Influence of Resource Allocation in the Photovoltaic R&D of Japan based on Technology Stock Modeling

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Keywords: Solar Cell, R&D, Resource Allocation, Technological Progress Model, Technology Stock, Module Price, Market Share.

Abstract: In Japan, crystalline silicon solar cells have a large market share in production, however they have not been a priority in R&D. This paper analyzes the influence of resource allocation in the photovoltaic (PV) R&D in Japan on the price of solar cells and the market share in world solar cell production. Firstly, it finds that the price of solar cells in Japan, with respect to the resource allocation in R&D of crystalline silicon solar cells, did not reduce significantly but maintained a constant level. For the projection, it does not use an experience curve, but models technological progress and price reduction of solar cells in Japan, excluding mass production effects, based on technological knowledge stock modeling. Secondly, solar cell prices in other countries are estimated based on their market share of the world's solar cell production. The estimated solar cell price in Japan is reduced by up to 40% from the actual price, and is competitive to the estimated solar cell prices in China and Taiwan. In this case, Japan could maintain its high share in the world solar cell production for a few years longer. This analysis will contribute to cost-effective R&D resource allocation by a simulation approach.

1 INTRODUCTION

Figure 1 shows the market share of the world solar cell production by country (IEA-PVPS, 1998, 2013, Maycock, 1982,…,2006). The market share of Japan had increased by up to 50% from 1995 to 2004. However, after that, Japan has lost its market share, declining rapidly to 7%. Instead of Japan, China and Taiwan have rapidly expanded their market share. A few of the reasons why Japan has lost its market share, according to New Energy and Industrial Technology Development Organization (NEDO), one of the governmental funding agencies of Japan, are that Japanese solar cell manufacturers could not import enough materials made of silicon and they could not keep up with the large investments made by China and Taiwan. However, prior studies point out other problems in the photovoltaic (PV) technology development and industrial policies of the government (Endo, 2003, Oshika, 2013).

Most analyses regarding solar cell technologies, for example, price projection, are based mainly on the experience curve (IEA, 2000). However, it cannot distinguish between the effects of mass production and technological progress. Other than the experience curve, other approaches, such as the analysis of cost factors (Nemet, 2006), life cycle assessment (LCA) (Yamada, 2012), and analysis of technology development (Watanabe, 2000), were used for analyzing solar cell technologies and projecting their costs, but there are no studies focusing on the resource allocation in PV R&D.

Based on the background mentioned above, this paper focuses on R&D of crystalline silicon solar cells (single and multi-crystalline silicon solar cells) in Japan, from a resource allocation point of view, and analyzes its effects on price reduction of solar cells and change in market share of the world's production of solar cells. This analysis is not based on the experience curve, but models price reduction as a result of R&D, excluding the effects of mass production, and adopts the technology knowledge stock approach. On the other hand, price ratios of solar cells between Japan and other countries are estimated based on their market share of the world solar cell production. The analysis shows the influence of resource allocation in PV R&D of Japan

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on the price of indigenous solar cells and market share of the world's solar cell production.

A combination of the technological progress model of solar cells, the world solar cell market model, and the dissemination model for residential PV systems (Endo, 2014) suggests the possibility of utilizing a simulation approach to achieve cost-effective resource allocation in PV technology development.

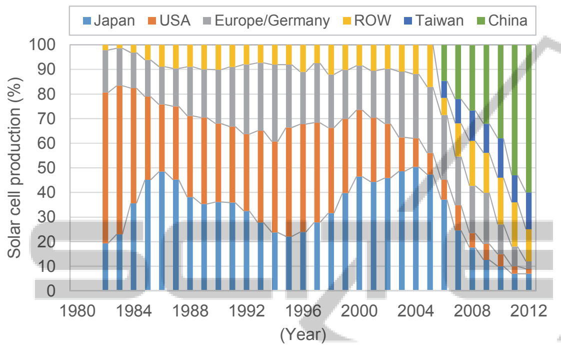

Figure 1: Market share of the world solar cell production by country.

