

Comparative Analysis of Institutional Elasticity on the Effect of Technology Policy

- Comparison of Diffusion Trajectory of PV Technology in Japan, the USA and Europe

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Abstract

Technological innovation and its diffusion are subject to institutional systems, more specifically, institutional elasticity. Since institution is a coherent entity indigenous to a nation, a comparative analysis of institutional elasticity and its impacts on technological innovation and diffusion could provide significant suggestions to technology policy.

Based on this expectation, this paper attempts a comparative analysis of institutional elasticity for maximizing effects of technology policy between Japan, the USA and Europe focusing on energy technology.

Through an empirical analysis on the diffusion process of photovoltaic power generation (PV), the following five postulates are demonstrated, thereby suggestive policy implications are extracted: (i) Institutional innovation (institutions play significant role in stimulating innovations and their diffusion); (ii) Functionality development (the state of innovations and their diffusion can be represented by the trends in functionality development); (iii) Institutional elasticity (trends in functionality development is sensitive to institutions, particularly their elasticity); (iv) Dynamic carrying capacity (functionality development can be traced by the trends in dynamic carrying capacity in a logistic technology diffusion process); and (v) Trajectory of PV development (development of the trajectory of PV using logistic growth within a dynamic carrying capacity approach could provide a good insight of institutional elasticity for maximizing the effect of energy technology policy).

Key words: Institutions, Institutional elasticity, Technological innovation and diffusion, and Photovoltaic power generation technology.

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1. Introduction

It goes without saying that innovation plays a significant role in maintaining sustainable global economy (e.g. Binswanger and Ruttan, 1978 [5], Romer, 1994 [42]). Most important is to recognize that innovation is a very subtle entity subject to conditions of institutional systems (Ruttan, 2001 [44]).

Given that institutional systems in every individual nation is a coherent system indigenous to the nation and a very inorganic entity created in the process of historical development (Nelson et al., 2001 [36]), how to maximize potential innovation in each country largely depends on how to best coordinate institutions. Thus, the effects of innovation policy depend on how it functions coordinate and deploy such institutions (Watanabe, 1995 [51]), and given that it relies on the state of institutional elasticity, maintaining institutional elasticity can be significant for maximizing the effect of the policy (Watanabe and Kondo, 2001 [55]). As referred above, since institution is a coherent entity indigenous to a nation, a comparative analysis of institutional elasticity from the viewpoint of innovation policy could provide significant historical suggestions.

To date, a number of studies have identified the impacts of technological innovation and its diffusion process with certain relevance with institutions. Noteworthy works can be summarized as follows:

Innovation, such as the development of new technologies, has been undoubtedly recognized as a significant driving force in sustaining economic growth. Romer (1994) [42] points out that for society as a whole, innovation, discovery and technological change offer large net gains because the new goods or processes are more efficient and more valuable than the old ones. The diffusion of technological innovation is an important topic for social study because economic and social welfare depends on the rate at which new technologies are adopted and put into use. As Rosenberg postulates, “new techniques exert their economic impacts as a function of the rate at which they displace older techniques and the extent to which the new techniques are superior to the old ones” (Rosenberg, 1976 [43]).

In light of the significance of the interrelationship between innovation and external circumstances, a number of works have focused on the identification of this interaction between **internal technology** and **external technology** (Baranson, 1967 [4]). Internal technology means qualification of R&D environment and consists of quality and quantity of R&D resources while external technology consists of the “economic environment,” “physical and natural environment,” “social and cultural environment,” and “policy system” (Watanabe, 1995 [51], 1997 [52]). These components of the external technology are collectively designated as “institutions.” North 1994 [39] defined institutions as: “the humanly devised constraints that structure human interaction. They are made up of formal constraints (e.g. rules, laws, constitutions), informal constraints (e.g. norms of behaviors, conventions, self-imposed codes of conduct), and their enforcement characteristics. Together they define the incentive structure of societies and specifically economies.” Given the significance of the interaction between innovation and external technology in which societies and economies provide major components of social and cultural environment as well as economic environment, institutions play a significant role in inducing innovation. This is also the case of diffusion of innovation.

While a number of works have conducted broad-ranging theoretical and empirical analyses on behavior of institutions (e.g. North, 1990 [38], 1994 [39], Knight, 1992 [22], Milner, 1997 [35]; see also Hodgson, 1993 [16]), their focus is not necessarily identification of **the role of institutions as a core inducing factor of innovation and stimulator for broad diffusion**. An exceptional pioneer

work can be found in Binswanger and Ruttan's *Induced Innovation: Technology, Institutions, and Development* (1978) [5]. This work paid special attention to the role of institutions in inducing innovation. Over the two decades since Binswanger and Ruttan's postulate was demonstrated, intensive work has been conducted on the identification of the behavior of institutions. Ruttan 2001 [44], in his recent postulate of "institutional innovation," suggests that "institutions are the social rules that facilitate coordination among people by helping them form expectations for dealing with each other" and also that "they reflect the conventions that have evolved in different societies regarding the behavior of individuals and groups." While his postulate develops a systematic insight on the role of institutions as a core-inducing factor of innovation, further comprehensive relationship between economic, physical and natural as well as social and cultural environments with policy system should be developed for pragmatic purposes. In addition, a systematic link with stimulator for broad diffusion is necessary.

Rogers defined "diffusion" as the process by which an innovation is communicated through certain channels over time among the members of a social system (Rogers, 1962 [41]). He also identified four main elements in the diffusion of innovations: innovation features, communication channels, time, and social system. These elements have significant relevance with institutions.

This diffusion process is actually quite similar to the contagion process of an epidemic disease (Griliches, 1957 [13]) and exhibits S-shaped growth. This process is well modeled by the **simple logistic growth function**, an epidemic function which was first introduced by Verhulst in 1845 (Meyer, 1994 [34]). Since the logistic growth function has proved useful in modeling a wide range of innovation processes, a number of studies applied this function in analyzing the diffusion process of innovations as well (e.g. Griliches, 1957 [13], Mansfield, 1963 [27], 1969 [28], Metcalfe, 1970 [31], Norris and Vaizey, 1973 [37]).

However, while simple logistic growth function has proved useful in modeling diffusion process of innovations, this function is based on imitators behavior rather than that of innovators.

Therefore, Bass (1969) [2] developed a model of diffusion including innovators behavior as well to estimate the speed of adoption of new technologies. This model of diffusion has been widely used to successfully predict the growth rate of numerous new and innovative technologies, including color TV, VCRs, telephone answering machines, overhead projectors, mainframe computers, direct broadcast satellite television, and recording media (records, tapes and CDs).

This model for forecasting first purchase has had a long history in marketing. It is most appropriate for forecasting sales of an innovation (more generally a new product) for which no closely competing alternatives exist in the marketplace. The Bass model offers a good starting point for forecasting the long-term sales pattern of new technologies and new durable products under two types of conditions.

While the simple logistic growth function treats the carrying capacity of a human system as fixed, this capacity is actually subject to change (Marchetti, 1976 [29], 1979 [30]). Among varieties of innovations, certain innovations alter their carrying capacity in the process of their diffusion which stimulates an increase in the number of potential users (Sharif and Ramanathan, 1981 [46], Coombs et al., 1987 [9]). This increase, in turn, incorporates new features in the innovations. Meyer 1994 [34] extended the analysis of logistic functions to cases where dual processes operate by referring to an example when cars first replaced the population of horses but then took on a further growth trajectory of their own. He postulated **bi-logistic growth** in an attempt to deal with the fact that this diffusion process that contains complex growth processes not well modeled by the single logistic growth function.

