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Photovoltaic deployment strategy in Japan and the USA —an institutional appraisal ☆

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Abstract

Photovoltaic (PV) is a renewable energy technology, along side with other modular energy generation technologies such as micro-turbines, fuel cells, etc., which will enable the alternative distributed generation paradigm compared to the incumbent fossil fuel based centralized generation paradigm. Distributed generation utilizing renewable energy resources offers opportunities for significant carbon dioxide and emissions reductions thus contributing solutions to broader climate change issues.

Yet, renewable energy technologies like PV face various barriers for their widespread adoption. Aside from technical and cost issues, renewable technologies have to overcome the so-called carbon lock-in effects. This refers to the techno-institutional complex associated with the fossil-fuel based centralized generation regime that currently dominates energy production and use. Governmental interventions to address these issues usually can be seen as composed of research, development, demonstration and deployment or RD3 [PCAST, 1999. Panel on International Cooperation in Energy Research, Development, Demonstration, and Deployment].

This paper focused on comparing the deployment aspect of PV technology in Japan and the USA. While both governments promoted PV as part of their larger strategies to address various environmental and energy security issues, Japan has built a PV installation capacity three times that of the USA as of December 2003 with over 90% of PV installation in the grid-connected small residential system category. This is in marked contrast to the case in the USA in which the cumulative installation is spilt among different types of applications involving the grid and off the grid.

We put forward two models to explain these differences in deployment strategies and their possible consequences. The first deployment model leverages upon PV as a *manufactured technology* with minimal customization to achieve massive deployment. The second deployment model leverages upon PV as an *information technology*-like technology focusing upon user oriented customization to achieve deployment. Different models have different implications to the system engineering aspect of solar PV. A *focus* upon the standard grid-connected distributed category in the residential setting avoids the heavy customized engineering associated with many off-grid and one-off type projects.

Japanese PV deployment strategy of concentrating upon a dominant category or niche with mass market potential also well matches the *institutional structure of production* [Coase, 1991. The Institutional Structure of Production, in Essays on Economics and Economists. The University of Chicago Press, Chicago] within the local PV technology suppliers industry. Major vertical integrated firms can facilitate system-related learning easier than a fragmented industry within the PV value chain with minimal transaction cost. This highly suggests that deployment strategy of PV or other renewable energy technologies must address the issues of adopting a globally developed technology to local (national) conditions and has strong institutional underpinnings in addition to financial subsidies, learning investment thinking.

Keywords: Open and close model; Institutional structure of production; Strategic niche management

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1. Introduction

Large scale deployment of renewable energy sources to supplement or even to replace fossil fuels for electricity generation offer a means to reduce greenhouse gas emissions and to minimize the risks of climate change caused by burning of the fossil fuels. Renewable energy refers to distributed energy resources that occur naturally and repeatedly in the environment and which can be harnessed for human benefit. Examples of renewable energy systems include solar, wind, and geothermal energy (getting energy from the heat in the Earth).

Among all these distributed renewable energy alternatives, modular photovoltaic (PV) technology is fundamentally well suited for decentralized electricity generation and is already market ready. Yet, despite these potentials, PV, along with other renewable technologies, faces various barriers for widespread adoption. Industrial economies have been locked into fossil-based energy systems through a process of technological and institutional co-evolution driven by path-dependent increasing returns to scale. In conceptual terms, Unruh (2000) suggested that this carbon lock-in or structuration arises from systemic interactions among technologies and institutions resulting in a techno-institutional complex (TIC). TIC is difficult to displace and can lock-out alternatives such as potential renewable energy technologies for extended periods, even when the alternatives demonstrate improvements upon the established TIC.

Others have conceptualized a more active and autonomous picture for the adoption of renewable energies in terms of their sustainable diffusion. Tsoutsos and Stamboulis (2002) suggested renewable energy technologies constitute a techno-economic system that is radically different from conventional systems or regimes. Incorporation of renewable into the existing regime of energy will have system-wide consequences. As long as renewable technologies seek to answer the old questions or problems, they will run up against established heuristics, infrastructure and complementary assets associated with the incumbent technological regimes.

One penetration strategy is therefore to seek novel ways to describe and address the energy problem, in terms of function, benefit, objectives and performance. The aim is to shift the focus of performance to new territory where conventional technologies would not be in an advantageous position. Formally, this can be cast in terms of a penetration-promotion strategy in market segments for the transition to a new technological regime (Kemp et al., 1998; Weber and Dorda, 1999) which is based on creation of protected niches for the development and use of renewable technologies.

A general outlook of the strategic niche management literature is that any discussion of technology must include the relations between the technological artifact and the social organization that brings the overall "socio-technological configuration" into use. In this niche theory, as Smith (2003) has suggested, growth is ensured through:

(a) degree of niche compatibility with the dimensions of incumbent regime,
(b) robustness or sustainability of performance of the niche chosen.

For a general physical technology with potentially many applications, it is therefore important to choose the right niche to start with that has the least disruption to the existing system and yet has the most development potential and possibly in terms of spillover to other applications in order for widespread adoption of the physical technology in the future.

