.88	(6.10)	0.04	(1.10)	0.956	2.57	1976–1990

[a] Model:

$$SCP=APey^{\alpha}[TPV_i+Z_j(\sum TPV_j-TPV_i)]^{\beta}$$

$$\ln SCP\approx\ln A+\ln Pey+\beta\ln TPV_i+\gamma\left(\frac{\sum TPV_j}{TPV_i}-1\right),$$

$$\gamma\equiv Z\beta$$

where SCP — solar cell production; Pey — relative energy prices; TPV_i — technology knowledge stock of PV R&D in firm i; and ΣTPV_j — technology knowledge stock of PV R&D in whole industry.

[b] A–F include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd.

Table 9
Trends in solar cell prices in Japan (1974–1995) — government purchasing prices (yen/w)[a]

	Current prices	1985 fixed prices
1974	20,000	26,120
1975	16,500	20,960
1976	13,500	16,230
1977	10,900	12,790
1978	8600	10,100
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	640	670
1992	600	650
1993	600	660
1994	600	680
1995	580	670

[a] Source: MITI (1988)/NEDO (1988).

prices in trajectories (1) and (2). Looking at Table 10(A) (inducement by technology knowledge stock and prices of energy), we note that technology knowledge stock both of proprietary PV R&D and assimilated spillover technology provides a significant contribution to a dramatic decrease in solar cell production prices (except for firm A, which is insignificant). In addition, an increase in relative energy prices provides a significant contribution to the solar cell production price decrease (except for firm F). Table 10(B) (effects due to learning effects and economies of scale) demonstrates that the effects of economics of scale provide a significant contribution to a decline in solar cell production prices in all leading Japanese PV firms examined over the last two decades while the impacts of learning effects are rather limited.[6]

4. Virtuous cycle between R&D, market growth and price reduction

4.1. Feedback loop to a further production increase

A dramatic decrease in solar cell production prices as demonstrated in Table 9 and Fig. 2 inevitably induces further production increases. This can be attributed to a demand increase from lower prices and also the stimulation of suppliers in order to maintain an increasing trend of sales value by supplementing price declines with greater production. In this case, energy price increases also induce a production increase. Eq. (12) depicts this behavior. In this simple Cobb–Douglas type function,

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[6] Contrary to the significant contribution of learning effects in firms A, E and F to a decrease in solar cell production, similar contributions in firms B, C and D are not significant. This is due to a rapid production increase in later years in firms B, C and D which provided significant opportunities for enjoying the advantages of economies of scale with limited opportunities for a learning exercise.

Table 10
Factors contributing to a change in solar cell production prices in Japanese industry (1976–1995)

A. Inducement by technology knowledge stock and prices of energy[a]

	α	(t-value)	β	(t-value)	γ	(t-value)	Adj. R^2	DW	
Industry total	−1.04	(−5.59)	−0.97	(−39.51)			0.988	1.53	
PV firm[b]									
A	−0.30	(−2.56)	−0.29	(−7.35)	−0.01	(−0.34)	0.992	2.79	1980–1990
B	−1.83	(−4.29)	−1.25	(−5.29)	−0.06	(−5.04)	0.961	2.91	1979–1990
C	−2.77	(−7.42)	−0.23	(−2.87)	−0.06	(−1.70)	0.873	1.80	1976–1990
D	−0.80	(−1.29)	−0.68	(−6.73)	−0.02	(−4.80)	0.963	2.40	1981–1990
E	−0.87	(−2.74)	−0.62	(−3.42)	−0.14	(−4.89)	0.988	1.62	1980–1990
F	−0.22	(−0.75)	−0.60	(−6.64)	−0.07	(−4.54)	0.966	1.98	1980–1990

B. Effects due to learning effects and economies of scale[c]

	λ	(t-value)	α	(t-value)	Adj. R^2	DW	
Industry total	−0.06	(−9.32)	−0.31	(−18.87)	0.995	1.38	
PV firm[b]							
A	−0.03	(−5.75)	−0.09	(−9.00)	0.979	2.30	1980–1990
B			−0.29	(−22.61)	0.983	2.38	1979–1990
C			−0.52	(−25.34)	0.979	1.57	1976–1990
D			−0.84	(−34.20)	0.993	1.74	1981–1990
E	−0.19	(−19.25)	−0.06	(−2.29)	0.977	2.73	1980–1990
F	−0.12	(−18.61)	−0.06	(−2.40)	0.973	2.42	1980–1990

[a] Model:

$$PSC=A\cdot Pey^{\alpha}[TPV_i+Z_j(TPV_j-TPV_i)]^{\beta}$$

$$\ln PSC\approx\ln A+\alpha\ln Pey+\beta\ln TPV_i+\gamma\left(\frac{\sum TPV_j}{TPV_i}-1\right),$$

$$\gamma\equiv Z\beta$$

where PSC — solar cell production price (fixed price); Pey — relative energy prices; TPV_i — technology knowledge stock of PV R&D in firm i; and ΣTPV_j — technology knowledge stock of PV R&D in whole industry.