In addition to the above diffusion processes exhibited by a single logistic growth and bi-logistic growth, in particular innovations, a correlation of the interaction between innovations and institutions displays systematic change in their process of growth and maturity. This is typically the case of the diffusion process of information technology (IT) in which **network externalities** (Oster, 1994 [40]) function to alter the correlation of the interaction which creates new features of the innovation, IT. In this case, the rate of adoption increases, usually exponentially until physical or other limits slow down the adoption. Adoption is a kind of “social epidemic.” Schelling 1998 [45] portrays an array of logistically developing and diffusing social mechanisms stimulated by these efforts. Meyer and Ausbel 1999 [33] introduced an extension of the widely used logistic model of growth by allowing it for a sigmoidally increasing carrying capacity. They stressed, “evidently, new technologies affect how resources are consumed, and thus if carrying capacity depends on the availability of that resource, the value of the carrying capacity would change.” This explains, the unique diffusion process of innovation with new functionality typically observed in IT, which diffuses by altering the carrying capacity or creating a new carrying capacity in the process. Meyer and Ausbel proposed **logistic growth within a dynamic carrying capacity approach** to model this diffusion behavior.

Kodama (2000) [23] and Watanabe *et al.* (2002) [57] traced logistic growth function within a dynamic carrying capacity to identify functionality development of IT and postulated that logistic growth within a dynamic carrying capacity approach entails major features of functionality development (Kodama (2000) [23] and Watanabe *et al.* (2002) [57]).

Watanabe *et al.* (2002) [58] postulated that photovoltaic power generation (PV) follows the similar trajectory of IT’s functionality development as it incorporates the following identical nature similar to IT:

- i. PV is categorically of the same nature as semiconductors,
- ii. the “footloose” character of the technology which can maximize the benefit of learning effects and economies of scale,
- iii. the interdisciplinary nature of its development, which can maximize the benefit of technology spillover, and
- iv. efficient learning is linked to technology spillover and both have mutually stimulation interactions.

Foregoing concept of institutions, their role as a core inducing factor of innovation as well as stimulator for broad diffusion, and also significance of logistic growth within a dynamic carrying capacity approach for depiction of innovations and their diffusion entailing functionality development lead us to pursue the following logical steps to identify the links between institutional elasticity and efficiency of innovation policy:

- i. institutions play significant role in stimulating innovations and their diffusion (**institutional innovation**),
- ii. the state of innovations and their diffusion can be represented by the trends in functionality development (**functionality development**),
- iii. trends in functionality development is sensitive to institutions, particularly its elasticity (**institutional elasticity**),
- iv. functionality development can be traced by the trends in dynamic carrying capacity in a logistic technology diffusion process (**logistic growth within a dynamic carrying capacity approach**), and
- v. trajectory of PV depicted by logistic growth within a dynamic carrying capacity approach could provide a good insight of institutional elasticity for maximizing the effect of energy

technology policy (**trajectory of PV characterized by dynamic carrying capacity approach**).

Thus, by comparing this carrying capacity, state of institutional elasticity and its structural sources can be interpreted. Promoted by this postulate, aiming at identifying conditions enabling elastic institutions which maximize the effects of innovation policy, this paper undertakes a comparative analysis of institutional elasticity between Japan, the USA and Europe focusing on energy technology by means of case study taking development and diffusion trajectory of PV over the last quarter century.

Section 2 provides a clear concept of institutions as a system. **Section 3** is devoted to constructing model synthesis and data construction necessary for the analysis of the synthesized model. Analysis and interpretation of its results are presented in **Section 4**. **Section 5** briefly summarizes policy implications.

2. Institutions as a System

Given that innovation is a very subtle entity subject to conditions of institutional systems (Ruttan, 2001 [31]) depending on interaction between internal technology and external technology as illustrated in **Fig. 1**. **Institutions can be manifested as the soft instrument which stimulates interaction between internal technology and external technology by coordinating external technology** consisting of “economic environment,” “physical and natural environment,” “social and cultural environment” and “policy system,” thereby inducing internal technology. Energy and geographical conditions are typical “physical and natural environment” while education, ethics, and aging trend are examples of “social and cultural environment.”

Although these institutional systems can function well leading to a virtuous cycle generating successive innovation and successful diffusion, they are very fragile and may readily change to a vicious cycle such as what prevailed in Japan during the 1990s lasting up to now (Watanabe and Kondo, 2001 [40]).

Fig. 2 illustrates the scheme which led Japan to lose its institutional elasticity by comparing it to the USA system which indicates that, contrary to the dual virtuous cycle up to the end of the 1980s, Japan has been suffering from a dual vicious cycle.

During the period of an industrial society initiated by manufacturing industry, Japan’s domestic institutions, based on young vitality, functioned efficiently towards “catching up” target leading to high economic growth. In the 1990s, Japan’s economy clearly contrasted with preceding decades. Facing a new paradigm characterized by a shift to an information society initiated by a service oriented industry and subsequent, globalization, diversification of nations interests, aging trend, and subsequent low, zero or negative economic growth, Japan’s traditional institutions did not function efficiently as they did in the preceding decades (Watanabe and Kondo, 2001 [55]).

Consequently, a virtuous cycle between institutional elasticity and economic development changed to a vicious cycle between non-elastic institutions and economic stagnation. This vicious cycle resulted in the loss of Japan’s international competitiveness that resulted in further economic stagnation. Thus, Japan has been facing a dual vicious cycle leading to a solid institutional elasticity.

Structural sources that compelled such a change from a virtuous cycle in the 1980s to a vicious cycle in the 1990s can be attributed to a fundamental difference of features between core technologies in an industrial society in the 1980s (manufacturing technology) and an information society in the 1990s (IT).

Contrary to manufacturing technology, IT strongly possesses a self-propagating feature that closely interacts with institutions and its functionality is formed dynamically during the course of interaction with institutions.

The foregoing vicious cycle which Japan is experiencing in an information society emerged in the 1990s demonstrates that Japan's traditional institutions do not function efficiently as they did in the preceding decades.

These observations suggest that the state of IT innovations and their diffusion in an information society can be represented by the trends in functionality development and that this functionality development is sensitive to institutions, particularly their elasticity. All supports a hypothetical view that institutional elasticity is crucial for innovations and their diffusion in an information society.

3. Model Synthesis and Data Construction

3.1 Model Synthesis

Provided that the state of innovations and their diffusion are traced by the trajectory of functionality and this functionality is formed dynamically during the course of interaction with institutions, a model tracing the trajectory of functionality is synthesized and data for the analysis by the synthesized model are constructed.

3.1.1 Modeling Technology Diffusion, Carrying Capacity and Functionality Development

While there are variety of efforts in modeling of the diffusion of innovations (Mahajan et al., 1990 [26]) including Bass model, epidemic function (logistic growth function), Gompertz curve, Weibull curve, and Lotka-Volterra model for competitive innovations, in order to identify self-propagating behavior of IT driven innovations in their diffusion process, particularly through dynamic interaction with institutional systems, epidemic function approach is focused as this behavior resembles epidemic diffusion.

1) Simple logistic growth function (SLF)

An epidemic function is used for analyzing the diffusion and maturity of innovative goods. The epidemic function enumerates the contagion process of an epidemic, and this model provides an analogy of the diffusion and maturity trajectory through the contagion process of innovative goods similar to a medical epidemic. The epidemic function incorporates a negative feedback in an exponential function as follows:

$$\frac{df(t)}{dt} = bf(t) \left(1 - \frac{f(t)}{K(t)} \right) \quad (1)$$

where $f(t)$: diffusion level of innovative goods; b : coefficient; K : carrying capacity (the upper limit of $f(t)$); and t : time trend.