This paper utilizes the strategic niche management (SNM) framework to compare the PV deployment strategies of Japan and the USA. We paid particular attention to the fact that a working PV system will involve customized system engineering and yet a dominant system design has not been established. In fact, the polymorphy and site-specificity (Tsoutsos and Stamboulis, 2002) of PV raise the necessity of dealing with system design, integration and installation case-by-case in the context of each application. This system engineering aspect of renewable technology received scant attention in the renewable energy literature.

Our contention is that the choice of an initial niche application, which constitutes the second phase[1] of bringing on new renewable technology to commercial maturity, needs to address this system engineering or system technology aspect strategically with a long-term perspective. System engineering concerns not only design but also have implications to installation, safety, quality and durability[2] and even re-cycling issues for a PV system. System engineering also has to be designed knowing that the downstream integration will necessarily involve a community of practice, spanning across boundary of firms and involving many independent market players. As a result, the more standardized the system engineering aspect of a chosen niche, the more the niche will lend itself to a mass production-deployment model, given an institutional structure of production (Coase, 1991) or community of practice.

The corollary is therefore that whether existing institutional structure of production matches the system engineering and production-learning implications of the choice of a niche application may determine the initial and sustaining success of a particular niche strategy. In this sense, the system engineering aspect of PV underscores the institutional underpinnings of its deployment in the context

[1] See e.g. Wene (2000) in his discussion of a "stage-gated" strategy in bringing new energy technology to commercial maturity; the first phase needs direct R&D support, but in the second phase the focus should be on providing learning opportunities in the market.

[2] PV system is supposed to be a durable system that should last 20–30 years.

of strategic niche management. The choice of a niche or, broadly, a niche strategy will necessitate a particular system design and production-learning economy which must match the learning characteristic of the underlying institutional structure of production in order for the niche to take off. In the context of this paper and PV deployment, an institutional structure of production may be a vertical integrated structure of a major firm for the case of Japan conducive to mass production learning or a somewhat fragmented structure with an independent professional community of system integrators mediated by industry standards engaging in cross-learning or spillover learning for the case of the USA.

The rest of the paper is organized as follows: Section 2 reviews the PV installation situation in Japan and the USA and proposes two deployment models based upon the general purpose nature of PV. Section 3 reviews the cost dynamics of constituents within a PV system. Section 4 attempts an explanation of difference of these models from an institutional perspective. We will conclude in Section 5 with some recommendations for future study.

2. PV deployment in Japan and the USA

A review of the cumulative PV installed base (as of December 2003) in Japan and the USA shows a marked contrast. Not only has Japan built an installed base three times that of the USA; in terms of PV applications, approximately 90% of the Japanese cumulative installed base is in grid-connected distributed category while in the USA, the distribution of applications is more uniform with the grid-connected category constituting approximately only 30% of the installed base. See Figs. 1 and 2 for comparison.

By the end of FY 2003, the cumulative PV power installed in Japan has reached 860 MWp with approximately 623 MWp installed as residential PV system; no single factor will explain the driving forces for residents to install PV systems, it may be a combination of growing public and environmental awareness, the subsidies offered as well as possibilities of selling generated electricity back to utilities. As we will show later, the fact that several major housing manufacturers combine PV installation in their newly built houses create a new and homogenous grid-connected market for PV installation. This, in turn, subscribes a *close* model of PV deployment.

For the case of the USA, there is no single dominant market for PV as yet. It is a conglomeration of regional markets and *special* applications for which PV offers the most cost-effective solution relative to centralized generated electricity. Until recently, the PV market has been dominated by off-grid applications, such as remote residential power, industrial applications, telecommunications and infrastructure, such as highway and pipeline lighting or buoys (Jager-Waldau, 2004). This deployment pattern leverages the general nature of PV principle and adapts it to applications not necessarily with market potential of massive magnitude. This, in turn, falls into an open or applications driven model of deployment.

