A Model of Technological Progress on Photovoltaic Cells

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Summary The objective of this work is to model relationship between invested research and development (R&D) resources and the attained level of R&D. In order to promote R&D efficiently under the restriction of R&D resources, it is very important to optimize the allocation of R&D resources to each R&D activity. For the optimization, relationship between invested R&D resources and their effects must be given. The relationship consists of relationship between invested R&D resources and the attained level of R&D and relationship between the attained level of the R&D and the diffusion level of the objective technology in the R&D. The model proposed here is based on logistic curve, which is known as a learning curve. The validity of this assumption is confirmed by examples of R&D. In this paper, R&D which goal is energy efficiency improvement is focused on. R&D expenditure and energy efficiency are chosen as the indices of R&D resources and the attained level of R&D. On modeling, annual R&D expenditure for photovoltaic (PV) cells in the Sunshine Project of Japan, annual conversion efficiency and the theoretical conversion efficiency of PV cells are investigated. Two parameters of the logistic curve are estimated by applying regressive analysis to the both annual data. They are not obtained in long term, but relationship between cumulative R&D expenditure for PV cells and conversion efficiency of PV cells in the Sunshine Project of Japan and estimated conversion efficiency based on the proposed model are almost the same in the year 1984 to 1993. The proposed model shows the increments of energy efficiency per R&D expenditure in PV cells, that is, technological progress in PV cells from the view point of conversion efficiency. This means logistic curve is appropriate as a model of technological progress in technologies without any special breakthroughs.

1. INTRODUCTION

Acceleration of research and development (R&D) for energy technologies which have large effects on carbon dioxide emission reduction should be effective to abating global warming. But any allocations of R&D resources without optimization from the view point of global warming mitigation is meaningless. Not only in global warming mitigation, but also in attaining of all R&D targets, optimization is very important for allocating R&D resources.

If we can estimate relationship between invested R&D resources and their effects, we can maximize effects of R&D activities and make R&D activities more efficient by optimizing allocation of R&D resources, which are allocated to each R&D activity at each time period under restrictions of upper and lower bounds.

Optimization problems of R&D activity could be classified into two categories based on their formulation. One is formulated so that amounts of resources which are allocated each R&D activity will be decided. In this case, all R&D activities are assumed to have opportunities to be allocated R&D resources depending on their effects.

The other is formulated so that R&D activities, to which R&D resources are allocated, are chosen. In this case, the chosen R&D activities are given enough R&D resources, if they are necessary. But the rest of the R&D activities are given nothing.

In this paper, formulation is based on the former one. At first, global warming is assumed to be able to mitigated by energy efficiency improvement. An efficient promotion of R&D which aim is energy efficiency improvement is treated as an allocation problem of R&D resources. Then a basic framework of the allocation problem is given and formulated. By the formulation, relationship between invested R&D resources and their effects is proved to be important to estimate. An estimating method for the relationship is, therefore, proposed.

Secondly, relationship between amount of invested R&D resources and an attained level of the R&D target is estimated based on actual data. In this paper, photovoltaic cells are focused on as an example of energy technologies. By using the proposed method, relationship between R&D expenditure and conversion efficiency is estimated. On the estimation, a hypothesis that relationship between invested R&D resources and its results fit to logistic curve and validity of the proposed method for estimating parameters of logistic curves are proved.

2. FRAMEWORK OF THE ALLOCATION PROBLEM

2.1 Hypothesis in the Allocation Problem

Let us define an allocation problem of R&D resources. R&D resources usually include staffs, budgets and facilities, which are necessary for attaining goals of R&D activities. But only budgets are considered in this paper. R&D activity, to which R&D resources are allocated, means supposed R&D projects. Each supposed R&D project corresponds to an energy conversion technology and its target is only energy efficiency improvement. The R&D resources are allocated under the four conditions as follows.

(1) The R&D resources are allocated in order to maximize effects

of all R&D activities on global warming mitigation during all time periods.