The Bass model which is used to estimate the speed of adopting new technologies is enumerated by the following equation:

$$\frac{df(t)}{dt} = \left[c + b' \frac{f(t)}{K} \right] (K - f(t)) \quad (2)$$

where b' : coefficient of imitation; and c : coefficient of innovation¹.

From equation (1), $f(t)$ can be developed as follows:

$$f(t) = \frac{K}{1 + a \exp(-bt)} \quad (3)$$

where a and b : coefficients.

2) Bi-logistic growth function (BLF)

$$f(t) = f_1(t) + f_2(t) = \frac{K_1}{1 + a_1 \exp(-b_1 t)} + \frac{K_2}{1 + a_2 \exp(-b_2 t)} \quad (4)$$

where a_1, a_2, b_1 and b_2 : coefficients; and K_1 and K_2 : carrying capacities.

This function can be considered a variation of equation (3) as equation (4) has the same structure as equation (3). Given $f_1(t)$ a parameter reflecting an influence that is independent of previous adoption ($f(t)$), equation (4) can be Bass model.

3) Logistic growth function within a dynamic carrying capacity (LFDCC)

The epidemic function expressed by equation (3) assumes that the level of carrying capacity (K in equation (3) as well as K_1 and K_2 in equation (4)) is constant through the diffusion process of innovation. However, in particular innovations, correlation of the interaction between innovation and institutions display a systematic change in the process of its diffusion. In such innovations, level of carrying capacity $K(t)$ will enhance as their diffusion proceeds and functionality develops.

Therefore, $K(t)$ can also be conceptualized as an epidemic function enumerated by equation (5):

¹ The Bass model can be expressed as:

$\frac{y(t)}{1 - Y(t)} = c + bY(t)$ where $y(t) = \frac{dY(t)}{dt}$ and $Y(t) = \frac{f(t)}{K}$; $Y(t)$: cumulative distribution function of the random variable time to adoption.

$y(t) = (c + bY(t))(1 - Y(t))$

$\frac{dY(t)}{dt} = (c + bY(t))(1 - Y(t))$

$\frac{d}{dt} \left(\frac{f(t)}{K} \right) = (c + b \frac{f(t)}{K}) (1 - \frac{f(t)}{K})$

$\frac{1}{K} \cdot \frac{df(t)}{dt} = (c + b \frac{f(t)}{K}) \cdot \frac{1}{K} (K - f(t))$

$\frac{df(t)}{dt} = \left[c + b \frac{f(t)}{K} \right] (K - f(t))$

$$K(t) = \frac{K_k}{1 + a_k \exp(-b_k t)} \quad (5)$$

where a_k , and b_k : coefficients; and K_k : ultimate carrying capacity.

From equation (1) the velocity (change rate) of diffusion ($\frac{df(t)}{dt} / f(t)$) can be enumerated by the following equations:

$$\frac{df(t)}{dt} / f(t) = b \left(1 - \frac{f(t)}{K(t)} \right) \quad (6)$$

Equation (6) suggests that the velocity of diffusion depends on a coefficient b .

From equation (5) time $t^\#$ when dynamic carrying capacity level reaches 50% of the ultimate carrying capacity (K_k) can be identified as follows:

$$K(t^\#) = \frac{K_k}{2} = \frac{K_k}{1 + a_k \exp(-b_k t^\#)}$$

$$\text{Therefore, } t^\# = \frac{\ln a_k}{b_k} \quad (7)$$

The solution of the differential equation (1) under the condition (5) can be obtained as equation (8).

$$f(t) = \frac{K_k}{1 + a \exp(-bt) + \frac{b \cdot a_k}{b - b_k} \exp(-b_k t)} \quad (8)$$

When $a_k = 0$, equation (8) is equivalent to equation (3) as $K(t) = K_k$ in $a_k = 0$ condition. Thus, equation (8) is a general function of the epidemic behavior encompassing a simple logistic growth function, and the ratio of a_k and a (a_k/a) indicates the degree of non-SLF structure (degree of functionality), similar is the ratio of b_k and b (b_k/b) as equation (8) can be transformed as follows:

$$f(t) = \frac{K_k}{1 + a \exp(-bt) + \frac{a_k}{1 - b_k/b} \exp(-b_k t)} \quad (8')$$

The dynamic carrying capacity $K(t)$ can be expressed by equation (8) by transforming equation (1):

$$K(t) = f(t) \left(\frac{1}{1 - (df(t)/dt) / bf(t)} \right) \quad (9)$$

Equation (9) demonstrates that $K(t)$ increases together with the increase of $f(t)$ as time goes by. This implies that equation (8) exhibits logistic growth within a dynamic carrying capacity which is assumed to demonstrate functionality development in the context of self-propagating behavior.

From equation (9) the allowance between the diffusion level and its ceiling ($K(t)/f(t)$) can be enumerated by the following equation:

$$K(t) / f(t) = \left[1 - \frac{1}{b} \left\{ (df(t)/dt) / f(t) \right\} \right]^{-1} \quad (10)$$

Equation (10) suggests that the allowance increases as the diffusion rate $((df(t)/dt)/f(t))$ increases and the value of coefficient b decreases.

3.1.2 Implications of Logistic Growth within Dynamic Carrying Capacity

Equation (9) demonstrates that the dynamic carrying capacity $K(t)$ increases with the number of adopters (customers) $f(t)$ as time goes by. Increase in $K(t)$ induces $f(t)$, which in turn activates interactions with institutions leading to an increase in potential customers (carrying capacity) by increasing the value and function stimulated by network externalities. This dynamism can be depicted as a mechanism illustrated in **Fig. 3**. Thus, IT's specific features, or functionality are assumed to be formed in this interactive process.

Personal computers and cellular phones that contain the higher IT density are technologies that match the logistic growth function within a dynamic carrying capacity approach (Watanabe et al., 2002 [57]). This is in line with the postulate that these technologies are self-propagating due to the nature of their interactivity. Consequently, IT's epidemic behavior closely interrelates with the continuous increase in the number of potential users. This means that during the course of diffusion, IT interacts with individuals, organizations, and society as a whole, dynamically transforms its functionality, and extending potential users in line with these newly acquired features.

Furthermore, this characterizes the unique diffusion process of IT in that it alters the carrying capacity or creates a new carrying capacity in the process of its diffusion, thereby acquiring new specific features.

As Fig. 3 demonstrates, IT's diffusion process is stimulated by an interaction with institutions and institutional change is also stimulated by an interaction with IT, leading to a co-evolution of technology itself and institutions. In this process, rising technology value increase the number of potential users and a "virtuous cycle" results.

This behavior indicates that IT behaves differently because of some unique features facilitated by the institutions involved in the innovation process. Whether a nation can fully exploit the benefits of IT largely depends on the nation's institutional ability to flexibly respond and adopt this technology given its unique features. In other words, institutional elasticity affects the nation's dependency on the benefits of IT leading to its competitiveness in an information society (Watanabe and Kondo, 2001 [55]).

Therefore, functionality development can be traced by the trends in dynamic carrying capacity as enumerated by equations (5) and (8) in a logistic technology diffusion process and, given the similar nature between IT and PV, trajectory of PV depicted by logistic growth within a dynamic carrying capacity approach could provide a good insight of institutional elasticity for maximizing the effect of energy and environmental technology policy.

3.2 Data Construction

In order to assess the institutional structure by means of degree of functionality by comparing development and diffusion trajectory of PV and its carrying capacity measured by equations (5) and (8), data construction is attempted with respect to cumulative PV production in Japan, the USA and Europe over the last quarter century.