2 MODELING OF TECHNOLOGICAL PROGRESS OF SOLAR CELLS

2.1 Solar Cell Price

Figure 2 shows the module price of solar cells in Japan (IEA-PVPS, 2013), which has been reducing steadily since 1992. However, it was affected by increases in silicon price and almost stabilized in the middle of the 2000s. After 2008, the price of solar cells dropped rapidly due to oversupply in the world solar cell market. The price can be regarded as the module price of crystalline silicon solar cells, as crystalline silicon has had a large market share in the solar cell production of Japan, except in the early years, when solar cells were used mainly in calculators, as shown in Figure 3.

The module price declined from 966 JPY/W in 1992 to 290 JPY/W in 2012. This price reduction to 0.300 (=290/966) of the 1992 level was because of technological progress and the effects of mass production, such as economies of scale and learning-by-doing. For modeling technological progress, that is, price reduction due to R&D, the effects of mass production are removed in the following manner.

Regarding the effects of mass production, economies of scale is estimated using LCA. Yamada, 2012 showed that the module cost was 350 JPY/W ten years ago, at a production scale of 10 MW/year. It is now 144 JPY/W at the production scale of 1 GW/year. In this case, the effects of economies of scale are computed to be 40 JPY/W. This means that the price, reduced by 10 times of the scale up, is 0.941 = ((310/350)^0.5). For this analysis, instead of the total annual production of crystalline silicon solar cells in a production line or a company, the indigenous production of Japan is used as the annual production. For the figures on cumulative production, total cumulative production of crystalline silicon solar cells in Japan is used. The annual and cumulative solar cell production increases are 401 times and 334 times, respectively, during the last 20 years. If the price, reduced by 10 times of the scale up, is rounded and assumed as 0.94, the price reduction due to economies of scale during the last 20 years is 0.851 = $(0.94\hat{}\log_{10}(401))$.

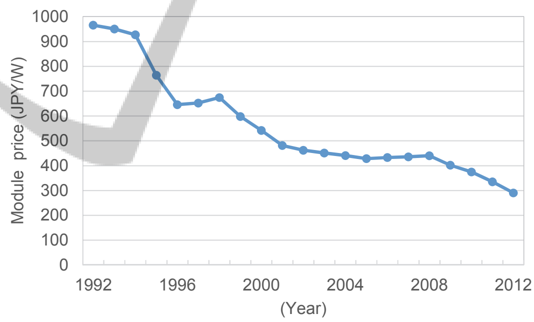

Figure 2: Solar cell price in Japan.

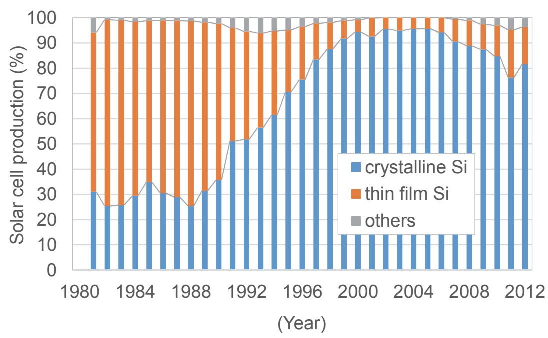

Figure 3: Solar cell production in Japan by cell technology.

The progress ratio (PR) (IEA, 2000) includes technological progress and the effects of mass production, and is 0.866 = $0.300\hat{}(1/\log_2(334))$ =

(2^-E), with (E=0.207). However, PR for only learning-by-doing is assumed to be 0.991 (price reduction of 0.97 for 10 times of the cumulative production). In other words, price reduction during the last 20 years is assumed to be 0.926 with learning-by-doing (=0.991^log$_2$(334) or 0.97^log$_{10}$(334)) and 0.381 (=0.300/(0.851*0.926)) with technological progress due to R&D.

2.2 R&D Expenditures for PV

Figure 4 shows the governmental budget for PV R&D in Japan. In the figure, budgets are categorized into three types of solar cells, crystalline silicon, thin film silicon, and others, PV systems including balance of system (BOS), and other PV related ones. From 1974 to 2000, PV R&D was promoted under the Sunshine Program (from 1993, the New-Sunshine Program) of the Ministry of International Trade and Industry (MITI). From 2001, PV R&D was conducted as a part of NEDO's technology development program (from 2008, the advanced solar cell technology development program was initiated). NEDO does not disclose R&D expenditures by themes. For the analysis, therefore, R&D expenditures from 2001 were estimated based on the budget for individual projects and the number of themes or sub-themes in the project.