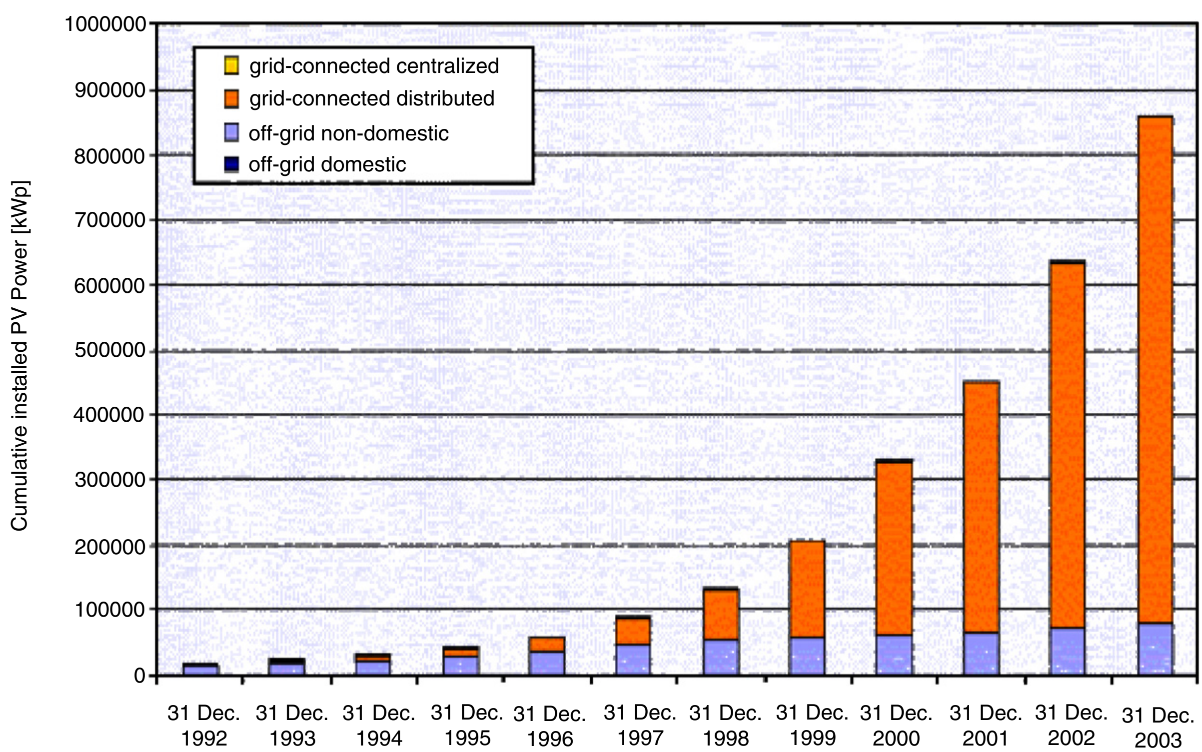

Fig. 1. Japanese PV historical installation data by category. IEA (2003)—a mass manufacturing deployment approach.

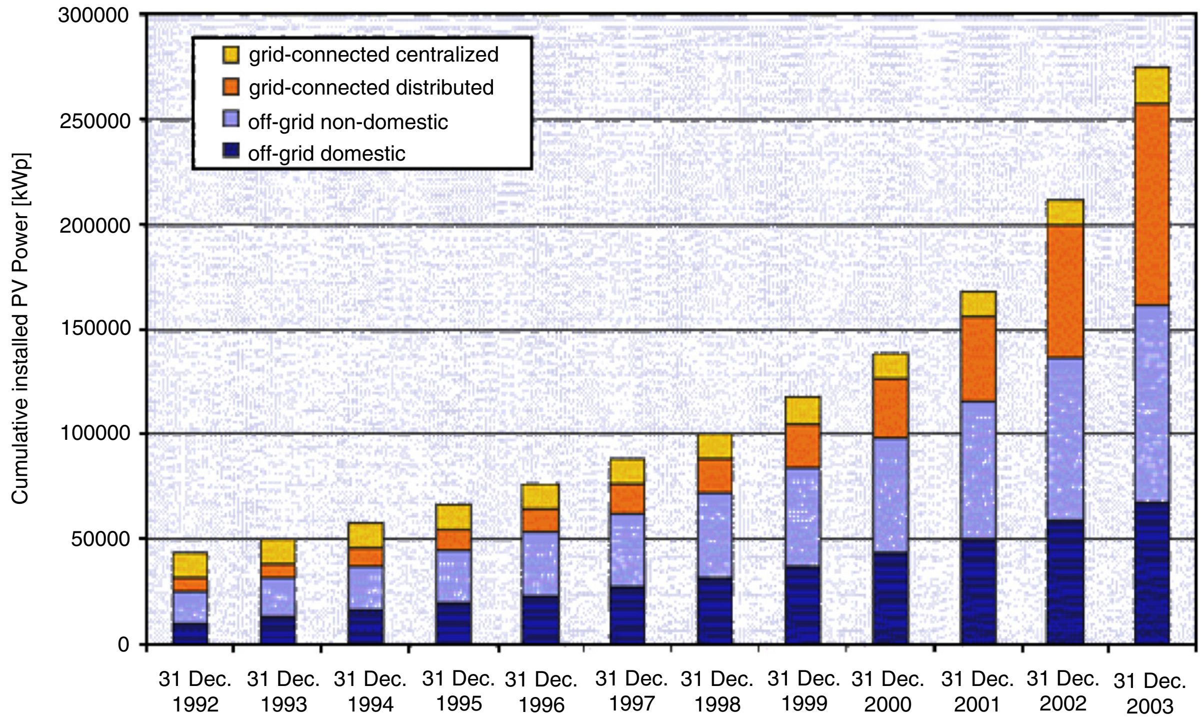

Fig. 2. USA PV historical installation data by category. IEA (2003)—a customization deployment approach.