[b] A–F include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd.

[c] Model:

$$PSC=A\,e^{\lambda t}SCP^{\alpha},$$

where PSC — solar cell production price (fixed price); and SCP — solar cell production.

prices of both solar cell production and energy in the previous year are used for explanatory variables:

$$SCP=A\cdot PSC_{-1}^{\alpha}Pey_{-1}^{\beta}. \tag{12}$$

By utilizing Eq. (12), Table 11 demonstrates this feedback loop and factors inducing this loop in leading PV firms over the last two decades. Looking at Table 11 we note that both a decrease in solar cell production prices and an increase in energy prices in the previous year provide significant inducement of production increase in all firms examined (except energy prices inducement in firm B, which is insignificant).

4.2. Feedback loop to further R&D investment

Similar to a feedback loop to further production increase following a dramatic decrease in production prices, this production increase induces further R&D investment. Eq. (13) depicts this inducement:

$$PVR=A\cdot SCP^{\alpha}. \tag{13}$$

By utilizing Eq. (13), Table 12 demonstrates this feedback loop in leading PV firms over the last two decades. Looking at Table 12 we note that solar cell production significantly induces PV R&D simultaneously[7] in all firms examined.

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[7] This can be imputed by the following simple identical equation: $\Delta R=\Delta R/Y+\Delta Y$, where R=R&D investment, R/Y=R&D intensity and Y=production. $\Delta R/dR/dt/R$.

Table 11
Factors contributing to a change in the solar cell production feedback loop in Japanese industry (1976–1995)[a]

	α	(t-value)	β	(t-value)	Adj. R^2	DW	
Industry total	−2.02	(−58.73)	2.98	(13.61)	0.995	1.25	
PV firm[b]							
A	−4.07	(−14.75)	2.03	(4.97)	0.974	2.82	1981–1990
B	−2.02	(−7.14)	0.80	(0.79)	0.902	2.01	1980–1990
C	−1.12	(−5.17)	2.10	(2.31)	0.967	2.48	1976–1990
D	−1.63	(−32.62)	2.54	(5.69)	0.990	1.79	1978–1990
E	−1.48	(−6.88)	11.10	(13.36)	0.963	1.62	1981–1990
F	−1.31	(−6.56)	6.65	(15.35)	0.975	1.94	1981–1991

[a] Model:

$SCP=A\cdot PSC_{-1}^{\alpha}Pey_{-1}^{\beta}$,

where SCP — solar cell production; PSC — solar cell production price (fixed price); and Pey — relative energy prices.

[b] A–F include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd.

Table 12
Impact of the inducement of solar cell production increase on PV R&D in Japanese industry (1976–1995)[a]

	α	(t-value)	Adj. R^2	DW	
Industry total	0.43	(25.96)	0.973	1.03	
PV firm[b]					
A	0.24	(13.61)	0.952	1.46	1980–1990
B	0.24	(10.12)	0.932	1.57	1979–1990
C	0.62	(15.62)	0.946	1.17	1976–1990
D	1.19	(10.04)	0.908	2.21	1980–1990
E	0.10	(6.10)	0.933	1.53	1980–1990
F	0.66	(6.32)	0.829	2.04	1979–1991

[a] Model:

$PVR=A\cdot SCP^{\alpha}$

where PVR — industry PV R&D expenditure; and SCP — solar cell production.

[b] A–F include the following leading Japanese PV firms: Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd.

4.3. *Creation of a virtuous cycle*

The above analysis suggests the possibility of creating a virtuous cycle for PV development. Fig. 4 demonstrates a virtuous cycle between R&D triggered by the Sunshine Project, steady market growth and consequently dramatic price reduction in the Japanese industry over the period 1976–1995. Noteworthy to this cycle is the “double boost effects” to solar cell production coming from both increased technology knowledge stock of PV R&D and decreased solar cell production prices. Similar “double boost effects” can be observed in PV R&D, which is the source of technology knowledge stock, coming from both increased solar cell production and MITI’s PV R&D budget.