Regarding R&D expenditures on crystalline silicon solar cells, it was reduced drastically in 1997. It came back to previous levels soon, but it has been kept at a low level after that.

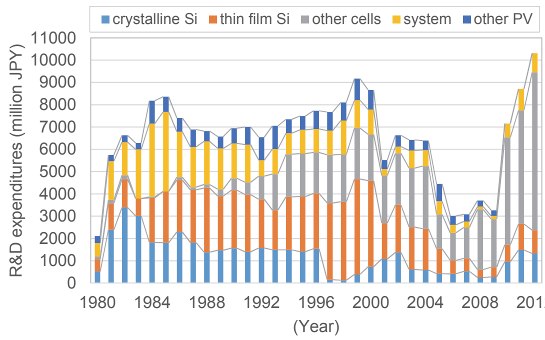

Figure 4: R&D expenditures for photovoltaics by the Japanese government by technologies.

2.3 Technology Knowledge Stock

Based on Watanabe, 2000, let us define technology knowledge stock by equation (1).

$$TS_t = TS_{t-1} * (1 - ro) + RE_{t-m} / rd_{t-m} \quad (1)$$

where

TS_t: technology knowledge stock of R&D in year t (million JPY)

m: lead-time from R&D to commercialization (year), m=5 is used based on NEDO's PV technology development (Ogawa, 2001)

ro: rate of obsolescence (%), ro=20% (Watanabe, 2000) and 10% (MRI, 1991) are used for PV R&D

RE_t: R&D expenditures in year t (million JPY)

rd_t: R&D deflator in year t (MEXT, 2013)

R&D expenditures become obsolete and contribute lesser to technological progress over time. Technology knowledge stock is the cumulative R&D expenditure, after considering the obsolescence of technologies. Obsolescence is defined not by period, but by the rate of obsolescence. ro=20%, 10% mean technologies become obsolete in 5 and 10 years, respectively. If the rate of obsolescence can be omitted (ro=0), then technology knowledge stock is the same as cumulative R&D expenditure.

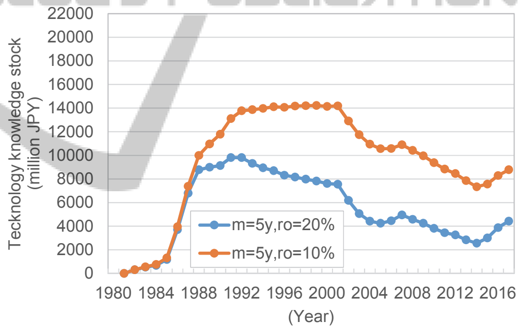

Figure 5: Technology knowledge stocks for crystalline silicon solar cells, through PV R&D by the Japanese government.

Figure 5 shows the technology knowledge stocks for crystalline silicon solar cells, through PV R&D, of the Japanese government in m=5 years, ro=20% and 10%, based on equation (1). R&D expenditures for crystalline silicon solar cells from 1988-1996 maintain technology knowledge stock until 2001 in the case ro=10%. However, the allocated R&D expenditure is not enough to keep technology knowledge stock constant in the case of ro=20%. After the drastic budget reduction in 1997, technology knowledge stock could not be maintained in both the cases.

2.4 Technological Progress Model of Solar Cells

If R&D expenditure is constant, technology knowledge stock will saturate at RE/ro, as shown in Figure 6. However, even if R&D expenditure is constant, technological progress is induced by the expenditure. This means that there is no correlation between technology knowledge stock of PV R&D and the price of the solar cells, but there exists a correlation between technology knowledge stock of PV R&D and solar cell price reduction. In this study, correlation between cumulative technology knowledge stock and solar cell price is modeled for stable parameter estimation (a and b in equation (2)).

Figure 7 shows the correlation between cumulative technology knowledge stock for crystalline silicon solar cells (given in Figure 5) and module price, excluding the effects of mass production in Japan (annual and cumulative production for 2012 is assumed during the entire period).