3.2.1 Trends in PV Production in Japan, the USA and Europe

Table 1 summarizes trends in PV development in the world over the period 1975-2000 and **Fig. 4** illustrates these trends. Looking at Table 1 and Fig. 4 we note that, while Japan maintained the world highest level of PV production despite the falling trend in the international oil prices started from 1983, the production level of the USA exceeded Japan's level from 1993 and maintained the position of the world leader of PV production. However, Japan's PV production dramatically increased from 1999 and substituted for the USA's world top level again. It resumed increasing rapidly since then and amounted to 1.5 times the USA production.²

Fig. 5 clearly demonstrates this "PV race" in the world market over the last 15 years.

3.2.2 Cumulative PV Production in Japan, the USA and Europe

Utilizing these data on the PV production in the world market over the last quarter century, **Table 2** and **Fig. 6** demonstrate trends in cumulative PV production in Japan, the USA and Europe over the last quarter century³.

4. Analysis and Interpretation

4.1 Analysis

Utilizing the foregoing constructed data on trends in cumulative PV production in Japan, the USA and Europe over the period 1976-2000 and applying these data in equation (8) which depicting diffusion trajectory by means of logistic growth within a dynamic carrying capacity, diffusion trajectory of PV in three countries/region over the last quarter century is estimated. The results of the numerical estimation are summarized in **Table 3** which demonstrates all coefficients indicate statistically significant with extremely high representability⁴.

Applying the estimation results to equation (5) and (8), **Fig. 7** illustrates trends in cumulative production both actual and estimated as well as its carrying capacity in Japan, the USA and Europe over the last quarter century.

4.2 Interpretation of the Current Trajectory

Based on the estimated results as summarized in Table 4, factors characterizing carrying capacity structure in Japan, the USA and Europe over the last quarter century are compared as summarized in **Table 4**.

Table 4 suggests that while Japan's ultimate carrying capacity is the highest, followed by Europe and that of the USA is the lowest, the USA demonstrates the highest velocity of diffusion while Japan and Europe share the similar lower level. The USA also demonstrates the lowest degree of

² According to the latest statistics by PV News, world PV production in 2001 amounted to 390.5 MW consisting of Japan: 171.2 MW; The USA: 100.3 MW; Europe: 86.4 MW and others: 32.6 MW.

³ Since PV Production used for calculation of cumulative PV production includes not only for domestic use but also for exports, trends in cumulative PV production do not necessary represent PV diffusion within a market of respective country/region.

⁴ Since objective value of the equation ($f(t)$) is cumulative production which inevitably autocorrelative nature, DW value is generally lower value than the value indicating statistically significant range.

functionality while Japan and Europe demonstrate higher level. Consequently, the USA's dynamic carrying capacity is anticipated to reach 50% of the ultimate ceiling in 2009 while Japan and Europe are anticipated in 2016 and 2012, respectively.

Table 5 interprets institutional structure affecting the differences of these carrying capacity structures in Japan, the USA and Europe.

Noteworthy observations obtained from Table 5 include that export oriented supply side initiative in the USA PV development is considered the major source of the USA's highest velocity in its PV diffusion while the lowest functionality development. Contrary to such USA's policy, Japan's equilibrium in supply push (primarily by the National R&D Program such the New Sunshine Program) and demand pull (primarily by the New Energy Foundation's Subsidy Program), and Europe's strong demand inducement lead to higher functionality while their diffusion velocities are lower than the USA. Government's strong initiative in inducing PV R&D in Japan and Europe as well as strong R&D consortium in Japan (PVTEC) and EU initiative collaboration in Europe also can be appreciated to contribute to higher degree of functionality in Japan and Europe. Contrary to Europe's strong standardization and the USA's well proceeded deregulation, Japan's standardization and deregulation are behind the level of Europe and the USA, which are expected to learn Europe and USA's system.

In addition to the foregoing, as depicted in the following equation (see the details in Appendix), since highest carrying capacity can be attributed to higher learning coefficient (λ), Japan's highest ultimate carrying capacity can be attributed to its high level of learning exercise in PV development.

$$\frac{1}{1-\lambda} = \frac{h \cdot K_k}{1 + a \exp(-bt) + \frac{a_k}{1-b_k/b} \exp(-b_k t)} \quad (11)$$

In general, contrary to its less elastic institutional system in an information society emerged in the 1990s, Japan's institutional system in PV development and diffusion demonstrates elastic performance which could be a model for Japan's efforts in adopting a shift from an industrial society to an information society.

4.3 Interpretation of the Ensuing Trajectory

If the market for PV products consists of several different sub-markets with different institutional interactions, one can not infer much about the market penetration in distant future from the current pattern. PV's market penetration in distant future, therefore, should be considered as a function of institutional interactions in respective period.

Thus, carrying capacity of the diffusion trajectory which leads PV's market penetration should be expressed as follows:

$$K = K(\text{effects of interaction with institutions}) \quad (12)$$

Since learning effect postulate (LE) exactly represents the effects of interaction with institutions, carrying capacity should be depicted by the following equation (see equation (11)):

$$K = K(\text{LE}) \quad (13)$$

While learning effects are traditionally considered as the correlation between price decrease and cumulative production increase, under different institutional interactions, not only internal factors

but also external factors must be taken into account as suggested in **Table 6**. Thus, the following multifactor learning function incorporating such internal factors as cumulative production and economies of scale, as well as external factors such as technology stock should be considered:

$$LE = LE(t, Y(t), T(t)) \quad (14)$$

where t : time trend; $T(t)$: technology stock at time t ; and $Y(t)$ production at time t avoiding duplication with $T(t)$.

Therefore, carrying capacity should be depicted as follows:

$$K = K(t, Y(t), T(t)) \quad (15)$$

Substituting eq. (15) for $K(t)$ in eq. (6), the following diffusion function is obtained:

$$\frac{df(t)}{dt} = bf(t) \left[1 - \frac{f(t)}{K(t, Y(t), T(t))} \right] \quad (16)$$

Equation (16) reflects institutional interaction in each respective internal and external circumstance and expected to contribute to inference about future market penetration.

Table 7 compares this novel approach with the traditional approach.

Table 7 clearly demonstrates the significance of this novel approach in PV market penetration in distant future consisting of several different sub-markets with different institutional interactions.

5. Conclusions

In light of an understanding that innovation is a very subtle entity subject to institutional elasticity while institutions are coherent entities indigenous to a nation, this paper attempts a comparative analysis of institutional elasticity between Japan, the USA and Europe.

With an expectation to extract significant suggestions with respect to institutional elasticity for maximizing effects of technology policy an empirical analysis was conducted focusing on PV diffusion trajectories in three countries/region over the last quarter century.

Based on the following five postulates, numerical comparison by means of a logistic growth function within a dynamic carrying capacity was conducted:

- (i) Institutions play significant role in stimulating innovations and their diffusion;
- (ii) The state of innovations and their diffusion can be represented by the trends in functionality development;
- (iii) Trends in functionality development is sensitive to institutions, particularly their elasticity;
- (iv) Functionality development can be traced by the trends in dynamic carrying capacity in a logistic technology diffusion process; and
- (v) PV diffusion trajectory using logistic growth within a dynamic carrying capacity approach could provide a good insight of institutional elasticity for maximizing the effect of energy technology policy.

As a result of the analysis it was identified that while Japan demonstrates the highest ultimate carrying capacity, followed by Europe and that of the USA is the lowest, the USA demonstrates the highest velocity of diffusion while Japan and Europe share the similar lower level. The USA also demonstrates the lowest degree of functionality while Japan and Europe demonstrate higher level.