5. Implications for techno-economics

On the basis of the above empirical analyses of Japan’s PV development path focusing on a mechanism of (1) encouraging the broad involvement of cross-sectoral industry, (2) stimulating inter-technology stimulation and cross-sectoral technology spillover, (3) inducing a vigorous industry investment in PV R&D leading to an increase in industry’s PV technology knowledge stock, and steps for creating a virtuous cycle between R&D, market growth and price reduction, the following suggestions were obtained:

1. Institutional and technological demonstrations should be carried out.
2. Technological improvement and organizational learning should be accelerated.
3. R&D on renewable energy technologies (RETs), and the development of market reward structures that promote the industrial dynamism of a virtuous cycle involving market growth and price reductions for technically proven advanced RETs, should be intensified.
4. Coherent policies aimed at unleashing the industrial dynamism of a virtuous cycle involving market growth and price decreases for RETs should be formulated.
5. Market opportunities for RETs mobilizing private sector resources, and establishing viable RETs industries, should be pursued.

We should bear in mind that timing, pace and intensity are of major importance in creating a virtuous cycle between R&D, market growth and price reduction.

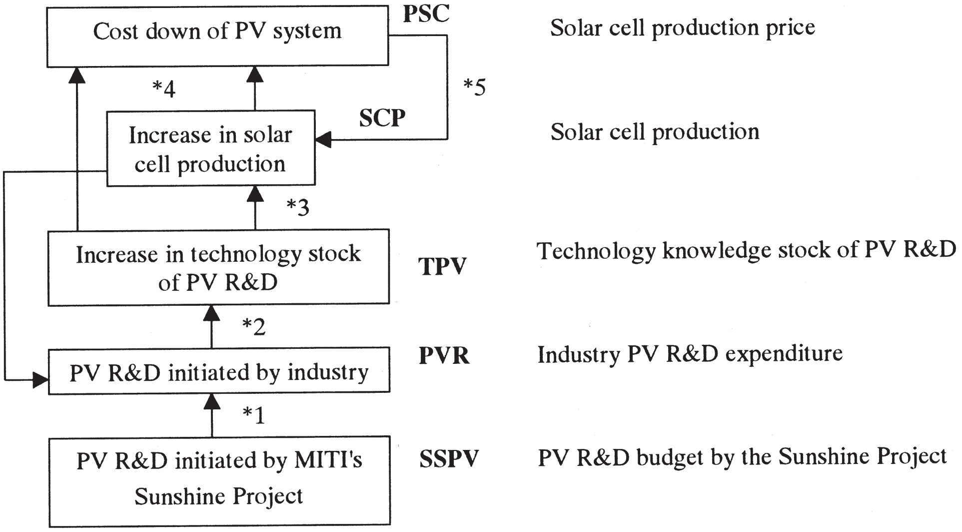

Fig. 4. Steps for creating the virtuous cycle for PV development in Japan (1976–1995).

Appendix A. Measurement of time lag between PV R&D and commercialization, and rate of obsolescence of PV technology

In order to measure technological knowledge stock of PV R&D, it is essential to estimate a reliable, up-to-date time lag and the rate of obsolescence data. However, there has been no reliable survey estimating these factors on PV R&D. Therefore, with the support of AIST of MITI, we prepared a questionnaire for 19 leading PV firms (including the eight firms examined) out of 26 member firms of the Photovoltaic Power Generation Technology Research Association (PVTEC) in 1993 which included questions related to the time lag and the lifetime of PV technology. Reliable responses were received from the following 15 firms (also including the eight firms examined): Sanyo Electric Co., Ltd, Kyocera Corp., Sharp Corp., Kaneka Corp., Fuji Electric Co., Ltd, Hitachi, Ltd, Mitsubishi Electric Corp., Sumitomo Electric Industries, Ltd, Daido-hoxan Co., Matsushita Battery Industrial Co., Ltd, Showa Shell Sekiyu K.K., Tonen Co., Japan Energy Co., Osaka Titanium Co., Ltd and Matsushita Electric Industries Co., Ltd.

Distribution of the reliable answers from 15 firms are summarized in Tables A1 and A2.

Table A1
Number of valid samples on the time lag between PV R&D and commercialization

Time lag (yr)	Number of valid samples
1	13
2	18
3	11
4	5
5	4
6	3
7	2
8	1
Average: 2.8 yr	Total: 57

Table A2
Number of valid samples on the lifetime of PV technology

Lifetime (yr)	Number of valid samples
2	3
3	4
4	5
5	6
6	4
7	3
8	2
9	1
Average: 4.9 yr (20.3% pa)	Total: 28

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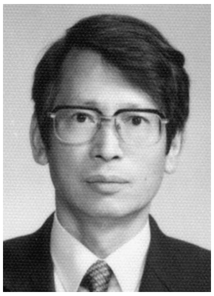

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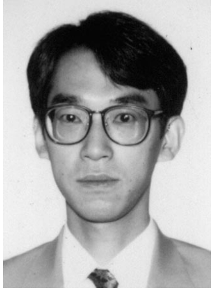

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