2.1. *The essence of the two deployment models*

To fix idea, we proposed two different market deployment models based upon the differences between the nature of information technology and manufactured technology (Watanabe et al., 2003) to formalize our inquiry. The *information technology development* model refers to an open model in which diffusion is based upon developing a variety of new application categories for PV leveraging its self-propagation, general-purpose nature driven by customization and user requirements. The *manufactured technology development* model refers to a close model in which a dominant category of PV application is developed revolving around the existing utility grid infrastructure or grid-connected distributed applications. The resultant PV system features are therefore dictated by technology suppliers and the economy of production driven by that of mass production rather than customization or value-based. These two deployment models draw upon the same global cost dynamics of PV cell and other components of PV system but have differing implications on local installation and balance-of-system (BOS) system engineering requirements. The next section reviews the cost structure of a PV system to illustrate the possible effects of deployment on different cost drivers of a PV system.

3. Existing studies on cost dynamics of PV systems

A PV system consists of the PV modules and the so-called BOS as shown in Fig. 3.

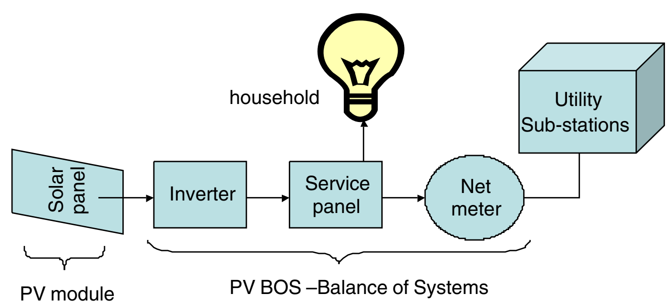

Fig. 3. A simplified PV system schematics.

BOS is an equipment which is needed to integrate the modules into the user's system, and it contains different components for different categories of applications. The cost of BOS and installation and that of the modules are the major cost drivers of a PV system and these two are of the same order of magnitude (Fig. 4). The PV modules remain a significant proportion of system prices (generally about 50–60% for grid-connected systems; IEA, 2003) and, compared to the widely varying non-technical and BOS costs, continue to present a useful 'international' indicator for tracking the changes in PV technology costs over time. However, the learning patterns for these two drivers are quite different.

3.1. *Existing studies on PV modules cost dynamics (in this section, PV means PV cell or module)*

Research and development plus actual experimentation (technological learning) or learning by doing are the

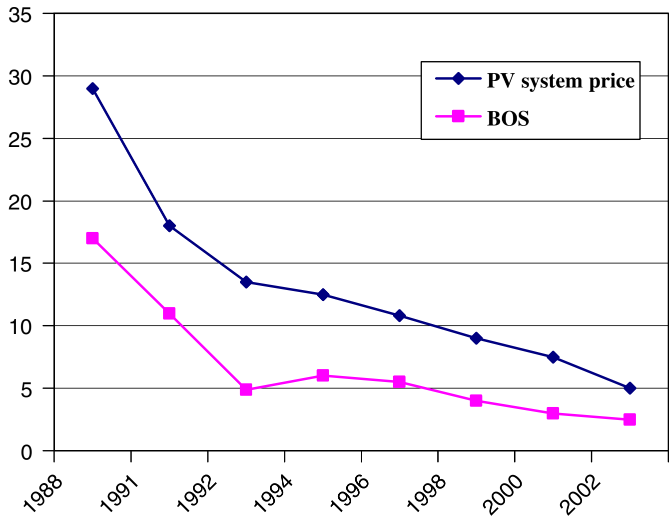

Fig. 4. A typical breakdown of price development of small grid-connected systems (Schaeffer and De Moor, 2004).

essential endogenous (Aghion and Howitt, 1998) mechanisms for reducing uncertainty and improving performance and costs of an infant technology. These two activities cannot be treated separately as sources of technological dynamics. Watanabe (1995a, b) has empirically demonstrated that there is a 36% reduction in PV cost per each doubling of cumulative production. However, when the same PV cost time series data is empirically regressed against the logarithm of cumulative expenditure consisting of R&D expenditure (a proxy for the technology knowledge stock) and production investment (a proxy for accumulated experience), there is a 54% drop in PV costs per doubling of cumulative expenditures. It strongly suggests that the PV cost dynamics is more sensitive to cumulative expenditure than cumulative production. This is due to that cumulative expenditure embodied both the effects of accumulated production experience and technological knowledge. This suggests that cost learning of PV modules is driven by the joint effects of production learning and knowledge stock due to research and development. In fact, their effects on cost of PV modules may be directly modeled by a single learning curve[3] (Grubler, 1997).

However, both production learning and research and development of module technology exhibit international spillovers due to two mechanisms. According to IEA PV working group's system price survey in 2004, very few countries have a balance between local production and capacity installed (six or seven countries can be said to have significant production available for export, eight countries produce between zero and 40% of their local demand). This suggests that PV module production learning will be spillover among countries. In fact, there are now a number of examples of imported modules selling for considerably less than the local production. In addition, most of the module manufacturing is done by internationally operating countries and there is extensive exchange of scientific and technological information on module technology between nations. As a result, cost of PV module can be assumed to be globally the same (Wene, 2000; Schaeffer, 2003; Alsema, 2003).