Consequently, the USA's dynamic carrying capacity is anticipated to reach 50% of the ultimate ceiling in 2009 while Japan and Europe are anticipated in 2016 and 2012, respectively.

As a consequence of the interpretation of institutional structure affecting the differences of these carrying capacity structures in Japan, the USA and Europe, noteworthy observations obtained include that export oriented supply side initiative in the USA PV development is considered the major source of the highest velocity in its PV diffusion while the lowest functionality development. Contrary to such USA's policy, Japan's equilibrium in supply push and demand pull policies, and Europe's strong demand inducement policy lead to higher functionality while their diffusion velocities are lower than the USA. Government's strong initiative in inducing PV R&D in Japan and Europe as well as strong R&D consortium in Japan and EU initiative collaboration in Europe also can be appreciated to contribute to higher degree of functionality in Japan and Europe. Contrary to Europe's strong standardization and USA's well proceeded deregulation, Japan's standardization and deregulation are behind the level of Europe and the USA, which are expected to learn Europe and USA's system. In addition, Japan's highest ultimate carrying capacity can be attributed to its high level of learning exercise in PV development.

In general, contrary to its less elastic institutional system in an information society, Japan's institutional system in PV development and diffusion demonstrates elastic performance which could be a model for Japan's efforts in adopting a shift from an industrial society to an information society.

These findings demonstrate the significance of this new approach to identify carrying capacity structure as a proxy of functionality development of the innovation, institutional structure and its elasticity.

However, provided that the market for PV products consists of different sub-markets with different institutional interactions, future market penetrations can not be inferred solely by current pattern. In order to cope with such a difficulty, the effects of interactions with respective institutions should be taken into account in estimating carrying capacity of the diffusion trajectory which leads PV's market penetration.

In this regard incorporating multifactor learning effects which reflect not only internal circumstances but also external circumstances into carrying capacity in the diffusion process should be indispensable.

Further works should be, therefore, focused on the exploration and application of this novel approach for broader policy assessment.

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Appendix: Learning and Diffusion of Technology

It is assumed that there exists in PV development firms the following twice differentiable aggregate production function which relates the flow of output (PV production) Y to the services of inputs: labor (L), capital (K) and technology stock of PV R&D (T):

$$Y = F(L, K, T) \quad (A-1)$$

where L: labor; K: capita and T: technology stock.

Depicting cumulative production in terms of production and depreciation rate as follows:

$$Y^* = \sum Y \approx \frac{Y}{\rho + g}$$

where Y*: cumulative production, $g = \frac{dY}{dt}$, and ρ : depreciation rate. (A-2)

Learning function can be expressed as follows:

$$P = \frac{GC}{Y} = B(\sum Y)^{-\lambda} \approx B\left(\frac{Y}{\rho + g}\right)^{-\lambda} = B\left(\frac{1}{\rho + g}\right)^{-\lambda} \cdot Y^{-\lambda} \quad (A-3)$$

where GC: gross cost.

Taking logarithm of equation (A-3)

$$\ln P = \ln GC - \ln Y = \ln B - \lambda \ln Y + \lambda \ln(\rho + g) \quad (A-4)$$

Differentiating equation (8) by lnGC

$$1 - \frac{\partial \ln Y}{\partial \ln GC} = -\lambda \frac{\partial \ln Y}{\partial \ln GC}$$

$$\therefore \frac{\partial \ln Y}{\partial \ln GC} = \frac{1}{1 - \lambda} \quad (A-5)$$

Learning is a function of cumulative production (Arrow, 1962 [1]):

$$\lambda = \lambda(\sum Y) \quad (A-6)$$

Trajectory of cumulative production can be treated by an epidemic growth function within dynamic carrying capacity approach.

$$\sum Y = \phi_1(Y) = \frac{K_k}{1 + a \exp(-bt) + \frac{a_k}{1 - b_k/b} \exp(-b_k t)} \quad (A-7)$$

where a , b , and a_k and b_k : coefficients; and K_k : ultimate carrying capacity.

Combining equations (A-5), (A-6), and (A-7), we obtain:

$$\begin{aligned} \frac{\partial \ln Y}{\partial \ln GC} &= \frac{1}{1 - \lambda} \approx 1 + \lambda = \phi_2(\lambda) = \phi_2(\lambda(\sum Y)) = \phi_2(\lambda(\phi_1(Y))) = \phi_2(Y) \\ \phi_2(Y) &\approx \frac{h \cdot K_k}{1 + a \exp(-bt) + \frac{a_k}{1 - b_k/b} \exp(-b_k t)} = \frac{1}{1 - \lambda} \end{aligned} \quad (A-8)$$

Let λ :

$$\lambda = A - \lambda' > 0$$

$$\frac{1}{1 - \lambda} = \frac{1}{1 - (A - \lambda')} = \frac{1}{(1 - A) + \lambda'} = \frac{1}{(1 - A) \left[1 + \frac{\lambda'}{1 - A} \right]} = \frac{\frac{1}{1 - A}}{1 + \frac{1}{1 - A} \lambda'} \quad (A-9)$$

Given $\frac{1}{1 - A} \equiv h \cdot K_k$ with certain coefficient h ,

$$\frac{1}{1 - \lambda} = \frac{h \cdot K_k}{1 + h \cdot K_k \lambda'} = \frac{h \cdot K_k}{1 + a \exp(-bt) + \frac{a_k}{1 - b_k/b} \exp(-b_k t)} \quad (A-10)$$

From equation (A-10)

$$\begin{aligned} h \cdot K_k \lambda' &= 1 + a \exp(-bt) + \frac{a_k}{1 - b_k/b} \exp(-b_k t), \\ \lambda' &= \frac{1}{h \cdot K_k} \left[1 + a \exp(-bt) + \frac{a_k}{1 - b_k/b} \exp(-b_k t) \right] \\ \frac{1}{1 - A} &= h \cdot K_k, \quad \therefore A = 1 - \frac{1}{h \cdot K_k} \\ \lambda &= A - \lambda' = 1 - \frac{1}{h \cdot K_k} \left[1 + a \exp(-bt) + \frac{a_k}{1 - b_k/b} \exp(-b_k t) \right] \end{aligned} \quad (A-11)$$

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Table 1 Trends in PV Production in the World (1975-2000): MW

Year	Japan	USA	Europe	Others	World
1976	0.01	0.32	0	0	0.33
77	0.03	0.42	0	0	0.45
78	0.06	0.84	0	0	0.9
79	0.09	1.24	0	0	1.33
1980	0.29	2.5	0.3	0	3.09
81	1.02	3.5	0.8	0	5.32
82	2.1	5.2	1.4	0.1	8.8
83	5.0	8.2	3.3	0.3	16.8
84	8.9	8.0	3.6	0.8	21.3
85	10.1	7.7	3.4	1.4	22.6
86	12.8	7.1	4.0	2.3	26.2
87	13.2	8.7	4.5	2.8	29.2
88	12.8	11.1	6.7	3.0	33.6
89	14.2	14.1	7.9	4.0	40.2
1990	16.8	14.8	10.2	4.7	46.5
91	19.8	17.1	13.4	5.0	55.3
92	18.8	18.1	16.4	4.6	57.9
93	16.7	22.4	16.6	4.4	60.1
94	16.5	25.6	21.7	5.6	69.4
95	17.4	34.8	20.1	6.4	78.6
96	21.2	38.9	18.8	9.8	88.6
97	35.0	51.0	30.4	9.4	125.8
98	49.0	53.7	33.5	18.7	154.9
99	80.0	60.8	40.0	20.5	201.3
2000	116.7	78.5	58.5	24.2	277.9

Sources: Paul Maycock, PV News and Chihiro Watanabe.