(2) A total amount of allocable R&D resources are constant through all R&D activities during all time periods.

(3) A total amount of allocable R&D resources through all R&D activities are in a certain range at each time period.

(4) An amount of allocable R&D resources are in a certain range in each R&D activity at each time period.

Effects on global warming, on which effects on global warming mitigation are based, are considered as follows. Once carbon dioxide is emitted, ability of warming maintains throughout all time periods. Based on this assumption, if carbon dioxide emission is reduced by energy efficiency improvement at a certain time period, effects of carbon dioxide emission reduction on global warming mitigation will continue after the time period.

The effects on carbon dioxide emission reduction or global warming mitigation are depend on not only a level of energy efficiency improvement in each energy technology, but also depend on an amount of energy flows, that is, introducing level of each energy technology, which is correspond to each R&D activity.

2.2 Formulation of the Allocation Problem

Let us formulate the allocation problem of R&D resources by linear programming.

Objective function

$$\text{maximize } f(x_{ik}) \quad i=1,\dots,m \quad k=1,\dots,\tau \tag{1}$$

Upper and lower bounds

$$0 \leqq x_{ik} \quad i=1,\dots,m \quad k=1,\dots,\tau \tag{2}$$

$$r_{ik} \leqq x_{ik} \leqq R_{ik} \quad i=1,\dots,m \quad k=1,\dots,\tau \tag{3}$$

$$\sum_{i=1}^{m} x_{ik} \leqq R_k \quad k=1,\dots,\tau \tag{4}$$

$$\sum_{k=1}^{\tau} R_k \leqq R \tag{5}$$

$$f(x_{ik}) = \sum_{k=1}^{\tau} \left((\tau - k + 1) \cdot \left(\sum_{j=1}^{n} c_j \cdot \left(\sum_{i=1}^{m} C_{ijk} \right) \right) \right) \tag{6}$$

$$C_{ijk} = S_{ijk} \cdot \Delta \eta_{ik} / \eta_{ik} \quad i=1,\dots,m \quad j=1,\dots,n \quad k=1,\dots,\tau \tag{7}$$

$$\begin{aligned} \Delta \eta_{ik} &= \eta_{ik} - \eta_{ik-1} \\ &= g_i(x_{ik}, \eta_{ik-1}, \eta_{i\infty}) \quad i=1,\dots,m \quad k=1,\dots,\tau \end{aligned} \tag{8}$$

where,

x_{ik} : amounts of R&D resources which are allocated to R&D activity i at time period k,

r_{ik} : lower bound for amounts of R&D resources which are allocated to R&D activity i at time period k,

R_{ik} : upper bound for amounts of R&D resources which are allocated to R&D activity i at time period k,

R_k : upper bound for amounts of R&D resources which are allocated to all R&D activities at time period k,

R : upper bound for amounts of R&D resources which are allocated to all R&D activities during all time periods,

η_{ik} : energy efficiency of technology i, which is correspond to R&D activity i, at time period k,

$\eta_{i\infty}$: theoretical energy efficiency of technology i,

C_{ijk} : energy savings for technology i in energy source j at time period k,

c_j : carbon dioxide emission coefficient of energy source j,

$f(\cdot)$: function which gives effects of invested R&D resources on global warming mitigation,

$g_i(\cdot,\cdot,\cdot)$: functions which give energy efficiency improvement of technology i,

S_{ijk} : Fossil fuel equivalent energy input for technology i in energy source j at time period k.

Based on the definition of effects on global warming mitigation, R&D resources are allocated to R&D activities which can contribute to global warming mitigation from earlier time period, if they can reduce same amount of carbon dioxide emissions during all time periods. The proposed formulation of the allocation problem means, therefore, R&D resources are allocated to efficient R&D activities from the view point of technological maturity, which is defined by present and theoretical energy efficiency, and introducing level of each technology.