Prior models indicate that the module price of solar cells converge with the material price. However, the silicon necessary for solar cells (g/W) and the silicon price (JPY/g) are both changing. In this paper, for convenience, the exponential curve in equation (2) is used for modeling technological progress of solar cell price.

$$y = \exp(a * x + b) \quad (2)$$

where

x: cumulative technology knowledge stock (million JPY)

y: solar cell price (JPY/W)

a, b: parameters, a<0

Using equation (2) means continuity and additivity are assumed for R&D. By applying the regression analysis in equation (3),

$$\log_e(y) = a * x + b \quad (3)$$

a and b are estimated as -6.61 E-6 and 7.02, respectively, with the coefficient of determination (R^2) being 0.922 when ro=20%, and -3.30 E-6 and 6.82 with coefficient of determination at 0.910 when ro=10%.

The estimated regression line and technological progress model, when ro=20%, are shown in Figures 8 and 9, respectively. The projected module price of 50 JPY/W is the present target of PV R&D for crystalline silicon solar cells in Japan.

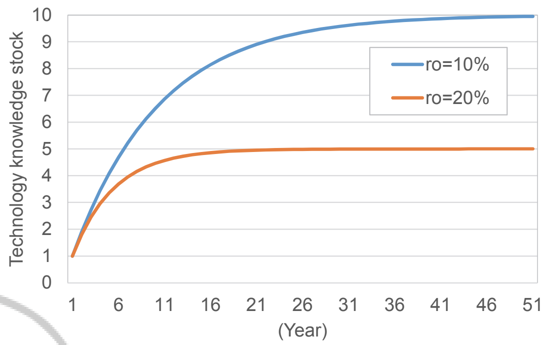

Figure 6: Relationship between constant R&D expenditure (=1) and technology knowledge stock.

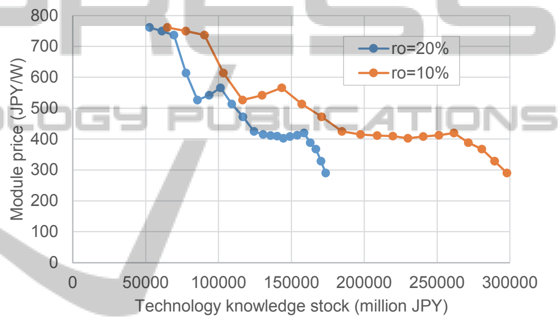

Figure 7: Correlation between cumulative technology knowledge stock for crystalline silicon solar cells and solar cell price, excluding mass production effects.

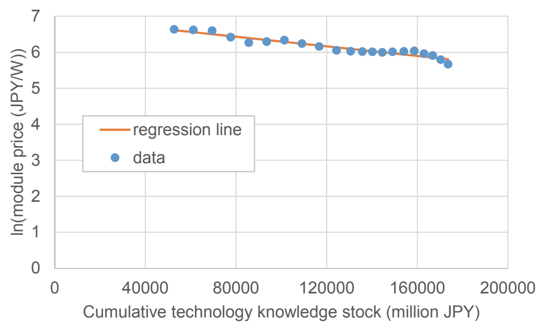

Figure 8: Correlation between cumulative technology knowledge stock for crystalline silicon solar cells and solar cell price excluding mass production effects, in logarithm, and its regression line, with ro=20%.

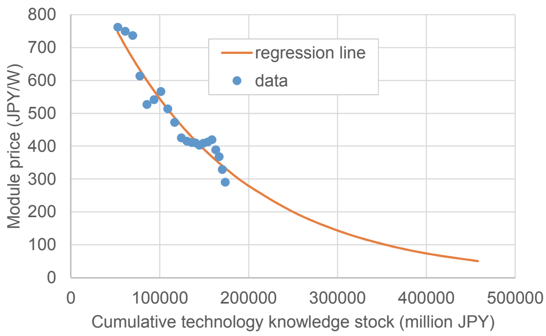

Figure 9: Correlation between cumulative technology knowledge stock for crystalline silicon solar cells and solar cell price, excluding mass production effects and the technological progress model, with ro=20%.

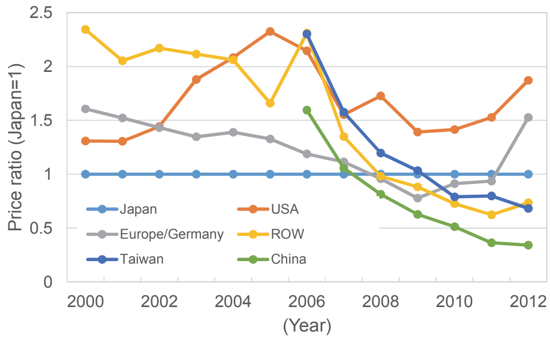

Figure 10: Estimated solar cell price ratios by country, with Japan=1.