Table 2 Trends in Cumulative PV Production in Japan, the USA, and Europe and Others (1976-2000): MW

Year	Japan	USA	Europe	Others	Total
1976	0.02	0.32	0	0	0.34
77	0.05	0.74	0	0	0.79
78	0.11	1.58	0	0	1.69
79	0.2	2.82	0	0	3.02
1980	0.49	5.32	0.3	0	6.11
81	1.51	8.82	1.1	0	11.43
82	3.63	14.02	2.5	0.1	20.25
83	8.63	22.22	5.8	0.4	37.05
84	17.53	30.22	9.4	1.2	58.35
85	27.63	37.92	12.8	2.6	80.95
86	40.43	45.02	16.8	4.9	107.15
87	53.63	53.72	21.3	7.7	136.35
88	66.43	64.82	28	10.7	169.95
89	80.63	78.92	35.9	14.7	210.15
1990	97.43	93.72	46.1	19.4	256.65
91	117.23	110.82	59.5	24.4	311.95
92	136.03	128.92	75.9	29	369.85
93	152.73	151.36	92.45	33.4	429.94
94	169.23	177	114.15	39	499.38
95	186.63	211.75	134.25	45.35	577.98
96	207.83	250.6	153.05	55.1	666.58
97	242.83	301.6	183.45	64.5	792.38
98	291.83	355.3	216.95	83.2	947.28
99	371.83	416.1	256.95	103.7	1148.58
2000	488.53	494.6	315.45	127.9	1426.48

Sources: Calculation of Table 1.

Table 3 Estimation Results for the Diffusion Process Analyses of PV Production in Japan, the USA and Europe (1976-2000)

Japan						
K_K	a	b	a_K	b_K	$adj. R^2$	DW
9452.8	17964	0.587	947.2	0.167	1.000	0.64
(3.31)	(1.57)	(5.74)	(3.89)	(29.79)		
USA						
K_K	a	b	a_K	b_K	$adj. R^2$	DW
3355.1	26142	0.890	444.5	0.182	1.000	0.69
(15.36)	(1.45)	(8.42)	(26.60)	(139.88)		
Europe						
K_K	a	b	a_K	b_K	$adj. R^2$	DW
7937.6	9367	0.540	629.4	0.173	1.000	1.18
(2.31)	(33.94)	(7.90)	(3.16)	(28.79)		

Table 4 Comparison of Factors Characterizing Carrying Capacity Structure in Japan, the USA and Europe (1976-2000)

	Ultimate carrying capacity K_k	Velocity of diffusion b	Extent of non-simple-S-curve (degree of functionality)		Year to reach $K(t) = K_K / 2$
			$\frac{a_K}{a}$	$\frac{b_K}{b}$	$\frac{\ln a_K}{b_K}$
Japan	9452.8	0.587 ⁽²⁾	0.05 ⁽²⁾	0.28 ⁽²⁾	41.0 years ⁽³⁾ (2016)
USA	3355.1	0.890 ⁽¹⁾	0.01 ⁽³⁾	0.20 ⁽³⁾	33.5 years ⁽¹⁾ (2009)
Europe	7937.6	0.540 ⁽³⁾	0.06 ⁽¹⁾	0.32 ⁽¹⁾	37.3 years ⁽²⁾ (2012)

a Small figures in the parentheses indicate ranks among three countries/region.

Table 5 Comparison of Institutional Structure and Its Elasticity in PV Development and Diffusion between Japan, the USA and Europe

<u>Carrying capacity structure</u>		USA	Japan	Europe
1. Ultimate carrying capacity		Lowest (3355.1)	Highest (9452.8)	Middle (7937.6)
2. Velocity of diffusion (b)		Highest (0.890)	Middle (0.587)	Lowest (0.540)
3. Degree of functionality ($\frac{a_K}{a} / \frac{b_K}{b}$)		Lowest (0.01 / 0.20)	Higher (0.05 / 0.28)	Highest (0.06 / 0.32)
4. Time when dynamic carrying capacity reaches 50% of the ultimate ceiling ($\frac{\ln a_K}{b_K}$)		Earliest (2009)	Latest (2016)	Middle (2012)
		↓	↓	↓
<u>Institutional structure</u>				
Production		Mass production based on conventional technology	R&D driven mass production	Steady production
Exports share out of shipment in 1998		70%	27%	28% (Germany)
Supply / Demand		Supply / export oriented	Equilibrium in supply push and demand pull	Strong demand inducement
R&D		University / industry initiative	Strong Government initiative	Central Government initiative
Consortia		University-industry tie-ups	Strong R&D consortia	EU initiative collaboration
Standardization		Reasonable	Developing	Strong
Network Externalities		Not necessarily well	Well-functioned	Well-functioning
Deregulation		Well	Underdeveloped	Well-developed
<u>Institutional elasticity</u> (cf Institutional elasticity for IT)		Less elastic (Elastic)	Elastic (Less elastic)	Elastic (Reasonable)

Table 6 Governing Factors of Multifactor Learning Function

Internal factors	Economies of scale Cumulative production
External factors	Technology stock

Table 7 Comparison of Carrying Capacity Estimation Approaches

Traditional approach	$K = K(t)$	Estimated solely by past hysteresis not reflecting new policies and conditions which did not exist previously.
Incorporation of multifactor learning effects	$K = K(t, Y(t), T(t))$	Estimated by reflecting not only past hysteresis but also cumulative production and technology stock incorporating new policies and conditions of the estimated point of time.

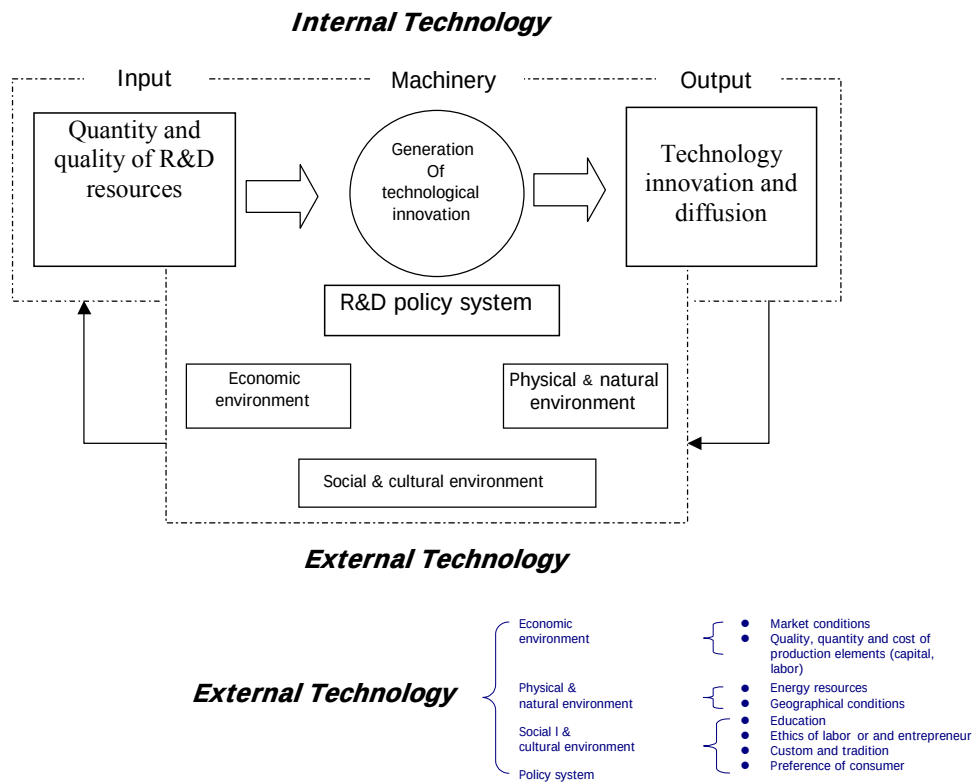


Fig. 1. Scheme of Institutional Systems for Innovation.