3. EFFECTS OF R&D RESOURCES

3.1 Assumption by Logistic Curves

To solve the allocation problem, $g_i(\cdot,\cdot,\cdot)$ and S_{ijk} must be given concretely. In this paper, $g_i(\cdot,\cdot,\cdot)$, which represents relationship between amount of invested R&D resources and its effects on energy efficiency of a technology, is assumed to be given by a logistic curve, which is known as a learning curve. It is represented by (9).

$$y = K / (1 + \exp(-\alpha - \beta x)) \tag{9}$$

where,

x : Summation of invested R&D resources, which is a function of time.

y : Attained level of R&D target, e.g. energy efficiency.

α : Starting point parameter.

β : Starting velocity parameter.

K : Final attained level of R&D target, e.g. theoretical enrgy efficiency.

3.2 Method for Estimating Parameters of Logistic Curve

$g(\cdot,\cdot,\cdot)$ can be given by estimating parameters, α, β and K by using data concerning R&D expenditure of each R&D activity and energy efficiency of each technology by a following proposed method.

step 1 Estimate parameter K based on theoretical efficiency of each technology.
step 2 Give initial and final energy efficiency of each technology during time periods when summation of R&D expenditure can be obtained.
step 3 Estimate parameter α by inputting the initial energy efficiency and the summation of R&D expenditure, zero to (9). Then estimate parameter β by inputting the final energy efficiency, the summation of R&D expenditure and the estimated parameter α to (9).

If energy efficiency and the summation of R&D expenditure are obtained in each time period, such as annual data, the parameters α and β could be estimated by regressive analysis based on (10).

$$\alpha + \beta x = -\ln(K / y - 1) \qquad (10)$$

4. Results of Case Study

4.1 R&D Expenditure and Conversion Efficiency of Photovoltaic Cells

In the *Investigation Report of Energy Researches* (in Japanese), which is one of the official statistics investigated by the Japanese government (Agency of General Affairs), R&D expenditure and number of engaged researchers are included concerning energy technology R&D in almost of all universities, governmental research institutes and private companies. But the statistics classify energy technology R&D into only 25 categories as shown in Table 1. Photovoltaics is, therefore, not separated from other solar energy R&D, such as solar thermal power generation and utilization.

Table 1 25 Categories of Energy Technology R&D in the *Investigation Report of Energy Researches*.

Fossil Energy	Petroleum, Natural Gas, Coal, Other Fossil Energy
Renewable Energy	Geothermal, Solar, Ocean, Wind, Biomass, Other Renewable Energy
Nuclear Energy	Nuclear Power Generation, Nuclear Reactor Multipurpose Utilization, Nuclear Fuel Cycle, Nuclear Fusion, Other Nuclear Energy, Nuclear Ship, Radio Active Rays Utilization, Radio Active Rays Safety
Energy Conservation	Industrial Field, Residential and Commercial Field, Transportation Field, Electric Power Conversion and Electric Power Storage, Hydrogen, Other Energy Conservation
Others	