3.2. Existing studies on cost of BOS

As we have defined above, BOS of a PV system consists of all the systems or engineering components apart from the PV modules or cells. The BOS is a significant part of the cost of an installed PV system, and is responsible for controlling and managing the power output of the PV modules-array. BOS primarily consists of an inverter to transform the direct current (DC) output from the PV array into a form of alternating current (AC) electricity that can be synchronized with and connected to the electric utility grid. Other equipment includes wiring, switches, an electric meter, and circuit breakers and fuses. Some systems are equipped with a charge controller and battery to provide backup power, but due to large expense of batteries, they are currently included in only 1–2% of new installations (Sterzinger and Svrcek, 2005).

The cost learning of BOS has not been studied as widely as the cost learning of PV cells or modules. Noted exceptions are from Schaeffer (2003) and Hegedus and Okubo (2004). For grid-connected residential systems, the BOS experience curve is sustaining a progress ratio of 0.78 during 1992–2000. However, unlike PV module learning which is inherently both R&D driven and production or manufacturing driven, BOS learning has not been attributed to cost reductions of individual hardware components. In fact, most of these hardware components comprised of mass-produced electrical components with mature markets outside the solar industry except for discrete technological innovation due to development of important components such as inverter. Therefore, BOS learning can mostly be attributed to cumulative experience of system designers and installers, attained through greater system integration and a reduction in the number of BOS parts. A significant opportunity for further reducing BOS costs is standardizing BOS to the greatest degree possible or to minimize the on-site customization proportion (Harmon, 2000). This effectively changes customization oriented BOS engineering to a manufactured activity subjected to economies of scale and factory production learning.

One of the key questions in the study of BOS learning is if BOS learning is *local or global* in character? Inverter part

[3] In this vein, more recently, Nagamatsu et al. (2004) have applied the concept of a two-factors learning model to model the joint effects of cumulative production and technology stock on the cost of PV and its effect upon sustaining the dynamics of carrying capacity of PV diffusion trajectory in Japan. The resultant estimated dynamic carrying capacity maintains a nice margin encapsulating the actual cumulative PV trajectory. This empirically established that PV module cost dynamics is driven by R&D and deployment.

is partially an international market as several manufacturers deliver inverters to several countries. On the other hand, there are substantial different national standards for dealing with islanding and connectors. There are also differences in building norms and practices and policy. This results in non-ideal and less than perfect system engineering knowledge spill-over effects between countries or even applications categories (Schaeffer, 2003). As a result, cost learning of BOS hinges upon *local standardization* impacting system design, planning and interfacing to the grid and economies of integration of components within the solution architecture.

3.3. Comparing system costs in Japan and the USA

To provide some empirical evidences for our hypothesis that BOS learning is local driven, we draw upon the international statistics from the respective country reports from IEA (2003). This tracks the system price for small-scale grid connected residential systems in our study period and is shown in Fig. 5.

System price is defined as the per wattage price of the system net of that of module and the unit is in 2006 US$. We assume system price is a proxy of BOS and construction cost controlled for market effects. The depicted trends seem to confirm that Japan sustains a lower system price than that of the USA during the studied period when Japan is theorized to deploy PV using a closed manufacturing model with a deployment focus vs. the States' using an open and diversity or information technology approach.

More detailed analysis can derive the learning rates of the respective system cost curves with respect to cumulative installation in the grid-connected residential category. We utilized the following cost dynamics formulation for our analysis:

$$c_{t+1} = c_0\,[v_{\text{cuml},t+1}]^b,$$
$$c_{t+1} = \text{instantaneous system cost},$$
$$v_{\text{cuml},t+1} = \text{cumulative installation up to time } t+1,$$
$$b = \text{learning rate},$$
$$c_0 = \text{constant}.$$

Our findings (more advanced analysis are available from authors upon request) are such that Japan sustains a learning rate, b, of 33.7% (adj. $R^2 = 0.85$) over the period 1993–2003 while that of the USA sustains a learning rate of 27.6% (adj. $R^2 = 0.935$) from 1994 to 2003. It must be noted that learning rate may depend upon a whole host of factors such as process and product innovations, product redesign and standardization. Our hypothesis in this paper is that this may be dependent upon the particular local model of PV deployment. This particular set of data seems to support that a closed manufacturing model of deployment sustains both a lower level of system [BOS] cost and a higher learning rate.

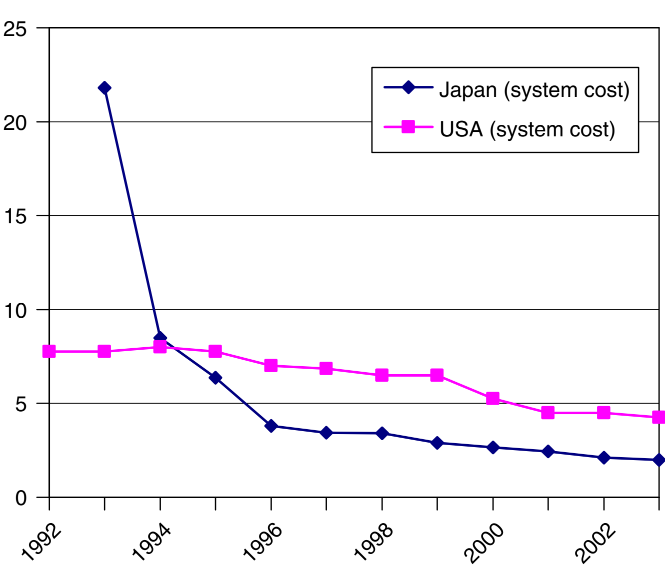

Fig. 5. Historical trend of PV system cost [price] in Japan and the USA.