Source: Watanabe et al. (1991) [50], Watanabe (1997) [52].

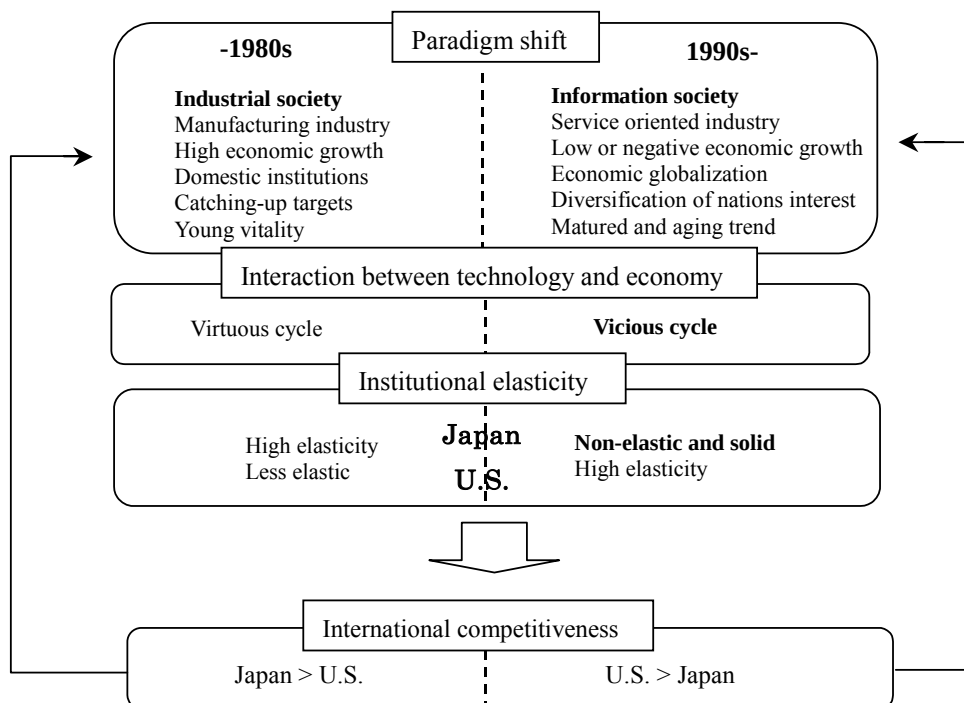


Fig.2. Scheme Leading Japan to Lose Its Institutional Elasticity.

Source: Watanabe et al. (2002) [58].

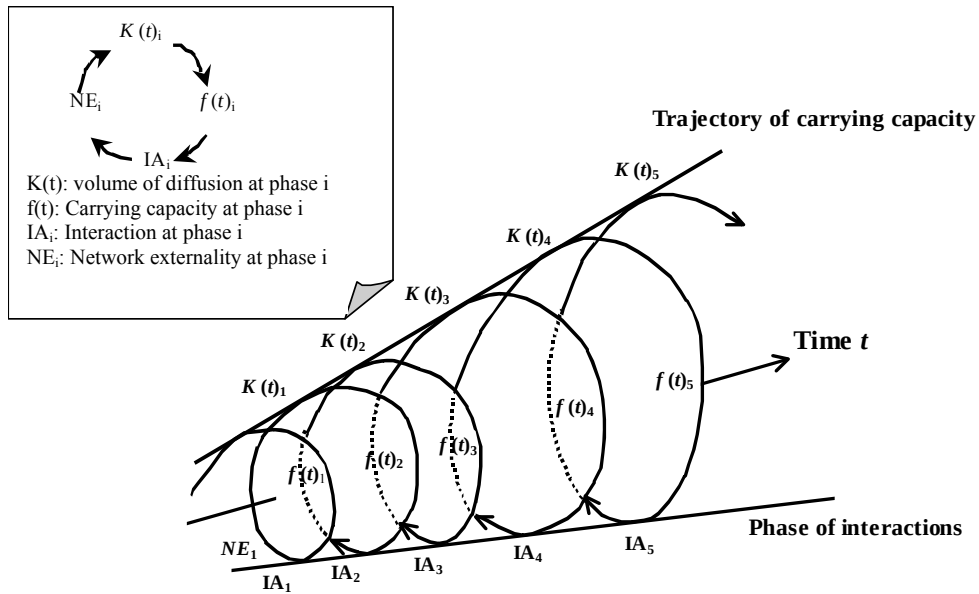


Fig. 3. Mechanism in Creating a New Carrying Capacity in the Process of IT Diffusion.

Source: Watanabe et al. (2002) [58].

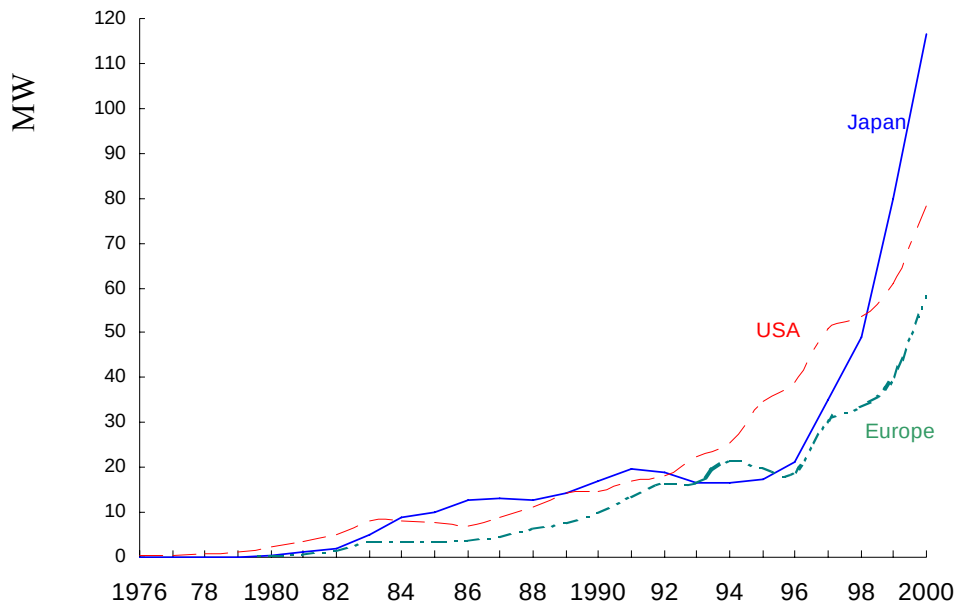


Fig. 4. Trends in PV Development in Japan, the USA and Europe (1976-2000).

Sources: Paul Maycock, PV News and Chihiro Watanabe.