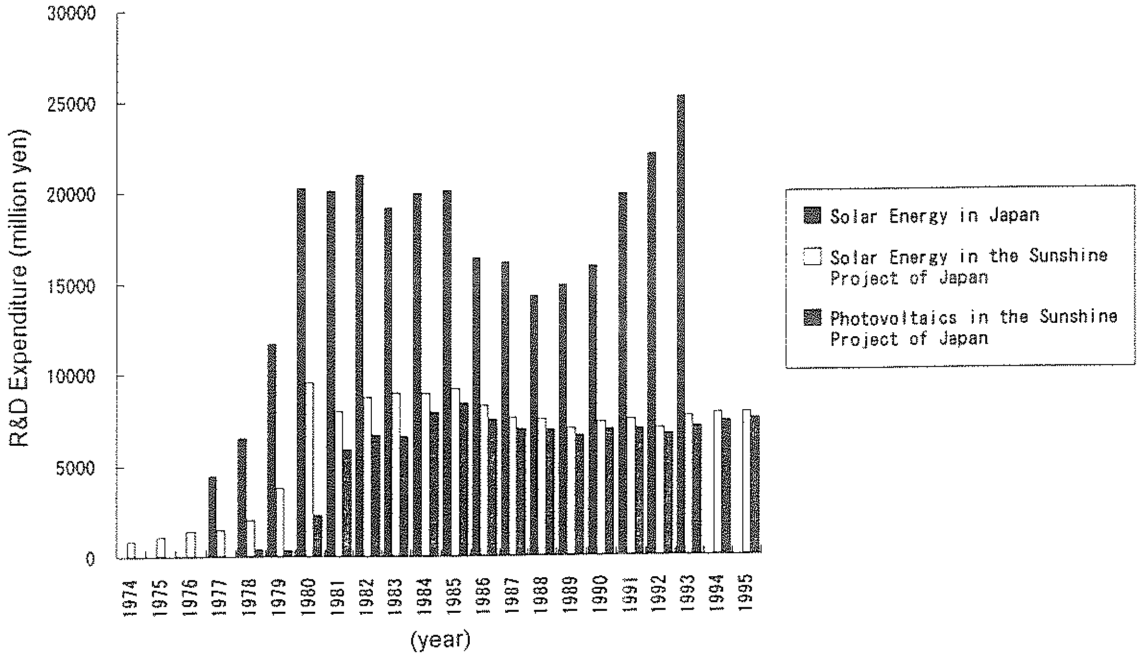

Fig. 1 Annual R&D Expenditure for Solar Energy and Photovoltaics.

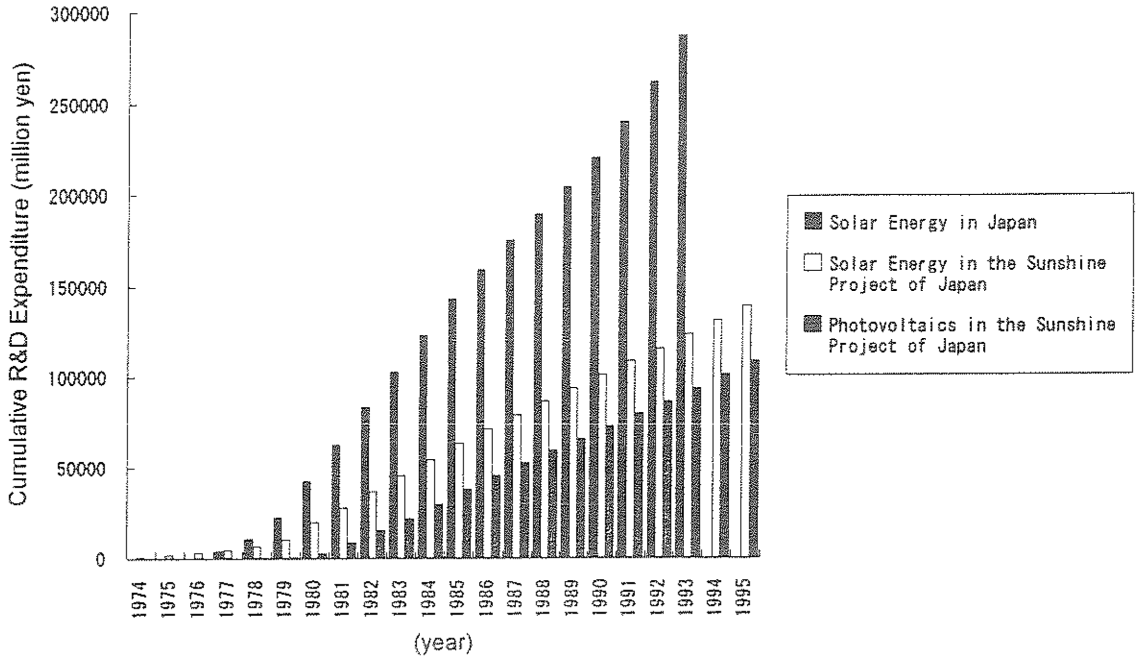

Fig. 2 Annual Cumulative R&D Expenditure for Solar Energy and Photovoltaics.