4. The two PV development models—from an institutional standpoint

It is the contention in this review that different models of deployment as elucidated in Section 2 would have most effects upon the PV BOS learning. A deployment strategy that focuses upon building installation base in a specific application category will expedite this local learning process of BOS and system engineering of this application, assuming a global cost learning dynamics for PV cell. This confers local (national) advantages and creates a virtuous cycle for the subsequent further development of the niche market. On the other hand, a strategy which deploys among several applications categories will sustain several BOS trajectories. This will spilt the learning investment among different categories and dramatically slows down the BOS learning process.

The differences of these models can also be studied from a formal institutional perspective in the context of strategic niche management (SNM) approach for technical change. Since the manufacturing technology model focuses upon mass deployment of a niche, the choice of this initial niche, as we have elaborated in Section 2, is especially critical. What is a right niche? The next section proposes that the choice should take into account the degree of *niche compatibility* with the dimensions of incumbent regime. This compatibility can be measured in terms of magnitude of PV BOS cost.

4.1. Niche compatibility in terms of magnitude of BOS cost

The initial system engineering efforts for different niches or applications are different and can be measured in terms of the magnitude of respective BOS cost. For two different applications or niches, the higher the BOS cost, the more the customization is necessary and this may be due to the application's incompatibility with the existing electricity infrastructure. As Hegedus and Okubo (2004) have empirically demonstrated, BOS cost for off the grid system is much higher than that of on-grid since grid-tied systems do not need batteries or charge controller. In a grid-connected PV system, the grid acts like a battery with an unlimited storage capacity. Therefore, the total efficiency of a grid-connected PV system will be better than the efficiency of an off-grid system. There is virtually no limit to storage capacity whereas in off grid application, the batteries of the PV system will be sometimes fully loaded and excessive generated electricity cannot be utilized.

Since Japan is almost entirely covered by the electric utilities, it was quite natural course to focus upon grid tied standardized residential system if large deployment of PV is the objective. In fact, the project—"utility-connected, residential applications mounted on roofs" has been chosen as Japan's major target from an early stage of PV research and development (Kurokawa, 1994). Grid-connected residential PV system has a lower BOS cost and higher total efficiency *to start with* than other PV application categories and is the *most compatible to the existing electricity infrastructure or the built environment.* This therefore justifies that Japan's choice of this category for mass deployment, at least from a myopic point of view.

However, the system-oriented BOS is also partially driven by the institutional environment rather than mere technical considerations. Institutions are the rules of the game in a society or, more formally, are the humanly devised constraints that shape human interaction. In consequence, they structure incentives in human exchange. General as this definition from North (1990) may be, he continues to propose that transaction costs are the most *observable* dimension of the institutional framework that underlines constraints in exchange. Transaction costs consist of those measurable costs that go through the market and those hard-to measure costs that include time acquiring information, queuing, bribery and so forth as well as the losses due to imperfect monitoring and enforcement. These hard-to-measure costs make it difficult to assess precisely the real transaction costs of conducting exchange from a particular institution. Nevertheless, to the degree we are able to measure, we progress in measuring and performing *comparative analysis* of the effectiveness of institutions.

Connecting small scale PV system to the grid is subjected to safety [islanding], legal and other institutional requirements and this will have an impact upon the BOS cost or component counts. Different countries, through new legislative packages, facilitate deployment of grid-tied PV systems by standardizing interconnection protocols, net metering, no-hassle power purchase contracts from PV system owners. These actions strive to minimize the institutional impact upon BOS cost. It goes without saying that policies of some countries may be more "institutions friendly" than others to the grid tied small system category of application. This highlights that niche compatibility, in terms of BOS cost magnitude, is co-determined by inherent technical factors related to the built environment and actions in the institutional environment.

4.2. Niche sustainability in terms of learning potential

Having established the niche compatibility in terms of the BOS cost implications of different initial niches, it is further postulated here that the continual development of the initial niche depends upon BOS cost learning dynamics and is subjected to whether the chosen deployment model matches the institutional structure of production of each country. The learning drivers for PV BOS correspond to the specific barriers, related to system engineering, to widespread use of PV. These include (Ginn et al., 2003):

- specific technical problems related to balance-of-systems BOS components (such as inverters) and systems engineering,
- lack of standard approaches to interconnection to the utility grid,
- lack of awareness and experience with the technology by potential users,
- lack of sound data regarding field performance and true life-cycle costs,
- *lack of certification* (italics added) and unmet need for *system* quality assurance in installation and system management.