3 ESTIMATION OF SOLAR CELL PRICE RATIO

In some countries, reliable average module prices of solar cells over a long period are not available. In this paper, solar cell price is estimated based on the market share of the world's solar cell production, which is more reliable, as shown in Figure 1. For the estimation, market share of the world's solar cell production is assumed to be proportional to the inverse square of the solar cell price ratio, as shown in equation (4). This relationship is also used for estimating market share based on price ratios of solar cells in Japan and other countries. Equation (4) means that the same market share estimates the same solar cell price (price ratio=1). Larger market share estimates lower price, while smaller market share estimates raise the price. However, small differences in prices are enlarged in the estimation of market share. If solar cell price data are available, estimated prices are compared and discussed with respect to the data.

$$MS_i = (1 / PR_i)^2 / \sum_{i=1}^{n} (1 / PR_i)^2 \qquad (4)$$

where
MS_i: market share of i, i=1,…,n
PR_i : price ratio of i.

Figure 10 shows the estimated solar cell price ratios, as compared to Japan, by country, based on equation (4).

4 INFLUENCE OF RESOURCE ALLOCATION OF PV R&D

4.1 Influence on Solar Cell Price

Comparing Figures 3 and 4, shares of solar cells by technology type are completely different in production and R&D, even when considering a 5-year lead-time. It seems market projection after the lead-time is not reflected in R&D resource allocation. In this study, a case where crystalline silicon solar cells are allocated, adequate R&D expenditures are assumed. 50%, 40%, 30%, and 20% of R&D expenditure for solar cells is allocated to crystalline silicon solar cells during the Sunshine Program (1974-1992), New-Sunshine Program (1993-2000), and NEDO's technology development program (2001-2007, and 2008-2012), respectively. These figures are assumed considering gradual increase in priority of new solar cell technologies.

R&D expenditures for crystalline silicon solar cells and technology knowledge stock under the assumption are shown in Figures 11 and 12, respectively. Actual and assumed R&D expenditures for crystalline silicon solar cells are different, especially in 1997-2000, when major budget cuts were made. In this assumption, technology knowledge stock is maintained and increases until 2005 at ro=20% and 10%, respectively. However, it decreases after 2005 in both the cases. Cumulative technology knowledge stock in 2012 goes from 183 billion JPY to 268 billion JPY when ro=20% and 316 billion JPY to 445 billion JPY when ro=10%.

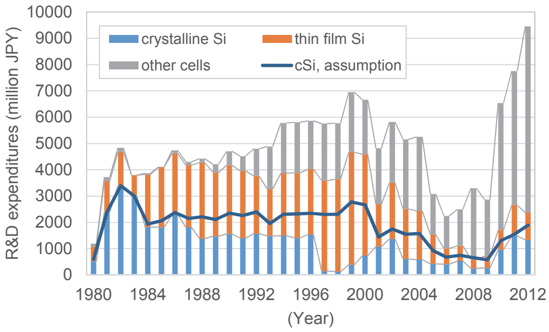

Figure 11: R&D expenditures for solar cells with assumptions about crystalline silicon solar cells.

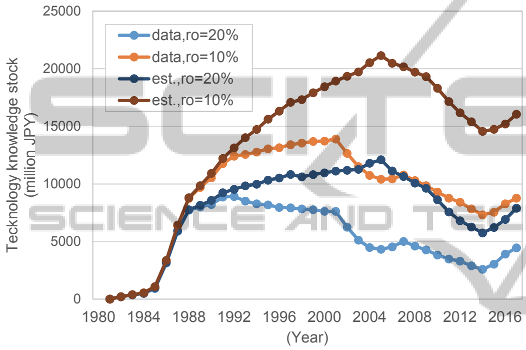

Figure 12: Technology knowledge stocks for the assumed R&D resource allocations.

Increase of cumulative technology knowledge stock accelerates solar cell price reduction. It gives 191 JPY/W and 212 JPY/W in 2012 when ro=20% and 10%, respectively, as shown in Figure 13. This price is not reflected in the secondary effects of price reduction through R&D.