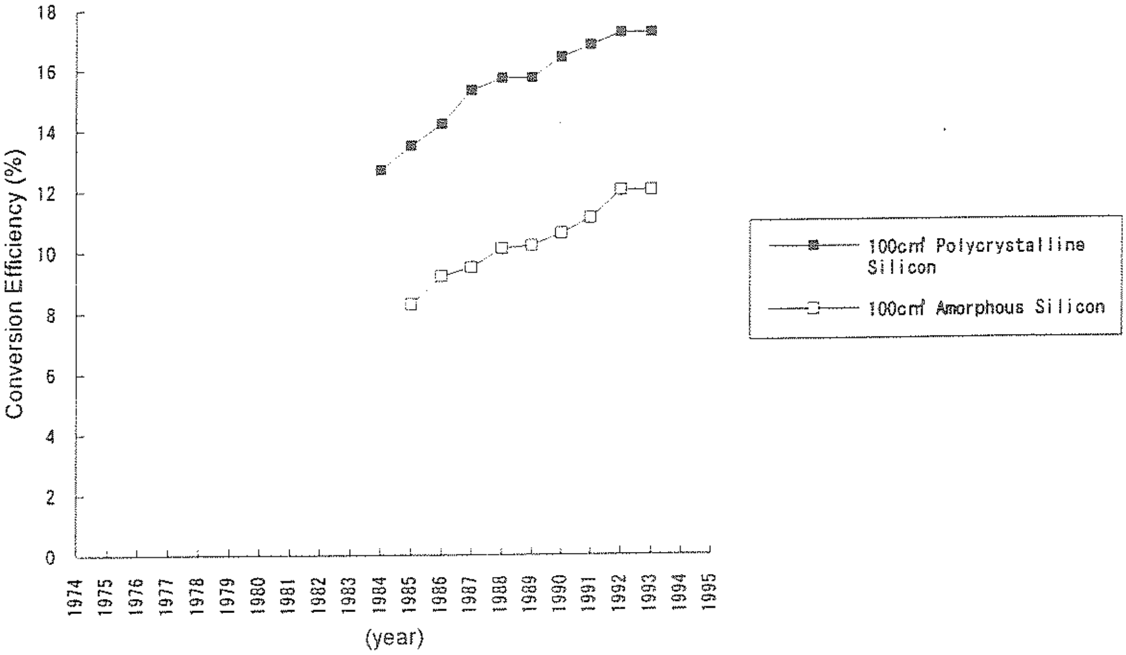

Fig. 3 Annual Top Conversion Efficiencies of Photovoltaic Cells.