In the Japanese deployment model of focusing upon the grid-tied PV residential application, since the application is homogenous, a standard approach to interconnection to the grid and a dominant design can be set up which avoids the highly customized engineering aspect associated with a lot of the off-grid applications due to unique on-site conditions. Deploying PV in the relatively standardized small grid-tied residential setting reduces it into a PV *appliance* subjected to mass production learning.

A special feature of the institutional structure of production of the Japanese PV industry is that a few large and integrated companies bundle the whole or at least large portions of the PV value chain inside their own company. These may include solar cell, module (many solar cells combined together), BOS components such as inverters, power electronics and sometimes even the installation and maintenance of the PV systems are offered from the same company. Since the average life-time of a residential home is 25–35 years and corresponds well with that of solar modules, a lot of houses are prefabricated using standardized building components highly favorable for the integration of solar modules at the time of pre-fabrication. This advantage was immediately recognized by the solar cell manufacturers and the latter have either bought housing or construction companies or forged strategic alliances with such companies (Jager-Waldau, 2004). There are several economic advantages to this development:

(a) the locus of learning is within a company and can be internalized rather than involving many different independent players in the markets;
(b) the pre-installation and mass fabrication of the unit home enable the manufacturer to limit actual installation work of the PV system on the building site to fine tuning or optimizing of system performance and lead to considerable savings for the installation aspect;
(c) with respect to the BOS learning barriers mentioned, a large potential volume will sustain innovation efforts on continual improvement of components and system engineering. These innovation efforts will in turn be applied to future installation. This strong multiplier or rate (Arrow, 1999) effect is the basis of increasing return. Niche sustainability may ultimately depend upon this virtuous cycle of large volume drives innovation in BOS and innovation in BOS will drive ever larger potential volume.

On the other hand, the current institutional structure of production in the USA PV industry consists mostly of small intermediary systems integrators and a very fragmented PV value chain. USA has consistently pursued a PV deployment policy of explorations of the high-value diverse markets (Serchuk and Singh, 1998). This alternative approach is contingent upon the advantage of characteristics of PV such as reliability and customizability. While allowing the self-propagation or information technology like characteristics of PV to play out, it requires the *emergence of a new knowledge infrastructure* to enhance *cross-learning* (Shum, 2003; Nagamatsu et al., 2004) or *knowledge spillover* among diverse PV customization applications. This cross learning will need to take place among systems integrators in critical areas such as systems engineering, maintenance, capitol formation or management. Cross learning leads to a dynamic economy of scope (Shum and Watanabe, 2004) to compensate for the foregone mass production economy of focusing upon a standard category of application.

Due to the fragmented nature of the PV value chain, inter-projects learning among different market players will be more challenging than mass production learning within a vertical integrated structure. Even though training and certification of the system integrators or installers community in the USA is emerging (IEA PV status report, 2003) and will somewhat accelerate standardization of professional practices and learning, this will not happen immediately and the new institutional structure of production mediated by professional system integration or engineering practice will need time to co-evolve.

From a niche sustainability point of view, one of a kind system may not have the volume to sustain disciplined learning and innovation among different market players. Instead of a volume driven virtuous cycle we have seen for a mass deployment strategy, a viscous cycle may emerge.

4.3. Implications to learning investment in the experience curve framework

These two separate institutional appraisals of the strategic niche management aspect can also be understood

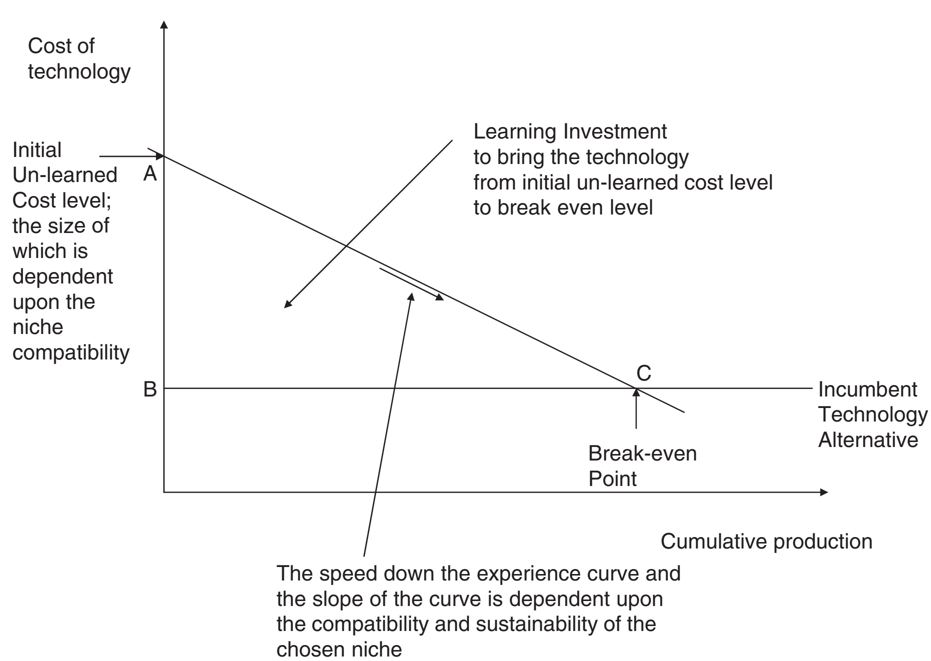

Fig. 6. An experience curve for the PV BOS cost for the grid tied small-scale residential PV system and conceptual illustration of effects of niche compatibility and sustainability.