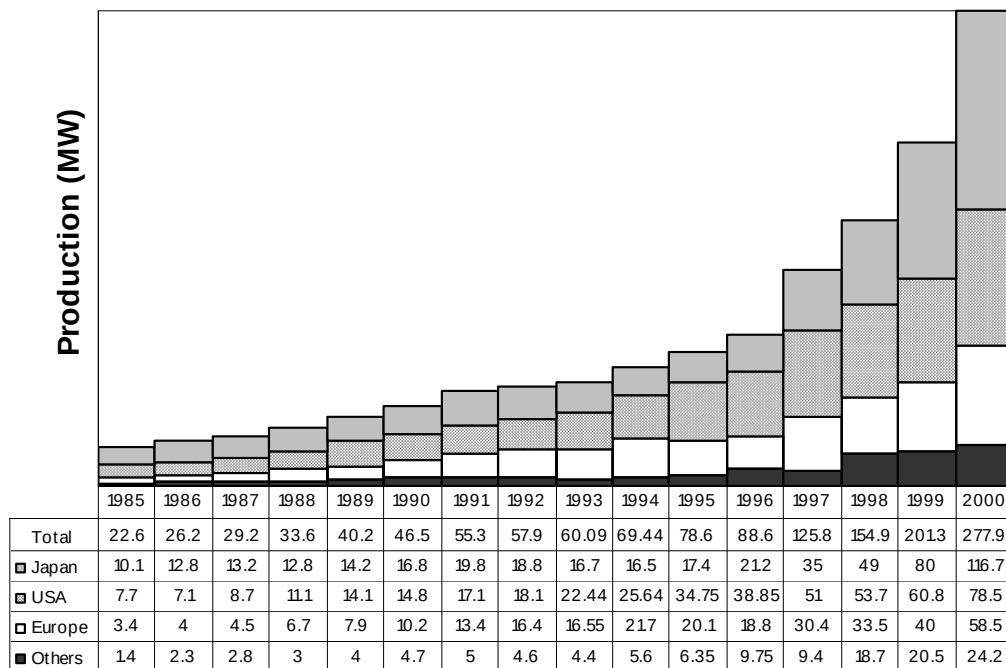


Fig. 5. Trends in World PV Development (1985-2000).

Sources: Paul Maycock, PV News and Chihiro Watanabe.

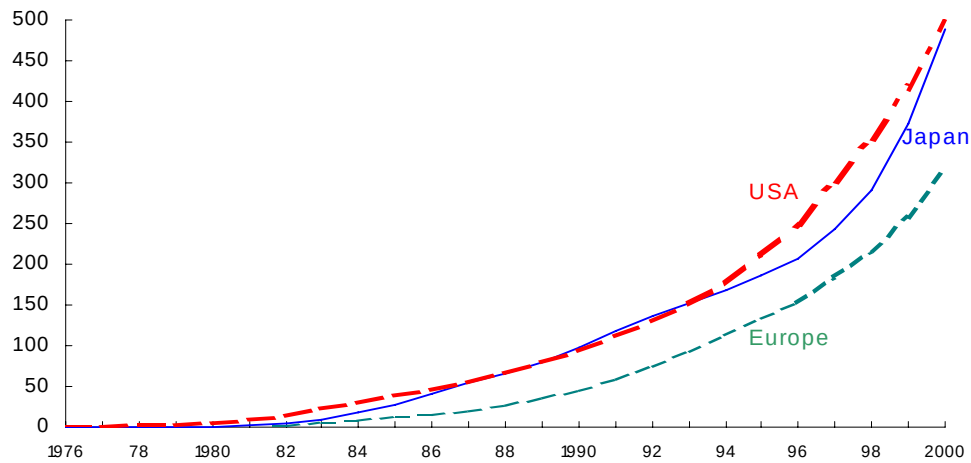


Fig. 6. Trends in Cumulative PV Production in Japan, the USA and Europe (1976-2000): MW

Sources: Same as Table 3.

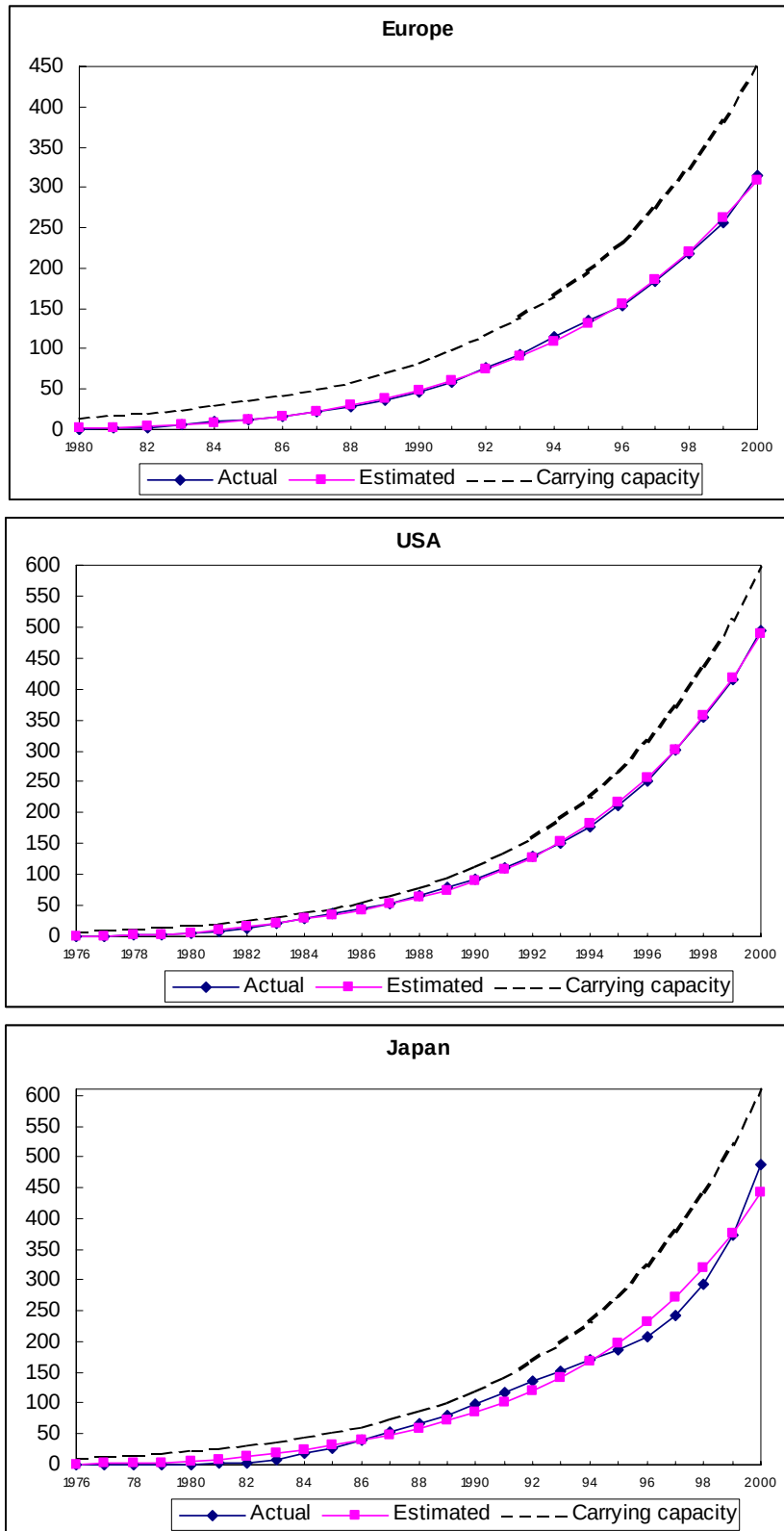


Fig. 7. Cumulative PV Production (Actual and Estimated) and Its Carrying Capacity in Japan, the USA and Europe (1976-2000) – MW.