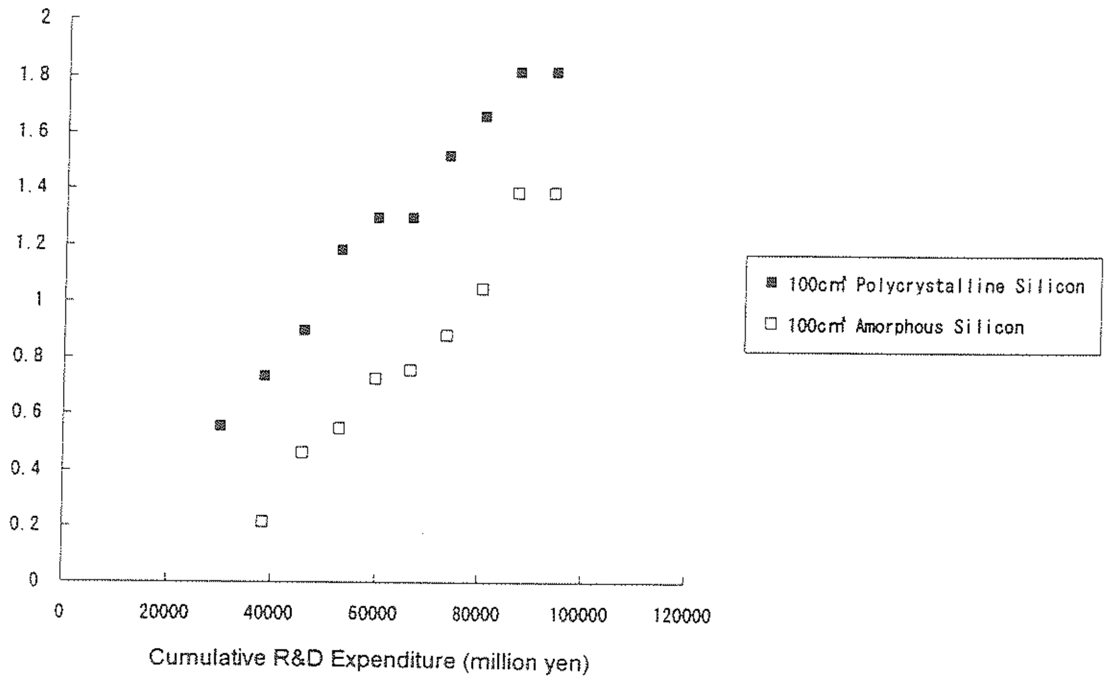

Fig. 4 - ln (Theoretical Conversion Efficiency / Annual Top Conversion Efficiency - 1)

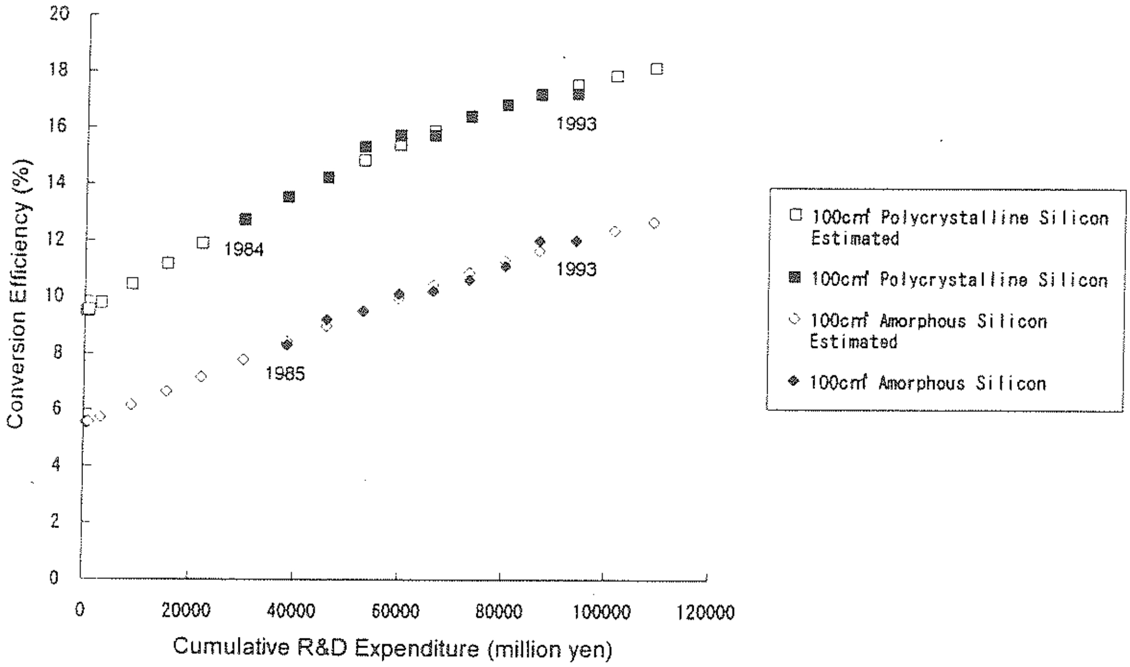

Fig. 5 Actual and Estimated Conversion Efficiencies of Photovoltaic Cells.