from the unified framework of experience curve for new technologies (Wene, 2000). Many such new technologies such as renewable are too expensive, at the outset, for commercial deployment. While publicly supported research and development are important, policy focus is also addressing measures to bring such technologies to the market. Experience curves suggest that to drive down cost for new technologies, financial investment is necessary. Learning investments are financial investments needed to "buy the volume" necessary for the ride down the experience curve in order to make the new technology cost competitive to the incumbent. Learning investments are primarily provided through market mechanism and they always involve different actors in the market and the socio-economic system at-large and are therefore subjected to institutional factors. Fig. 6 illustrates the concept of learning investment, in the context of experience curve (IEA, 2003). Two quantities characterize the learning curve, the initial unlearned cost level[4] and the slope of the experience curve related to the progress ratio. Learning investment is graphically shown as the triangle area (ABC) which will bring an emerging technology to the breakeven level.

In the context of our discussion of the niche compatibility and sustainability in PV deployment in Japan and the USA, niche compatibility can be understood in terms of the *level* of the initial un-learned BOS cost to start with associated with the niche or application. As we have explained, this level is both contingent upon the application itself and the institutional actions or policies.

On the other hand, the *slope* of the learning curve is dependent upon many factors including research and development, system innovation and design, etc. The niche sustainability, based upon a volume potential and match of learning requirements to existing institutional structure of production, will influence the slope of learning. The joint effects and synergy of having a lower level of cost to start with and a steep learning curve are decisive in terms of reducing the learning investment necessary (a smaller triangle in Fig. 5) and achieving the break-even cost level faster. Our empirical results in Section 3.3 seem to verify that a manufactured technology deployment model focusing upon a niche with large potential volume using a vertical integrated structure may show better BOS cost learning performance in the small grid tied system category compared to the information technology approach.

5. Conclusion

The incorporation of clean and benign renewable energy into our existing energy system will help to address both environmental and energy security concerns and is therefore the focus on policy making in these respective areas. Yet, despite the potential of renewable energy, it faces many technical, market and non-technical barriers. No single effort will dominate in the introduction of renewable into the mainstream. But there is certainly a place government may play in facilitating research development, demonstration and deployment (PCAST, 1999) of renewable. Research development and demonstration are relatively upstream efforts to address the scientific and technical aspects of renewable while deployment activities need to address downstream market, social and institutional aspects of the technology.

This paper focused on the deployment aspect of introduction of PV. We have adopted a manufactured technology vs. information technology framework to aid our research. Our finding is that PV as a renewable energy technology is in essence a general-purpose energy technology that has potential applications in many areas and contexts. In this sense, PV is similar to a general-purpose *information technology* with numerous applications supporting different business models. However, deploying PV along many applications at the outset will hinder downstream and local oriented BOS learning especially when a learning infrastructure facilitating cross-learning among these applications (Shum, 2003) is not in place. In fact, due to the one off nature of many PV projects contingent upon unique site conditions, a lot of project specific system level knowledge is not easily transferable. In addition, different applications do not necessarily have a large volume of deployment to sustain a mass production type of efficiency thus rendering cost learning slower.

A more prudent approach to deploy PV is therefore to leverage its characteristic as a *manufactured technology* which is less dependent on on-site customization engineering and which can be subjected to factory mass production learning economy. This depends upon focusing on a right niche that has massive potential volume to sustain learning and most compatible to the learning characteristic of existing institutional structure of production. The Japanese focus on grid-connected distributed small-wattage (3–5 KW) residential application in newly fabricated houses meets several criteria of niche compatibility and sustainability. In addition, the Japanese PV industry features PV companies that are highly vertically integrated which can facilitate learning in manufactured products in the areas of quality and durability. In a nutshell, the institutional characteristics in the Japanese PV industries match the production learning requirements for a manufactured model of deployment.

An important topic that needs to be addressed is as more and more applications for PV are envisioned, how will the manufacturing model of PV deployment need to be adapted? There is a fundamental contradiction as less standardized applications are increasingly difficult to be addressed by a mass production logic or institution since they involve extensive on-site customization system engineering efforts. On the other hand, for an information

[4] In the management or strategy literature, this initial level of unlearned cost in the experience curve can be reduced by so-called learning before doing, to contrast from the learning achieved during production, or learning by doing.

technology model of deployment, the problem is how to standardize as much as possible and builds up volume for system engineering learning given the constraints of customization. Ongoing PV *system engineering technology* research to develop a general PV technology platform customizable to various applications, in additional to R&D at the individual component level, may hold the key to address these dilemmas.

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