The estimated solar cell price shows that the assumed resource allocation in R&D for crystalline silicon solar cells gives around a 30% price reduction in solar cells in 2012. However, the difference between the actual and estimated module prices peaks at around 40% in 2008-2010. This is because actual module price dropped after that due to the price reduction of silicon and solar cells because of oversupply. This is, however, not reflected in the estimated solar cell prices.

Figure 13 compares solar cell prices in Japan, China, and Taiwan, based on the estimated price ratios in Figure 10. Estimated solar cell prices of China and Taiwan come close to that of Japan in 2007 and 2009, respectively. However, under the assumed R&D resource allocation, the catching-up by China and Taiwan is delayed by 2 and 3 years, respectively.

Regarding China, estimated solar cell price based on its market share is different when compared to the data (Lv, 2013) in 2007 and 2008, but it shows a relatively good fit after that, as shown in Figure 13.

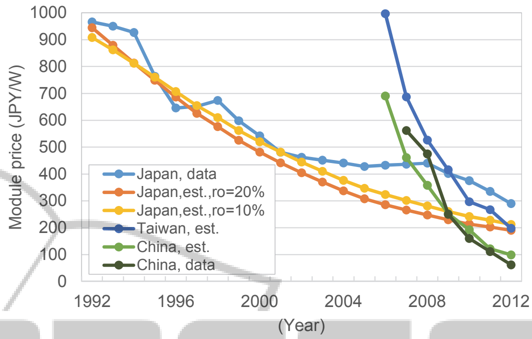

Figure 13: Solar cell price in Japan, estimated under the assumed R&D resource allocation, in comparison to China and Taiwan.

4.2 Influence on Solar Cell Market Share

Based on the estimated solar cell prices in Japan and other countries, market share in the world solar cell production can be estimated by assuming a market share that is proportional to the inverse square of the price ratio shown in equation (4). Figure 14 shows the estimated market share of the world solar cell production by country, under the assumed R&D resource allocation, when ro=20%.

In actuality, the market share of Japan is the same as that of China in 2007 and Taiwan in 2009. Japan could not maintain its top share and fell behind China and Taiwan in 2008 and 2010, respectively. However, under the assumed R&D resource allocation, the catch up delays to 2009 for China and 2012 for Taiwan. This means that the assumed R&D resource allocation could not keep Japan's top share, but allows Japan to maintain a price advantage and keep the top share in the market 2 or 3 years longer. It shows that Japan could have had the highest market share of 63.5% and 58.2% in 2004 with ro=20% and 10%, respectively. This is around 10 points larger than the actual market share. Japan could have maintained a 14.8% and a 12.3% market share in 2012 with ro=20% and 10%, respectively. This is around 2 times larger than the actual market share.

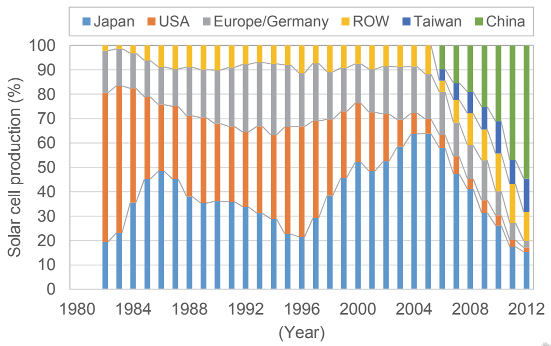

Figure 14: Estimated market share in world solar cell production by country, under the assumed R&D resource allocation, with ro=20%.

4.3 Secondary Effects of Mass Production

Annual and cumulative production of crystalline silicon solar cells in Japan can be calculated using the world solar cell production, estimated market share of Japan in the world solar cell production, and the share of crystalline silicon in the solar cell production of Japan. The estimated peak of solar cell production in Japan is 6.10 GW/year in 2010 with ro=20%. This is 2.24 times higher than the actual maximum annual production of 2.73 GW/year in 2011, as shown in Figure 15. Similarly, the cumulative production increases to 1.9 times in 2011. The increase of both annual and cumulative production causes a price reduction due to increased production. Solar cell prices reflect secondary effects and become 188 JPY/W and 211 JPY/W in 2012 with ro=20% and 10%, respectively.