The other official statistics of R&D expenditure investigated by the Japanese government (Agency of Industrial Science and Technology) separate photovoltaics from solar thermal energy. But it covers only the Sunshine Project, which is the Japanese national R&D project of advanced energy technologies started from the year 1974. The R&D expenditure is not separated for single crystalline silicon, polycrystalline silicon and amorphous silicon.

Figure 1 shows annual R&D expenditure of solar energy and photovoltaics according to the both two statistics.

Figure 2 shows annual cumulative R&D expenditure of solar energy and photovoltaics according to the both two statistics.

Figure 3 shows annual top conversion efficiencies of 100 cm^2 polycrystalline silicon and amorphous silicon photovoltaic cells in the Sunshine Project.

Table 2 shows theoretical conversion efficiency of singlecrystalline silicon, polycrystalline silicon and amorphous silicon photovoltaic cells.

Table 2 Theoretical Conversion Efficiency of Photovoltaic Cells.

	Theoretical Conversion Efficiency (%)
Singlecrystalline Silicon	28-29
Polycrystalline Silicon	20
Amorphous Silicon	15

4.2 Relationship between cumulative R&D expenditure and conversion efficiency in photovoltaic cells

Based on the theoretical conversion efficiencies of polycrystalline silicon and amorphous silicon photovoltaic cells, the annual cumulative R&D expenditure of photovoltaic cells and the annual top conversion efficiencies of polycrystalline silicon and amorphous silicon photovoltaic cells in the Sunshine Project, parameters α and β for polycrystalline silicon and amorphous silicon photovoltaic cells are calculated by regressive analysis in (10). Figure 4 shows (10) of both polycrystalline silicon and amorphous silicon photovoltaic cells. For the restriction of available data, annual cumulative R&D expenditure cannot separate into polycrystalline silicon and amorphous silicon photovoltaic cells.

From Figure 4, regressive lines of both polycrystalline silicon and amorphous silicon photovoltaic cells are obtained. Estimated parameters K, α and β of the logistic curves (9) are shown in Table 3.

Based on the parameters shown in Table 3, relationship between the cumulative R&D expenditure and the conversion efficiency of polycrystalline silicon and amorphous photovoltaic cells are given as shown in Figure 5. In this case, the R&D expenditure is used for not only energy efficiency improvement, but also other goals of R&D. And the conversion efficiency of polycrystalline silicon and amorphous silicon photovoltaic cells are improved simultaneously by spending the R&D expenditure.

The annual top conversion efficiencies of photovoltaic cells are obtained from the year 1984 to 1993. They are not for long time periods, but estimated and observed conversion efficiency of polycrystalline silicon and amorphous silicon photovoltaic cells are identical with each other in these time periods.

Table 3 Estimated Parameters of the Logistic Curves.

	K (%)	α	β (1/million yen)
Polycrystalline Silicon	20	0.11	-0.000022
Amorphous Silicon	15	0.54	-0.000021

5. Conclusions

In this paper, R&D concerning photovoltaic cells is focused on and the relationship between R&D expenditure and energy efficiency is estimated by using actual data. The results show that relation ship between R&D resources and their effects could be assumed by the logistic curves and the proposed estimating method for parameters of logistic curves are appropriate.

The proposed model shows increments of energy efficiency for R&D expenditure, that is, technological progress in photovoltaic cells from the view point of conversion efficiency. This means the logistic curves are appropriate as a technological progress model of technologies without any special breakthroughs, such as photovoltaic cells.

Concerning estimation of relationship between R&D resources and their effects, the author intended to apply the proposed method to many kinds of technologies, such as fuel cell and other general technologies.

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References

Cooms, R., P. Saviotti and V. Walsh, *Economics and Technological Change*, The Macmillan Publishers Limited, United Kingdom, 1987.