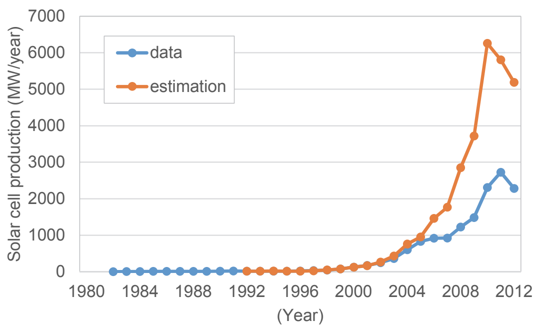

Figure 15: Estimated annual solar cell production in Japan, under the assumed R&D resource allocation, with ro=20%.

5 DISCUSSION

In this section, among the assumptions and parameters used in this study, R&D expenditures of the private sector are discussed.

Figure 16 shows R&D expenditures on solar energy in Japan during 1977-1997 (Statistic Bureau of Japan, 1979,…,1999). This figure can be categorized into R&D expenditures for solar energy in Japan by government and non-government owned funds, as shown in Figure 17. The R&D expenditures include not only those on solar cells, but also on PV systems including BOS and solar thermal power generation and utilization. As the survey has since been terminated, there is no recent data. Both government and non-government funds have a correlation of 0.762 during the entire period of 1977-1997 and have a very strong correlation of 0.950 during 1989-1997. This means that the non-government sector promotes R&D in solar energy at the same pace as the government. If both sectors have the same lead-time, the non-government sector could be omitted in the modeling of this study.

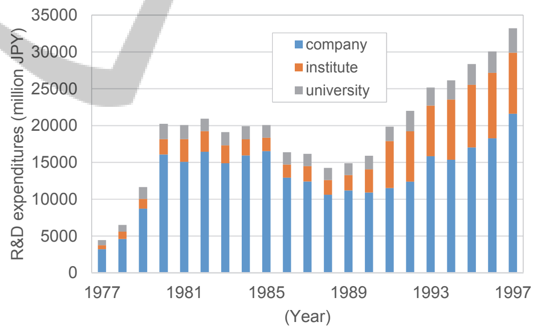

Figure 16: R&D expenditures for solar energy in Japan by companies, institutes, and universities.

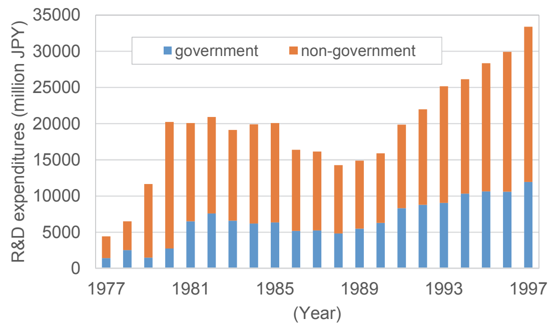

Figure 17: R&D expenditures for solar energy in Japan by government and non-government owned funds.

6 CONCLUSIONS

In this paper, the price reduction of solar cells in Japan is modeled, excluding mass production effects, based on the technology knowledge stock approach. By using the technological progress model of solar cells and the relationship between price ratio and market share, possible influence of resource allocation in the PV R&D of Japan is analyzed.

Conclusions of this study are as follows.
(1) The estimated influence of resource allocation in the PV R&D of Japan on module prices of solar cells and market share in world solar cell production is not small and should not be ignored.
(2) Japan could achieve a module price of solar cells of around 200 JPY/W, which is 30% cheaper than presently available. The price is comparable to solar cell prices in China and Taiwan,
and (3) though Japan could not keep its top share, it could have maintained a large share in world solar cell production for several more years by reducing solar cell prices, if the assumed R&D resources had been allocated to crystalline silicon solar cells, which are very affordable.

The analysis depends on assumptions such as continuity and additivity in R&D and the relation between price and market share, which needs more discussion. Sensitivity analysis for assumed data and parameters, such as R&D expenditures after 2000 and mass production effects of learning-by-doing, are necessary.

For further study, we could look at combining the technological progress model of solar cells, the world solar cell market model, both shown in this study, and the dissemination model for residential PV systems model (Endo, 2014). The study of cost-effective resource allocation will be simulated for PV technology development in Japan, in terms of not only R&D expenditure, but also subsidies by the government.

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